ADDIS ABABA UNIVERSITY SCHOOL OF GRADUATE STUDIES

DEPARTEMENT OF EARTH SCIENCES

GROUNDWATER RESOURCE EVALUATION AND SUSTAINABLE MANAGEMENT IN ADELLE AND HAROMAYA DRY LAKE CATCHMENT, EASTERN 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

Seid Adem

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Disclaimer

This document describes work undertaken as part of hydrogeology master degree program at the Addis Ababa University, Department of Earth Sciences. All views and opinions expressed therein remain the sole responsibility of the author, and don not necessarily represent those of the institute.

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Acronyms

ABH: Adelle Borehole

AET: Actual Evapotranspiration

CSA: Central Statistical Agency

CWR: Crop Water Requirement

dec: Deca

DRo: Direct surface runoff

Ec: Electrical conductivity

FAO: Food and Agricultural Organization

FBH: Finkile Borehole

GWRR: Renewable Groundwater Resource

ha: Hectare

HHDW: Haromya Hand dug well

IWR: Irrigation Water Requirement

m: Meter

MAFF: ministry of agricultural food and fisheries

MCM: Million m^3

mg: Mili gram

mm: Mili meter

NE: North East

PET: Potential Evapotranspiration

RF: Rain Fall

SAR: Sodium Adsorption Ratio

SW: South West

SWL: Static Water Level

TDS: Total Dissolved Solids

UNICEF: United Nation Children's Fund

WHO: World Health Organization

WTRBLN: Water Balance Model

Abstract

The Adelle – Haromaya dry lake catchment is characterized by intensive groundwater abstraction since the demise of Lake Haromaya. Despite the small catchment size, the study area has different rock types ranging in age from Precambrian to recent unconsolidated deposits. The unconsolidated formations host the main aquifer system of the area. Groundwater is the only major source for both domestic and irrigation supplies in the area. A total water volume of 10.06 MCM per year is estimated to recharge the aquifer system. The present annual groundwater abstraction is 13.78 MCM. The estimated exploitable groundwater reserve and safe yield of the catchment are 6.73 MCM/year and 8.29MCM/year. The total groundwater abstraction is greater than the recharge and the safe yield of the aquifer. Groundwater balance in the Adelle – Haromaya dry lake catchment is in disequilibrium condition. The estimated water balance shows that the total groundwater abstraction from the catchment exceeds the annual recharge. It is obvious that the aquifer system of the catchment is overexploited. Groundwater overexploitation being practiced by abstraction from the existing wells and boreholes had resulted in significant head decline that had reached 4 meter during the year 2006. The integrated water resources management, securing water in the future should include measures that augment groundwater budget in the study area.

Keywords: Groundwater recharge; Groundwater balance; Safe yield; Adelle-Haromaya dry lake catchment.

CHAPTER I: INTRODUTION

1.1 Background

Groundwater offers a major life support to humankind in terms of meeting the domestic, irrigation and industrial demands. It accounts the largest available source of fresh water where the distribution is uneven throughout the earth. Groundwater occurs in a wide range of rock types and usually requires little or no treatment (Thangarajan, 2007); On account of this, it is often considered as the cheapest and simplest water supply option.

Groundwater plays a crucial role in Ethiopia in providing drinking water, increasing food and agricultural production, and facilitating industrial developments. It is the most preferred source of water in all climatic zones for its convenient availability, drought dependability, excellent quality and low cost of development. The rural areas which account more than 85% of the country's population are encountered with shortage of potable water supply which can be solved by proper groundwater utilization (Tamiru Alemayehu, 2006). This shortage of potable water supply in the rural parts of the country can be addressed via the following three steps. The first step is identifying the main aquifers located in different geological environment and climatic conditions. Second through proper development and utilization, this requires understanding of the exploitable groundwater resource and abstraction of groundwater to meet the domestic, irrigation and industrial demands. The third step is through promoting proper groundwater management activities depending on its availability and demand.

In most cases irrigation relies on surface water. However, the erratic variability in rain fall distribution and the scarcity of perennial streams in the country have augmented the dependability of the groundwater for irrigation. The rapid expansion of agricultural sector and the rising population growth heavily demanded groundwater. Consequently, many boreholes are drilled, and groundwater have been developed and exploited. This inevitably may lead to an excessive extraction and depletion of groundwater resource. Hence, it is crucial to regulate and maintain the groundwater reserve in the state of dynamic equilibrium over a period of time without disturbing the natural condition of the ecosystem.

1.2 General groundwater management issues

Groundwater management can be defined in brief as the planned and coordinated management of groundwater basin with a goal of long-term sustainability of the resource. The management of a groundwater basin implies a program of development and utilization of subsurface water for some stated purpose, usually of a social or economic nature. In general, the desired goal is to obtain the maximum quantity of water to meet predetermined quality requirements with the least cost. Groundwater can be regarded as a renewable natural resource, if there exists to a balance between the recharge and abstraction from the basin. If pumping exceeds the total amount of recharge, groundwater depletion may occur and the aquifers are no longer sustainable. Generally, groundwater is a flow resource, a scarce one and also prone to negative externalities (over pumping and pollution). Hence, proper groundwater management is vital for the implementation of sustainable water resource development and conservation.

Understanding the quantity and quality of groundwater resources along with identifying the existing groundwater constraints are the fundamental issues for proper groundwater management over a given basin. Without considering such concerns, the effects of past development and prediction of the influences of future development can’t be adequately determined. Identification of major constraints related to groundwater resource is the main driving force for the commencement of groundwater management actions. It is highly important in designing and implementing appropriate future management tools and strategies. Degradation both in quantity and quality of groundwater are the main constraints that can be distinguished by the lowering of groundwater levels, subsidence, seawater intrusion and water quality degradation.

Hescock (2006) as cited in Tizro et al. (2007) has explained that the assessment and development of groundwater resource can be conceived by the application of water balance method that equates demand for water against abstraction requirement needs. A water balance represents the total amount of surface and groundwater entering and leaving a given basin over a specific period of time. It is used to evaluate whether the quantity of groundwater is abstracted at safe condition or not. The estimation of groundwater balance is essential in order to assess the safe yield of the aquifer systems and therefore to establish their rational exploitation and sustainable management (Voudouris, 2006).

In groundwater management the concept of safe yield has been used to indicate the limits of pumpage from an aquifer. Safe yield is the rate at which groundwater can be withdrawn from an aquifer without producing an undesirable adverse effect (Dottridge and Jaber, 1999). The rate depends on the hydraulic parameters of the aquifer and the location of boreholes. Safe yield should be less than the average annual recharge in order to compensate for minor groundwater losses. Any withdrawal in excess of safe yield is an overdraft (Freeze and Cherry, 1979). The traditional definition of the safe yield assumes the pumpage rate is equal to the total recharge, but Feng-Xiang (2001) as cited in Voudouris (2006) assumed that the safe yield is 50% of the total natural recharge of groundwater.

The quality of groundwater had been given little attention in groundwater management issues in the past. However, it is now recognized just as important as its quantity. The quality of water is used to determine whether the water is satisfactory for the proposed use or not. Once groundwater has become polluted, it usually requires a very long, complex, and expensive task to restore the water quality in to its original condition. For these reasons, identification and assessment of threats to groundwater quality, and monitoring and prevention of groundwater pollution are considered as one component of groundwater management issue. Groundwater quality management can be implemented to avoid groundwater pollution through assessing pollution hazards and risks, delineating groundwater vulnerability zones, controlling effluent discharges and constructing contaminant structures. Complete groundwater management describes the above mentioned groundwater management theories which will be addressed in this paper work.

1.3 Statement of the problem

The Highland of Eastern Hararghe comprises Haromaya, Adelle and Tinikie lakes which had historically served for the surrounding areas as a domestic and irrigation water supply and fishery tanks as well. Lake Haromaya was the most important source of domestic water supply for Harar, Haromaya and Awaday towns. After serving for thirty years, the lake had deteriorated both in quality and quantity which finally got dried up in 2005 (Wakgari Furi, 2005). Intensive abstraction for domestic and irrigation purposes, water losses through natural process (open water evaporation) and siltation are believed to be the main reasons for the reduction and disappearance of Adelle and Haromaya lakes respectively. The three major towns (Harar, Awaday and Haromaya) and the rural communities become entirely dependent on the groundwater resource of the Adelle – Haromaya lake catchment since the demise of Lake Haromaya. Following the dry up of Lake Haromaya, many shallow wells have been drilled and developed in localized area particularly in the near Haromaya dry lake well field for domestic supplies of the stated towns. In addition, the Haromaya University and the rural farmers have developing their own wells for their daily consumption and irrigation requirements respectively.

In general, the people have been exploiting groundwater from these wells without understanding the groundwater potential and the consequence of over pumping. In the area, there is no any regulation for the abstraction of water from these wells, and also there is no any predetermined prioritisation between different water uses and water users (Abdulaziz Mohamed, 2006). Well interferences among hand dug wells and hand dug wells with shallow boreholes are also the common problems of the area. Likewise, the current ground water resource management practice is poor. The combined effects of the above mentioned practices have brought about unnecessary threats of declining groundwater levels and depletion of shallow aquifer which resulted in dried up of wells near the Haromaya dry lake well field. Moreover, it was reported that water demand conflicts have occurred among different groundwater users since the past five years which resulted in loss of human lives in the rural villages of the catchment.

Generally, the current groundwater management practices in the aforementioned area are poor. Despite the existence of evident challenges which are pervasive and devastating in nature, immediate and proper responses have not yet been given to the problem. Thus, such frustrating threats and challenges have initiated the researcher to work in the project area.

1.4 Objective

This study has the general objective of quantifying the groundwater resource potential and assessing the sustainability of groundwater reserve with respect to appropriate groundwater sustainability indicators.

Specifically this research aims at achieving the following objectives:

- Evaluate annual recharge, total abstraction, exploitable groundwater resource and safe yield of the catchment.

- Estimate the current, future domestic water demand and irrigation water requirements.
- Provide general overview of the water quality for irrigation and drinking based on limited physico-chemical tests.
- Asses the current groundwater development stage, groundwater use condition and management practices of the area.
- Identify the major groundwater management constraints of the area for implementation future groundwater management practices.
- On the basis of the outcome of the research suggest proper strategies that foster sustainable groundwater resource management in the area.

1.5 Research questions

I. How much the total groundwater potential reserve in the catchment?

II. What is the current domestic water demand and irrigation water requirement of crops?

III. Is the agricultural practice based on the appropriate irrigation requirement of crops?

IV. Is the total ground water potential reserve sustainable at the current condition? If not, what appropriate measures should be taken to attain the sustainability of groundwater in the area?

V. What is the stage of groundwater development of the area?

VI. How can local communities participate in regulating groundwater and in implementing groundwater management practices?

VII. What are the major groundwater management constraints and prospects in the study area?

1.6 Significance of the study

The research is important in the sense that it provides the true nature of groundwater management practices in the Adelle - Haromaya dry lake catchment, and the major challenges that the groundwater resource potential faces leading to social conflict in the short run and over exploitation and depletion of the main aquifer in the long run.

Despite the existence of numerous hydrogeological studies in the country, practical study on the Adelle – Haromaya dry lake catchment in relation to estimating the total groundwater resource, the sustainability of groundwater reserve and the major challenges of groundwater management however is scanty, and this research intends to fill in these gaps.

Moreover, the outcome of the research may also shed lights on effective groundwater regulating mechanisms and management practices which will be implemented by the communities. It also gives an important in puts to administrative managers, and decision and policy makers.

1.7 Methodology

To achieve the objectives of the project, various methodologies and approaches have been used. The study was commenced through defining the boundary of the project area, review of previous works and collection of valuable secondary data. Land sat ETM obtained in ftp://ftp.glcf.umd.edu/glcf/Landsat/WRS2/ server having a resolution of 15 meter were used to prepare the primary input thematic maps like soil, and land use and land cover. All the input data sets were georeferenced in to Adindan UTM zone 37N co-ordinate system. Detailed Interpretation of Satellite imageries which embrace delineating major regional lineaments, and understanding the geomorphologic and drainage pattern of the area have also been carried out during desk study phase.

Primary data have been collected systematically during field work observations along the targeted villages of the area. The field work was also supported by oral interview of the local inhabitants for gathering and generating essential information. The acquired primary data includes information on the nature of current water use condition, major constraints of groundwater management practices, static and dynamic water levels of the existing wells and boreholes, the actual discharge of springs and wells, and the nature of the irrigable land and types of crops cultivated in the area. Moreover, water samples from different sources (boreholes, dug wells, springs and lakes) have been collected for laboratory analysis. In-situ measurements such as electrical conductivity (EC), temperature, pH, and total dissolved solids (TDS) were carried out at the site as well.

Data compilation, processing, analysis and interpretation have been conducted in the post fieldwork phase. A total of fifty four years meteorological data combined with the different necessary primary and secondary data have been considered for analysis and interpretation. Estimation of areal depth precipitation, potential evapotranspiration and actual evapotranspiration were carried out through the use of isohytal, penman and water balance model methods respectively. Hence, groundwater recharge and water balance of the catchment have been carefully evaluated. The current and projected domestic water demand and irrigation water requirement have been also estimated for understanding the current and future groundwater condition of the area. The analysis and interpretations were supported by the application of different software like Arc GIS 10, ERDAS IMAGINE 9.2, Global Mapper 10, SURFER 12, WTRBLN model, CROPWAT 8.0, Aquchem 4.0 and Aqui test 3.5.

1.8 Previous works

Several researchers have worked in the study area both at regional and local levels in the past. Most of previous works focused on the hydrogeology, lake level and land use changes. The most important works in relation to groundwater system analysis were done by Wakgari Furi (2005), Geletu Belay (2006) and Abdulaziz Mohammed (2006). These studies demonstrated the groundwater flow system and model based groundwater flow system analysis which is believed to be important for the groundwater management. Abdulaziz Mohamed (2006) tried to estimate the groundwater recharge based on conventional water balance approach. Characterization of aquifers based on the various hydraulic parameters and the suitability of groundwater both in quality and productivity have been described by Nata et al. (2010).

Meklit Tariku (2003) studied the temporal changes of the Haromaya lake level. This study demonstrated that the change in lake level is attributed to both land use changes and pumping of water for irrigation. The study of land degradation and soil loss and consequent siltation of the lake played a role in the drying up of the lake (Muleta et al. 2006).

The previous works have their own limitations and don't provide any comprehensible ideas with respect to the current major groundwater management constraints and future groundwater management prospects, estimation of the current and projected domestic water demand and irrigation water requirements, and the sustainability of groundwater reserve of the catchment. Most of the previous studies are not detail and do not focus on groundwater use for irrigation. Therefore, this study is proposed to address some clear ideas in these and other related aspects regarding the groundwater resource evaluation and sustainable management in Adelle - Haromaya dry lake catchment.

CHAPTER II: OVERVIEW OF THE STUDY AREA

2.1 Location

The study area is located in the East Harargehe Zone of Oromia Regional State, Eastern Ethiopia. It is found 515 km south east of Addis Ababa bounded between $41^{o}\,54^{'}$ E to $42^{o}\,06^{'}$ E longitude and $9^{o}\,21^{'}$ N to $9^{o}\,30^{'}$ N latitude covering a total area of 250 km^2 (Figure 2.1). It can be accessed through all-weather asphalt road which runs from Addis Ababa to Haromaya town, and the rest part of it is accessible by seasonal gravel roads and trails. The study area encompasses Adelle and Haromaya sub catchments which contain two seasonal lakes (Adelle and Haromaya) and one perennial lake (Tinikie).

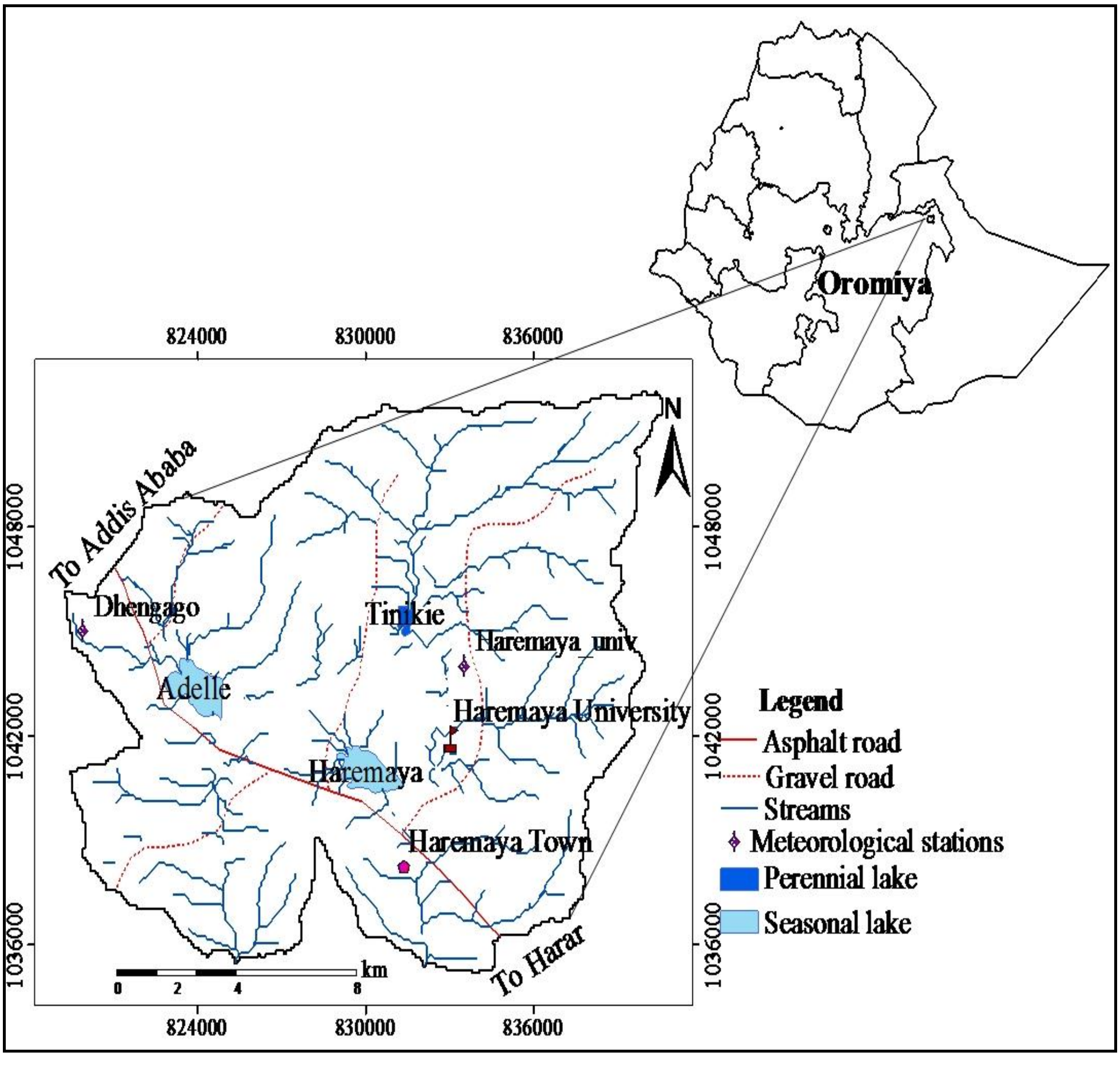

Figure 2.1. Location map of the study area.

2.2 Climate

The climatic condition of the study area is the result of the Inter Tropical Convergence Zone (ITCZ) which represents a low pressure area of convergence between tropical easterlies and equatorial westerlies. These pressure systems and air circulation have strongly controlled the rainfall distribution of the area. The climate of the area is sub humid with relatively high rain fall. According to the Ethiopian traditional way of climate zoning, it can be grouped as Weina Dega (Subtropical) with an altitude ranging from 1967m to 2429m above sea level, and monthly mean temperature is between 14.47 °C and 19.13°C.

2.3 Topography and drainage

The major land form of the area is composed of local ridges, hills and relatively flat topography. The flat topography of the area is mainly localized to the Haromaya and Adelle seasonal lakes with an altitude ranging from 2010m to 2024m while the hilly landscape bounded the study area in the NW and NE part close to Damota village with an altitude ranging from 2270m to 2400m above mean sea level (Figure 2.2).

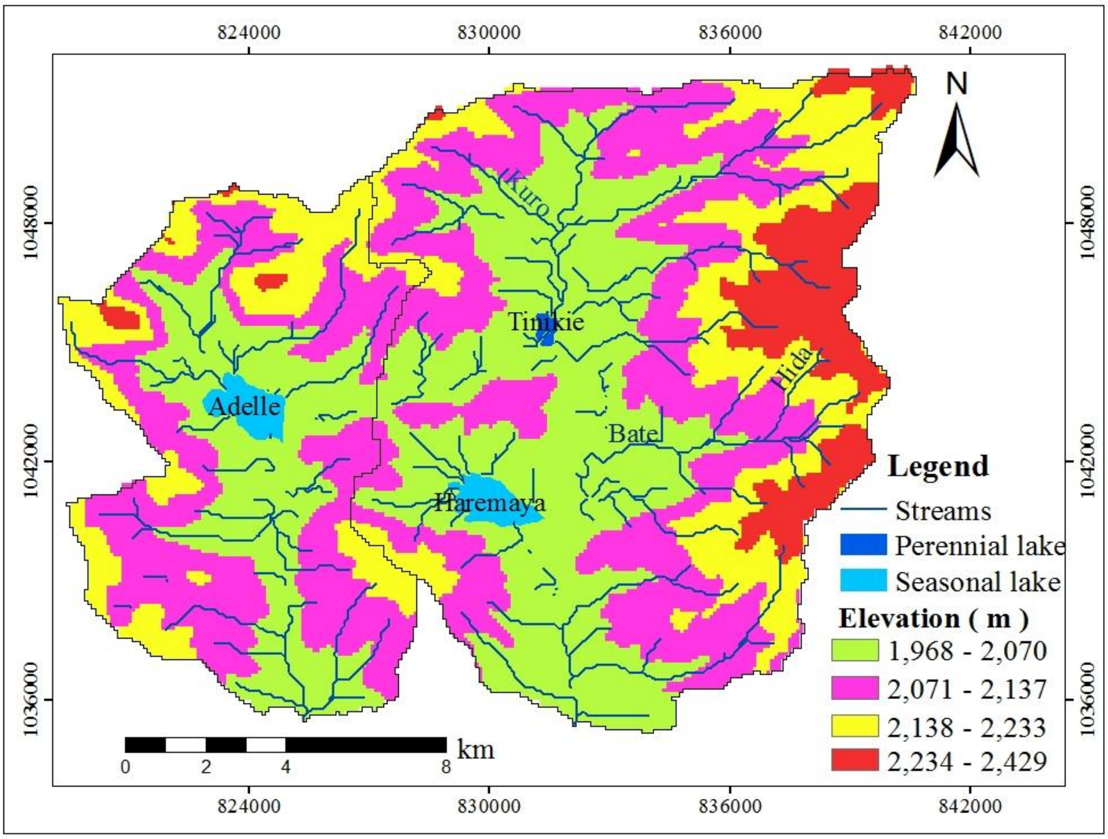

Figure 2.2. Topography and drainage map.

The Adelle – Haromaya dry lake catchment is part of Wabishebel drainage basin and located at the upper stream part of the basin. It consists of two sub catchments, the Adelle and Haromaya lake sub catchments covering 34% and 66% of the study area respectively. The slope, landform and the configuration of the hills and peaks surrounding the study area have created a drainage network, which takes the surface flow and overland flow from the surrounding ridges and hills to towards the flat depressed topography of the two lake areas independently.

The major seasonal streams in the catchment area are Lega Ambo, Lega Bati, Lega Hida and Lega Kuro. These streams are supplied by gullies, ephemeral streams, road channels, and sometimes directly from overland flows of adjacent farmlands (Abdulaziz Mohamed, 2006). The dominant drainage pattern of the catchment is dendritic pattern. The competences of the streams are limited to a maximum of third – order hydrographic networks. The natures of drainage pattern and stream orders of the catchment indicate that the local ridges and hilly landscapes have the same resistance to erosion, and the top weathered rocks of the area are moderately permeable.

2.4 Soil distribution

The major portions of the agricultural soils in the catchment are shallow in depth. Most of the steeper slope soils of the catchment are unproductive and exposed on the surface through erosion and weathering processes. The five major soil types in the catchment are lithosols, regosols, cambisols, fluvisols and vertisols (Tamirie, 1981 cited in Shimelis et al., 2011). Classification was made based on organic content, texture and other physical properties of the soils (Table 2.1). The majority of the soils are cambisols and regosols which comprise 50.7% and 28.6 % of the study area (Figure 2.3). The rest soils types (lithosols, fluvisols and vertisols) cover 13.7 % of the study area.

Table 2. 1 Physical characteristics of soil of the area.

Vegetation	Rooting depth (m)	Soil type	% of area coverage	Soil texture	Average available water capacity of the root zone (mm)
Shallow rooted vegetables (onion, cabbage, potato, etc.), and grasses	0.6	Fluvisols	3.4	Silt loam, loam	120
		Cambisols	50.7	Clay loam	150
		Vertisols	10	Silt loam	120
Moderately deep rooted chat , crops (sorghum, maize) and shrubs	1.2	Regosols	28.6	Clay loam	300
		Lithosols	7.3	Clay	360

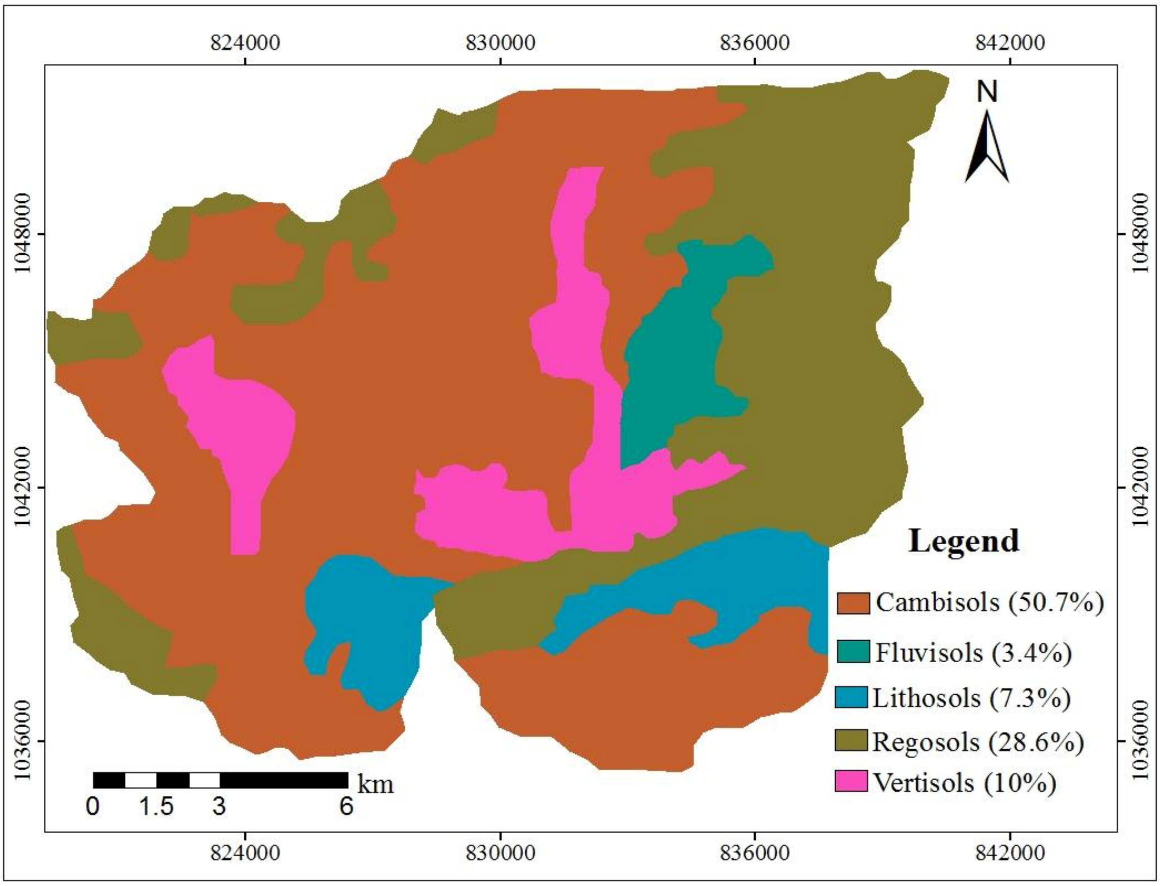

Figure 2.3. Soil distribution map.

2.5 Land use and land cover

The principal land use within the study area is agricultural activities, where crops and vegetables such as sorghum, maize, chat, etc, are cultivated. Almost all vegetables are generally cultivated in the low land topography of the study area while chat (*Catha Edulis*), sorghum and maize are highly cultivated in the hilly landscapes. Most marginal and grazing lands brought under cultivation.

The study area constitutes five land cover classes namely agriculture, vegetation (grassland, shrubs and forests), settlements, water bodies and bare land (Figure 2.4). Vegetation may increase water loss by evaporation or they may facilitate to recharge by reducing run off, and intercepting water and infiltrating its droplets slowly to the ground surface.

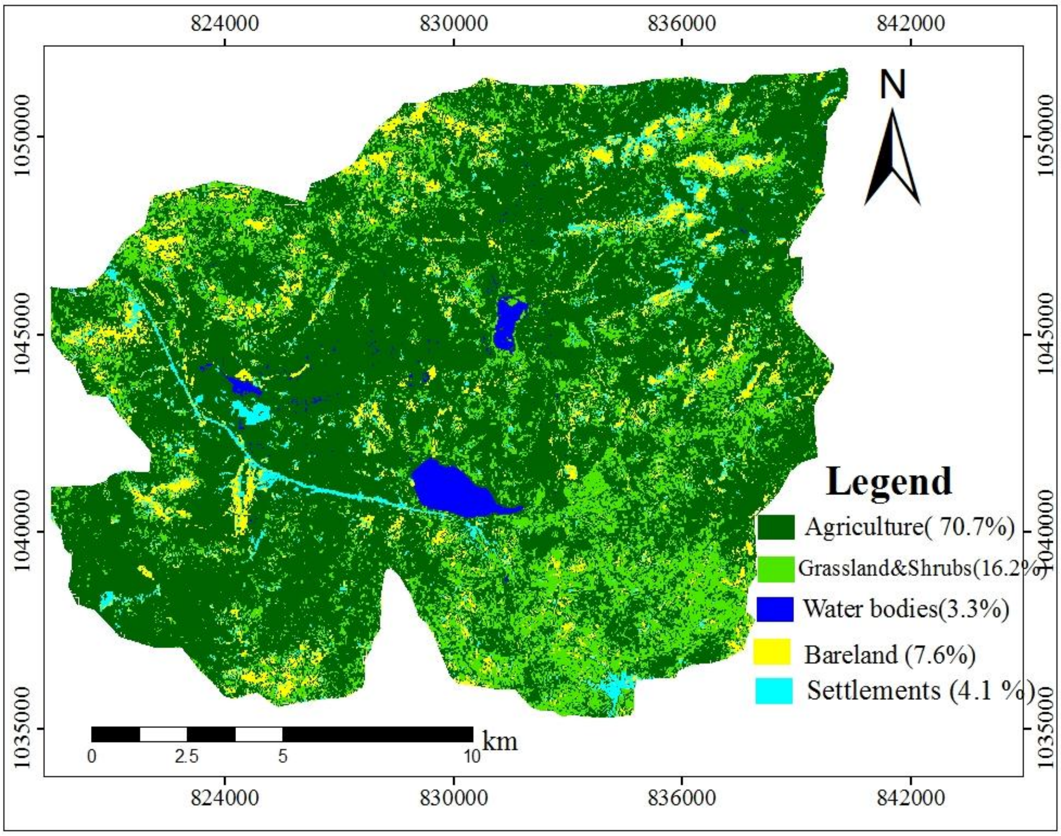

Figure 2.4. Land use and land cover map (Land sat ETM, 2001).

2.6 Socio economy

As per the national population and housing census of 2007, the total population of the Addele-Haromaya dry lake catchment is about 297,904. Out of this, 91% of the population belongs to Haromaya woreda while about 6% and 3% are that of Haromaya University and Aweday town. The livelihood of the community in the catchment is mainly based on mixed farming by growing crops and livestock production. Groundwater irrigation entirely dominated the area since the dry of preexisting Lake Haromaya. The ease access of shallow groundwater sources and the erratic variability of rainfall distribution of the area made the communities to depend highly on it. According to the Haromaya Woreda Agricultural and Development Office, the current irrigable land in the catchment is 6162 ha. The major crops grown in the area under irrigated conditions are chat (*Catha Edulis*) and vegetables (potato, lettuce, carrot, onion, tomato and cabbage). Sorghum and maize are grown under rain fed conditions. Chat (*Catha Edulis*) is an evergreen, mildly narcotic and stimulant perennial shrub usually has 2–7 m height. It is a highly profitable cash crop for the communities as well as for Ethiopia.

2.7 Water use trend

Lake Haromaya and Sofi spring served as a traditional source of domestic water supply for Harar, Haromaya and Aweday towns approximately a century ago. In the beginning of 1940’s the water supply system of the surrounding towns was also supported by capping of other springs. Owing to the increased water demand with the corresponding population growth, in 1960 Lake Haromaya had been constructed as the principal water source supply for water dependent towns. The system was designed to serve the estimated population of 70,000 with per capita consumption of 38 l/day for 30 years. However, the system was forced to stay in function beyond the designed period and obliged to over-pumpage of 50 – 60 l/sec with pumping hours of 22 hr/ day for the past 13 years (Harar Water Supply Authorithy Office cited in Meklit Tariku, 2003). The dramatic decline in water level of the lake was started since 1976. Brook Lemma (2003) reported that the maximum depth of the lake was 7.0-8.5m in the mid 1980’s, and decreased to 3.0-3.5m by 2000 where the ranges area recorded at dry and wet seasons. The gradual decline of water level increased from year to year finally dried in 2005 (Figure 2.5).

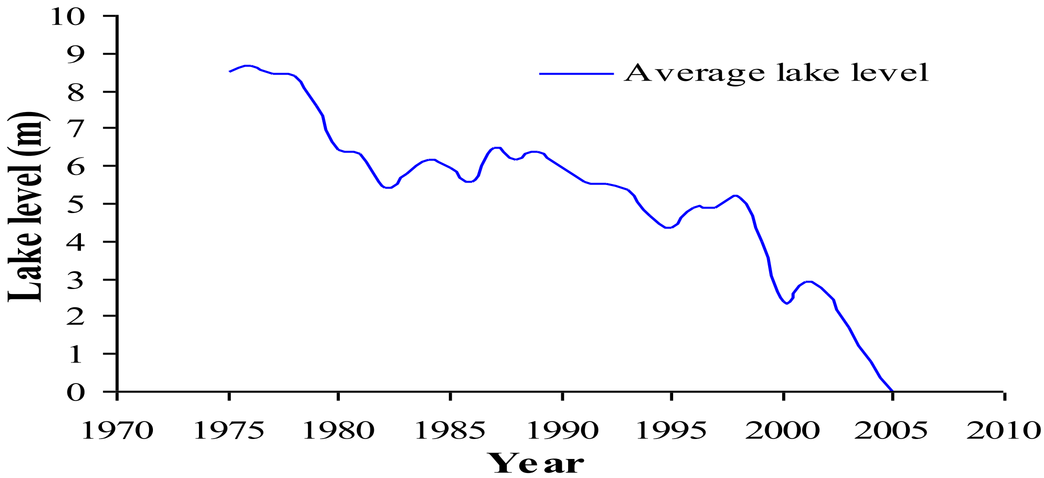

Figure 2.5.Yearly water level fluctuation of former Haromay Lake (After Wakgari Furi, 2005).

The drying of Haromaya Lake, the scarcity of perennial rivers and the erratic distribution of rain fall have imposed the people of major towns (Harar, Haromaya and Awaday) to depend entirely on the groundwater resource. The groundwater resource has been serving as a major source for domestic supply and irrigation requirement.

2.8 Water supply system

The existing water points in the catchment include boreholes, hand dug wells and springs (Figure 2.6). The boreholes and springs have been used as means for domestic water supply while the hand dug wells are used both for domestic and irrigation supplies. Some of the water points were visited during field trip.

According to the Haromaya Woreda Water Office, about 50 shallow boreholes and 1300 hand dug wells are existed in the catchment. From fifty shallow wells, 46% of them are motorized schemes and the rest are fitted with hand pumps. All the twenty shallow boreholes are located in the Haromaya lake sub catchment. From these, 35% of them are localized in the Lake Haromaya well field, 60% of them belong to the Haromaya University, Addele and Bate, and the rest boreholes are located in Tinikie area. The Haromaya Lake well field has been supplying for Aweday and Harar towns whereas; the boreholes found in Haromaya University, Addele and Bate are serving for the University, Haromaya town and Bate villagers. The Tinike boreholes have been used for Harar brewery.

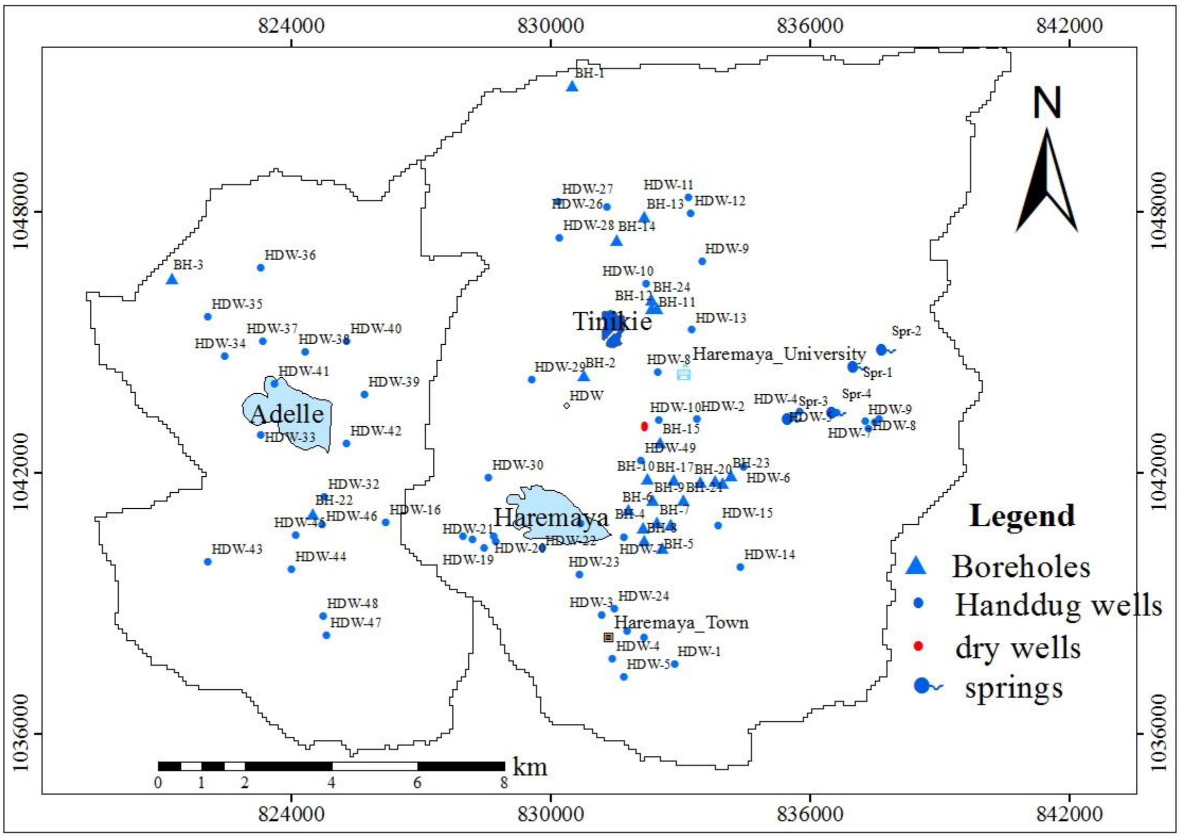

Figure 2.6. Spatial distribution of water points map.

Unlike the shallow boreholes, the hand dug wells are distributed spatially all over the catchment. The greater number of the hand dug wells are confined around Damota village. The boreholes, dug wells fitted with hand pump and some dug wells fitted with small lifting pump capacity (dynamo) have been serving for the rural communities as domestic water supply. On the other hand, the rest hand dug wells fitted with small lifting pump capacity (dynamo) and open dug wells are used for irrigation purpose. There are also three developed springs located in the Damota village serving the community as source of domestic and irrigation supplies. Table 2.2 shows all water points in the catchment.

Table 2.2. Summary for water points in the Adelle-Haromaya catchment.

No	Water points	Scheme	Location	Total No.	Depth (m)	SWl (m)	Average discharge (L/ s)	Average pumping hour (hr / day)
1	Shallow Boreholes	Motorized	Haromaya lake well filed	7	42–65	2.5–14	10	24
			Haromaya University	9	38–70	7.8–13	7	24
			Near Bate and Adelle	3	40-60	8- 12	8	18
			Tinikie area	4	42–50	16	8	16
		Hand pump	Distributed all over the catchment	30	36–60	18–24	0.5	8
2	Hand dug wells	Hand pump	>>	70	4–12	2–8	0.5	8
		Small lifting pump (Dynamo)	>>	1300	12–18	10–15	0.5- 1	6
		Dewatering pump	>>	50	4–8	1–5	4	6
3	Springs	Developed	Damota village	3	-	-	1–15	24

Source: - Haromaya Woreda Water Office and (Geletu Belay, 2006).

CHAPTER III: HYDROMETEOROLOGICAL ANALYSIS AND WATER BALANCE

3.1 Meteorological elements

3.1.1 Rainfall

A total of 54 and 25 years monthly rain fall data from Haromaya University and Dhengogo stations were used to see the patterns of rainfall distribution in the catchment. The long term monthly mean rainfall varies between 18.05mm and 161.91mm while the annual rainfall of the catchment is 826.26mm.

There is a significant seasonal variation of rainfall in the catchment. This has been identified from the monthly precipitation of coefficient. A month is designated as “rainy” when the monthly rainfall coefficient is equal and more than 0.6. Any value below 0.6 indicates dry (UNFAO, 1995 cited in Daniel Gamachu, 1977). The calculated rainfall coefficient values (see annex 3.1) indicate that the main rainy months last from March to September while the dry months last from October to December. According to Daniel Gamachu (1977), the rainfall regime of the catchment has been classified as Type-I with one rainy season (Figure 3.1).

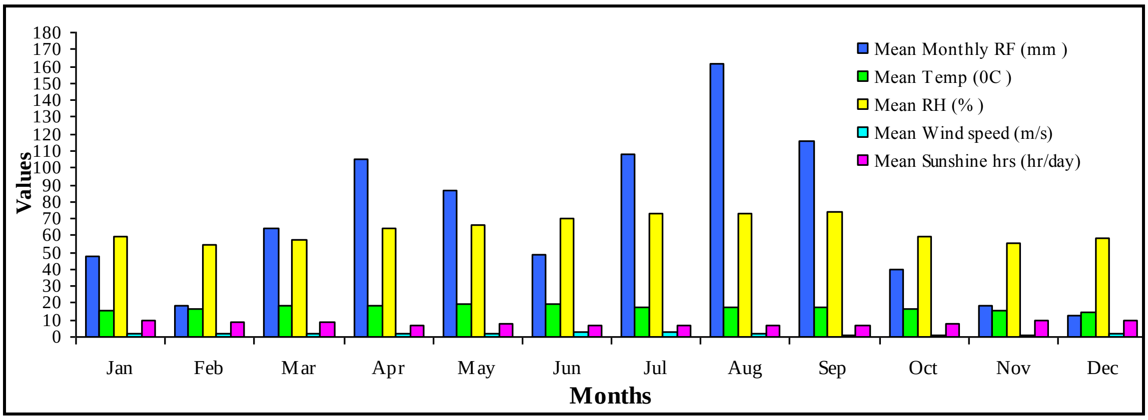

Figure 3.1. Long-term mean monthly climatic data in the catchment.

3.1.2 Temperature

The mean monthly temperature have been computed as the arithmetic average from long term meteorological stations. Air temperature in Adelle - Haromaya catchment shows small variation throughout the year. The monthly mean maximum and minimum temperature are 23.83 °C and 10.63 °C. The long term monthly mean varies between 19.13°C and 14.47 °C while the annual average temperature is 17.23°C.

3.1.3 Relative humidity, wind speed and sunshine hours

Relative humidity is the ratio between the amount of water that the ambient air actually holds and the amount it could hold at the same temperature. It is dimensionless and is commonly given as a percentage. The study area is characterized by relatively high values of relative humidity. Monthly average of maximum relative humidity varies between 90 % and 99 %. Monthly average of minimum relative humidity oscillates between 25 % and 55 %. The mean monthly relative humidity varies between 54.62 % and 74.08 % with an annual average of 63.81%.

The general wind condition of the catchment can be grouped as light air and light breeze wind. The light air wind (0.28 - 1.60 m/s) occurs from the month of September to December while the light breeze wind (1.67- 3.05 m/s) occurs from January to August (Table 3.1). The average monthly wind speed for a period of seventeen years varies between 1.71 m/sec and 2.71 m/sec with an average value of 1.89 m/sec.

The average monthly sunshine hour for a period of twenty seven years fluctuates between 6.66 hr/day and 9.41 hr/day with a mean value of 7.92 hr/day. High sunshine hour occurs in the dry Season (October-February) whereas low values of sunshine hour are recorded in the rainy season (March-September).

Table 3.1. Long-term monthly average weather parameters of the Adelle-Haromaya lake catchment from Haromaya University & Dengago stations (1954-2008).

No	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Mean Monthly RF (mm)	47.29	18.05	64.48	104.61	86.83	48.6	107.79	161.91	115.52	40.06	18.53	12.6
2	Mean Temp (^{o}C)	15.16	16.49	18.15	18.55	19.13	19.13	17.97	17.95	17.94	16.64	15.17	14.47
3	Mean RH (%)	59.25	54.62	57.08	64.27	66.3	70.42	73.44	73.39	74.08	58.94	55.4	58.52
4	Mean Wind speed (m/s)	1.79	1.96	2.05	1.91	1.96	2.71	2.64	2.16	1.4	1.17	1.42	1.54
5	Mean sunshine hrs (hr/day)	9.39	8.74	8.36	7.23	7.66	7.21	6.74	6.74	6.66	7.57	9.41	9.28

Source: National Meteorological Agency of Ethiopia

3.2 Hydrology

Hydrology deals with occurrence, distribution and movement of water throughout the earth. It also addresses both the hydrologic cycle and water resources. Hydrology helps to know the groundwater resource and development condition of the basin through providing information on the recharge facilities like, streams, reservoirs and rainfall patterns. Hydrologic cycle is the water transfer cycle which occurs continuously in nature. The three important components of the hydrologic cycle are precipitation, evaporation, and run off.

3.2.1 Precipitation

Precipitation is defined as any form of water (rain, snow, hail, etc) which falls on the surface of the earth by the process of condensation and sublimation (Tamiru Alemayehu and Tenalem Ayenew, 2001). The main precipitation in the study area is in the form of rainfall. The distribution of rain fall is highly influenced by the position of Inter Tropical Convergence Zone (ITCZ). It is a low pressure area of convergence between tropical easterlies and equatorial westerlies where equatorial wave disturbances take place. When the ITCZ is located south of Ethiopian and moving north words, the study area experiences limited precipitation between March and May. Likewise, when it is located north of Ethiopia and moving south words, the study area gets relatively higher precipitation from June to September. The remaining months are relatively drier when the ITCZ is near the equator.

3.2.1.1 Determination of aerial depth of precipitation,

A precipitation event recorded by rain gauge is a point observation at specific location and may not be used as a representative value for the entire catchment under consideration. Hence, the recorded point precipitation has to be averaged over the catchment. Different methodological approaches exist for the estimation of aerial depth precipitation over a given basin. The most frequently applied methods are arithmetic averaging, thiessen polygon and isohyetal methods. The criteria for selecting the best method include the densification of meteorological networks, the characteristics of the relief within the catchment and the size of the watershed.

The rainfall distribution of the area is uneven and strongly influenced by orographic effects. Accordingly, isohyetal method has been used for estimation the aerial depth of precipitation of the catchment. Moreover, isohyetal method is the most accurate approach for determining the average rainfall over an area (William, 2007). A total of five stations with their long-term average annual rainfall data have been used for the computation (Table 3.2). Of which, three of them are outside the catchment area but they are relatively close to the study area. The general formula which has been used for estimation the average aerial depth of rainfall is given by:

$$P_{av} = \frac{\sum A_{1-2} P_{1-2}}{\sum A_{1-2}} \quad (3.1)$$

Where P_{av} = average aerial depth precipitation in the catchment

A_{1-2} = area between the two successive isohyets P_1 and P_2

$$P_{1-2} = \frac{P_1 + P_2}{2}$$

$\sum A_{1-2} = A =$ Total area of the catchment

Table 3.2. Rain gauge stations and their long-term mean annual rain fall values.

No	Stations	Utm E (m)	Utm N (m)	Altitude (m)	Average annual RF (mm)	Year of record
1	Haromaya University	831720	1040410	2125	801.02	(1954-2008)
2	Harar*	842813	1029436	2100	710.39	(1969-2008)
3	Dhangago	820000	1045000	2240	851.50	(1981-2006)
4	Kombolcha*	842378	1044359	2101	724.54	(1994-2005)
5	Kersa*	812933	1046072	2073	721.50	(1996-2004)

Source : National Meteorological Agency of Ethiopia

* Stations outside the catchment but close to the study area

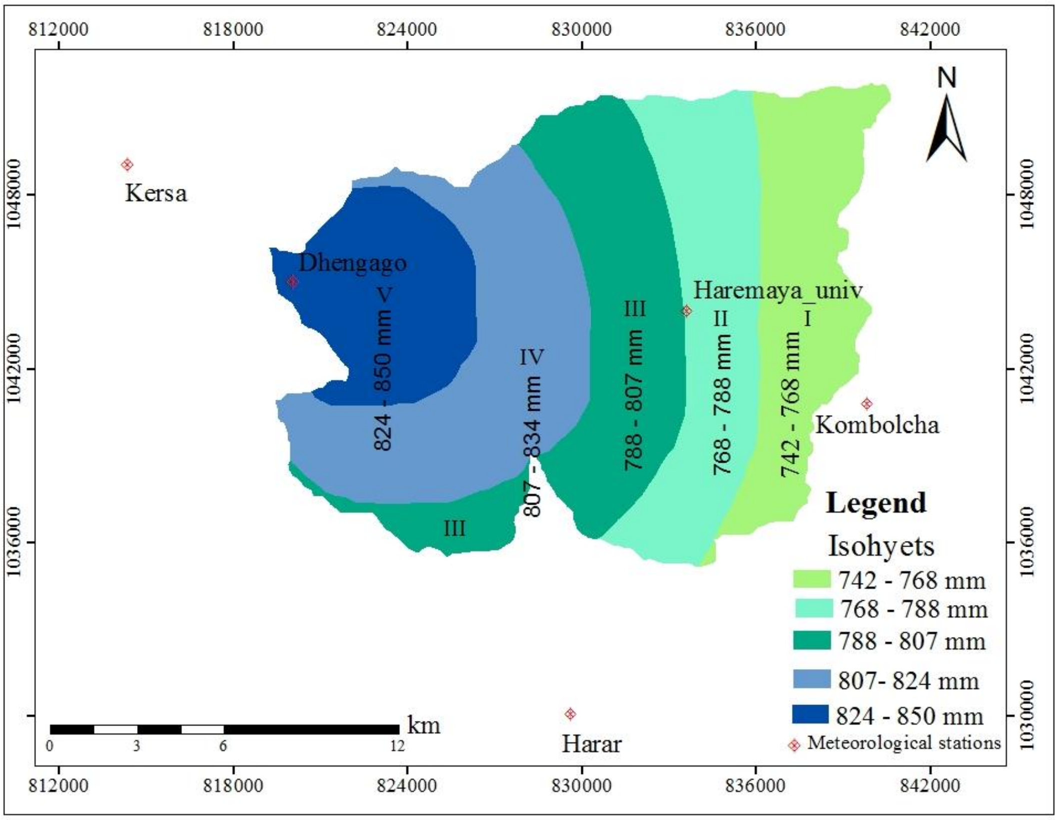

Figure 3.2. Isohyetal map.

The north western part of the study area is characterized by a relatively higher amount of precipitation than the other parts. Generally, the amount of rainfall increases from east to west direction (Figure 3.2). The estimated mean annual rainfall of the catchment by using isohyetal method is 796mm (Table 3.3).

Table 3.3. Estimated mean annual rainfall using isohyetal method.

Zone	Isohyets (mm)	Mean Isohyetal value, P_{1-2} (mm)	Area between isohyets, A_{1-2} (km^2)	Products (2) X (3) (km^2 mm)	Mean aerial depth of RF (mm)
	1	2	3	4	5
I	768 - 742	755	28	21459.9	$P_{av} = \frac{\sum A_{1-2}P_{1-2}}{\sum A_{1-2}}$ P_{av}= 796
II	788 - 768	778	30	23607.2	
III	807 - 788	797.5	37	29632.8	
IV	824 - 807	815.5	39	31673.1	
V	850 - 824	837	23	19449.1	
Total			$\sum A_{1-2} = 158$	$\sum A_{1-2}P_{1-2} = 125822.2$	

3.2.2 Evapotranspiration

Evapotranspiration is the total loss of water by evaporation and transpiration from a land surface and vegetation cover. Its value varies according to the type of vegetation and the availability of water in the soil. There are two types of evapotranspiration: potential evapotranspiration and actual evapotranspiration.

3.2.2.1 Potential evapotranspiration

Potential evapotranspiration can be defined as the total evaporation and transpiration from a vegetated surface with unlimited water supply (Shaw, 1994). It constitutes the maximum possible loss rate under the prevailing meteorological conditions. A value of the actual evapotranspiration (AET) over a catchment is more often obtained by first calculating the PET. Several methods have been developed to estimate the PET. In this work, the modified penman and thornthwaite methods are used to compute PET.

3.2.2.1.1 Penman modified method

Penman had produced a formula to describe the conditions under which evaporation plus transpiration takes place from a vegetated surface. The formula was later modified by MAFF (1967) cited in Shaw (1994) and given by:

$$PET = \frac{(\Delta/\gamma)H_T + E_{at}}{(\Delta/\gamma)+1} \quad (3.2)$$

In this equation to signify the effects of transpiration, the subscript t is added unlike Penman (1948) formula for calculating open water evaporation.

H_T is the available heat often calculated from incoming *(R_I)* and outgoing *(R_o)* radiation determined from sunshine records, temperature and humidity, using:

$$H_T = R_I(1-r) - R_o \quad (3.3)$$

Where, r is the reflective coefficient for incident radiations or the albedo which depends on the nature of the surface. For our case it is taken as 0.23 assuming majority of land cover of the study area as short grass surface. Hence,

$$H_T = 0.77R_I - R_o \quad (3.4)$$

R_I is a function of R_a, the solar radiation (fixed by latitude and season) modulated by a function of the ratio, n/N, of measured to maximum possible sunshine duration. Using r = 0.23 gives:

$$R_I(1-r) = 0.77R_a f_a(n/N) \quad (3.5)$$

For the study area within latitudes south of $54/2^0$N,

$$f_a(n/N) = (0.16 + 0.62n/N) \quad \text{(MAFF, 1967 cited in Shaw, 1994)} \quad (3.6)$$

The empirical equation for the outgoing reduction takes the form:

$$R_o = \sigma T_a^{\,4}(0.47 - 0.075\sqrt{e_d})(0.17 + 0.83n/N) \quad (3.7)$$

The term E_{at} (parameter including wind velocity and saturation deficit) can be given as

$$E_{at} = 0.35(1 + u_2/100)(e_a - e_d) \quad (3.8)$$

Where: e_a = saturated vapour pressure at air temperature T_a

e_d = vapour pressure of the air (saturated vapour pressure at dew point)

$(e_a – e_d)$ = the saturation deficit

U_2 = mean wind speed at 2m above the surface meter/second

Δ Represents the slope of the curve of saturated vapour pressure plotted against temperature.

γ is the hygrometric constant (0.27 mm of mercury/°F)= (0.5mmHg/°K)

Based on the above basic formula (4.2), the calculated annual PET of the study area according to penman modified method is 1101.10 mm/year (Table 3.4).

Table 3.4. PET of the Adelle-Haromaya lake catchment according to penman modified method.

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T (°C)	15.16	16.49	18.15	18.55	19.13	19.13	17.97	17.95	17.94	16.64	15.17	14.47
e_a (mm/day)	12.5	13.63	15.1	15.5	16	16	15	15	14.98	13.6	12.5	11.99
RH (%)	59.25	54.62	57.08	64.27	66.30	70.42	73.44	73.39	74.08	58.94	55.40	58.52
e_d (mm/day)	7.41	7.45	8.62	9.96	10.61	11.27	11.02	11.01	11.11	8.02	6.93	7.02
u_2 (m/s)	1.79	1.96	2.05	1.91	1.96	2.71	2.64	2.16	1.40	1.17	1.42	1.54
T (°K)	288.31	289.64	291.30	291.70	292.28	292.28	291.12	291.10	291.09	289.79	288.32	287.62
n (hr/day)	9.39	8.74	8.36	7.23	7.66	7.21	6.74	6.74	6.66	7.57	9.41	9.28
N (hr/day)	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
n/N	0.81	0.74	0.70	0.59	0.61	0.57	0.53	0.54	0.55	0.64	0.81	0.81
f_a (n/N)	0.66	0.62	0.59	0.52	0.54	0.51	0.49	0.50	0.50	0.56	0.66	0.66
R_a (mm/day)	12.8	13.9	14.8	15.2	15	14.8	14.9	15	14.8	14.2	13.1	12.5
R_I (1-r) (mm/day)	6.52	6.62	6.75	6.14	6.20	5.84	5.64	5.74	5.71	6.10	6.68	6.36
σT_a^4 (mm/day)	13.3	14.1	14.45	14.5	14.6	14.6	14.37	14.37	14.36	14.1	13.95	13.75
R_o (mm/day)	2.98	2.93	2.70	2.23	2.22	2.04	1.95	1.97	1.98	2.55	3.21	3.13
H_T	3.55	3.69	4.04	3.91	3.98	3.79	3.69	3.77	3.73	3.55	3.48	3.22
Δ/γ	1.7	1.84	2	2.05	2.12	2.12	1.98	1.98	1.96	1.85	1.7	1.66
E_{at}	1.81	2.21	2.31	1.98	1.92	1.70	1.43	1.43	1.37	1.98	1.98	1.77
PET (mm/month)	87.14	95.03	104.04	98.34	99.56	93.68	87.95	89.47	88.04	89.87	87.70	80.28
PET (mm/year)	1101.10											

3.2.2.1.2 Thornthwaite method

Thornthwaite method relates PET to temperature with an adjustment being made for the number of daylight hour and gives figures for the consumptive use of short closed vegetation with adequate water supply. An estimate of the potential evapotranspiration (PET_m) calculated on a monthly basis is given by:

$$PET_m = 16 N_m \left(\frac{10 \bar{T}_m}{I} \right)^a \text{mm} \tag{3.9}$$

Where $_m$ is the months 1, 2, 3…12, N_m is the monthly adjustment factor related to hours of daylight, $\bar{T}_m$ is the monthly mean temperature °C, I is the heat index for the year, given by:

$$I = \sum i_m = \sum \left(\frac{\bar{T}_m}{5} \right)^{1.5} \qquad \text{for } m = 1,2\ldots.12$$

And: $a = 6.7x10^{-7} I^3 - 7.7x10^{-5} I^2 + 1.8x10^{-2} I + 0.49$

The calculated annual PET of the study area according to thornthwaite method is 781.18 mm/year (Table 3.5).

Table 3.5. PET of the Adelle-Haromaya lake catchment according to thornthwaite method.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
T (^{0}C)	15.16	16.49	18.15	18.55	19.13	19.13	17.97	17.95	17.94	16.64	15.17	14.47	
N_m	0.96	0.98	0.99	1.02	1.04	1.05	1.04	1.03	1.00	0.98	0.96	0.95	
i_m	5.28	5.99	6.92	7.15	7.48	7.49	6.81	6.80	6.79	6.07	5.29	4.92	76.99 = I
PET_m (mm/month)	49.59	58.33	70.08	74.59	80.56	81.22	72.29	71.02	69.21	59.29	49.66	45.34	781.18 mm/year
a = 1.73													

In general for rational estimation of the PET of the study area, the average value of the two methods (penman modified and thornthwaite) has been considered for the water balance analysis (Table 3.6).

Table 3.6. Average PET in mm/year of the study area.

Methods	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Penman	87.14	95.03	104.04	98.34	99.56	93.68	87.95	89.47	88.04	89.87	87.7	80.28	1101.1
Thornthwaite	49.59	58.33	70.08	74.59	80.56	81.22	72.29	71.02	69.21	59.29	49.66	45.34	781.18
Average	68.37	76.68	87.06	86.47	90.06	87.45	80.12	80.25	78.62	74.58	68.68	62.81	941.14

3.2.2.2 Actual evapotranspiration

The term actual evapotranspiration refers the evapotranspiration form cropped land under limited water supply to the root zone, i.e. when there is no sufficient water availability in the soil moisture. It is controlled by soil moisture content and the capacity of the plants to transpire, which are conditioned by the meteorological factors. Though there are several ways of estimating the actual evapotranspiration (AET), the WTRBLN (water balance model) is deployed in this work. WTRBLN is a computer program that calculates water balance based on the long term average monthly precipitation, PET, soil and vegetation characteristics and surface runoff. The important input parameters for the model are mean monthly precipitation, PET, direct surface run off, and available water capacity of root zone in mm.

The mean monthly precipitation and PET of the area have been estimated as indicated above. Direct surface runoff refers the portion precipitation that flows over the ground surface (overland flow). It is strongly influenced by the climate, geology, topography, soil and vegetation of the area. The quantity (volume) of surface runoff is commonly assumed as a proportion (percentage) of the rainfall depth. The mean monthly direct surface runoff can be given by:

$\text{Run off (mm)} = K * \text{Rain fall depth (mm)}$, Where K is runoff coefficient.

The runoff coefficient (K) represents the percentage of rainfall that becomes runoff. The runoff coefficient has been determined based on the land use and land coverage of the area. The value of K has been calculated as an area-weighted composite of the different land uses in the catchment. Accordingly, the K of the catchment is estimated to be 0.16. The estimated average mean monthly direct surface runoff the catchment has been given in the annex part (see water balance annex).

The values of the available water capacity of the root zone are estimated on the basis of the rooting depth of the various vegetables and crops, and the soil texture of the different soil types of the catchment. The average rooting depth for shallow rooted vegetables and grasses has been considered as 0.6m while the average rooting depth for moderately deep rooted chat and crops has been taken as 1.2m. Considering the different soil types of the catchment with their respective soil textures, the average available water capacity of the root zone has been estimated for each soil type (table 2.1).

The WTRBLN model was run and the computed AET values for the regoslos, lithosols, fluvisols, cambisols and vertisols are 838, 866, 678, 716 and 678mm/year respectively.

Based on the aerial coverage of each soil types in the catchment, the AET and other water balance parameter values have been weighted. Accordingly, the adjusted AET of the catchment is found to be 757mm/year (annex 3.7).

3.2.3 Runoff

Runoff refers the portion precipitation that makes its way towards channels, streams, rivers, lakes or oceans etc., as overland flow. It is strongly influenced by the climate, geology, topography, soil and vegetation of area. Since the Adelle-Haromaya lake catchment is a closed basin, there is no any runoff which leaves out the catchment. Unfortunately there is no gauged stream to estimate surface runoff using actual data. Instead the above mentioned approach is used to estimate surface runoff.

3.3 Water balance and groundwater potential evaluation

3.3.1 Recharge

Groundwater recharge can be defined as the amount of water that will eventually reach the water table. The amount of this recharge depends upon the rate and duration of rainfall, the surface conditions at the upper boundary, the soil moisture conditions, the water table depth and the geology (lithology and structure).

The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the groundwater recharge. Quantification the natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management. It is important in areas with large demands for groundwater supplies, where such resources are the key to economic development. Though there are several techniques to estimate the natural groundwater recharge, the soil water balance approach is used in this work.

3.3.1.1 Soil water balance method

Soil water balance model was developed by Thornthwaite and later revised by Thornthwaite and Mather. It estimates the balance between the inflow and outflow of water in the soil. The soil water balance can be represented by:

$$G_r = P - AET + \Delta S_m - R_o \quad (3.10)$$

Where, G_r = Groundwater recharge

P = Precipitation

AET = Actual evapotranspiration

ΔS_m = Change in soil moisture

R_o = Runoff

The previous calculated values of aerial precipitation and actual evapotranspiration of the catchment are 796mm/year and 757mm/year. The adjusted value of change in soil moisture is found to be zero. Since, the catchment is a closed basin, the value of runoff is also assumed to be zero. Substituting the values in the above equation, the total recharge of the study area is 39mm/year. Considering the total area of the catchment as 258 km^2, the annual groundwater recharge of the Adelle-Haromaya catchment is estimated to be 10.06 MCM.

3.3.2 Safe yield, exploitable groundwater reserve and specific yield

3.3.2.1 Specific yield

Specific yield can be defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the water table. The values of the specific yield range from 0.01 to 0.30 and are much higher than the storativities of confined aquifers (Kruseman and de Ridder, 1994). It can be estimated using the formula:

$$R = S_y * A * Dl_w + Q_b + Ls_o \qquad (3.11)$$

Where R is the recharge, S_y is the specific yield, A is the effective area for groundwater recharge, Dl_w is the average water level rise in wet period, Q_b is the groundwater abstraction during the recharge period that is equal to the volume of water used for domestic use in rainy season and Ls_o is the lateral subsurface out flow. The average water level rise in wet period (Dl_w) for the year (2005 to 2006) is 4 m (Figure 3.3). The rainy seasons of the catchment are from March to September and January. Considering the domestic water consumption as 20 liters per capita per day and assuming 100% of the groundwater dependable population of the catchment has an access to clean water, the volume of water used for domestic use in rainy season (Q_b) of the area is estimated to be 1.56MCM/year. The effective area for groundwater recharge (A) is estimated to be 33 Sq.km. Since the basin is closed, the lateral subsurface out flow (Ls_o) is assumed to be zero. Using the above mentioned parameters, the specific yield is estimated to be 0.06 or 6%.

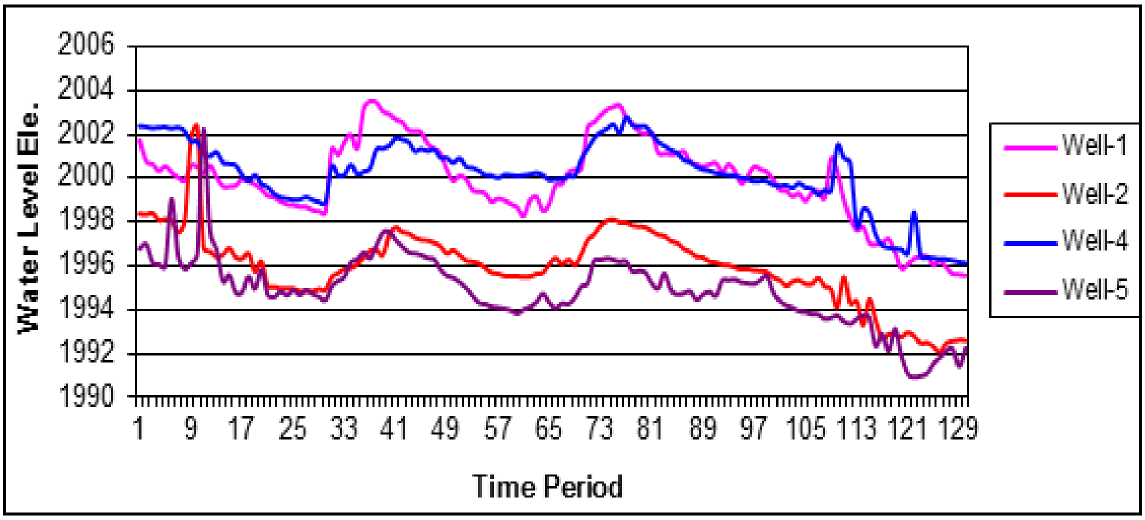

Figure 3.3. Groundwater level trend at four observation wells (after Geletu Belay, 2006)

3.3.2.2 Exploitable groundwater reserve

The exploitable groundwater reserve is the volume of groundwater that can be annually abstracted under the current ecological condition. It represents the long-term average annual recharge under condition of maximum groundwater use (Voudouris, 2006). Estimation of exploitable groundwater reserve (Q_{ed}) requires defining the effective area for groundwater recharge (A), specific yield (S_y), and average water level decline in dry period (D_L). It can be calculated using the formula:

$$Q_{ed} = A * S_y * D_L \tag{3.12}$$

The estimated specific yield of the main aquifers is 0.06 as calculated earlier. The rainfall coefficient values indicate that the dry periods of the catchment are from October to December and February. The past groundwater level recorded data (2005 to 2006) shows that the average groundwater level decline during dry seasons is 3.4m (Figure 3.3). The effective area for groundwater recharge of the catchment is considered to be 33Sq.km. Putting these values in to equation (4.14), the exploitable groundwater reserve of the catchment is 6.73 MCM per year.

3.3.2.3 Safe yield

In groundwater management, safe yield is defined as the rate at which groundwater can be withdrawn annually without producing an undesirable adverse effect (Dottridge and Jaber, 1999). The traditional definition of the safe yield assumes the pumpage rate is equal to the total annual recharge of the basin. In this work safe yield is used as a management concept and is estimated from (Naik and Awasthi, 2003 cited in Tizro et al., 2007):

$$\text{Safe yield} = Q_{ed} + Q_{dom} + Q_{ri} + Q_{si} \tag{3.13}$$

Where:

Q_{ed} = Exploitable groundwater reserve

Q_{dom} = Volume of water used for domestic use in rainy season.

Q_{ri} = Recharge due to irrigation returns

Q_{si} = Sewage infiltration

The exploitable groundwater reserve of the catchment and the volume of water used for domestic use in rainy season of the area from the previous estimation are 6.73MCM and 1.56 MCM per year. Since the values of recharge due to irrigation returns and sewage infiltration are insignificant, they are taken as zero. Thus, the annual safe yield of the Adelle-Haromaya lake catchment is 8.29MCM per year.

3.3.3 Water balance

Water balance is a quantitative evaluation of the total water gained or lost from a given hydrological system during a specific period of time (Tamiru Alemayehu and Tenalem Ayenew, 2001). It considers all surface and groundwater that are entering, leaving or stored within the system. The study of water balance of a given basin forms a basis for the hydrological confirmation of projects for the rational use, control and redistribution of water resources in time and space. It is also used to make a quantitative evaluation of water resources and their change under the influence of man's activities. Knowledge of the water balance assists the prediction of the consequences of artificial changes in the regime of the given basin. Thus, for sustainable groundwater management, the water balance should be established for a given unit system over a given period of time. The water balance equation for any natural area such as a river basin or water body indicates the relative values of inflow, outflow and change in water storage for the area or water body under consideration which can be given by:

$$\text{Inflow} - \text{Outflow} = \text{Change in storage } (\Delta S) \tag{3.14}$$

The inflow part of the water balance equation for the study area includes the precipitation (P) as rain fall. The out flow component of the equation comprises the actual evapotranspiration (AET) from surface and cropland, groundwater abstraction or withdrawal (W), and discharge from springs (Q_s). If we consider only the groundwater system, the water balance equation can be reduced in to:

$$G_r - W - Qs = \Delta S \qquad (3.15)$$

Where, Gr is the groundwater recharge

It should be noted that the spring discharge is fully used i.e. there is no return of spring flows into the groundwater downstream. Withdrawal indicates water use for irrigation and drinking and industry from all water sources.

3.3.3.1 Abstraction

The total amount of withdrawal throughout the catchment consists of irrigation, domestic and industrial water uses. Pumping from both hand dug wells and boreholes is the major way by which groundwater is abstracted from the system.

The shallow boreholes and hand dug wells fitted with submersible and hand pumps have been serving for domestic water supply for both the urban and rural communities. The seven shallow boreholes serving for Harar town are abstracted with an average discharge of 10 l/s while the nine boreholes for the Haromaya University are pumped with an average discharge of 7 l/s. The pumping hour for both boreholes is 24 hour per day. There are also three boreholes which have been supplying for Bate, Adelle and Haromaya towns with average discharge of 8 l/s and pumped for 18 hours per day. According to Haromaya Woreda Water Office, there are about 100 hand pump mounted wells in the catchment. The hand pumps yield on average 0.5l/s pumping for 8 hours per day. Beside to these, the hand dug wells fitted with small lifting pump capacity (Dynamo) are also used as a domestic supply. They are 650 in number with the same discharge and pumping hours as hand pumps. Based on the above average discharge and pumping hours, the groundwater abstraction for domestic supply is 8.7 MCM/year.

The hand dug wells fitted with small lifting pump capacity (dynamo), and the rest open dug wells that have been pumped through dewatering pump are used for irrigation purpose. The total numbers of wells fitted with small lifting pump capacity are 650 and the other open dug wells are around 50 in number. The former wells are pumped with an average discharge of 1 l/s whereas; the latter one is 4 l/s. Both of them are pumped for 6 hours per day. The groundwater abstraction from these wells considered for dry months is 4.41MCM/year.

There are also four boreholes which have been supplying for industrial demand of the area. The boreholes are located near Tinikie Lake and pumped with an average discharge of 8 l/s for 16 hours per day. Considering the discharge and pumping hours, the groundwater abstraction for industrial demand is 0.67MCM/ per (Table 3.7).

Table 3.7. Contributions of water points to the total annual groundwater abstraction.

Water points	Location	Abstraction (MCM)	Abstraction (%)	Water uses	Major users
Shallow Boreholes	Haromaya lake well filed	2.21	16.02	Domestic	Harar town
	Haromaya University well field	1.99	14.41	"	Haromaya University
	Tinnikie lake well field	0.67	4.88	Industrial	Harer brewery
	Adelle-Bate wells found near Adelle &Bate village	0.57	4.12	Domestic	Adelle - Bate villagers
	Mounted with hand pumps & distributed in the catchment	0.16	1.14	Domestic	Rural communities
	Total	5.60	40.57		
Hand dug wells	Mounted with hand pumps & distributed in the catchment	0.37	2.67	Domestic	Rural communities
	Small lifting pump & distributed all over the catchment	3.42	24.79	"	"
		3.37	24.45	Irrigation	"
	Pumped through dewatering pump & distributed all over the catchment	1.04	7.52	"	"
	Total	8.20	59.43	"	"

The major groundwater abstraction in the catchment is from hand dug wells which cover 59.43% of the total abstraction. From the total abstraction, the higher abstraction is 30.43% accounted by Haromaya well field. Whereas, the lower value is 1.14 % related to boreholes mounted with hand pumps. Considering the groundwater uses, domestic water use takes 63.15% of the total ground water abstraction (Table 3.8). Industrial water use account only 4.88% of the total abstraction.

Table 3.8. Annual groundwater abstraction for different water uses.

No	Water uses	Current abstraction (MCM)	Abstraction (%)
1	Domestic	8.7	63.15
2	Irrigation	4.41	31.97
3	Industrial	0.67	4.88
Total		13.78	

3.3.3.2 Spring discharge

Unlike boreholes and dug wells, springs are localized to the eastern part of the catchment at Damota village. The existing springs in the catchment are used for both domestic water supplies as well as for irrigation. The inventoried springs during field work are Lega-Masion, Genda-Bere, Genda-Qadi and Lega-Hida. The estimated discharge of Lega-Masion, Genda-Bere, and Genda-Qadi are 0.2 l/s, 1 l/s, and 1.5 l/s respectively. The Lega-Hida spring is approximated to an average discharge of 15 l/s is considered to be the highest discharge spring in the catchment (Plate 1). The total annual discharge for the above springs is found to be 0.56MCM.

Plate 1. Lega-Hida spring located at damota village (estimated discharge is 15 l/s).

Based on the previous estimation, the groundwater recharge is (Gr = 10.06MCM/year), the total groundwater abstraction or withdrawal (W) and the discharge from springs (Qs) are 13.78MCM and 0.56MCM per year. Using the above basic water balance equation (4.17), the computed change in storage of the catchment is – 4.28MCM per year. The total annual inflow of the catchment is lower than the total out flow of the catchment. Thus, the current groundwater abstraction is higher than the safe yield of the aquifers and the annual groundwater recharge of the catchment.

CHAPTER IV: GEOLOGY AND HYDROGEOLOGY

4.1 Geology

Despite the small catchment size, the study area has different rock types ranging in age from Precambrian to recent. In the study area Precambrian basement complex rocks, Mesozoic sedimentary rocks and Quaternary deposits are found. The Precambrian basement complex rock includes the high grade metamorphic gneisses and migmatites, and the intrusive granites. The Mesozoic sedimentary rock comprises sandstone and limestone rocks while the quaternary deposits are alluvial, lacustrine and eluvial deposits (Figure 4.1).

4.1.1 Precambrian basement complex rocks

Gneisses: The rock units are exposed in the southern and central part of the study area. The out crops of these rock units form small isolated ridges and low-lying topography covering 8.3 % of the total area. They are exposed as heterogeneous in association with various rocks. Lithological intercalations of biotite gneiss, quartzofeldspathic-gneiss, biotite-amphibole gneiss and some migmatites form the rock unit. The biotite-amphibole gneiss is grey to black grey, medium grained foliated, and show continuous parallel bands of mafic and felsic minerals, which is frequently interlayered with biotite gneiss and often grades to amphibole gneiss and amphibolite (Workineh Haro, 2010).

Migmatite: Complex granites and gneisses under intense metamorphism result in partial melting; and granitic magma collects in layers within the foliation planes of the solid rock. When the magma solidifies, the rock becomes a migmatite (mixed igneous and metamorphic rock). Migmatite is common to exist in association with gneisses and located in the northern, western and small patches in southern part of the study area. The rock unit covers 11% of the study area. It is composed of multi-folded granitic gneisses and biotite gneisses where lenses of amphibolite xenoliths are engulfed within the body of migmatite.

Granite: The granites are one of the Precambrian basement complex and intrusive rocks of Ethiopia. They are mainly exposed in northeastern, southeastern and central parts of the catchment. This unit covers about 21% of the total area of the catchment. They form small ridges in the north and southeastern parts of the study. It also forms sub circular body forming localized hills in some places. The granite rock unit is massive and shows light pinkish color. It is characterized by medium grained Na- feldspar (plagioclase), k-feldspar, quartz as well as white micas as major composition. Unlike the northeastern out crop, the central and southeastern part of the catchment of the rock unit is highly weathered and show light color. The lithological logs of the boreholes indicate that the maximum thickness of the weathered granite section is 20m.

4.1.2 Mesozoic sedimentary rocks

Sandstone: The sandstone unit outcrops in the eastern, northeastern, western and southwestern part of the study which placed on the top of the Precambrian basement complex rocks (Figure 4.2). It covers about 15% of the total catchment area. The rock unit (the lower sandstone or Adigrat sandstone) is highly weathered and fractured one, and found as forming hills and ridges in the exposure area. The rock unit shows yellowish to light pinkish color and consists of fine to medium grained quartz. It is also characterized by moderately sorted, weathered and rounded grains. In the southwestern part, reddish brown massive mudstone intercalations are found in sandstone varying in thickness from 20 cm to 1 m. The average thickness of the sandstone unit ranges from 20 to 200 m and shows well developed vertical joints (Nata et al., 2010).

Limestone: This unit is known to be Hananalie limestone in southeastern Ethiopian and Antalo limestone in northern Ethiopia. The unit is out cropped in the northeastern, western and southwestern part of the catchment overlying the sandstone unit. It is fossiliferous rock consisting of very fine grained calcite crystals. The limestone unit is characterized by intercalations of thin beds of light brownish color marl. It shows gray and light yellowish to black colors due to weathering. The unit is highly weathered and shows well developed karst topography. The rock occupies high elevations in the topography and forms steep cliffs in the area (Figure 4.2).

4.1.3 Quaternary deposits

Alluvial: The alluvial deposits are mainly found in the central part of the catchment along the margins of the major rivers and their tributaries. It covers 26.5 % of the total catchment area. The alluvial deposits are composed of medium to fine grained sands with variable silt and clay content. In general, towards the mountain front where steep topographic slopes exist, the alluvial sediments are dominated by sub-angular to sub-rounded coarse grained fragments with variable content of coarse grained sand. However, in central part of the catchment in the flat depressed topography in particular, the dominant alluvial deposit is medium to fine grained sand with variable content of silt and clay. The lithological logs of boreholes show that the thickness of alluvium ranges from 26 to 45 meter.

Lacustrine sediment: The lacustrine sediments are confined to the seasonal Haromaya and Adelle lakes, and also to the current perennial Tinikie lake area of the catchment. As the name indicates they are lacustrine origin covering small area. The sediments might be mixed with wash sediments of the nearby uplands. Compositionally the lacustrine sediments are comprised of clay and silt in different proportions. They are characterized by well-developed hexagonal cracks.

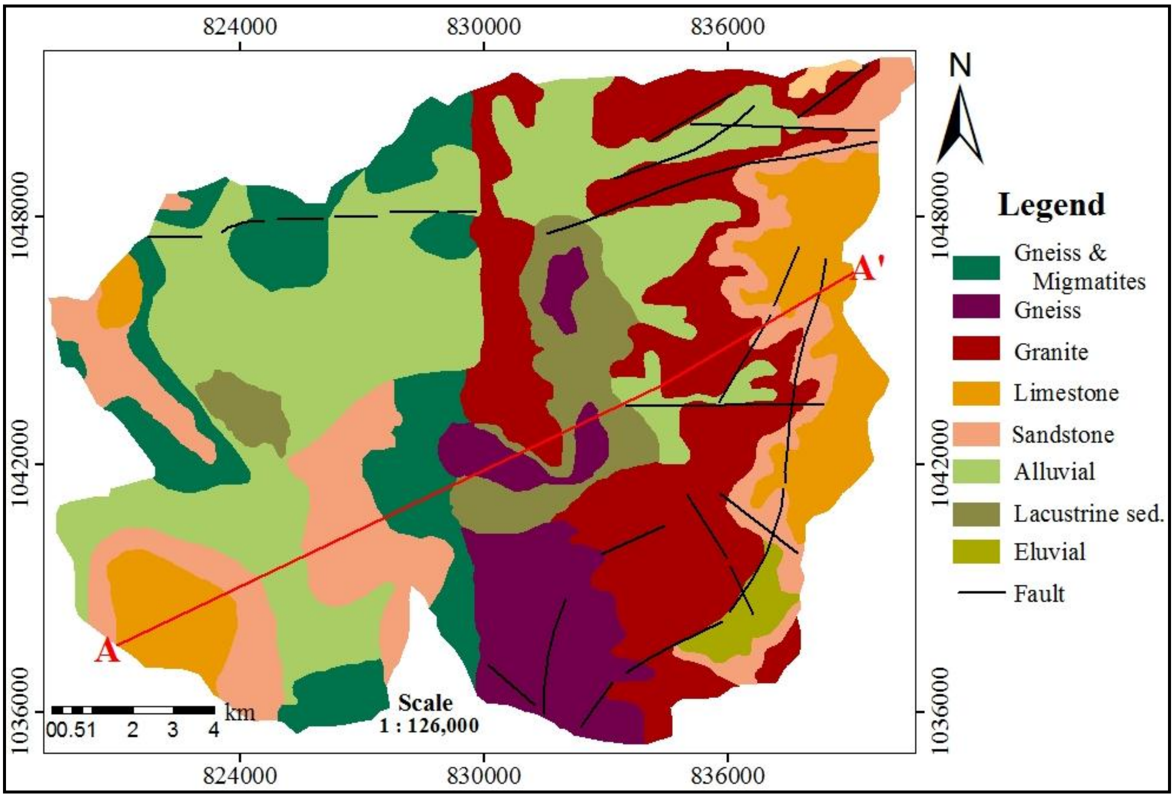

Figure 4.1. Geological map.

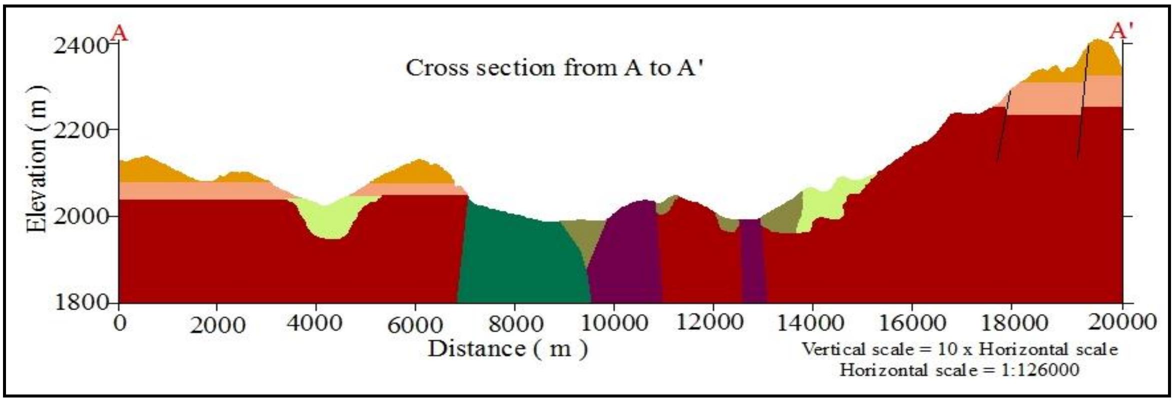

Figure 4.2. Geological cross section map.

Eluvial sediment: the eluvial sediments are exposed in the south eastern part of the catchment covering minor area. They are formed as the result of weathering, leaching and erosion of the near sandstone and limestone rock units. The eluvium sediments are mainly deposited on the slopes of the area, and consist of fine sand and silty-clayey materials.

4.1.4 Geological structures

The study area is located close to the water divide of the two large river basins (Awash and Wabishebele) at the edge of the Ethiopian rift. To the east of the study area there are many rift marginal faults in the Awash basin. However in the studied catchment there are very few faults. Few lineaments are traced from geological map of Harar and Dire Dawa sheets compiled by the Geological Survey of Ethiopia. They are oriented in the NE-SW and NW-SE direction.

Joints are common in Precambrian basement rocks and Mesozoic sedimentary rocks. They are systematic in arrangement and generally trend in NW-SE direction. In general Mesozoic rocks are highly fractured although the degree and trend of fracturing vary from place to place. The faults are only localized in the eastern part and orient in NW-SE and E-W directions (Figure 4.1). The intergranular permeability plays more important role than the fracture permeability in the catchment.

4.2 Hydrogeology

Hydrogeology encompasses the interrelation ship of various geologic materials and movements with water. The topography, surficial geology, drainage system, land use and land cover of the area influenced the hydrogeological condition of the catchment.

4.2.1 Hydrostratigrahpy

The lithological units of the catchment are characterized in to different hydrostratigraphic units or aquifer units using qualitative and quantitative approaches. Hydrostratigraphic units are geological formations having similar hydrogeological characteristics. The qualitative approach is based on the field observation of primary and secondary porosities while the quantitative one is made using pumping test and borehole log data. Since pumping test and well log data are not adequate and evenly distributed in the study area, both qualitative and quantitative approaches have been used for the classification. Based on transmissivity and optimum yield, the above lithologies in the catchment have been categorized in to five major aquifer units (Figure 4.3).

4.2.1.1 Intergranular aquifers with moderate potential

These aquifers are part of the unconsolidated sediments placed in the flat depressed topography near the central part of the catchment around the lake areas and the margins of the streams covering 27% of the catchment area. The alluvial deposits are composed of medium to fine grained sands with variable silt and clay content while the lacustrine sediments are dominated by fine grained silt and clay. The unconsolidated sediments are generally characterized by primary porosities. The nature of depressed topography and the availability of primary porosity made the unconsolidated sediments to store a large volume of water emanating from the surrounding highland areas. Both hand dug wells and shallow boreholes were drilled in these formations. A total of 21 shallow boreholes and more than 300 hand dug wells were identified in these formation. The depth of hand dug wells ranges from 4 to 8 m, for shallow boreholes it ranges from 38 to 70m depth. Borehole log data show that the average total thickness of unconsolidated sediments is between 4 to 60m. The static water level of the boreholes range from 2.5 to 13.5m, and the yields vary from 1.5 to 15 l/sec. The lithological log data and the symmetrical matching of the actual pumping test plots with theoretical plots of the unconfined aquifers indicate that, the aquifers of unconsolidated sediments are unconfined system. The average drawdown, transmissivity and yield of the seven shallow boreholes are 9.8m, 59.15m^2/day and 86.4m^3/day respectively (Abdulaziz, 2006). According to Sen (1995) aquifer transmissivity classification, transmissivity values ranging from 50 to 500 m^2 /day can be considered as moderate potential aquifer. Hence, aquifers of the unconsolidated sediments are grouped in to moderate potential.

4.2.1.2 Fractured aquifers with moderate potential

The sandstone unit is characterized by fine to medium grained sands exhibiting moderate sorting and roundness. The unit is also intercalated by shale and siltstones containing calcite and iron oxide as cementing materials. The average thickness of this unit ranges from 20 to 200 meters. The sandstone unit is moderately weathered and fractured one, and exposed as small hills and ridges in the study area. Though the sandstone contains primary porosities, the higher proportion of cementing materials made the intergranular permeability very low. However, the secondary porosity associated with fracturing and bedding planes have given a significant influence for groundwater circulation and storage with in this unit. So far one shallow well with 60 m depth have been drilled in this unit, and the discharge of the borehole was estimated to be 3 to 4 l/s. During field trip, few numbers of springs with variable discharges were observed. The springs are emerged at the contact of the sandstone with the underlying basement rock, and also at the contact of the sandstone with the overlying limestone. The discharges of the springs vary from very low discharge (0.2 l/s) to a higher discharge up to a maximum of 15 l/s. Based on the existing data and field observations, the potential of sandstone aquifer is considered to be moderate.

4.2.1.3 Intergranular and Fractured aquifers with low potential

The intrusive granite rock and the high grade metamorphic gneiss are included in this category. They are mainly exposed in the north, northeastern, eastern, southeastern and central parts of the catchment covering 28% of the catchment area. Its groundwater potentiality is highly associated with the occurrence of weathering zone and tectonic fractures, contact with the surrounding metamorphic rocks and differences in composition, structure and texture with the same rock. Several number of hand dug wells are existed in these units. The weathered layers and fractures are the main sources of groundwater supply in both rocks of the catchment. The depth of the hand dug wells ranges from 4 m to 25 m, and the static water lever varies from 3m to 9m. The discharge of the wells range from 0.5 to 1.5 l/ s. Due to limited thickness of weathered zones and fractured layers, the aquifers of the granite and gneiss units are considered to be low potentiality.

4.2.1.4 Karstic aquifers with very low potential

The limestone units are mainly exposed in the north and north east parts of the study forming steep cliffs. They are characterized by secondary porosity and permeability which resulted from fracturing, solution cavities and opening along bedding planes. The geomorphological feature of the lithology and the moderate permeability of the underlying sandstone have facilitated the down ward movement of groundwater from this unit. Hence, the availability of groundwater resource in this unit is quite limited. There are only few low discharge springs (0.2 l/s) emanating along the contact with the underlying sandstone. Therefore, the limestone unit can be taken as an aquifer of very low potentiality.

4.2.1. 5 Less fractured aquifers with extremely low potential

The rock units which are characterized by very poor permeability are migmates. They are mainly exposed in the northwestern part of the study. The rock units are less affected by tectonic activity and weathering. The existing of fracturing and weathering sections in such unit is almost insignificant. It has been noticed that in the northwest part of the catchment along the margins of this unit, small seepage zones are existed. Thus, considering the existing of seepages, the massiveness and non-weathered conditions of the rock unit, the migmatite unit has been taken as negligible potentiality.

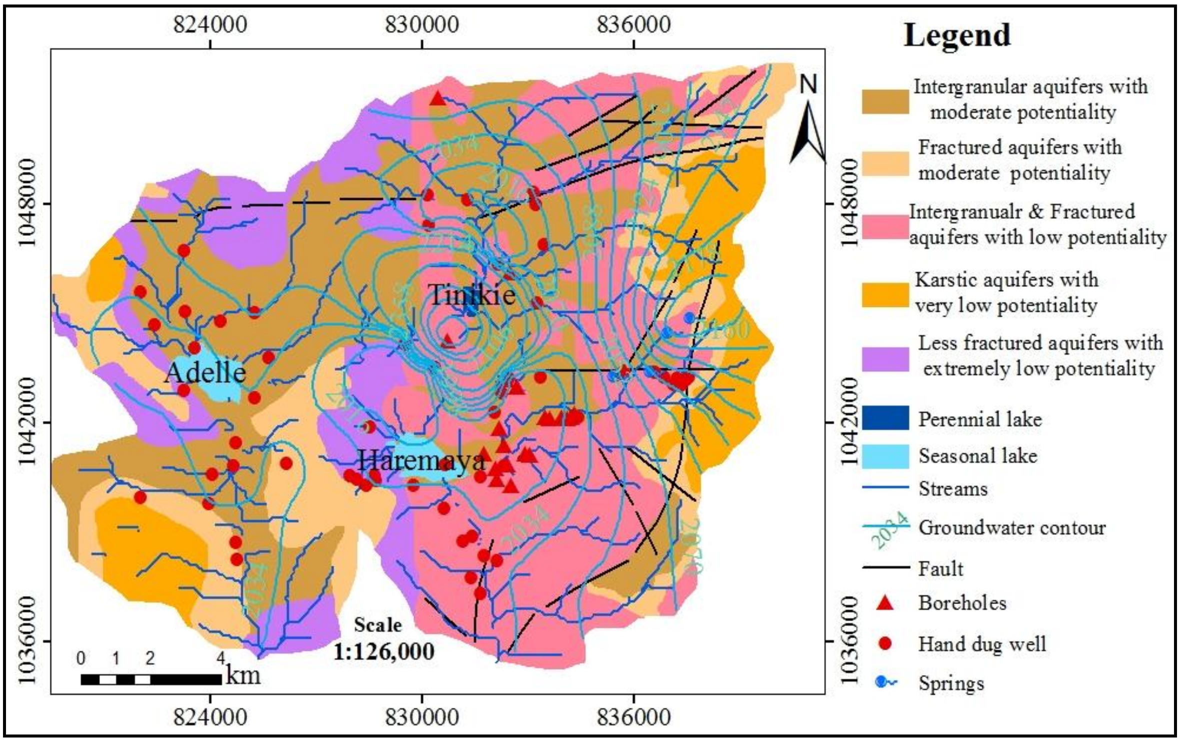

Figure 4.3. Hydrogeological map.

4.2.2 Groundwater movement, recharge and discharge mechanisms

The Addele- Haromaya dry lake catchment is recharged through direct recharge from precipitation, and indirect recharge through infiltration from seasonal streams and lakes. The hilly landscapes bounded the catchment in the north west and north east parts are the main recharge zones. They are completely recharged through direct precipitation while small parts of the depressed topography are recharged from the surface run off emanating from the near up lands.

Both artificial and natural discharge zones are existed in the catchment. The artificial discharge zones are characterized by the boreholes and hand dug wells. They are located and uniformly distributed in the low depressed topography of the catchment. The natural discharge zones are confined to the eastern highlands of the catchment where the springs are emerged (Figure 4.3).

The general groundwater flow system of the catchment is highly controlled by its topography, geology and structures (contact zones). On the basis of the hydraulic head distribution from various boreholes and wells in the same aquifer system, groundwater contour map has been constructed to show the groundwater flow direction. The general trend of groundwater flow is towards the depressed flat topography from the surrounding hilly landscapes. The groundwater flow is almost in the same direction with that of surface flow. The temperature recorded from both the springs and the boreholes is almost same with ambient temperature of the study area; moreover, low discharge springs are existed at relatively higher topographic elevation. Accordingly, the groundwater system of the catchment can be considered as relatively shallow or local groundwater circulation system.

4.3 Hydrochemistry

The chemical composition of natural water is derived from many different sources of solutes, including gases and aerosols from the atmosphere, weathering and erosion of rocks and soil, solution or precipitation reactions occurring below the land surface, and cultural effects resulting from human activities. Solutes contained in natural water represent the net effect of a series of antecedent chemical reactions that have dissolved material from another phase, have altered previously dissolved components, or have eliminated them from solution by precipitation (Hem, 1985). The ways in which solutes are taken up or precipitated, and the amounts present in solution are influenced by environmental factors such as climate, structure and position of rock strata and biochemical effects associated with life cycle of plant and animals. The main objective of the hydrochemical study in this paper work is only to understand its quality for human use and irrigation purposes based on limited physico – chemical tests. Only very important and relevant parameters are addressed.

4.3.1 Electrical conductivity, Total Dissolved Solids (TDS) and P^H

Electrical conductivity (Ec) is the ability of water to conduct electrical current. It is a function of temperature, type of ions present and concentration of various ions. The calcium bicarbonate and calcium sulfate water types have the lowest conductance; on the contrary, sodium chloride water type has the highest conductance for a given total concentration of dissolved solids (Davis & De Wiest, 1966). The Ec values of groundwater samples range from 535 to 3157 µs/cm with an average value of 1010 µs/cm.

The total dissolved solids (TDS) in a water sample include all solid material in solution, whether ionized or not. It does not include suspended sediment, colloids, or dissolved gases. The TDS values of water samples range from 321 to 1984 mg /l with an average value of 607 mg/l. except three groundwater samples, the TDS values of all samples are below 1000 mg /l.

P^H represents the concentration of hydrogen ion [H^+] as the result of the dissociation of water. The P^H of pure water at 25°C is 7.0 (neutral). When the water has more than 7, it will be alkaline and if it is less than 7 it becomes acidic. The water samples of the area are close to neutral. It ranges from 7.19 to 7.92. The P^H values of all samples satisfy the WHO water quality standard permissible for drinking.

4.3.2 Major Cations

The chemical analysis of groundwater samples show that calcium is the most dominant cation followed by sodium, magnesium and potassium. The concentration of calcium varies from 72 to 543 mg/l with an average value of 208 mg/l. The source of calcium in the groundwater is related to clay material produced from weathering of silicate minerals which overlays the water bearing zones. The second dominant cation in the analyzed groundwater samples of the catchment is sodium. The range of its concentration varies from 458 mg/l to 30 mg/l with a mean value of 113mg/l. Its source in groundwater is from the release of soluble products during weathering of feldspar rich granite. Except in one hand dug well (HHDW-7), the concentration of sodium in groundwater is less than calcium concentration. The higher concentration sodium in HHDW-7 could be cation exchange process. Aquifers with high proportion of clay have usually high cation exchange capacity. In case of magnesium the concentration varies from 224 mg/l to 18 mg/l with an average value of 60mg/l. Unlike calcium, sodium and magnesium, the concentration of potassium shows slight variation. It varies from 7.6 mg/l to 0.4 mg/l with a mean value of 2.89 mg/. Generally, the concentration of potassium is low. This is related to the relative immobility of potassium due to the fact that potassium enters into the structure of clay and clay-like minerals during weathering; and the higher resistance to weathering of potassium mineral in relation to the sodium minerals.

4.3.3 Major Anions

The major anions in groundwater samples of the study area are bicarbonate, chloride, sulfate and nitrate in their decreasing order of concentration. In the study area, bicarbonate (HCo_3^-) is the most dominant ion among anions. Its concentration varies from 393.5 mg/l to 173 mg/l with an average value of 299 mg/l. The origin of HCo_3^- ions in groundwater are from the carbon dioxide in the atmosphere, carbon dioxide in soil, and solution of carbonate rocks (Davis and De Wiest, 1966). Chloride (Cl^-) is the next dominant anion in the groundwater next to bicarbonate. Chloride values range from 255mg/l to 38mg/l with a mean value of 106 mg/l. Sulfate is the third most dominant anion. The values range from 7.2 to 51.80 mg/l with a mean concentration of 25.03 mg/l. Although igneous rocks contain small amounts of soluble nitrate, most of nitrate in natural water comes from organic sources or from industrial and agricultural chemicals (Davis and De Wiest, 1966). The concentration of nitrate ($NO3^-$) in the groundwater varies from 790 to 0.34 mg/l with an average value of 54mg/l. Three hand dug well samples show above the recommended WHO water quality guide line for drinking (45 mg/l). The prevalence of high concentration of nitrate in groundwater could be associated with the use of synthetic agricultural fertilizer (ammonia) and poor domestic waste management.

4.3.4 Water type classification

4.3.4.1 Classification based on dominant cations and anions

An important task in geochemical investigation is the compilation and presentation of chemical data in a convenient manner for visual inspection. Several commonly graphical methods are available. Among the different methods, piper diagram have been used for water type classification. It is the most common and widely used method which classifies water based on the percentage of miliequivalent per liter of major cations and anions.

Using aquachem computer program, the chemical analysis results of twenty one water samples have been plotted in piper diagram. Accordingly, the identified groundwater types are Ca-Mg-HCO_3, Ca-Mg-Cl-HCO_3, Mg-Na-Ca-SO_4 and Na-Mg-Cl-SO_4 types (Figure 4.4). The water chemistry of seasonal lakes of the catchment varies form Mg-Na-

Ca-SO4 to Na-Mg-Cl-SO_4 water types. The perennial lake (Tinikie) has Na-Mg-Ca-HCO_3-Cl water type.

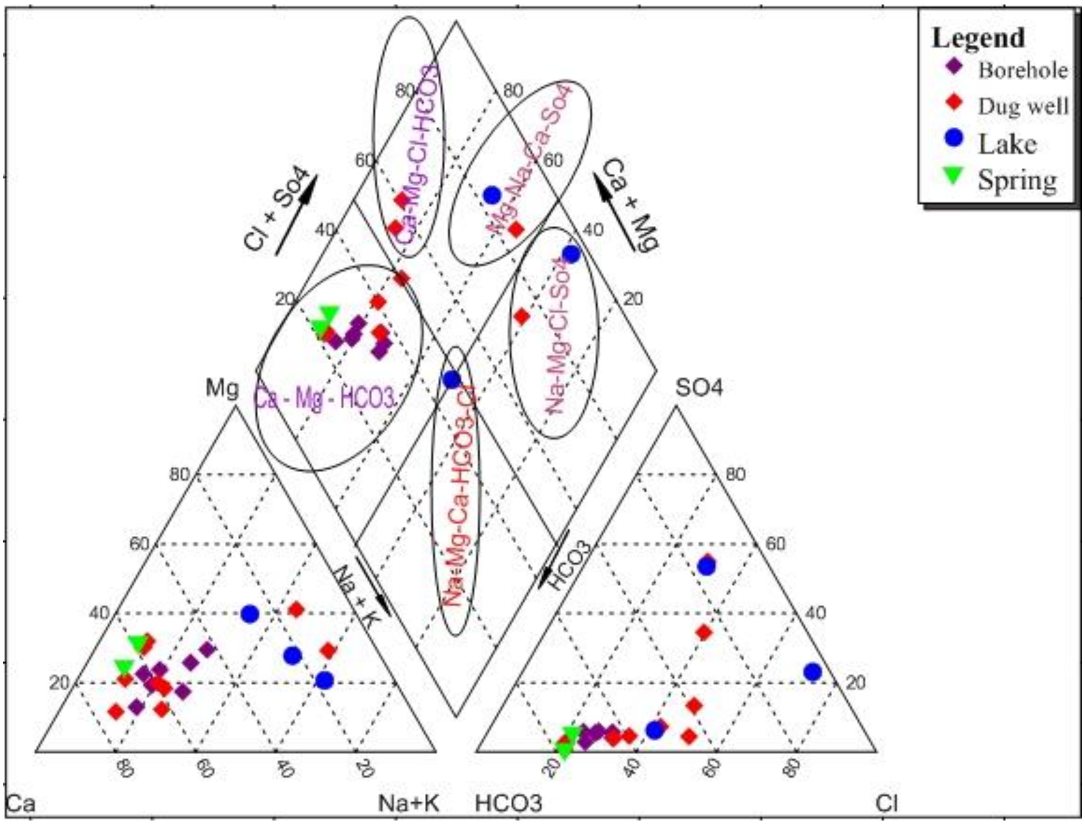

Figure 4.4 Piper diagram for water type classification of the study area.

4.3.5 Groundwater quality assessment

The quality of groundwater is just as important as its quantity. Groundwater quality comprises the physical, chemical and biological qualities. The chemical water quality parameters include Total dissolved solids (TDS), electrical conductance (EC), hydrogen ion activity (PH), hardness, sodium adsorption ratio (SAR), and major, minor and trace ion constituents. Temperature, turbidity, taste and odor make up the list of physical water quality parameters while coliform bacteria are related to biological water quality parameter. Since most groundwater is colorless, odorless and taste-less, emphasis is given to chemical and biological qualities. The primary purpose of groundwater quality analysis is to determine the suitability of water for the intended use. Accordingly, the drinking and irrigation water qualities of the study area are briefly described below.

4.3.5.1 Drinking water quality assessment

In order to determine the suitability of groundwater for drinking purpose, water samples were collected from different water points of the catchment. The collected samples were analyzed and compared with the WHO (2008) water quality standards for drinking. The values of the selected water quality parameters in comparison with WHO drinking water quality standards are presented in table 4.1. In general, the majority of spring and groundwater lies within the permissible limit of the WHO drinking water quality standards.

Table 4.1. Comparison of water quality analysis with WHO guide line.

Quality parameters	Analyzed water samples			WHO guide line	
	Max. con	Min. con	Total no. in % above recommended concentration	Recommended concentration	Max.allowable concentration
No_3 (mg/l)	790	0.32	16.67	< 50	50
Cl (mg/l)	255.2	38.3	5.55	< 250	250
F (mg/l)	3.84	0	11.11	< 1.5	1.5
So_4 (mg/l)	571.5	1.46	11.11	<250	250
B (mg/l)	0.67	0.09	27.78	< 0.3	0.3
Na (mg/l)	458	30	11.11	< 200	200
TDS (mg/l)	1894	321	16.67	< 1000	1000

Note: Max = maximum, Min= minimum, con = concentration, no= number

Some of the drinking water quality concerns in the area are boron, nitrate, fluoride, sulfate and sodium. Boron ranges from 0.09 mg/l to 0.67 mg/l, and 27.78% of the water samples are well beyond the recommended value. Long term exposure to high boron concentration will lead to gastrointestinal irritation. Nitrate concentration in the catchment have shown an extreme variability which ranges from 0.32 mg/l to 790 mg/l. Out of the analyzed water samples, 16.67 % of them are out of the WHO standard value. The ingestion of water containing nitrates in excess of 50 mg/l (as nitrate) may give rise to methaemoglobinaemia in infants under one year of age. Excessive quantities of fluoride in drinking water can cause health effects in human. Eleven percent of the water samples lie above the recommended limit for drinking. Exposure to high levels of fluoride which occurs naturally can lead to mottling of teeth, and in severe cases crippling skeletal fluorosis. Chloride is found to be more than the guideline value in a single hand dug well. High concentrations of chloride will result in salty taste. Sulfate in the water samples range from 1.46 mg/l to 571.5 mg/l, and 11.11% of the water samples are well beyond the recommended value. The presence of sulfate in drinking-water can cause noticeable taste. The concentration of sodium is between 30 mg/l to 458 mg/l, and 11.11% of the water samples are well beyond the recommended value. Sodium concentrations in excess of 200 mg/l may give rise to unacceptable taste.

4.3.5.2 Irrigation water quality assessment

The suitability of groundwater for irrigation is dependent on the effects of the mineral constituents of the water on both the plant and the soil. Good quality water permits maximum yields consistent with proper soil and water management. The irrigation water qualities of the study area have been evaluated with respect to salinity hazard, water infiltration rate and specific ion toxicity (Table 4.2).

Table 4.2. Guide lines for interpretations of water quality for irrigation.

Potential Irrigation Problem				Units	Degree of Restriction on Use		
					None	Slight to Moderate	Severe
Salinity hazard							
	EC			μs/cm	< 750	750 – 3216	> 3216
	TDS			mg/l	< 450	450 – 2000	> 2000
Infiltration rate (Evaluated using EC and SAR together)							
SAR	= 0 – 3	and EC	=	μs/cm	> 750	750 – 214	< 214
	= 3 – 6		=	μs/cm	> 1286	1286 – 322	< 322
	= 6 – 12		=	μs/cm	> 2037	2037 – 536	< 536
	= 12 – 20		=	μs/cm	> 3109	3109 – 1394	< 1394
	= 20 – 40		=	μs/cm	> 5360	5360 – 3109	< 3109
Specific Ion Toxicity							
	Sodium (Na)			SAR	< 3	3 – 9	> 9
	Chloride (Cl)			mg/l	< 142	142 – 345.5	> 345.5
	Boron (B)			mg/l	< 0.7	0.7 – 3.0	> 3.0

Source : (FAO, 1985)

4.3.5.2.1 Salinity hazard

Water used for irrigation can vary greatly in quality depending upon the type and quantity of dissolved salts. They originate from dissolution or weathering of the rocks and soil, dissolution of lime, gypsum and other slowly dissolved soil minerals. These salts are carried with the water to wherever it is used. Salts can harm plants growth physically by limiting the uptake of water through modification of osmotic process. Its effects on soils can also cause changes in soil structure, permeability and aeration which indirectly affect plant growth. The salinity hazard of any water commonly expressed in terms of its TDS or EC values. According to FAO (1985) irrigation water quality guide line, water with TDS value less than 450 mg/l is non-salinity hazard, waters in range of 450 – 2000 mg/l are slight to moderate salinity hazard while waters greater than 2000 mg/l are considered as sever salinity hazard.

Water samples from different water sources (groundwater, springs and lakes) have been collected and analyzed. Out of the analyzed sixteen groundwater samples, nine samples have TDS values below 450 mg/l, and the remaining seven samples have TDS ranging from 451 to 1894 mg/l (see annex 4.1). Based on TDS values, two types of groundwater are recognized in both shallow boreholes and hand dug wells. These are groundwater which is not hazardous and needs no restriction on use, and groundwater which needs slight to moderate degree of restriction on use. Water samples from springs have shown different TDS values. The TDS values of springs range from 397 to 921 mg /l. Like water from boreholes, spring water varies from non-restriction on use to slight to moderate degree of restriction on use. The TDS of the perennial lake water is below 450 mg/l indicating the lake water needs no restriction on use while the seasonal lake water is ranging from 617 to 1455 mg/l which fall under slight to moderate degree of restriction on use. Generally, the TDS values indicate that two types of water are identified in the catchment from all sources. The first type is water which is not hazardous and needs no restriction on use, and the second water type needs slight to moderate degree of restriction on use. The first type of water can be used for irrigation for almost all crops and for almost all kinds of soils. No soil or cropping problems will rise in using it. It is possible to use the second water type through practicing salinity management alternatives. The most common salinity management methods are drainage, salinity control by leaching and selection of crop tolerance to salinity.

4.3.5.2. 2 Water infiltration rate

An infiltration problem related to water quality occurs when the normal infiltration rate for the applied water is appreciably reduced, and water remains on the soil surface too long or infiltrates too slowly to supply the crop with sufficient water to maintain acceptable yields. An infiltration rate as low as 3 mm/hour is considered low while a rate above 12 mm/hour is relatively high. The infiltration rate of water into soil varies widely and can be greatly influenced by the quality of the irrigation water, soil factors such as structure, degree of compaction, organic matter content and chemical make-up of the soil.

The two principal effects of sodium are a reduction in soil permeability and hardening of soils. Both effects are caused by the replacement calcium and magnesium ions by sodium ions on the soil clay and colloids. The extent of this replacement can be estimated by the sodium adsorption ratio (SAR) which can be expressed by:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \quad \text{where : Na, Ca, and Mg are in miliequivalents per liter}$$

The two most common water quality factors which influence the normal infiltration rate are the salinity of the water (total quantity of salts in the water) and its sodium content relative to the calcium and magnesium content (SAR). High salinity water will increase infiltration. Low salinity water or water with high sodium to calcium ratio will decrease infiltration. Both factors may operate at the same time. The infiltration rate generally increases with increasing salinity and decreases with either decreasing salinity or increasing the sodium adsorption ratio (SAR). Therefore, the two factors, salinity and SAR must be considered together for a proper evaluation of the ultimate effect on water infiltration rate.

The relative infiltration rate of the catchment water has been evaluated by its sodium adsorption ratio (SAR) and corresponding salinity values. From the analyzed groundwater samples, 44% of them have indicated no reduction in rate of infiltration while the remaining 56% of the samples indicated slight to moderate in reduction in rate of infiltration. Except one seasonal lake (Addele) which has no reduction in rate of infiltration, the SAR values of all springs and lakes are between 0.56 to 3, and the corresponding salinity values ranges from 553 to 1029 μs/cm. Thus, the spring and lake waters have slight to moderate capacity of reducing the infiltration rate.

4.3.5.2.3 Toxicity

Toxicity problems occur if certain constituents (ions) in the soil or water are taken up by the plant, and accumulate to concentrations high enough to cause crop damage or reduced yields. Toxicity can also complicate salinity or water infiltration problem. The degree of damage depends upon the concentration by the toxic ion, crop sensitivity and the volume of water transpired by the crop. The ions of primary concern are sodium, chloride and boron. Damage results when the potentially toxic ions are absorbed in significant amounts with the water by the roots.

Sodium occurs in almost all irrigation water. It is the most injurious of the major cations. The toxicity of sodium ion is measured with respect sodium adsorption ratio (SAR) values. With the exception of two groundwater samples and one lake water sample (Adelle), all the remaining groundwater and spring water samples have SAR Values less than 3. These values indicate that no sodium toxicity will rise by using the water from these sources for surface irrigation (FAO, 1985). The SAR values of the Adelle Lake and the two groundwater samples lie within the range from 3.13 to 8.12. It suggests the necessity of slight to moderate degree of restriction on use of the water for surface irrigation.

Chloride is the most common toxic ion in the irrigation water. Except the seasonal lake (Adelle) and two dug well water samples, all the groundwater, lake and spring water samples have chloride concentration below 142 mg/l which indicate water from these sources are non-chloride toxic for irrigation. However, the two dug wells are slight to moderate degree of restriction on use while the Adelle Lake is highly chloride toxic.

Boron is a constituent of practically all natural waters. The concentration varies from traces to several parts per million. It is essential for plant growth, but extremely toxic when it is at slightly above optimum concentration. In the study area, all the groundwater, spring and lake water sources were found to have a concentration well below 0.7 mg/l. the values indicate that the water sources are completely free from boron toxicity.

4.3.5.3 Irrigation water classification

The irrigation water in the catchment has been classified based on Wilcox diagram. Accordingly, four classes of water are identified (Figure 4.5). These are S_1-C_2 (low Sodium and medium salinity hazards), S_1-C_3 (low Sodium and high salinity hazard), S_2-C_3 (Medium Sodium and high salinity hazard) and S_2- C_4 (Medium sodium and very high salinity hazards). As shown in figure 4.5, all the spring water, the perennial lake (Tinnikie) and 69 % of the analyzed groundwater samples are in the class of S_1-C_2 (low Sodium and medium salinity hazards), and 2% the groundwater samples and one seasonal lake (Haromaya) are in the class of S_1-C_3 (low Sodium and high salinity hazard), one groundwater sample is in the class S_2-C_3 (Medium Sodium and high salinity hazard), and the remaining one groundwater sample and one seasonal lake (Adelle) are in the class S_2- C_4 (Medium sodium and very high salinity hazard).

The suitability of groundwater for irrigation purposes have been evaluated based upon estimation of parameters like Na% and EC values. The percentage of sodium (Na %) for classification of groundwater suitability for irrigation can be calculated as:

$$Na\% = \frac{(Na + K) * 100}{(Ca + Mg + Na + K)} \text{ where : Ca, Mg, Na and K are in miliequivalents per liter}$$

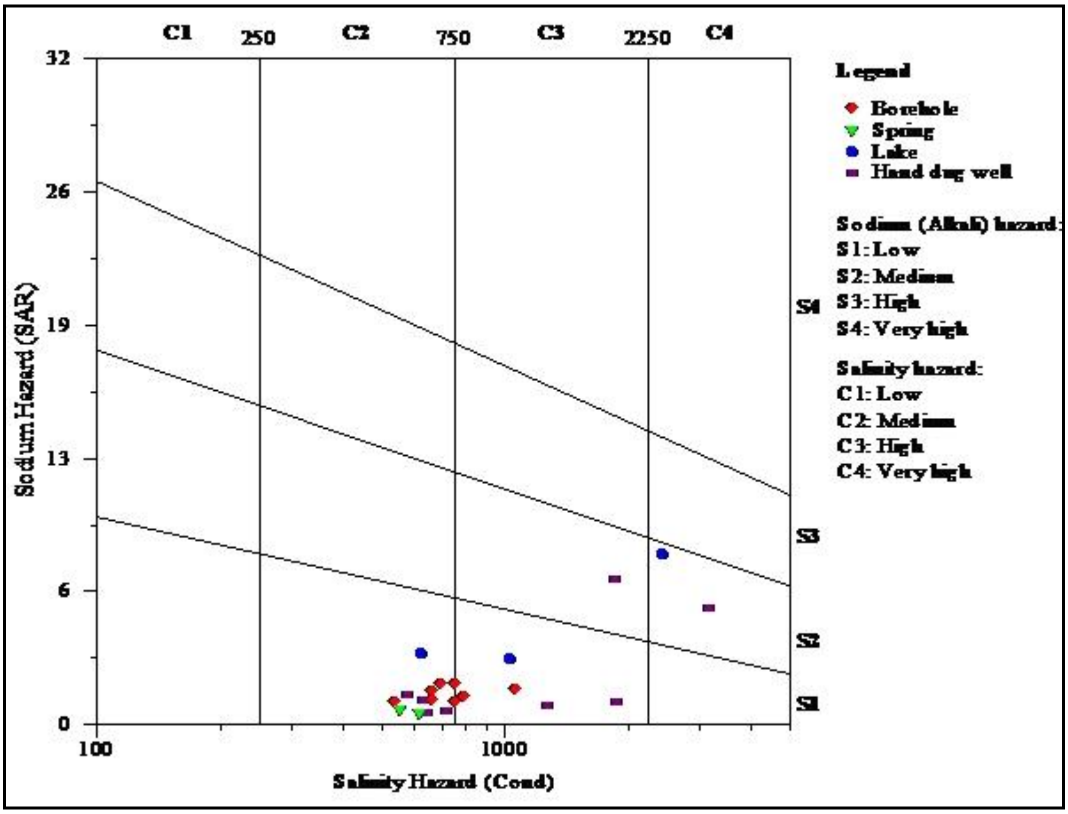

Figure 4.5. Irrigation water classes using Wilcox diagram.

The suitability of irrigation water quality in the catchment has been classified using Wilcox (1955) irrigation water classification scheme (Karmegam et al., 2010). Accordingly, the groundwater can be categorized into excellent, good, permissible, doubtful and unsuitable classes. Considering the EC values, 56.25% of groundwater samples are in good class, and the remaining 37.5% and 6.25% are in permissible and doubtful class respectively (Table 4.3). On the other hand, 100% of the analyzed spring water and perennial lake (Tinikie) are lying in good class while the seasonal lakes are in permissible class. Likewise, the Na % values indicate that except the doubtful suitability of Adelle lake water, all the groundwater, spring and the lake water samples have quality ranging from excellent to permissible quality class.

Table 4.3. Irrigation water quality classification of the study area.

Classification schemes	Grade	Total % water samples		
EC Wilcox (1955)		Groundwater	Spring	Lake
Excellent	< 250 µs/cm	nil	nil	nil
Good	250 - 750 µs/cm	56.25	100	33.33
Permissible	750 - 2250 µs/cm	37.5	nil	66.67
Doubtful	2250 - 5000 µs/cm	6.25	nil	nil
Unsuitable	> 5000 µs/cm	nil	nil	nil
Na % Wilcox (1955)				
Excellent	0 - 20	56.25	100	nil
Good	20 - 40	31	nil	33.33
Permissible	40 - 60	11.75	nil	33.33
Doubtful	60 - 80	nil	nil	33.33
Unsuitable	> 80	nil	nil	

Generally, the Na % and EC values indicate that more than 80% of the groundwater samples are in the range of excellent to permissible quality class.

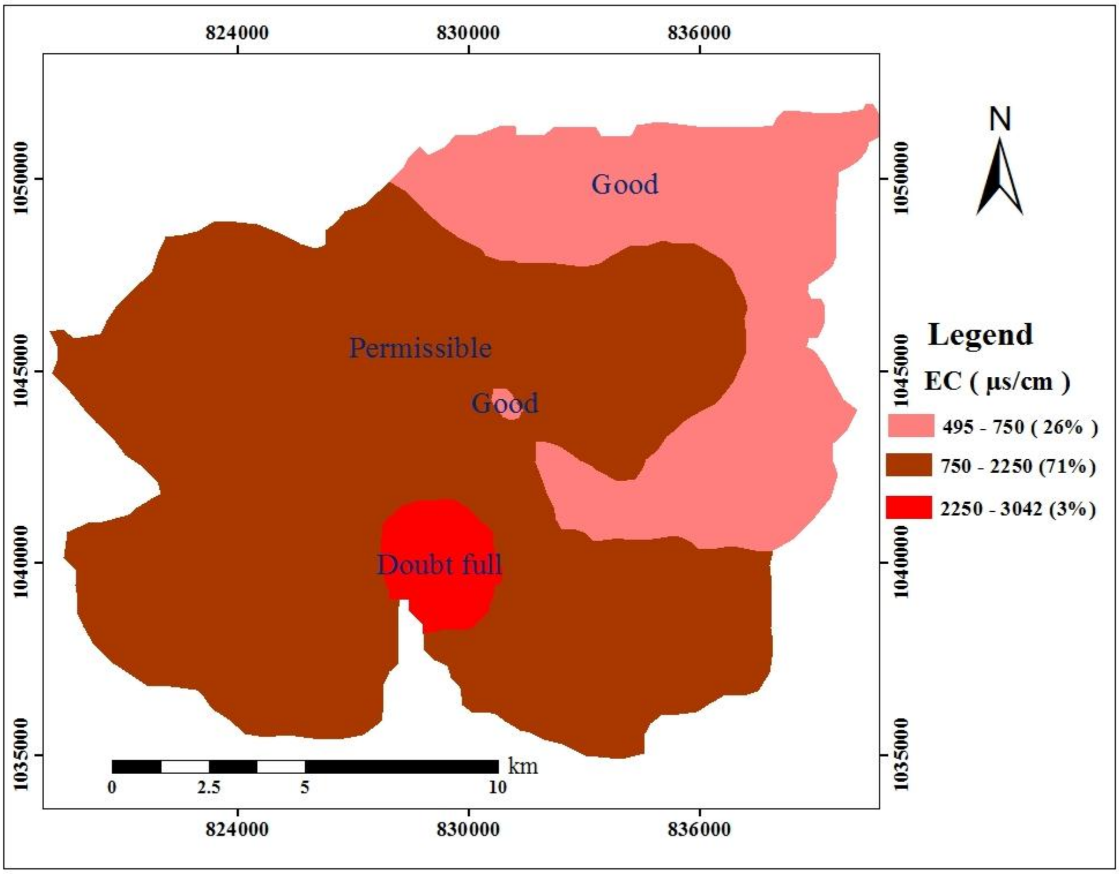

Figure 4.6. Groundwater irrigation suitability map.

The spatial distribution of groundwater suitability for irrigation is shown in the above figure 4.6. The groundwater located in north eastern part of the catchment which account 26% of the total study area are good for irrigation purpose. Groundwater in the central, north western and western part of the study which covers 71% of the total catchment area has an acceptable quality for irrigation. However, only groundwater localized as small patches in the southern part of the catchment covering 3% of the total study area has suspicious quality to be used safely for irrigation.

CHAPTER V: WATER DEMAND ASSESMENT AND GROUNDWATER SUSTAINABILITY INDICATORS

5.1 Water demand assessment

5.1.1 Irrigation water demand

It is well known that water is important for plant growth and food production. The water applied to agricultural crop land entirely dependent on the needs of the crops as each crops has different needs over the growing season. Estimating crop water requirements accurately is important for water project planning and management activities. Hess (2005) as cited in Adeniran et al. (2010) has defined crop water requirements as the total water needed for evapotranspiration, from planting to harvest for a given crop in a specific climate regime, when adequate soil water is maintained by rainfall and/or irrigation. The water requirements of crops mainly dependent on the type and growth stage of crops, the properties of soils, and the prevailing climatic condition of the area.

The major crops grown in the catchment under irrigated conditions are Chat (*Catha Edulis*) and vegetables (potato, lettuce, carrot, onion, tomato and cabbage). Chat (*Catha Edulis*) is an evergreen, mildly narcotic and stimulant perennial shrub which usually has 2-7 m height. It covers 37% of the current irrigable land (Figure 5.1). It is a highly profitable cash crop for the communities living in the area.

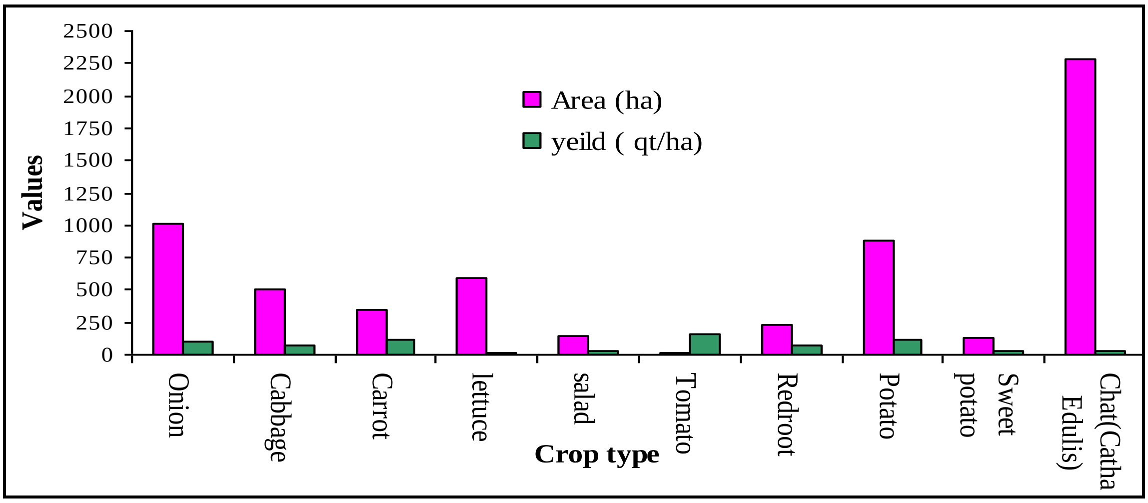

Figure 5.1. The size of irrigated farmland and yields of the different crops in the catchment.

The crop water requirement has been determined from the interrelationships of the evapotranspiration, soil type and the effective root zone of plants of the study area. It was estimated by using the CROPWAT software. The CROPWAT software is a practical tool which computes reference crop evapotranspiration, crop water requirement, irrigation water requirement and irrigation scheduling. In this work only crop water requirement and irrigation water requirement are considered. Climatic parameters that haven been used in the calculation of irrigation water requirements are the monthly maximum and minimum temperatures, average rainfall, air humidity and sunshine hours. The standard values of crop data and cropping pattern including crop coefficient, stage of crop growth/growing period, root depth, soil moisture depletion percentage, yield response factor, planting and harvesting dates are also used for the calculation (Table 5.1).

Table 5.1. Important crop parameters used for crop and irrigation water requirement estimation.

Crop type	Crop coefficient (Kc)			Yield response factor (K_y)					Depletion factor	Rooting depth (m)
	Initial season	Mid-season	Harvest season	Vegetative	Flowering	Yield formation	Ripening	Total		
Chat	0.7	0.65	0.65	0.35	0.8	1.2	0.5	1.2	0.5	1.2–1.5
Potato	0.5	1.15	0.95	0.45	0.8	1	0.4	1.1	0.35	0.4–0.6
Lettuce	0.7	1.05	0.95	0.8	0.4	1.2	1	1	0.3	0.3–0.5
Carrot	0.7	1.05	0.95	0.8	0.4	1.2	1	1	0.35	0.5–1.0
Onion	0.7	1.05	0.8	0.45	0.8	0.3	0.3	1.1	0.3	0.3–0.6
Tomato	0.6	1.15	0.8	0.4	1.1	0.8	0.4	1.05	0.4	0.7–1.5
Cabbage	0.7	1.05	0.95	0.2	0.4	0.45	0.6	0.95	0.45	0.5–0.8
Sweet potato	0.5	1.15	0.95	0.45	0.8	1	0.4	1.1	0.35	0.4–0.6
Red root	0.8	0.4	0.8	0.8	0.4	1.2	1	1		
Salad	0.7	1.05	0.95	0.8	0.4	1.2	1	1	0.3	0.3–0.5

Source: (Allen et al., 1998 and FAO, 1992 cited in Doria et al., 2009 and Shemelis et al., 2011)

5.1.1.1 Reference evapotranspiration

The term reference evapotranspiration (ET_o) refers to the evapotranspiration rate from a reference surface. A large uniform grass or alfalfa field is considered worldwide as the reference surface. The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices (FAO, 2009). The soil factors do not affect the reference evapotranspiration when water is abundantly available at the reference evapotranspiration surface. The only factors affecting ET_o are climatic parameters. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year, and does not consider the crop characteristics and soil factors (Allen et al., 1998).

FAO (1992) CROPWAT software which reflects the Penman-Monteith method is used to calculate the reference crop evapotranspiration.

5.1.1.2 Crop evapotranspiration

Crop evapotranspiration (ET_c) is the evapotranspiration of crops under standard conditions. It is the evapotranspiration from disease free, well fertilized crops, which grown in a large fields under optimum soil, water and a given climatic conditions. The crop evapotranspiration differs distinctly from the reference evapotranspiration (ET_o) as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The characteristics of field crops are basically distinguished from grasses by their crop coefficient (K_c) parameter. Hence, the ET_c can be given by:

$$ET_c = Kc*ET_o \tag{5.1}$$

5.1.1.3 Effective rain fall

For agricultural production, effective rainfall (E_r) refers to that portion of rainfall that can effectively be used by plants. It excludes the rain water which is lost through Runoff (R_O) and Deep Percolation (D_P). It is strongly affected by the soil type, slope, crop canopy, storm intensity and the initial water content of the soil. The most accurate method to determine effective rainfall is through field observation. Rainfall is highly effective when little or no R_O takes place. Small amount of rainfall is not very effective as it is lost by evaporation. Er can be written as:

$$E_r = T_r - (R_o + E) \tag{5.2}$$

Where, Tr = Total rain fall and E is evaporation

5.1.1.4 Irrigation water requirement and crop water requirement

Irrigation is required when rainfall is insufficient to compensate for the water lost by evapotranspiration. The primary objective of irrigation is to apply water at the right period and in the right amount. The general equation to determine the irrigation water requirement (IWR) can be given by:

$$IWR = ET_c - E_r \tag{5.3}$$

In most cases IWR can be found by subtracting the effective rain fall from crop water requirement (CWR). i.e

$$IWR = CWR - Er \quad (5.4)$$

The irrigation and crop water requirements of the catchment are directly calculated by the CROPWAT software. The effective rainfall is also calculated with this software using the US soil conservation service method.

Based on the current irrigated land coverage of the catchment and the prevailing climatic condition of the area, both crop and irrigation water requirement for each crop have been estimated. Thus, the total amount of water required to irrigate all crops is 1.82MCM/year (Table 5.2). The total estimated irrigation water requirement is lower than the current groundwater abstraction which has been used for irrigation. The farmers irrigated their farmland by 140 % more than the actual irrigation water requirement. Due to low irrigation water application efficiency, a total of 2.59MCM/year of water is lost as it is not used by crops.

Table 5.2 Annual Crop and Irrigation water requirement for each crops in the study area.

No	Crop type	Area (ha)	CWR (mm/dec)	Eff.rain (mm/dec)	IWR (mm/dec)	CWR (MCM/yr)	IWR (MCM/yr)
1	Catha Edulis (chat)	2290.00	401.40	122.90	278.40	0.92	0.64
2.	Potato	882.00	429.40	91.40	336.80	0.38	0.08
3	Lettuce	595.00	330.60	40.10	293.80	0.20	0.17
4	Carrot	349.00	300.30	32.30	268.00	0.10	0.09
5	Onion	1011.00	481.90	123.10	355.50	0.49	0.36
6	Tomato	20.00	274.60	109.20	167.60	0.01	0.00
7	Cabbage	508.00	291.00	53.90	238.70	0.15	0.12
8	Sweet potato	127.00	617.70	214.10	400.40	0.08	0.05
9	Red root	230.00	264.40	62.60	200.90	0.06	0.05
10	Salad	150.00	330.60	40.10	293.80	0.05	0.04
	Total	6162.00	3721.90	889.70	2833.90	2.43	1.82

According to the Haromaya Woreda Agricultural and Rural Development Office, the total irrigable land area has been increasing by 3% each year. Considering the irrigable land expansion rate with respect to crop type is constant in the coming years, the total irrigable land has been projected. Likewise, the total crop and irrigation water requirements for each crop have also been estimated for the coming few decades (Table 5.3).

Table 5.3. Projected Irrigable land, IWR and CWR of the catchment.

Baseline		Projected Irrigable land, IWR and CWR						
Year	2012	2017	2027	2037	2047	2057	2067	2077
Irrigable land area (ha)	6162	8317.83	11227.9	15156.07	20458.6	27616.17	37277.93	50319.94
IWR (MCM)	1.83	2.47	3.33	4.5	6.07	8.19	11.06	14.93
CWR(MCM)	2.43	3.28	4.43	5.97	8.06	10.89	14.69	19.83

5.1.2 Domestic water demand

According to (CSA, 2007) population and housing census report, the population size of Addele-Haromaya dry lake catchment is about 297,904. Out of this, 91% of the population belongs to Haromaya woreda while about 6% and 3% are that of Haromaya University and Aweday town. Based on the annual population growth rate of Oromiya Region which is 2.9%, the current population has been projected for the coming seventy years.

WHO (2002) defines domestic water as being water used for all usual domestic purposes including consumption, bathing and food preparation. Identifying the different domestic water uses is important in determining the water requirement for domestic water supply. The domestic water uses can be categorized in to four types. These are 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). Estimation of domestic water demand mainly confined to the ingestion use and hygiene use.

The estimation of per capita water requirement varies from country to country. However the researcher has estimated the total amount of domestic water demand using the standards of (WHO/UNCEF 2000). The domestic water demand for basic ingestion and hygiene needs is usually considered as 20 liters per capita per day (WHO/UNICEF, 2000 cited in Chenoweth, 2008). Assuming 100% of the groundwater dependable population of the catchment has an access to clean water, the current domestic water demand of the area is estimated to be 2.51MCM/year (Table 5.4).

Table 5.4. Projected groundwater dependable population and their domestic water demand

Baseline		Projected population and water demand								
year	2007	2012	2017	2027	2037	2047	2057	2067	2077	2087
Total population	297904	343679	398127	532068	711070	950294	1269999	1697261	2268267	3031374
Domestic water demand (MCM)	2.17	2.51	2.91	3.88	5.19	6.94	9.27	12.39	16.56	22.13

Considering the current irrigable land coverage and the 2007 population number as baseline, the future total groundwater demand of the catchment is evaluated and projected (Table 5.5).

Currently, the total groundwater abstraction from the catchment is 13.78MCM per year. It is higher than the safe yield of the catchment which has been calculated earlier. The groundwater dependable population of the catchment can safely abstract the groundwater resource for the next 17years provided that they have used the groundwater according to the estimated domestic water demand and irrigation water requirement of the crops as well as by increasing irrigation efficiency to reduce water loss.

Table 5.5. Projected total water requirement in the Adelle-Haromaya lake catchment.

Baseline		Projected population, irrigable land area and total water demand								
Year	2007*	2012*	2017	2027	2037	2047	2057	2067	2077	2087
Total population	297904	324982	398127	532068	711070	950294	1269999	1697261	2268267	3031374
Irrigable land area (ha)	5632	6162	8318	11228	15156	20459	27616	37278	50320	67925
Domestic water demand (MCM)	2.17	2.51	2.91	3.88	5.19	6.94	9.27	12.39	16.56	22.13
IWR (MCM)	1.67	1.83	2.47	3.33	4.5	6.07	8.19	11.06	14.93	20.15
Total water demand (MCM)	3.84	4.34	5.38	7.21	9.69	13.01	17.46	23.45	31.49	42.28

2007* and 2012* are the actual baseline years for population and irrigable land area.

5.2 Groundwater sustainability indicators

5.2.1 Significance of indicators

Indicators can serve for a variety of policy goals. They help in the improvement of water resource management policy through better assessment of the water resource situation in a given hydrological and hydrogeological system. This can be achieved by identifying critical problems and their causes, which provide a basis for comparison with similar spatial units elsewhere (Groundwater indicators working groups, 2007). This also leads to improved monitoring and reporting of progress against set targets as well as improved evaluation of water policy strategy and actions which provide better mobilization of resources.

The main functions of indicators are to simplify, quantify, organize and communicate data for comparison of different regions of hydrogeological units. Indicators provide information on the system or process under consideration in an understandable way. They evaluate the effect of performed policy actions and plans; and also they can help to develop new actions. Thus, indicators act as an important communication tool for policy-makers and managers. The most common use of indicators is in description the state of the resource. Regular measurement of indicators provides time series (showing trends) that may provide information on the functioning of the system or its response to management activities. An indicator value can be compared to a reference condition, and used as a tool for assessment which ultimately used for predicting the future condition of the resource.

5.2.2 Proposed indicators

In the proposed list of indicators each indicator describes a specific aspect of groundwater systems and/or processes. These include the use of groundwater, groundwater quality and vulnerability to pollution. Indicators can be combined into index which provides compact and targeted information for groundwater planning, policy and management. An index is dimensionless in which various weighting and rating systems can be applied to its construction. The proposed groundwater indicators are based on measurable and observable data. They provide information about groundwater quantity and quality (contemporary state and trend). They are also focused on social (groundwater accessibility, exploitability and use), economic (groundwater abstraction, protection and treatment requirements) and environmental (groundwater vulnerability, depletion and pollution) aspects of groundwater resources policy and management. However, groundwater indicators can be integrated into various water and environmental related indicators, and water dependent human activities (e.g. industry, agriculture and mining).

Considering the current availability of data and the type of the groundwater resource of the catchment, four groundwater indicators have been proposed to evaluate groundwater sustainability of the study area at catchment level (Table 5.7). These are Renewable groundwater resources per capita, total groundwater abstraction / groundwater recharge, total groundwater abstraction / exploitable groundwater resource and groundwater quality. In order to describe the above indicators, it is important to define the following terms:

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

Exploitable groundwater resource: - the amount of water that can be annually abstracted from a given aquifer under the current socio-economic constraints and ecological conditions.

Non-renewable groundwater resources: - groundwater bodies (deep aquifers) that have negligible rate of recharge on the human time-scale and thus can be considered as non-renewable.

Renewable groundwater resources: **-** the average annual flow of rivers and recharge of aquifers generated from precipitation. They can be computed on the basis of the water cycle. They represent the long-term average annual flow of rivers (surface water) and groundwater.

Renewable groundwater resource (GWRR) can be computed by using the following formula:

GWRR = Recharge + Seepage – Base flow + Inflow - Outflow + Art.Recharge

From previous estimation the values of recharge, outflow and inflow in the catchment were found to be 10.06, 14.34 and 10.06 MCM/year respectively. Since the catchment is closed one, both surface runoff and base flow are considered to be zero. The values of seepage and artificial recharge in the catchment are also negligible. Thus, GWRR of the catchment is estimated to be 5.78MCM/year (Table 5.6).

Table 5.6. Groundwater resources of the study area.

No	Groundwater resource	MCM/year
1	Total recharge (Gr)	10.06
2	Total abstraction (W)	13.78
3	Exploitable groundwater resource (Q_{ed})	6.73
4	Renewable groundwater resource (GWRR)	5.78

5.2.2.1 Renewable groundwater resources per capita

The indicator is defined as the total renewable groundwater resources without considering groundwater quality but excluding brackish and saline waters. The objective of this indicator is to estimate the amount of good (safe) drinking water, water for agriculture (particularly for irrigation) and for industry that exists in a defined area. It is an important factor for social and economic development of a country. In relative terms, the higher the value of this indicator is the better the possibility of using renewable groundwater resources for development purposes. It can be given by:

$$\frac{\text{Renewable groundwater resource}}{\text{Number of inhabitants}}$$

The calculated renewable groundwater resource per capita of the catchment is 53 L/day/capita. This value indicates that at current condition, the possibility of using renewable groundwater resource for development purposes could have a high negative impact on groundwater resource (Table 5.8).

Table 5.7. Proposed groundwater sustainability indicators with their scenarios.

No	Indicators	Scenarios	Descriptions
1	$\frac{\text{Renewable groundwater resource}}{\text{Number of inhabitants}}$	> 1500 L/day/capita	Low negative impact on groundwater
		500 – 1500 L/day/capita	Moderate » »
		< 500 L/day/capita	High » »
2	$\frac{\text{Total groundwater abstraction}}{\text{Groundwater recharge}} * 100\%$	< 90%	Under developed groundwater resources
		=100%	Developed groundwater resources
		>100 %	Over exploited groundwater resources
3	$\frac{\text{Total groundwater abstraction}}{\text{Exploitable groundwater resource}} * 100\%$	< 90%	Under developed groundwater resources
		=100%	Developed groundwater resources
		>100 %	Over exploited groundwater resources
4	$\frac{\sum \text{areas with natural groundwater quality problem}}{\text{Total studied area}} * 100\%$	< 5%	Low natural quality problem
		0.05 – 10%	Moderate » »
		>10%	High » »

Source: (Groundwater indicators working groups, 2007).

5.2.2.2 Total groundwater abstraction/Groundwater recharge

Groundwater abstraction as part of the groundwater recharge has been proposed as a catchment level indicator. It considers the natural and induced recharge, and total groundwater abstraction. This indicator may encourage managers to judge the likely level of sustainability through linking the abstraction to groundwater recharge. The result belongs to one of the three scenarios (see table 5.7). The formula for this indicator is:

$$\frac{\text{Total groundwater abstraction}}{\text{Groundwater recharge}} * 100\%$$

The indicator value for total groundwater abstraction / groundwater recharge is 137%. According to the classification of the groundwater indicators working group, the defined indicator value falls into the third scenario (>100%) which shows that the groundwater resource have been overexploited. Thus, the current abstraction of groundwater should be minimized.

5.2.2.3 Total groundwater abstraction/Exploitable groundwater resources

The indicator relates the groundwater abstraction to exploitable groundwater resource. This indicator may encourage managers to link the total volume of groundwater that can be abstracted annually to groundwater recharge and recognize possible over-abstraction. This indicator tells whether groundwater abstraction is sustainable or not. The result belongs to one of the three scenarios. It can be given by:

$$\frac{\text{Total groundwater abstraction}}{\text{Exploitable groundwater resource}} * 100\%$$

The estimated indicator value for groundwater abstraction/exploitable groundwater resource is 205%. The current groundwater abstraction is much greater than the exploitable groundwater resource. Hence, the groundwater resource of the catchment has been overexploited.

5.2.2.4 Groundwater quality

Groundwater quality indicators provide information on the current status and trends in groundwater quality, and may help to analyze and visualize groundwater quality problems in space and time. It may be developed and implemented with respect to drinking water standards, food processing, irrigation requirements, industrial use and others. It can also be devised for the special circumstances of naturally occurring contamination mainly associated with inorganic species.

The proposed indicator for naturally occurring quality problem is defined by the relationship:

$$\frac{\sum \text{areas with natural groundwater quality problem}}{\text{Total studied area}} * 100\%$$

The area of aquifer that represents natural groundwater-quality problems means the sum of those parts of the aquifer in which the concentration of the indicator parameter exceeds the maximum level specified in the WHO drinking water guidelines or equivalent. For naturally-occurring contamination, the substances of concern are arsenic, chloride (salinity) and fluoride, and less frequently magnesium, Sulphate, manganese, selenium, Boron or other inorganic species. The total studied area means the total area of an aquifer or total area of the catchment under consideration. The concentration of the indicator parameters considered in this paper is based on the WHO drinking water guideline. Cl^-,F^-, $SO4^{2-}$, Mg^{2+}, Na^+ and B ions are the selected inorganic quality indicator parameters of the catchment that have been considered for this indicator analysis. The spatial distributions of these ions have been labeled in the map for estimating the aerial coverage. Accordingly, the total area with natural groundwater quality problems of the catchment is estimated to be 158 Sq.km (Figure 5.2). The estimated indicator value is found to be 61%. Thus, the indicator value falls in the third scenario (>10%) of quality indicator which shows that the groundwater of the catchment have high natural quality problem (Table 5.8).

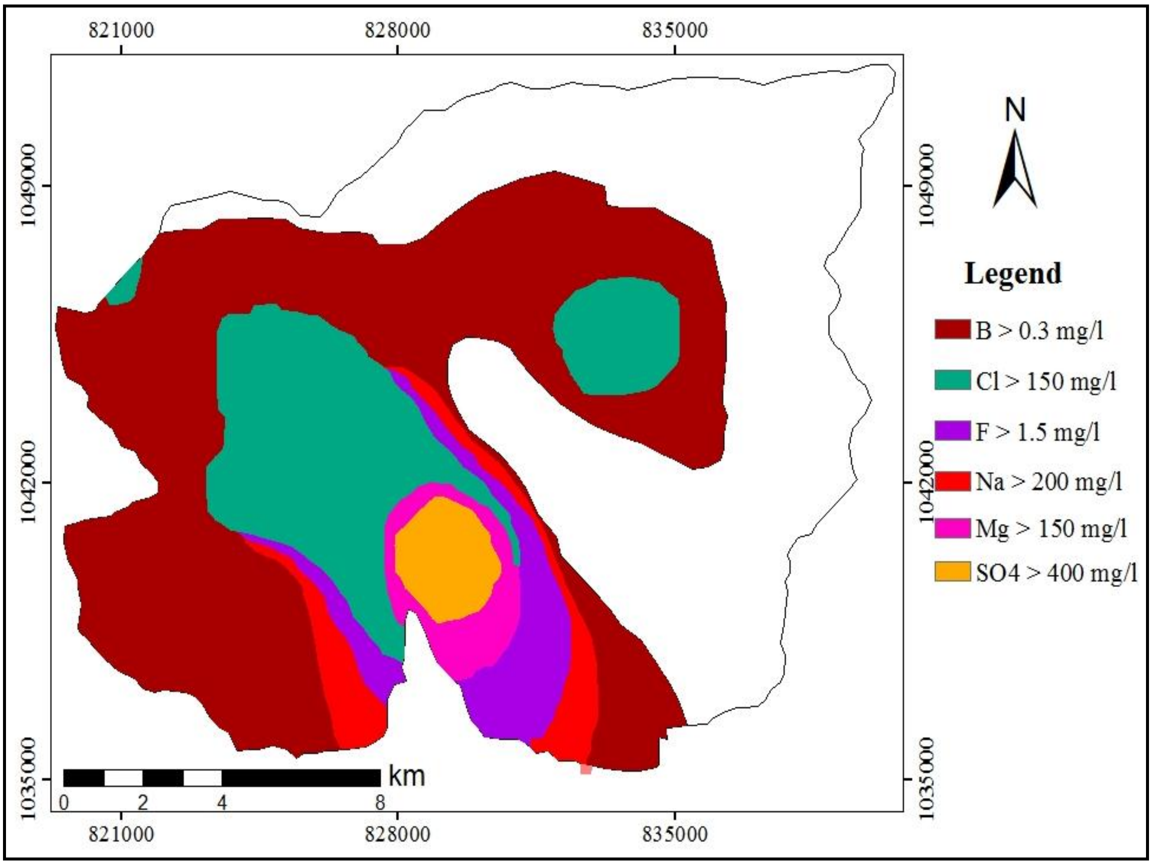

Figure 5.2. Spatial distribution of natural quality indicator parameters of the catchment.

Table 5.8. Results of the proposed groundwater sustainability indicators.

No	Indicators	Values	Scenarios	Status
1	$\frac{\text{Renewable groundwater resource}}{\text{Number of inhabitants}}$	53 L/day/capita	< 500 L/day/capita	High negative impact on groundwater resource of the catchment
2	$\frac{\text{Total groundwater abstraction}}{\text{Groundwater recharge}} * 100\%$	137 %	>100 %	Over exploited groundwater resource
3	$\frac{\text{Total groundwater abstraction}}{\text{Exploitable groundwater resource}} * 100\%$	205%	>100 %	Over exploited groundwater resource
4	$\frac{\sum \text{areas with natural groundwater quality problem}}{\text{Total studied area}} * 100\%$	61%	>10%	High natural groundwater quality problem

CHAPTER VI: MAJOR GROUNDWATER MANAGEMENT CHALLENGES AND PROSPECTS

6.1 Major groundwater management challenges

6.1.1 Over abstraction

The current groundwater withdrawal for domestic consumption and irrigation is 13.78.MCM/year. On the other hand, the total estimated annual groundwater abstraction and recharge of the catchment are 4.34MCM and 10.06MCM. The current groundwater abstraction is higher than both the estimated groundwater abstraction and annual recharge of the catchment. Annually 3.72MCM of water is abstracted above the recharge capacity of the catchment. Thus, the groundwater resource of the catchment has been overexploited. This resulted in the decline of groundwater table and drying of shallow hand dug wells.

There is no control on abstraction of groundwater in the catchment. In places there are some evidences of water demand conflicts. This is going to be real challenge for the society residing in and around the study area.

6.1.2 Well interference

It is the most common problems faced in the study area. Currently, around 1300 hand dug wells are existed in the catchment. More than half of them are localized in damota village (Haromaya woreda water resource office). Most of the hand dug wells are not well distributed. i.e they closely spaced to each other. The density of wells in the village (Damota) can be roughly estimated as one hand dug well per house hold level. The field survey indicates that wells with an average distance separation more than 100 meter and pumping with lower discharge (0.5 l/sec) are free of interference. However, only small numbers of wells are existed within this separation distance. Hence, most of the wells have experienced well interference. The main consequences of well interference are decrease in discharge of wells and decline in groundwater levels which ultimately result in drying of wells.

The well interference is not only restricted to hand dug wells but also observable to shallow boreholes being used for urban water supply. The considerable decrease in discharge of shallow boreholes located in Haromaya University compound may also be related to well interference. The Haromaya dry lake well field contains seven shallow boreholes serving for Harar and Awaday towns. The boreholes are pumped for a long and continuous pumping hours (24 hr/ day). The larger abstraction of the catchment is confined to this well filed. The long term pumping and abstraction from these boreholes have affected the hydrological condition of the hand dug wells located near the well filed. Consequently, most hand dug wells in the area got dry (Plate 2).

Plate 2. Abandoned and dismantled dry hand dug wells around the Haromaya dry lake well field.

6.1.3 Water demand conflict

In the study area, irrigation has played a major role in enhancing the agricultural production. It has been greatly intensified through development of small irrigation schemes since the drying of Haromaya Lake. Consequently, more than one thousand hand dug wells were developed for irrigation to grow vegetables and cash crops. Every farmer has over pumped his own well beyond the limit of maximum discharge without considering the effects on the neighboring wells. Unregulated over pumping and the closely spaced nature of wells are the major causes for well interferences , decline in groundwater level and drying of wells particularly in the rural parts of the study area. When the wells are over pumped, the upstream nearby wells will decline in water level, such circumstance is common all over the catchment. The lack of clear well spacing and pumping rule had already resulted in a number of conflicts in the study area. According to the woreda agricultural extension workers, the water conflict between groundwater users has increased since the past five years. People died because of the water conflict in Damota, Fendicha lencha, Medata and Melka Gemechu villages (Figure 6.1).

6.1.4 Groundwater pollution

Groundwater pollution refers to the artificially induced degradation of natural groundwater quality (Todd, 2007). It is primarily associated to the phreatic or water table aquifers especially when the vadose zone is thin and the water table is shallow. Groundwater pollution is usually very difficult to detect as its monitoring is costly and time consuming. Likewise, its remediation is also very difficult and costly, or sometimes even impossible. Most of the hand dug wells in the study area are shallow depth, open and unprotected ones. Hence, they are highly liable for pollution. Besides, the land fill management of the communities is poor.

The groundwater pollution of the area is highly associated with the agricultural pollutants and improper land fill management. Agriculture is one of the most widespread human activities that affect the quality of groundwater. The main agricultural activities in the area that cause degradation of groundwater quality are the usage of fertilizers and pesticides. The pollutants can enter the groundwater by two ways. The chemical fertilizers added to the soil in order to increase the yield in the area can be lost during the rainy season by surface runoff which ultimately entered the open hand dug wells and pollute the groundwater easily. The second condition is the downward movement of pollutants facilitated by percolation through porous soil media which finally joins the water table. In some hand dug wells the water quality test displays high nitrate probably associated with poor waste management and fertilizers.

6.1.5 Poor irrigation techniques

Irrigation method refers to the technique of delivering water to the field being irrigated. The type of irrigation method has a significant effect on the volume of water used. The most common irrigation technique exercised in the study area is furrow irrigation. It is a type of flood irrigation where water is applied in furrows or rows. Its application is best for uniform flat slopes of most soil types. It is less efficient in terms of water use compared to other techniques. In furrow irrigation the size of the wet soil surface is large enough, consequently, the amount of direct evaporation will be higher, and furthermore, there is a chance to have a huge water loss due to wind. Hence, furrow irrigation losses huge water. It was stated previously that the total estimated irrigation water requirement is lower than the current groundwater abstraction which has been used for irrigation. The farmers irrigated their farmland by 140 % more than the actual irrigation water requirement. Due to low irrigation water application efficiency, a total of 2.59MCM/year of water is lost as it is not engaged for crop use.

6.1.6 Lack of awareness

Until recently, people used to understand that groundwater is unlimited resources. They do not have knowledge about well interference, crop-water requirement and issues of irrigation efficiency and sources of groundwater pollutants. The interview made during the field work clearly indicates lack of knowledge about groundwater resource utilization and management. A lot has to be done in this regards to raise the awareness of the community.

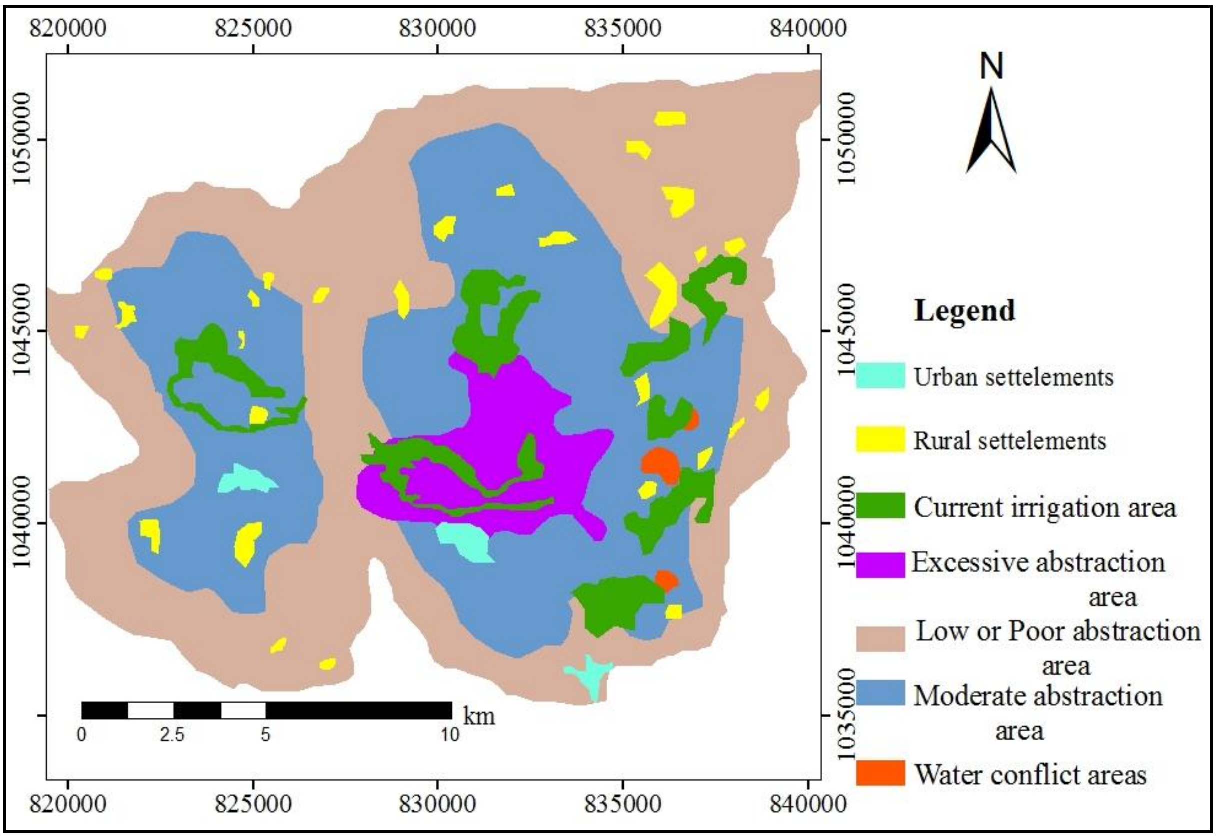

Figure 6.1. Current irrigable area and groundwater abstraction zones map.

6.2 Groundwater management prospects

6.2.1 Artificial recharge

Excessive groundwater abstraction has resulted in depletion of the main aquifers of the area. In order to improve the groundwater situation it is necessary to artificially recharge the depleted groundwater aquifers. The proposed techniques are easy, cost-effective and sustainable in the long term. They can be adopted by the individuals and village communities with locally available materials and manpower.

Ditch and Furrow method: - The method is suitable in areas with irregular topography. Shallow and flat-bottomed, and closely spaced ditches or furrows can provide maximum water contact area for recharge water from source stream or canal. This technique is less sensitive to silting and requires less soil preparation.

Check dams: - Check dams are constructed across small streams having gentle slope, and are feasible in alluvial formation. The site selected for check dam should have sufficient thickness of permeable bed to facilitate recharge of stored water within short span of time. The water stored in these structures is mostly confined to stream course and the height is normally less than 2 m. These are designed based on stream width and excess water which is allowed to flow over the wall. In order to avoid scouring from excess run off, water cushions are provided at down streamside.

Recharge of dug wells: - The open dug wells can be used as structures to recharge the groundwater reservoir. Storm water, tank water and canal water can be diverted into these structures to directly recharge the depleted aquifer. In urban and rural areas of the catchment, the roof top rainwater can be conserved and used for recharge of groundwater. This approach requires connecting the outlet pipe from rooftop to divert the water to the designed dug wells.

Improved land and watershed management:- Improved land and watershed management techniques such as: contour bunding, contour trenching, bench terracing and gully plugging can reduce run off and improve the recharge capacity of the catchment.

6.2.2 Developing well spacing rule

Groundwater can be managed smoothly through establishing water committees which implement well spacing and zoning rules. The effectiveness of any groundwater management rule is often linked to its simplicity and visibility. Rules that are easy to monitor are often the easiest to implement. Well spacing or zoning requires only measuring the distance among the existing wells. Therefore, it can be considered as the simplest rule in groundwater management. The well spacing rule should avoid the interference between wells and maintain them for a long period of time with the required discharge. During field survey, it has been observed that wells with separation of hundred meters or less are likely to be affected by well interference. However, the existing well interference all over the catchment can be totally avoided by formulating a rule which bans development of wells within hundred meters or less distance separation.

6.2.3 Reducing agricultural water demand

There are several simple techniques which can be used to reduce the groundwater demand for irrigation. The principle is that only part of the irrigation water is taken up by plants and the rest part lost through evaporation from the surface will be minimized. Therefore, by improving the efficiency of water use as well as by reducing its loss due to evaporation, it is possible to reduce the irrigation water demand. The methods to reduce such losses and to improve soil moisture are:

Land leveling: - Leveling the farm land precisely improves the effectiveness and efficiency of irrigation. It also ensures a better distribution of water in the fields, and improves the overall crop performance and production.

Low cost micro irrigation techniques: - Low cost micro irrigation techniques have been used as the major water saving methods in agriculture. The common low cost micro irrigation techniques are Pepsi drip irrigation, Nica drip irrigation and Spray head irrigation. These micro irrigation techniques save water by decreasing the wet soil surface and the amount of direct evaporation. Moreover, they also reduce water losses by wind.

Mulching:- Mulching is the application of organic or inorganic material such as plant debris, compost and other inorganic material to the farm land. It decreases the surface run off and evaporation losses which ultimately improve the soil moisture content and fertility of the farm field.

6.2.4 Conflict resolution

The root cause of water conflict in the catchment is the existence of well interference which mainly arose from the closely nature of dug wells. In order to solve the existing water conflicts in the catchment, two opinions are proposed by the researcher. These are: any development of groundwater should be obeyed to the rules of well spacing and zoning which can totally avoid the well interference. The second one is promoting the farmers to use the common dug wells (community irrigation wells) and maintain equitable and fair distribution of water between the users.

6.2.5 Creating awareness

Since groundwater is an invisible resource, its limitations and threats are often not well understood. Special efforts are required to create awareness about groundwater and its use so as to use the resource sustainably. A wide variety of awareness creating methods can be used ranging from basic knowledge to detailed information that actively engages water user groups. The groundwater awareness of the communities can be increased through providing groundwater management trainings, preparation workshops dealing on groundwater and introducing new feasible irrigation technologies. Moreover, special groundwater media publicity has to be used so as to disseminate the required message about groundwater.

6.2.6 Protecting groundwater from pollution

Management of groundwater quality requires both the protection of aquifers and groundwater from entrance of pollutants, and also the remediation or treatment of polluted resources. However, treatment of polluted groundwater is complex, expensive, and often only partially successful and it may take many years. Groundwater quality management should be pro-active and attempt to prevent the contamination of groundwater resources. There are two important methods to avoid a lengthy, expensive, and ineffective remediation of contaminated aquifers. These are assessment of aquifer pollution vulnerability and mapping of groundwater pollution hazards. The two methods are used to generate a groundwater pollution risk map. Such maps may be used to guide the location of proposed new developments where the risk of groundwater contamination is minimal.

CHAPTER VII: SYNTHESIS

7.1 Hydrometeorology

The meteorological analysis of the catchment has been carried out based on the long term meteorological data (1954 – 2008) from both Dengago and Haromaya university stations. The monthly mean maximum and minimum temperature are 23.83 °C and 10.63 °C with annual average value of 17.23°C. Likewise, the estimated monthly average values for relative humidity, wind speed and sun shine hours are 63.81%, 1.89 m/sec and 7.92 hr/day respectively.

The distribution of precipitation in the catchment is not uniform both in space and time. The main rainy months of the catchment last from March to September while the dry months last from October to December. According to (Daniel Gamachu, 1977), the rainfall regime of the catchment has been classified as Type-I with one rainy season. The north western part of the catchment receives more precipitation which ranges from 824mm to 850mm than the other parts of the study area. Since the rainfall distribution of the area is uneven and strongly influenced by orographic effects, isohyetal method has been used for estimation the aerial depth of precipitation of the catchment. Accordingly, the estimated mean areal depth of precipitation of the catchment is 796mm/year.

The PET of the area has been computed using both penman modified and thornthwaite methods. The computed values of PET from penman modified and thornthwaite methods are 1101.1mm/year and 718.81mm/year. The computed PET value from thorthwaite method seems to be very low. Thus, the average value obtained from the two methods is found to be 914.41mm/year, and the average value has been considered for computation of the AET of the catchment. The AET is computed using WTRBLN model software. It is computed based on the various soil texture and vegetation cover of the catchment. Considering the aerial coverage of each soil types and vegetation cover, the weighted / adjusted AET of the whole catchment is estimated to be 757mm/year. The AET value is nearly close to the annual precipitation. It accounts 95 % of the annual precipitation of the catchment which shows that AET is the principal cause of water loss from precipitation.

7.2 Water balance

According to the thornthwaite and mother soil water balance model, the total recharge of the study area is 39mm/year. Considering the total area of the catchment as 258 km^2, the annual groundwater recharge of the Adelle-Haromaya lake catchment is estimated to be 10.06 MCM. The present total annual groundwater abstraction is 13.78MCM. Approximately, 63% and 32% of the total abstraction are consumed for domestic and agricultural water supplies. The estimated exploitable groundwater reserve and safe yield of the catchment are 6.73 MCM/year and 8.29MCM/year. The total groundwater abstraction is greater than the recharge and the safe yield of the aquifer. The computed change in storage of the catchment is – 4.28 MCM per year which shows that the total annual inflow of the catchment is lower than the total out flow of the catchment. Groundwater balance of the Adelle – Haromaya lake catchment is in disequilibrium condition. Estimated water balance shows that the total groundwater abstraction from the catchment exceeds the annual recharge. It is obvious that the aquifer system of the catchment is overexploited. Groundwater overexploitation being practiced by abstraction from the existing wells and boreholes had resulted in significant head decline that had reached 4m during the year 2006.

7.3 Hydrogeology

Based on the quantitative borehole log, pumping test data and qualitative field description of primary and secondary porosities, the rock units of the catchment are categorized in to five major hydrostratigraphic units. These are intergranular aquifers with moderate potentiality, fractured aquifers with moderate potentiality, intergranular & fractured aquifers with low potentiality, karistic aquifers with very low potentiality and less fractured aquifers with extremely low potentiality.

The intergranular aquifers comprise the unconsolidated formations placed in the flat depressed topography near the central part of the catchment. They are characterized by primary porosities with unconfined shallow aquifer system. Their aquifer transmissivity values range from 10 to 100 m^2 /day which can be considered as moderate potential aquifer.

The fractured aquifers are confined to sandstone unit. Though the sandstone contains primary porosities, the higher proportion of cementing materials made the intergranular permeability very low. The secondary porosity associated with fracturing and bedding planes have given a significant influence for groundwater circulation and storage with in this unit. The discharges of the springs vary from very low discharge (0.2 l/s) to a higher discharge up to a maximum of 15 l/s. Based on the existing data and field observations, the potential of sandstone aquifer is considered to be moderate.

The granite and gneiss rock units are related to intergranular & fractured aquifer. Their groundwater potentiality is primarily associated with the availability of weathered sections and fractures. The discharge of the wells range from 0.5 to 1.5 l/ s. Due to limited thickness of weathered zones and fractured layers, the aquifers of the granite and gneiss units are considered to be low potentiality.

The karistic aquifers of limestone are characterized by secondary porosity and permeability which resulted from fracturing, solution cavities and opening along bedding planes. The geomorphological feature of the lithology and the moderate permeability of the underlying sandstone have facilitated the down ward movement of groundwater from this unit. The discharge of springs emerging from this unit is 0.2 l/s. Therefore, the limestone unit can be taken as an aquifer of very low potentiality.

The massive and non-fractured migmatites characterized by very poor permeability have been considered as extremely low potential aquifers for groundwater movement and circulation.

The general groundwater flow direction has been determined by construction of groundwater contour map on the basis of the hydraulic head distribution from various boreholes and wells in the same aquifer system. The general trend of groundwater flow is towards the depressed flat topography from the surrounding hilly landscapes. The groundwater flow is almost in the same direction with that of surface flow.

7.4 Hydrochemistry

The TDS values of water samples range from 321 to 1984 mg /l with an average value of 607 mg/l. except three groundwater samples, the TDS values of all samples are below 1000 mg/l. The chemical analysis of groundwater samples showed that calcium is the most dominant cation followed by sodium, magnesium and potassium. Their mean values are 208mg/l, 113mg/l, 60mg/l and 2.89mg/l respectively. The major anions in groundwater samples of the study area are bicarbonate, chloride, sulfate and nitrate in their decreasing order of concentration. The concentration of nitrate (NO_3^-) in the ground water varies from 790 to 0.34 mg/l with an average value of 54mg/l. Three hand dug well samples show above the recommended WHO water quality guide line (45 mg/l). The prevalence of high concentration of nitrate in groundwater could be associated with the use of synthetic agricultural fertilizer (ammonia) and poor domestic waste management. The groundwater types identified in the catchment are Ca-Mg-HCO_3, Ca-Mg-Cl-HCO_3, Mg-Na-Ca-SO_4 and Na-Mg-Cl-SO_4 types. The water chemistry of seasonal lakes of the catchment varies form Mg-Na-Ca-SO4 to Na-Mg-Cl-SO_4 water types. The perennial lake (Tinikie) has Na-Mg-Ca-HCO_3-Cl water type.

The majority of the spring and groundwater lies within the permissible limit of the WHO drinking water quality standards except the three wells with high nitrate. Some of the drinking water quality concerns in the area are boron, nitrate, fluoride, sulfate and sodium. From analyzed total water samples, their total percentage above the recommended concentration are 28%, 17%, 11%, 11% and 11% respectively.

The irrigation water qualities of the study area have been evaluated with respect to salinity hazard, water infiltration rate and specific ion toxicity. The salinity hazard of the irrigation water has been expressed in terms of TDS values. The TDS values of all water sources of the catchment have shown the existence of two water types. The first type has TDS value below 450 mg/l which is non-hazardous and needs no restriction on use. The second water type ranges from 451 to 1894 mg/l which needs slight to moderate degree of restriction on use for surface irrigation.

The relative infiltration rate of the catchment water has been evaluated by its sodium adsorption ratio (SAR) and corresponding salinity values. From the analyzed groundwater samples, 44% of them have indicated no reduction in rate of infiltration while the remaining 56% of the samples indicate slight to moderate in reduction in rate of infiltration. Except one seasonal lake (Adelle) which has no reduction in rate of infiltration, all the spring and lake waters have slight to moderate capacity in reduction rate of infiltration.

The toxicity of irrigation water of the catchment has been evaluated with respect to sodium, chloride and boron concentrations. Except two groundwater and one lake water sample (Adelle), all water source samples have SAR values less than 3. These values indicate that no sodium toxicity will rise by using the water from these sources for surface irrigation (FAO, 1989). The SAR values of the Adelle Lake and the two groundwater samples lie within the range from 3.13 to 8.12. It suggests the necessity of slight to moderate degree of restriction on use of the water for surface irrigation. Except the seasonal lake (Adelle) and two dug well water samples, all the groundwater, lake and spring water samples have chloride concentration below 142 mg/l which indicate water from these sources are non-chloride toxic for irrigation. However, the two dug wells are slight to moderate degree of restriction on use while the Adelle Lake is highly chloride toxic. The concentration of boron in all water sources is well below 0.7 mg/l. The value indicates that the water sources of the catchment are completely free from boron toxicity.

Based on the EC and Na% values, the suitability of groundwater for irrigation has been evaluated. Groundwater in the north eastern part of the catchment which accounts 26% of the total study area is good for irrigation purpose. Groundwater in the central, north western and western part of the study which covers 71% of the total catchment area has an acceptable quality for irrigation. However, only groundwater localized in small patches in the southern part of the catchment covering 3% of the total study area has suspicious quality to be used safely for irrigation. In general, more than 90% of the catchment area has groundwater irrigation quality in the range of good to permissible class.

7.5 Water demand assessment

The current groundwater dependent population of the catchment is 343679. Considering the domestic water demand for basic ingestion and hygiene needs as 20 liter per capita per day, the estimated domestic water demand of the area is 2.51MCM/year. But, the current groundwater abstraction for domestic water use is 8.9MCM/year. The current abstraction for domestic use is much greater than the estimated domestic water demand. Approximately, 6.39MCM/year of water is abstracted for domestic use above the estimated domestic water demand.

The current irrigated land coverage of the catchment is 6162 ha. Based on the area of irrigated land and prevailing climatic condition of the area, both crop and irrigation water requirement for each crop have been estimated. The estimated irrigation water requirement of the catchment is 1.82MCM/year. On the other hand, the current abstraction for irrigation is 4.41MCM/year. The current groundwater withdrawal for irrigation is higher than the estimated irrigation water requirement. The farmers have irrigated their farmland by 140 % more than the actual irrigation water requirement. Due to low irrigation water application efficiency, a total of 2.59MCM/year of water is lost as it is not used by crops.

The groundwater dependable population of the catchment can safely abstract the groundwater resource for the next 17years provided that they have used the groundwater according to the estimated domestic water demand and irrigation water requirement of the crops as well as by increasing irrigation efficiency to reduce water loss.

7.6 Groundwater sustainability indicators

Four groundwater indicators have been used to evaluate the groundwater sustainability of the area at catchment level. The proposed indicators are Renewable groundwater resources per capita, total groundwater abstraction / groundwater recharge, total groundwater abstraction / exploitable groundwater resource and groundwater quality. The annual recharge, groundwater abstraction, exploitable groundwater resource and renewable groundwater resource of the catchment are 10.06MCM, 13.78MCM, 6.73MCM and 5.78MCM respectively.

The renewable groundwater resource per capita of the catchment is 53 L/day/capita. The indicator value shows that at current condition, the possibility of using renewable groundwater resource for development purposes could have high negative impact on groundwater resource. The indicator value for total groundwater abstraction / groundwater recharge is 137%. The value falls into the third scenario (>100%) which indicates that the groundwater resource of the catchment have been overexploited. The estimated indicator value for groundwater abstraction/exploitable groundwater resource is 205%. The value indicates that the current groundwater abstraction is much greater than the exploitable groundwater resources and the groundwater resource of the catchment have been overexploited. The groundwater quality indicator is defined as the sum of areas with natural groundwater quality problem divided by the total studied area. The selected inorganic quality indicator parameters are Cl^-,F^-, $SO4^{2-}$, Mg^{2+}, Na^+ and B ions. The total area with natural groundwater quality problems of the catchment is estimated to be 158 Sq.km. The estimated indicator value is found to be 61%. Thus, the indicator value falls in the third scenario (>10%) of quality indicator which shows that the groundwater of the catchment have high natural quality problem. Generally, the proposed indicators show that the groundwater resource of the catchment has been deteriorated both in quantity and quality.

7.7 Groundwater management challenges and prospects

Over abstraction, well interference, water conflicts, poor irrigation techniques, lack of awareness and groundwater pollution are the major groundwater management challenges of the catchment. Abstraction according to the estimated domestic water demand and irrigation water requirement can maintain the sustainability of groundwater. Poor irrigation can be improved by using effective and efficient irrigation techniques. Some of the important irrigation techniques are land leveling and low cost irrigation methods (pepsi, nica and spray head drip irrigation). Water conflicts and well interference can be avoided by using common /community irrigation wells and implementing well spacing rules respectively. The awareness of the communities can be increased through providing groundwater management trainings and preparation workshops dealing on groundwater.

CHAPTER VIII: CONCLUSION AND RECOMMENDATION

8.1 Conclusions

- In the Adelle - Haromaya dry lake catchment evapotranspiration is the principal cause of water loss from precipitation.
- The current groundwater abstraction is higher than the safe yield of the aquifers and the annual groundwater recharge of the catchment. Thus, the catchment can't sustain the current domestic and irrigation water requirements of the area.
- The current groundwater abstraction is much greater than the exploitable groundwater resources. This indicates that, the groundwater resource of the catchment has been overexploited.
- The present groundwater abstraction for domestic and irrigation supply is greater than the estimated domestic and irrigation water demand of the catchment.
- The current irrigation practice of the catchment is not proper. Due to low irrigation water application efficiency, a total of 2.59MCM water is lost annually from the catchment.
- The groundwater potential of the catchment can sustain for the next seventeen years provided that the communities have used the groundwater according to the estimated domestic water demand and irrigation water requirement of the crops as well.
- More than 90% of the catchment area has an irrigation groundwater quality in the range of good to permissible quality class.
- Generally the groundwater resource of the catchment has been deteriorated both in quantity and quality (drinking water quality).

8.2 Recommendations

- Groundwater abstraction in the catchment should be in accordance with the estimated domestic water demand and irrigation water requirements of the crops.
- Encouraging the use of common dug wells or community irrigation wells, and maintain equitable and fair distribution of water between the users particularly in areas where water conflict is frequent.
- Micro irrigation technologies such as the different types of drip irrigation techniques should be introduced so as to alleviate the amount of water loss during irrigation.
- Observation wells have to be installed in selected areas of the catchment for regular groundwater level and quality monitoring purposes.
- Soil and water conservation has to be implemented to reduce runoff and enhance the recharge capacity of the catchment.
- To prevent the groundwater pollution from agricultural activities, a rational and planned use of nitrogenous fertilizers and other agrochemicals should be implemented.
- To prevent land degradation, erosion and siltation of the existing lake, the yearly expansion rate of agricultural farm land has to be decreased and rational land use in the catchment should promoted.
- The awareness of the communities has to be increased through providing groundwater management trainings and preparation workshops dealing on groundwater.

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Annex 2.1. Inventoried and secondary water point data in the catchment area.

Water points	ID	Well_Name	Utm E (m)	Utm N (m)	Elevation (m)	SWL (m)	Elevation of water level (m)	Well depth (m)	Discharge (L/s)
HDW	HDW-1	Gendajuru	830356	1043531	2050	4.9	2045.1		
HDW	HDW-2	Damota	833377	1043239	2017	6.5	2010.5		
HDW	HDW-3	Bere	835588	1043319	2031	1	2030		
HDW	HDW-4	Bakari	835753	1043420	2092	1	2091		
HDW	HDW-5	Engineer HDw	836612	1043388	2113	0.5	2112.5		
HDW	HDW-6	Damota1	837578	1043234	2132	14	2118		
HDW	HDW-7	Damota2	837493	1043179	2125	13	2112		
HDW	HDW-8	Damota3	837340	1043024	2119	10	2109		
HDW	HDW-8	Damota5	837252	1043204	2128	15	2113		
HDW	HDW-4	nearharomaya	832478	1043224	2017	6.5	2010.5		
Spr	Spr-1	Lega_mesino	837097	1044454	2196	2196	2195		0.2
Spr	Spr-2	Lega_hida	837758	1044846	2196	2196	2195		15
Spr	Spr-3	Genda_bere	835583	1043234	2070	2070	2069		1
Spr	Spr-4	Genda_qadi	836607	1043394	2113	2113	2112		1.5
BH	BH-1	wichale	830481	1050911	2110	18.5	2091.5	60	
BH	BH-2	Gendamudea	830747	1044245	2924	22	2902		
Source: Researcher									
HDW	HDW-1	HDWPv-1	832844	1037611	2064	15.3	2048.7	18	
HDW	HDW-2	HDWPv-2	832137	1038222	2021	6.2	2014.8	8	
HDW	HDW-3	HDWPv-3	831168	1038733	2012	2.2	2009.8	4	
HDW	HDW-4	HDWPv-4	831414	1037739	2010	3	2007	4	
HDW	HDW-5	HDWPv-5	831668	1037322	2008	4.5	2003.5	7	
HDW	HDW-6	HDWPv-6	834441	1042135	2037	8	2029	10	
HDW	HDW-7	HDWPv-7	831675	1040513	2015	6	2009	7	
HDW	HDW-8	SDWPu-1	832449	1044323	2026	12	2014		
HDW	HDW-9	HDWPv-8	833486	1046880	2039	6	2033	7	
HDW	HDW-10	HDWPv-9	832183	1046351	2015	4	2011	6	
HDW	HDW-11	HDWPv-10	833169	1048338	2038	6	2032	8	
HDW	HDW-12	HDWPv-11	833226	1047979	2043	9	2034	10.5	
HDW	HDW-13	HDWPv-12	833255	1045294	2048	10	2038		
HDW	HDW-14	SDWPu-2	834373	1039838	2115	9	2106	15	
HDW	HDW-14	SDWPu-3	833867	1040797	2025	16	2009	32	
HDW	HDW-15	HDWPv-13	826158	1040879	2072	32	2040	34	
HDW	HDW-16	HDWPv-14	827956	1040551	2043	20.7	2022.3	25	
HDW	HDW-17	HDWPu-1	828174	1040464	2039	18.5	2020.5		
HDW	HDW-18	HDWPu-2	828430	1040269	2048	30	2018	32	

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HDW	HDW-19	HDWPu-3	828658	1040537	2025	8	2017	10	
HDW	HDW-20	HDWPv-15	828717	1040429	2026	13	2013	14	
HDW	HDW-21	HDWPv-16	829776	1040269	2019	2.5	2016.5	4	
HDW	HDW-22	HDWPv-17	830651	1039655	2026	4	2022	7	
HDW	HDW-23	HDWPv-18	831447	1038873	2026	9.15	2016.85	18	
HDW	HDW-24	HDWPv-19	831757	1038360	2018	10.5	2007.5	11.5	
HDW	HDW-25	HDWPv-20	831291	1048132	2017	2.6	2014.4		
HDW	HDW-26	HDWPu-4	830154	1048253	2040	5.75	2034.25	12	
HDW	HDW-27	HDWPv-21	830186	1047416	2036	5.35	2030.65	6.5	
HDW	HDW-28	HDWPv-22	829544	1044150	2046	7.2	2038.8	8	
HDW	HDW-29	HDWPv-23	828532	1041893	2017	8	2009	9.5	
HDW	HDW-30	HDWPv-24	830672	1040852	2010	3	2007	4.5	
HDW	HDW-31	HDWPv-25	824744	1041458	2033	5.8	2027.2		
HDW	HDW-32	HDWPv-26	823268	1042870	2027	3.5	2023.5		
HDW	HDW-33	HDWPv-27	822435	1044681	2033	2.8	2030.2		
HDW	HDW-34	HDWPv-28	822030	1045591	2039	3.7	2035.3		
HDW	HDW-35	HDWPv-29	823256	1046715	2060	3.8	2056.2		
HDW	HDW-36	HDWPv-30	823306	1045039	2053	6.8	2046.2		
HDW	HDW-37	HDWPv-31	824284	1044797	2050	5.55	2044.45		
HDW	HDW-38	HDWPv-32	825664	1043797	2043	5.8	2037.2		
HDW	HDW-39	HDWPv-33	825256	1045033	2061	6.7	2054.3		
HDW	HDW-40	HDWPv-34	823576	1044053	2033	2.1	2030.9		
HDW	HDW-41	HDWPv-35	825255	1042672	2036	1.9	2034.1		
HDW	HDW-42	HDWPv-36	822035	1039950	2055	4.4	2050.6	5.5	
HDW	HDW-43	HDWPv-37	823975	1039792	2036	3	2033	4	
HDW	HDW-44	HDWPv-38	824068	1040583	2028	4	2024	5	
HDW	HDW-45	HDWPv-39	824679	1040809	2030	2.35	2027.65	4.35	
HDW	HDW-46	HDWPv-40	824779	1038257	2041	1.6	2039.4		
HDW	HDW-47	HDWPv-41	824719	1038718	2041	1.95	2039.05		
HDW	HDW-48	HDWPv-42	832061	1042297	2025	10	2015		
BH	BH-3	SDWPu-4	821208	1046485	2056	15	2041		
BH	BH-4	HTBH-1	832105	1040754	2018	2.2	2016	47	10.3
BH	BH-5	HTBH-2	832551	1040269	2023	13.99	2009	65	4.46
BH	BH-6	HTBH-3	831774	1041150	2015	3.78	2011	39	10
BH	BH-7	HTBH -4	832446	1040863	2013	3.95	2009	52.3	18
BH	BH-8	HTBH -5	832149	1040439	2014	2.89	2011	53	18
BH	BH-9	HTBH -6	832329	1041370	2011	4.86	2006	44	16.6
BH	BH-10	HTBH -7	832217	1041860	2020	5.52	2014	44	22

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BH	BH-11	HBBH-65	832432	1045791	2008	2	2006	64	8
BH	BH-12	HBBH-59	832300	1045792	2008	2.6	2005	59	3.5
BH	BH-13	HBBH-51	832140	1047901	2026	1	2025	51	6.7
BH	BH-14	HBBH-85	831498	1047365	2020	1.45	2019	85	8
BH	BH-15	AUBH1	832513	1042715	2024				1.0
BH	BH-16	AUBH2	832750	1040816	2021				5.0
BH	BH-17	AUBH3	832831	1041841	2028				3.0
BH	BH-18	AUBH4	833430	1041804	2032			58	3.5
BH	BH-19	AUBH5	833776	1041821	2034				4.5
BH	BH-20	AUBH6	833963	1041778	2037				1.5
BH	BH-21	AUBH7	833055	1041378	2030				0.3
BH	BH-22	ATBH	824465	1041067	2040				0.4
BH	BH-23	BTBH	834140	1041944	2036				0.5
BH	BH-24	FTBH	832300	1045990	2026				0.6

Source: (Geletu Belay, 2006).

Annex 3.1 Long-term monthly average weather parameters of the Adelle-Haromaya catchment from Haromaya University & Dengago stations (1954-2008).

No	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Mean Monthly RF (mm)	47.29	18.05	64.48	104.61	86.83	48.60	107.79	161.91	115.52	40.06	18.53	12.60
2	RF coefficient	0.69	0.26	0.94	1.52	1.26	0.71	1.57	2.35	1.68	0.58	0.27	0.18
3	Mean Max. Temp (^oC)	22.52	23.95	24.96	24.52	25.26	24.83	23.12	23.11	23.56	24.32	23.45	22.31
4	Mean Min. Temp (^oC)	7.80	9.02	11.35	12.59	13.00	13.43	12.82	12.80	12.32	8.97	6.89	6.62
5	Mean Temp (^0C)	15.16	16.49	18.15	18.55	19.13	19.13	17.97	17.95	17.94	16.64	15.17	14.47
6	Mean Max.RH (%)	97.00	90.00	90.00	94.00	95.50	98.00	99.00	99.00	97.00	99.00	95.00	93.00
7	Mean Min.RH (%)	35.00	26.00	30.00	36.00	36.00	49.00	55.00	46.00	50.00	27.00	25.00	29.00
8	Mean RH (%)	59.25	54.62	57.08	64.27	66.30	70.42	73.44	73.39	74.08	58.94	55.40	58.52
9	Mean Max.Wind speed (m/s)	2.1	2.58	2.69	2.37	2.65	3.76	3.55	2.86	1.77	1.48	1.71	1.84
10	Mean Min.Wind speed (m/s)	1.4	1.7	1.6	1.42	1.22	2.13	2.2	1.69	1.01	0.58	1.18	1.18
11	Mean Wind speed (m/s)	1.79	1.96	2.05	1.91	1.96	2.71	2.64	2.16	1.40	1.17	1.42	1.54
12	Mean Max.sunshine hrs (hr/day)	10.1	11.1	10.5	9.2	9.4	9.1	7.7	8.9	7.6	9.2	10.6	10.4
13	Mean Min.sunshine hrs (hr/day)	7.6	6.3	4.6	5.6	6.1	2.5	4.9	4.7	4.9	4.7	7.5	8.2

Source: National Meteorological Agency of Ethiopia.

Annex 3.2. AET for cambisols with an available water capacity of root zone 150mm under grasses and vegetables with estimated rooting depth of 0.6m. Such type of soil covers 50.7% of the study area.

(mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	46	17	62	101	84	47	104	156	111	39	18	12	796
DRo	7	3	10	16	13	7	17	25	18	6	3	2	127
P-DRo	39	14	52	85	71	40	87	131	93	33	15	10	670
Ref.PET	68	77	87	86	90	87	80	80	79	75	69	36	914
P-PET	-29	-63	-35	-1	-19	-47	7	51	14	-42	-54	-26	-244
A_{cc}PWL	-151	-214	-249	-250	-269	-316				-42	-96	-122	-1709
S_m	55	36	29	28	25	18	25	76	90	113	79	67	641
$\triangle S_m$	-12	-19	-7	-1	-3	-7	7	51	14	23	-34	-12	0
AET	51	33	59	86	74	47	80	80	79	56	49	22	716
SMD	17	44	28	0	16	40	0	0	0	19	20	14	198
S	0	0	0	0	0	0	0	0	0	0	0	0	0
TARO	0	0	0	0	0	0	0	0	0	0	0	0	0
Ro	0	0	0	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex 3.3 AET for fluvisols with an available water capacity of root zone 120mm under grasses and vegetables with estimated rooting depth of 0.6m. Such type of soil covers 3.4% of the study area.

(mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	46	17	62	101	84	47	104	156	111	39	18	12	796
DRo	7	3	10	16	13	7	17	25	18	6	3	2	127
P-DRo	39	14	52	85	71	40	87	131	93	33	15	10	670
Ref.PET	68	77	87	86	90	87	80	80	79	75	69	36	914
P-PET	-29	-63	-35	-1	-19	-47	7	51	14	-42	-54	-26	-244
A_{cc}PWL	-151	-214	-249	-250	-269	-316				-42	-96	-122	-1709
S_m	34	20	15	15	13	9	16	67	81	85	54	43	452
$\triangle S_m$	-9	-14	-5	0	-2	-4	7	51	14	4	-31	-11	0
AET	48	28	57	85	73	44	80	80	79	37	46	21	678
SMD	20	49	30	1	17	43	0	0	0	38	23	15	236
S	0	0	0	0	0	0	0	0	0	0	0	0	0
TARO	0	0	0	0	0	0	0	0	0	0	0	0	0
Ro	0	0	0	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex 3.4. AET for vertisols with an available water capacity of root zone 120mm under grasses and vegetables with estimated rooting depth of 0.6m. Such type of soil covers 10% of the study area.

(mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	46	17	62	101	84	47	104	156	111	39	18	12	796
DRo	7	3	10	16	13	7	17	25	18	6	3	2	127
P-DRo	39	14	52	85	71	40	87	131	93	33	15	10	670
Ref.PET	68	77	87	86	90	87	80	80	79	75	69	36	914
P-PET	-29	-63	-35	-1	-19	-47	7	51	14	-42	-54	-26	-244
A_{cc}PWL	-151	-214	-249	-250	-269	-316				-42	-96	-122	-1709
S_m	34	20	15	15	13	9	16	67	81	85	54	43	452
$\triangle S_m$	-9	-14	-5	0	-2	-4	7	51	14	4	-31	-11	0
AET	48	28	57	85	73	44	80	80	79	37	46	21	678
SMD	20	49	30	1	17	43	0	0	0	38	23	15	236
S	0	0	0	0	0	0	0	0	0	0	0	0	0
TARO	0	0	0	0	0	0	0	0	0	0	0	0	0
Ro	0	0	0	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex 3.5. AET for regosols with an available water capacity of root zone 300mm under moderately deep rooted cover (chat, sorghum, and few shrubs) with estimated rooting depth of 1.2m. Such type of soil covers 28.6% of the study area.

(mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	46	17	62	101	84	47	104	156	111	39	18	12	796
DRo	7	3	10	16	13	7	17	25	18	6	3	2	127
P-DRo	39	14	52	85	71	40	87	131	93	33	15	10	670
Ref.PET	68	77	87	86	90	87	80	80	79	75	69	36	914
P-PET	-29	-63	-35	-1	-19	-47	7	51	14	-42	-54	-26	-244
A_{cc}PWL	-151	-214	-249	-250	-269	-316				-42	-96	-122	-1709
S_m	181	147	131	130	122	105	112	163	177	261	218	200	1947
$\triangle S_m$	-19	-34	-16	-1	-8	-17	7	51	14	84	-43	-18	0
AET	58	48	68	86	79	57	80	80	79	117	58	28	838
SMD	10	29	19	0	11	30	0	0	0	-42	11	8	76
S	0	0	0	0	0	0	0	0	0	0	0	0	0
TARO	0	0	0	0	0	0	0	0	0	0	0	0	0
Ro	0	0	0	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex 3.6. AET for lithosols with an available water capacity of root zone 300mm under moderately deep rooted cover (chat, sorghum, and few shrubs) with estimated rooting depth of 1.2m. Such type of soil covers 7.3 % of the study area.

(mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	46	17	62	101	84	47	104	156	111	39	18	12	796
DRo	7	3	10	16	13	7	17	25	18	6	3	2	127
P-DRo	39	14	52	85	71	40	87	131	93	33	15	10	670
Ref.PET	68	77	87	86	90	87	80	80	79	75	69	36	914
P-PET	-29	-63	-35	-1	-19	-47	7	51	14	-42	-54	-26	-244
A_{cc}PWL	-151	-214	-249	-250	-269	-316				-42	-96	-122	-1709
S_m	237	199	180	180	171	150	157	208	222	320	276	257	2557
$\triangle S_m$	-20	-38	-19	0	-9	-21	7	51	14	98	-44	-19	0
AET	59	52	71	85	80	61	80	80	79	131	59	29	866
SMD	9	25	16	1	10	26	0	0	0	-56	10	7	48
S	0	0	0	0	0	0	0	0	0	0	0	0	0
TARO	0	0	0	0	0	0	0	0	0	0	0	0	0
Ro	0	0	0	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex 3.7. Monthly adjusted water balance of the Adelle-Haromaya catchment.

(mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	46	17	62	101	84	47	104	156	111	39	18	12	796
DRo	7	3	10	16	13	7	17	25	18	6	3	2	127
P-DRo	39	14	52	85	71	40	87	131	93	33	15	10	670
Ref.PET	68	77	87	86	90	87	80	80	79	75	69	36	914
P-PET	-29	-63	-35	-1	-19	-47	7	51	14	-42	-54	-26	-244
A_{cc}PWL	-151	-214	-249	-250	-269	-316				-42	-96	-122	-1709
S_m	102	78	67	67	62	51	58	109	123	167	130	116	1129
$\triangle S_m$	-14	-24	-10	-1	-5	-10	7	51	14	43	-37	-14	0
AETm	53	38	62	86	76	50	80	80	79	76	52	24	757
SMD	15	39	25	0	14	37	0	0	0	-1	17	12	157
S	0	0	0	0	0	0	0	0	0	0	0	0	0
TARO	0	0	0	0	0	0	0	0	0	0	0	0	0
RO	0	0	0	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex 4.1. Chemical analysis results of samples collected from different water points

Sample ID	Utm E	Utm N	pH	EC	TDS	Na	K	Mg	Ca	Cl	SO4	HCO3	NO3	F	B
HBH-1	171630	1050893	7.24	535	321	56.1	1.4	36.8	147	59.6	19.41	300	0.46	1.3	0.13
HHDW-1	173076	1042702	7.29	574	344	71.2	3.8	18.6	156	76.6	12.2	257.5	27.6	0.28	0.18
FHDW-5	174139	1048088	7.39	631	397	57	2.5	24.4	129	85.1	19.4	173	20.8	0.51	0.25
HHDW-2	178445	1043685	7.33	647	388	30	0.8	42.7	124	38.3	1.52	234	0.72	0.46	0.09
FBH-7	173431	1048174	7.33	657	395	67	1.2	35.1	185	63.8	9.1	302	34.8	0.25	0.36
FBH-2	171781	1044224	7.28	662	398	88.3	2.1	46.5	145	80.8	19.3	279.5	0.62	0.1	0.15
HBH-3	173285	1041027	7.38	691	414	111	2.7	62	148	76.6	21.8	315	0.44	0.88	0.18
HHDW-3	178766	1042413	7.26	720	433	42	7.6	60.8	193	55.3	8.56	348.5	24.4	0.29	0.2
HBH-5	175332	1042178	7.32	750	444	75	1.3	56.7	258	63.8	12	393.5	1.56	0.23	0.21
ABH-4	824612	1039760	7.25	752	451	109	0.4	35.4	184	85.1	14.1	291	3.9	0.34	0.15
HBH-8	173728	1042972	7.2	789	473	95	1.8	34.8	303	85.1	22.8	365	44	0.36	0.35
ABH-6	823328	1042947	7.19	1052	632	125	5.1	64.8	320	127.6	21.7	363	2.06	0.39	0.35
AHDW-4	820840	1046782	7.28	1278	769	65.8	2	28.4	302	153.1	17.8	230	790	0	0.26
AHDW-8	824348	1042309	7.78	1857	1114	397	5.2	105	73.2	255.2	299	284.5	0.32	3.84	0.5
FHDW-6	174565	1045290	7.32	1883	1129	109	4.3	103	543	251	93.8	351	155	0.39	0.57
HHDW-7	170675	1040552	7.92	3157	1894	458	7.3	224	129	234	571.5	194	86	3.47	0.48
SP-1	178801	1044704	7.32	616	372	32	1.1	41.2	181	51	1.46	306.5	31.6	0	0.09
SP-2	176613	1043142	7.3	553	921	47	1.5	76.3	235	68.1	21.6	392	18.8	0.36	0.31
LK-1	172425	1044419	7.63	620	372	131	4.4	38.8	50.4	97.8	19.7	211.5	0.34	1.55	0.67
LK-2	829366	1040608	7.63	1029	617	224	6.5	141	156	110.6	259.2	96.5	0.92	1.71	0.36
LK-3	823202	1043226	7.92	2425	1455	466	3.6	81.8	115	557.3	238.9	58	0.52	1.98	0.14

Annex 5.1. CWR and IWR for Catha Edulis (Chat)

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Oct	2	Init	0.70	2.88	17.30	7.50	11.00
Oct	3	Init	0.70	2.89	31.80	11.40	20.40
Nov	1	Init	0.70	2.90	29.00	11.00	18.00
Nov	2	Deve	0.70	2.89	28.90	9.50	19.40
Nov	3	Deve	0.68	2.76	27.60	7.10	20.50
Dec	1	Deve	0.67	2.62	26.20	3.90	22.30
Dec	2	Deve	0.65	2.49	24.90	1.30	23.70
Dec	3	Mid	0.64	2.49	27.40	1.80	25.50
Jan	1	Mid	0.64	2.52	25.20	2.00	23.20
Jan	2	Mid	0.64	2.57	25.70	1.80	23.90
Jan	3	Mid	0.64	2.60	28.60	5.20	23.40
Feb	1	Mid	0.64	2.63	26.30	8.90	17.40
Feb	2	Late	0.64	2.69	26.90	11.90	15.00
Feb	3	Late	0.64	2.67	21.30	14.90	6.40
Mar	1	Late	0.64	2.64	26.40	18.30	8.10
Mar	2	Late	0.64	2.62	7.90	6.40	0.00
					401.40	122.90	278.40

Annex 5.2. CWR and IWR for Potato

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.5	2.08	12.5	5.7	7.7
Nov	3	Init	0.5	2.02	20.2	7.1	13.1
Dec	1	Init	0.5	1.96	19.6	3.9	15.7
Dec	2	Deve	0.55	2.08	20.8	1.3	19.5
Dec	3	Deve	0.76	2.96	32.5	1.8	30.7
Jan	1	Deve	0.99	3.91	39.1	2	37.2
Jan	2	Mid	1.14	4.62	46.2	1.8	44.4
Jan	3	Mid	1.15	4.7	51.7	5.2	46.5
Feb	1	Mid	1.15	4.75	47.5	8.9	38.6
Feb	2	Late	1.13	4.7	47	11.9	35.2
Feb	3	Late	1.07	4.41	35.3	14.9	20.4
Mar	1	Late	1.01	4.13	41.3	18.3	23
Mar	2	Late	0.96	3.9	15.6	8.6	4.9
					429.4	91.4	336.8

Annex 5.3. CWR and IWR for Lettuce

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.7	2.91	17.5	5.7	12.7
Nov	3	Init	0.7	2.83	28.3	7.1	21.2
Dec	1	Deve	0.74	2.89	28.9	3.9	25
Dec	2	Deve	0.9	3.44	34.4	1.3	33.1
Dec	3	Mid	1.04	4.05	44.5	1.8	42.7
Jan	1	Mid	1.05	4.16	41.6	2	39.6
Jan	2	Late	1.04	4.2	42	1.8	40.2
Jan	3	Late	1.01	4.11	45.2	5.2	40.1
Feb	1	Late	0.97	4.01	40.1	8.9	31.2
Feb	2	Late	0.95	3.98	8	2.4	8
					330.6	40.1	293.8

Annex 5.4. CWR and IWR for Carrot

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.7	2.91	17.5	5.7	12.7
Nov	3	Init	0.7	2.83	28.3	7.1	21.2
Dec	1	Deve	0.77	3.02	30.2	3.9	26.3
Dec	2	Deve	0.96	3.67	36.7	1.3	35.4
Dec	3	Mid	1.05	4.08	44.9	1.8	43.1
Jan	1	Late	1.05	4.15	41.5	2	39.6
Jan	2	Late	1.02	4.12	41.2	1.8	39.4
Jan	3	Late	0.98	4.01	44.1	5.2	39
Feb	1	Late	0.96	3.95	15.8	3.6	11.3
					300.3	32.3	268

Annex 5.5. CWR and IWR for Onion

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.7	2.91	17.5	5.7	12.7
Nov	3	Init	0.7	2.83	28.3	7.1	21.2
Dec	1	Init	0.7	2.75	27.5	3.9	23.6
Dec	2	Init	0.7	2.67	26.7	1.3	25.4
Dec	3	Deve	0.73	2.84	31.2	1.8	29.4
Jan	1	Deve	0.85	3.35	33.5	2	31.6
Jan	2	Deve	0.96	3.89	38.9	1.8	37.1
Jan	3	Mid	1.05	4.28	47	5.2	41.9
Feb	1	Mid	1.05	4.34	43.4	8.9	34.5
Feb	2	Mid	1.05	4.39	43.9	11.9	32
Feb	3	Late	1.05	4.34	34.7	14.9	19.8
Mar	1	Late	1	4.08	40.8	18.3	22.5
Mar	2	Late	0.91	3.71	37.1	21.5	15.6
Mar	3	Late	0.83	3.49	31.4	18.8	8.4
					481.9	123.1	355.5

Annex 5.6. CWR and IWR for Tomato

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Sep	2	Init	0.6	2.32	13.9	17.3	0
Sep	3	Init	0.6	2.37	23.7	23.9	0
Oct	1	Deve	0.66	2.65	26.5	17.9	8.6
Oct	2	Deve	0.92	3.77	37.7	12.5	25.2
Oct	3	Mid	1.14	4.69	51.6	11.4	40.2
Nov	1	Mid	1.15	4.76	47.6	11	36.7
Nov	2	Late	1.08	4.51	45.1	9.5	35.6
Nov	3	Late	0.88	3.56	28.5	5.7	21.4
					274.6	109.2	167.6

Annex 5.7. CWR and IWR for Cabbage

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Oct	2	Init	0.7	2.88	17.3	7.5	11
Oct	3	Init	0.7	2.89	31.8	11.4	20.4
Nov	1	Deve	0.75	3.1	31	11	20
Nov	2	Deve	0.92	3.82	38.2	9.5	28.7
Nov	3	Mid	1.04	4.22	42.2	7.1	35.1
Dec	1	Mid	1.05	4.12	41.2	3.9	37.3
Dec	2	Late	1.04	3.95	39.5	1.3	38.3
Dec	3	Late	0.99	3.83	42.1	1.8	40.3
Jan	1	Late	0.95	3.78	7.6	0.4	7.6
					291	53.9	238.7

Annex 5.8. CWR and IWR for Salad

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.7	2.91	17.5	5.7	12.7
Nov	3	Init	0.7	2.83	28.3	7.1	21.2
Dec	1	Deve	0.74	2.89	28.9	3.9	25
Dec	2	Deve	0.9	3.44	34.4	1.3	33.1
Dec	3	Mid	1.04	4.05	44.5	1.8	42.7
Jan	1	Mid	1.05	4.16	41.6	2	39.6
Jan	2	Late	1.04	4.2	42	1.8	40.2
Jan	3	Late	1.01	4.11	45.2	5.2	40.1
Feb	1	Late	0.97	4.01	40.1	8.9	31.2
Feb	2	Late	0.95	3.98	8	2.4	8
					330.6	40.1	293.8

Annex 5.9. CWR and IWR for Sweet potato

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.5	2.08	12.5	5.7	7.7
Nov	3	Init	0.5	2.02	20.2	7.1	13.1
Dec	1	Init	0.5	1.96	19.6	3.9	15.7
Dec	2	Init	0.5	1.91	19.1	1.3	17.8
Dec	3	Deve	0.5	1.96	21.6	1.8	19.7
Jan	1	Deve	0.61	2.41	24.1	2	22.1
Jan	2	Deve	0.75	3.04	30.4	1.8	28.6
Jan	3	Deve	0.9	3.69	40.6	5.2	35.5
Feb	1	Deve	1.06	4.36	43.6	8.9	34.7
Feb	2	Mid	1.15	4.8	48	11.9	36.1
Feb	3	Mid	1.15	4.76	38.1	14.9	23.2
Mar	1	Mid	1.15	4.71	47.1	18.3	28.9
Mar	2	Mid	1.15	4.67	46.7	21.5	25.2
Mar	3	Mid	1.15	4.82	53	23	30
Apr	1	Late	1.13	4.89	48.9	24.7	24.2
Apr	2	Late	1.07	4.75	47.5	26.6	20.9
Apr	3	Late	1	4.41	44.1	27.1	17
May	1	Late	0.96	4.17	12.5	8.4	0
					617.7	214.1	400.4

Annex 5.10. CWR and IWR for Red root

Month	Decade	Stage	Kc (coeff)	ET_c (mm/day)	CWR (ET_c) (mm/dec)	Eff.rain (mm/dec)	Irr. Req. (mm/dec)
Nov	2	Init	0.8	3.33	20	5.7	15.2
Nov	3	Init	0.8	3.23	32.3	7.1	25.2
Dec	1	Init	0.8	3.14	31.4	3.9	27.5
Dec	2	Deve	0.77	2.94	29.4	1.3	28.2
Dec	3	Deve	0.64	2.49	27.4	1.8	25.6
Jan	1	Deve	0.5	1.98	19.8	2	17.8
Jan	2	Mid	0.4	1.63	16.3	1.8	14.5
Jan	3	Mid	0.4	1.63	18	5.2	12.8
Feb	1	Mid	0.4	1.65	16.5	8.9	7.6
Feb	2	Late	0.72	3.01	30.1	11.9	18.2
Feb	3	Late	0.8	3.31	23.2	13.1	8.3
					264.4	62.6	200.9