Addis Ababa University

School Of Graduate Studies

Addis Ababa Institute Of Technology

Groundwater Irrigation Possibility In Ethiopia

A Thesis Submitted To The School Of Graduate Studies In Partial Fulfilment Of The Requirements For The Degree Of Master Of Science In Civil Engineering (Stream Hydraulic Engineering)

By

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Advisor

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Addis Ababa University, Ethiopia

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I, the undersigned, certify that I read and hear by recommend for acceptance by Addis Ababa Institute of Technology a dissertation entitled **"ground water irrigation possibility in Ethiopia"** in partial fulfilment of the requirements for the degree of Master of Science in Hydraulic Engineering.

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ABSTRACT

Groundwater irrigation is an important factor to agricultural production in large parts of the world. The use of groundwater for agriculture in Ethiopia is low. Many irrigation schemes obtain water from river diversions in Ethiopia in which only farmers with land near the rivers gets profit from irrigation, while others are waiting for the rainy season rather than using groundwater for irrigation.This research investigates the possibility of ground water as complementary and/or supplemental irrigation, to increase agricultural productivity, creating food self-sufficiency, overcome the conflict between river water users and to involve farmers those waiting for rain season. Utilizing groundwater resource for irrigation purpose can be a key alternative to improve the country's deteriorating food supply. The main objective of the study is to assess the possibility of groundwater irrigation in Ethiopia. CROPWAT 8.0 model was used to calculate reference evapotranspiration. Reference evapotranspiration and agro ecological zones were used to first classify the evapotranspiration zones of Ethiopia. This classified evapotranspiration zones were also overlaid by the countries groundwater discharge and access depth maps using the Arc GIS software. Finally, degree one suitable, degree two suitable, degree three suitable and degree four suitable groundwater irrigation was determined in this research. Accordingly, the country has in general about 197,546km^2, 276,366km^2, 283,917km^2 and 374,709km^2 area degrees one, degree two, degree three and degree four suitable regions respectively, were identified and mapped. Such a map is useful for planning groundwater resources use for irrigation in Ethiopia. This study hopefully can be used as a base for further research work in the area.

Keywords: **Arc Gis, Ethiopia**, **Groundwater Irrigation**, **Reference Evapotranspiration**

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List of Abbreviations

AEZ..Agro-Ecological Zone

AGP..Agricultural Growth Program

a.s.l..Above mean sea level

cm..Centimetre

EIGS...Ethiopian Institute for Geological Surveys

Ft..Feet

ETo..Reference evapotranspiration

ET..Evapotranspiration

GMT..Greenwich Mean Time

Ha..Hectares

Hr...Hour

IWMI..International Water Management Institute

Km..Kilometre

Km...Kilometres

Km^2 ....Square kilometre

LSI ....Large Scale Irrigation

l/s...Litter per second

m...Meters

MoWR...Ministry of Water Resources

mm...Millimetre

$mmyr^{-1}$...Millimetre per year

Mha...Million hectares

R^2...Coefficient of Efficiency

RDPS..Rural Development Policy and Strategy

SCI ....Small Scale Irrigation

%..Percentage

RWS ....Rural Water Supply

UWS..Urban water supply

CHAPTER ONE

1. Introduction

1.1. General

Groundwater is the main source for domestic, industrial, and agricultural use in many parts of the world. In Ethiopia it can be used for irrigation in multiple ways, such as deep and shallow wells from underground aquifers. Ground water resources for irrigation have a number of advantages including: reliability of water source as compared with other. It has a naturally renewable capacity which is availability in many places, such as in highlands, steep terrains, inland valleys, and plain areas: (Awulachew S.B. 2010)

Developing Irrigation schemes is being promoted and becoming increasingly important in meeting the demands of food security, employment and poverty reduction in developing countries like Ethiopia. The use of groundwater for agriculture in Ethiopia is low and mostly used for domestic water supply (Getachew Ewonetu 2013). For that reason and to overcome the conflict between river water users, to involve farmers those waiting for rain season, to ensure rural communities food self sufficient and for proper utilization groundwater resources, this study will be helpful.

Supplemental irrigation is the addition of small amounts of water to essentially rained crops during times when rainfall fails to provide sufficient based moisture for normal plant growth, in order to improve and stabilize yields (Oweis and Hachum, 2003). Supplemental irrigation is not habitual in Ethiopia, but using groundwater resource as supplemental irrigation is the best solution for crops faced to problems of deficit rain fed. Consequently, in this research supplemental irrigation is investigated at the area of degree one groundwater utilization or at shallow and/or very shallow groundwater depth.

In this research, attempt has been made to determine groundwater irrigation possibility in Ethiopia, it begun with an overview of the area and analysis of the meteorological data of the area. Then it attempts to identify climatic condition, reference evapotranspiration, ground water depth and groundwater discharge condition using Arc GIS soft. The things that make this research differ from other works are: the possibility of groundwater irrigation was determined based on multiple view point such as agro ecological zones, reference evapotranspiration, and depth and discharge condition of ground water.

1.2. Statement of the Problem

Ethiopia is a country with high population in sub-Saharan Africa with poor food self-sufficiency. The use of groundwater for agriculture in Ethiopia is low and mostly used for domestic water supply. But it can be used for irrigation in multiple ways, such as deep and shallow wells from underground aquifers (Awulachew S.B. 2010). Many irrigation schemes obtain water from river diversions in which only farmers have land near the rivers get profit from irrigation. Most farmers are waiting for the rainy season rather than using groundwater irrigation. As the demand for irrigation water increases by an expanding number of farmers, the stream flow has decreased significantly this can cause conflict among the upstream and downstream water users. Different crops have faced problems like, erratic rainfall, drought which affect the total crop production. Groundwater irrigation can be expanded to increase agricultural production and to mitigate the existing challenging problem. And also utilizing groundwater resources as supplemental irrigation to reduce the failure of crop during shortage of rainfall and as complementary irrigation to increase income of farmers is useful. All in all, in Ethiopia the use of groundwater for irrigation though vital, haven't yet been explored let alone use for irrigation. Thus the first step in developing ground water for irrigation, where larger discharges are required, is to identify the possible potential sites for groundwater irrigation. Thus this research tries to identify and map suitable locations in Ethiopia as possible with the existing information.

1.3. Objective of the Study

1.3.1. General Objective

The main objective of the study is to assess the location of potential groundwater irrigation possibility in Ethiopia.

1.3.2. Specific Objective

- ✓ To identify location suitable for groundwater irrigation in Ethiopia with the existing information
- ✓ To classify Ethiopia in to evapotranspiration zone
- ✓ To develop reference evapotranspiration map, groundwater utilization map and groundwater irrigation suitability map of Ethiopia

1.4. Significance of the Study

The intended thesis will provide reliable and valid findings about the possibility of groundwater irrigation to increase agricultural products, increasing profit and ensure food self sufficient to the relevant stakeholders. To this effect the research will have the following significance.

- ✓ It informs that the location where groundwater irrigation is possible.
- ✓ The finding will serves as input in planning or/and designing the future irrigation development programs.
- ✓ It can be a base to other researchers who desire to assess about groundwater irrigation development at zonal or national level.

1.5. Scope and Limitation of the Study

The scope of this study is limited to determine the possibility of groundwater irrigation in Ethiopia on economic aspect. The study considers only those variables which determine the use of groundwater for irrigation like borehole drilling cost, pump cost, operational cost, construction cost, installation cost and maintenance cost. This research was conducted to assess the possibility of groundwater irrigation in which other factor such as groundwater quality is not included.

1.6. Organization of the Paper

The thesis is organized as follows: chapter one is an introduction of the study. This chapter contain statement of the study, objective of the study, significance of the study, scope and limitation of the study. The next chapter represents review of previous studies or literature review on groundwater resource for irrigation on socio-economic development of the society. Chapter three present research methodology. Chapter four present result and discussion. Chapter five present conclusion and recommendation

CHAPTER TWO

2. Literature Review

2.1. General

The major objective of this chapter is to highlight some facts and results from different past works of groundwater irrigation in general. Here only a summary of the literature orientated to the main objective of the study was presented.

2.2. Ground Water Use for Irrigation and its potential

Ethiopia has vast cultivable land (30 to 70 Mha), but only about a third of that is currently cultivated (approximately 15 Mha), with current irrigation schemes covering about 640,000 ha across the country. This means that there are potential opportunities to vastly increase the amount of irrigated land. Groundwater in Ethiopia can be used for irrigation in multiple ways, such as deep and shallow wells from underground aquifers. Compared with other sources of irrigation, groundwater as a resource for agricultural development offers a number of advantages, including: Reliability of the water source, since it has a naturally renewable capacity: on-demand water supply through natural water storage: Domestic water source, with no trans-boundary considerations: Availability in many places, e.g., in highlands, steep terrains, inland valleys, and plain areas and relative constancy of supply, which can help to buffer the high variability of surface water resources(Awulachew S.B. 2010). Despite these advantages of groundwater, it is not widely exploited in agriculture in Ethiopia due to the following constraints: (1) Costly development and operations (2) Depth of access can increase investment requirements (3) the average cost of per hectare of groundwater development, including operation, is two to four times higher than for surface water irrigation (e.g., stream diversion) (4) Lack of a comprehensive understanding of Ethiopia's groundwater resources, Information regarding aquifer characteristics, delineation, available water, sustainable recharge amount, etc., is limited and not well understood due to complex Ethiopian geology and lack of studies. (5) Difficulties and costs related to the need for specialized equipment (e.g., deep drilling rigs) and specialized and well-trained staff (e.g., well drillers). Despite these constraints, there are major opportunities for the development and protection of groundwater, including: (i) exploiting shallow groundwater; (ii) enhancing water recharge in aquifers, including forestation in hilly areas, infiltration galleries, and subsurface dams to increase the available water in the sub-surface; and (iii) using a watershed-based approach to enhance soil and water conservation and increase the groundwater level in the valley bottoms for easy access to groundwater.

Table 1 Groundwater potential in the three Ethiopian Zone

Zones and ground potential	Available water (BM3)	Irrigation potential (ha)
Zone 1 high potential	1.06	211,386
Zone 1 medium potential	0.83	137,636
Zone 1 low potential	0.23	32,317
Zone 2 high potential	0.63	126,806
Zone 2 medium potential	0.49	81,542
Zone 2 low potential	0.23	32,317
Zone 3 high potential	1.56	311,808
Zone 3 medium potential	0.85	141,989
Zone 3 low potential	0.63	90,081
Total	6.5	1,165,881
(Source: Awulachew S.B. 2010)		

As with surface water potential, this total means that there is significant potential to increase irrigation sources from groundwater. Since recent information indicates that Ethiopia's groundwater potential could be significantly higher than currently estimated, this 1.1 Mha estimate can be refined in the future when more relevant information can be generated through further research and study Awulachew S.B. 2010).

Ethiopia's geology and hydrogeology is well summarised by Getachew Hailemichael (2003), from which Table 2 is drawn

Table 2 Main aquifers of Ethiopia

Aquifer system	Depth to water, m	Well Yield-l/s	Location	Aquifer description
Weathered and fractured precambrian rocks(granit, metamorphi)	30-60	1-2	Western, south western part of the country	Three type of rocks have very low fracture permeability while the depth of fracturing shallow and accordingly ground water in this type of aquifer is also shallow, however if a thickness layer of weathered over burden exist, relatively good yields occurs
Sedimentary rocks (Mesozoic sand stone, karstic,lime stone)	200-300	2-5	Eastern, south eastern part of the country	These are thick layers of Mesozoic sedimentary rocks (in some area Palaeozoic rocks exists) that hve different layers of sand stone, marl, limestone, shale and conglomerate[14.] The primary porosity developed is very poor for some of the layers (lime stone) while secondary porosity and karistification is very common in the limestone. Therefore good yield of water is extracted from the karstifed limestone and the sand stone. However due to the depth of these layer, well striking these

				aquifers are very deep to as much as 400meter, the average depth being 250m
Tertiary volcanic (having primary and secondary porosity)	50-250	2-6	In the central, eastern and western highland of Ethiopia	These aquifers have both primary and secondary porosity with well depths extending to 250m. There are successive layers of aquifer systems and the upper most part yield smaller amount of water (0.5-1.0l/s). If drilled deeper, the occurrence of groundwater increases. These aquifers exist extensively throughout the country especially in the western, central and eastern highlands. The water quality in this type of aquifers is generally good
Quaternary volcanic	100-250	2-5	Rift valley	These are young volcanic of the rift floor where high tectonic activity is occurring which has resulted in highly fractured rocks and as a result a favourable situation for groundwater recharge and occurrence exist
Unconsolidated sediments (alluvial, colluvial, insitu developed soils, lacustrine sediments)	20-100	1-5	Mostly n the rift valley, western low land, river valleys, isolated depressions throughout the country	These are lacustrine and alluvium deposits of the flood plains and valley fills. They are valley important hydrogeology formations that are used good sources of groundwater in Ethiopia. The grain sizes of the alluvial deposits valley from clay to gravel with horizontal and vertical variation n grain sizes. A they are located exposed to the surface, seasonal recharge by direct rainfall occurs and as a result they are good source of groundwater.
In situ developed sol	5-20	0.1-1	Throughout the country (especially in the highlands and midlands of the country	These are soil developed with micro catchment where the rainfall directly infiltrate and stores in the saturated zones. These types of soils are found to be useful sources of soil especially in the highland of Ethiopia where traditional a nd improved HDWa are the major source water supply. Seepage springs are also common whenever there is a break in slope and/ lower contact of the soil is exposed to the surface. Springs from these types of sol have an average yield of about 0.1lit/sec
Souece: Getachew Hailemichael, 2003				

Table 3 a proposed new classification of aquifers in Ethiopia – made to make a distinction between the different shallow aquifer

Proposed Name	Depth-meters	Characteristics	Use	Intensity of use	Rock type
Very shallow Aquifer	0-30	Hand dug wells Phreatic aquifer Low yields Bacteriological pol.	RWS SCI	Medium	A B D
Shallow aquifer	30-100	Dug and drilled wells phreatic and confined, Low/medium yields Pollution hazards	RWS (UW) SCI	Medium to High	A B C D
Deep aquifers	100-250	Drilled wells, Main aquifers Medium yields, Pollution hazard	UWS LSI	Medium	A B C D
Very deep Aquifers	>250	Drilled wells,Medium/high yields, Recent development	UWS LSI	Low	B D
Source: Ministry of water and energy updated version, 2013					

Rock type: A - Precambrian metamorphic basement rocks (cover about 23% of the country). B- Mesozoic sedimentary rocks (cover about 25%): C-Tertiary volcanic rocks-largely flood basalts-(cover about 25%): D-Quaternary volcanic rocks-largely ignimbrites-and sediments (cover about 17%)

Depth of groundwater and discharge condition

Groundwater depth and discharge condition map which are shown in shown in Figure1 were collected from Geological survey of Ethiopia.

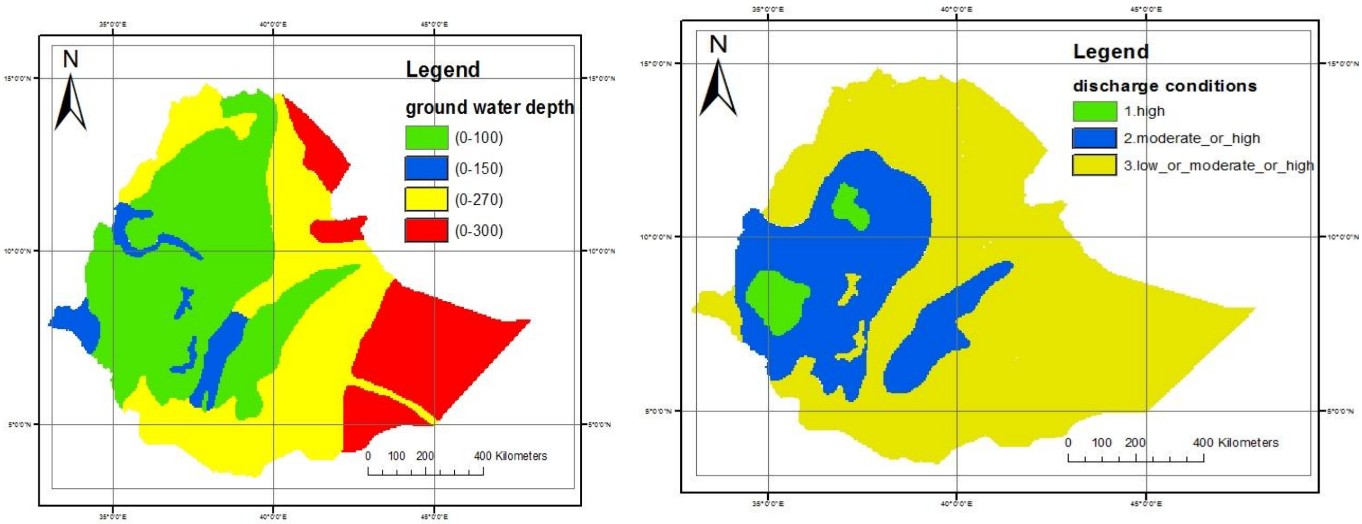


Figure 1 groundwater depths and ground water discharge conditions (A).Ground water depths (B) Groundwater discharge conditions [Source: EGS. 1996, re-digitized]

2.3. Agriculture and Rainfall variability in Ethiopia

Rain-fed crop production is the basis of all subsistence farming in most parts of the country. However, rainfall in much of the country is erratic and unreliable so that its variability and associated droughts have historically been major causes of food shortages and famines. There is a significant relation between climate and agricultural production in terms of the timing, variability, and quantity of seasonal and annual rainfall in Ethiopia. As a result, farmers during unexpected break in rainfall in early growing season may be able to recover and resume production despite the loss of some of their crops (Cheung *et al.* 2008).

Most Ethiopian rainfall variation, with the exception of the south and south-eastern parts of the country, is caused by the inter-tropical convergence zone (ITCZ) (Kassahun, 1999; and Romilly and Gebremichael, 2010).

Rainfall is the ultimate source of water in Ethiopia, with surface water, ground water, and other water sources fed by rain. To understand the country's irrigation potential, it is important to understand these water sources. Ethiopia has significant rainfall. Based on grid-based average annual rainfall and the land area, the study estimates that Ethiopia receives about 980 billion (~1 trillion) cubic meters (m^3) of rain a year. Ethiopia is divided into 32 major agro-ecological zones (AEZ) based on temperature and moisture regimes classification data. These 32 agro ecological zones (AEZs) can be classified further into three primary zones within Ethiopia. This classification mirrors that found in the Rural Development Policy and Strategy (2001) and the Plan for Accelerated and Sustained Development to Eradicate Poverty (PASDEP). The three zones are: high rainfall areas, moisture deficit zones, and pastoralist zones. Figure 2 shows these three zones, based on rainfall and evapotranspiration.

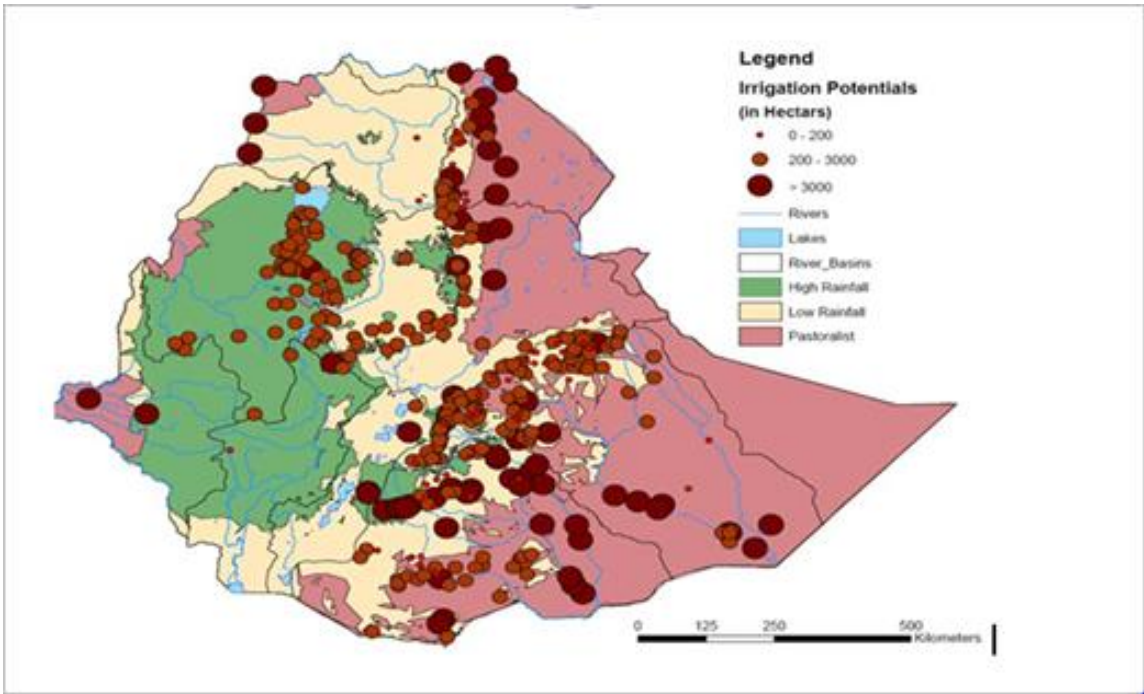


Figure 2 the three zones of Ethiopians' [IWMI]

The three zones have the following characteristics:

- **High rainfall zone**: Covers 24 percent of land, 43 percent of population, and 51 percent of permanent crop output. In these areas, rainfall tends to exceed 800 mm/year. Typical development is mixed crop-livestock systems, though crops dominate. The land is not particularly vulnerable, nor is it very productive. Here, irrigation would be supplementary to produce a second crop and increase productivity. Note that despite significant rainfall in this zone, the rainfall is highly variable, and occurs in a limited period of the year.

- **Moisture deficit zone**: Covers 32 percent of land, 47 percent of population, and 39 percent of permanent crop output. Rainfall is generally lower than 600 mm/year. Rainfall is highly variable, and the land is moderately to highly degrade. Production is typically mixed crop and livestock, with crops dominating. These areas are often vulnerable and degraded, and constrained by low productivity and overpopulation. Here, irrigation could secure food production, improve livelihoods, and increase food resilience.
- **Pastoralist zone**: Covers 44 percent of land, 10 percent of population, and 10 percent of permanent crop output. Except in the west part of the country, rainfall is lower than 600 mm/year. Pastoralist, livestock-based and non-sedentary lifestyles prevail, and these areas are constrained by vulnerability and low livestock productivity. Irrigation would create livelihood options and increase food resilience.

2.4. Irrigation Methods

To choose an irrigation method, the advantages and disadvantages of the various methods must be known. Even though all methods have their advantages and disadvantages, provide the best and sound choice of irrigation methods under the local conditions is essential. The suitability of the various irrigation methods, i.e. surface, sprinkler or drip irrigation depends mainly on natural conditions, type of crop, type of technology, previous experience with irrigation, required labour inputs, costs and benefits factors. Water availability Water application efficiency is generally higher with drip and sprinkler irrigation than surface irrigation and so these methods are preferred when water is in short supply. However, it must be remembered that efficiency is just as much a function of the irrigator as the method used. Type of crop Surface irrigation can be used for all types of crops. Sprinkler and drip irrigation, because of their high capital investment per hectare, are mostly used for high value cash crops, such as vegetables and fruit trees. They are seldom used for the lower value staple crops. Drip irrigation is suited to irrigating individual plants or trees or row crops such as vegetables and sugarcane. It is not suitable for close growing crops (e.g. rice). Costs and Benefits Before choosing an irrigation method, an estimate must be made of the costs and benefits of the available options (Fangmeier, D.D.1977). On the cost side not only the construction and installation, but also the operation and maintenance (per hectare) should be taken into account. These costs should then be compared with the expected benefits (yields). From above condition point of view drip and sprinkler irrigation methods have been selected as more water application efficiency for ground water irrigation in this study.

2.5. Supplemental Irrigation

Supplemental irrigation may be defined as ‘the addition of small amounts of water to essentially rained crops during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields’ (Oweis and Hachum, 2003). Supplemental irrigation is useful for early sowing during deficit of rainfall. Since rainfall is the major source of water for crop production in rain fed systems, the amount of water added through Supplemental irrigation cannot alone support economic crop production. Unlike full irrigation, the timing and amount of supplemental irrigation cannot be determined in advance owing to uncertainty of rainfall, but can alleviate the critical periods of water shortage. The purposes of supplementary irrigation are supplying crops with water when natural precipitation and irrigation waters are insufficient to satisfy full crop water requirements to satisfy the evapotranspiration demand of the atmosphere.

2.6. Reference evapotranspiration

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ETo. The reference surface is a hypothetical grass reference crop with specific characteristics. Reference evapotranspiration has an important role as controlling factor of irrigation water requirement (Arumugam et al 1996). Generally, Estimates of reference evapotranspiration (ETo) are widely used in irrigation engineering to defined crop water requirements. Hydrological changes constitute one of the most significant potential impacts on global climate change in the tropical regions (IPCC, 2007). It is now clear that climate change will cause a steady rise of temperature and changes in rainfall pattern. Higher temperature will induce higher evapotranspiration which in turn will affect the hydrological system and water resources (Shahid, 2011). Thus, quantifying the changes in Evapotranspiration due to climate change is very important for the management of long-term water resources. Especially in the crop lands, it is essential to measure the possible changes in Evapotranspiration and probability of water losses due to climate change. Penman-Monteith method is reliable over a broad climatic region to estimate reference evapotranspiration. Reliability of this method has been tested in different parts of the world including Malaysia and they are found to estimate Evapotranspiration very close to field observation. Unfortunately, these methods are parameter rich model and require extensive data and information for reliable estimation of Evapotranspiration. This poses a problem in making accurate future ET projection for data scarce region. Most meteorological stations only measure temperature and rainfall while other meteorological parameters that are required for parameter rich models for ET estimation are rarely measured.

2.7. Penman-Monteith method

Use of this method in estimating evaporation Ethiopia and the wider East African region could be found in the literature (Yin and Nicholson, 1998; Vallet-Coulomb *et al.*, 2001; Kebede *et al.*, 2006). Penman method provides the most reasonable estimation of reference evapotranspiration (ETo) and it is one of the most reliable methods which consider the atmospheric changes comprehensively (Allen *et al.*, 1998, 2006; Sentelhas *et al.*, 2010; Ravazzani *et al.*, 2011): Reliability over a broad climatic region of these methods has been tested in different parts of the world and it is found to estimate reference evapotranspiration (ETo) very close to field observation (walter et al.2000). Penman-Monteith method is now the sole recommended method for calculating reference evapotranspiration (ETo) and this method, its derivation and the required meteorological data are air temperature, air humidity, solar radiation and wind. The Penman- Moteinth equation provides the best method and considered to offer the best results with minimum possible error in relation to a living grass reference (FAO, 1998). As such in this theses paper CROPWAT 8.0 model was selected because it use the penman Monteith formulae.

2.8. CROPWAT 8.0

The main purpose of CROPWAT is to calculate crop water requirements and irrigation schedules based on data provided by the user. These data can be directly entered into CROPWAT or imported from other applications. For the calculation of crop water requirements (CWR), CROPWAT needs data on evapotranspiration (ETo). It allows the user to either enter measured ETo values, or to input data on temperature, humidity, wind speed and sunshine, which allows CROPWAT to calculate ETo using the Penman-Monteith formulae. Rainfall data are also needed, and are used by CROPWAT to compute effective rainfall data as input for the CWR and scheduling calculations. Finally, crop data are needed for the CWR calculations and soil data if the user also wants to calculate irrigation schedules. CROPWAT normally calculates CWR and schedules for 1 crop, it can also calculate a scheme supply, which is basically the combined crop water requirements of multiple crops, each with its individual planting date (a so-called cropping pattern). The data input modules of CROPWAT are: Climate/ETo: for the input of measured ETo data *or* of climatic data that allow calculation of

ETo Penman-Monteith; Rain: for the input of rainfall data and calculation of effective rainfall; Crop (dry crop or rice): for the input of crop data and planting date; for the input of soil data for (only needed for irrigation scheduling). CROPWAT 8.0 has been developed by Joss Swennenhuis for the Water Resources Development and Management Service of FAO. CROPWAT 8.0 is based on the DOS versions CROPWAT 5.7 of 1992 and CROPWAT 7.0 of 1999. Procedures, algorithms and documentation were developed and/or tested by Martin Smith, Gerardo Van Halsema, Florent Maraux, Gabriella Izzi, Robina Wahaj and Giovanni Munoz. FAO [2009]. In this thesis paper reference evapotranspiration (ETo) was computed by CROPWAT 8.0 model.

2.9. Thiessen polygon method

Thiessen polygon can be used to apportion a point's coverage in to polygon. This tool is used to divide the area covered by the input point feature in to Thiessen or proximal zones. These zones represent full areas where any location within the zone is closer to its associated in put point than to any other input point. Thiessen polygons can be used to describe the area of influence of a point against other points. If one takes a set of points and connects each point to its nearest neighbour, then a triangulated irregular network is obtained (Collins and Bolstad, 1996); closed polygons are created by generating perpendicular bisectors for each triangle edge. The locations at which of the bisectors intersect determine the locations of the Thiessen polygon vertices. All the agricultural areas of the island were categorized according to the nearest meteorological station which is considered as "representative" of the area. Thiessen polygons methodology was used for this purpose. The intended goal was to illustrate what can happen to a crop, in terms of water requirements. For the purposes of crop evapotranspiration estimation in Cyprus, Thiessen methodology was employed to divide Cyprus geographically according to the distance from the five main meteorological stations situated in the territory of the island; Based on Thiessen polygons method ETc was estimated for five agricultural sites in Cyprus. (G. Papadavid et al. 2011).

In order to determine the suitability of the meteorological stations for estimating ETc, a spatial analysis called Thiessen polygons was applied (Burrough and McDonnell, 1998). Thiessen polygon is a local interpolation technique where the interpolated meteorological data (value) equals the nearest observation value. The technique gives all the estimations the values at the point observations and no new values are added (E.G. Beek, 1991).

2.10. Agro ecological zones of Ethiopia

The climate of Ethiopia is mainly controlled by the seasonal migration of the Inter Tropical Convergence Zone, which follows the position of the sun relative to the earth and the associated atmospheric circulation, in conjunction with the complex topography of the country. (NMSA 2001)

There are different ways of classifying the climatic systems of Ethiopia, including the traditional, the rainfall regimes, and the agro-climatic zone classification systems. The most commonly used classification systems are the traditional and the agro ecological zones (AEZs). According to the traditional classification system, this mainly relies on altitude and temperature. (Yohannes, 2003)

Table 4 Traditional Ethiopia Agro ecological zones: (Source: MoA, 2000).

Zone	Altitude (meters)	Mean (Rainfall (mm)	Average annual temperature (ºC)
Berha (dray- hot)	500 -1500	<900	>22
Weynadega (dry-warm)	1,500 – 2,500	<900	18-20
Erteb Kola (sub-moist-warm)	500-1,500	900-1,000	18-24
Weinadega (sub-sub-moiest)	1,500 – 2,500	900-1,000	18-20
Erteb weindega(moist-cool)	1,500 – 2,500	>1,000	18-20
Wurch(very cool or alpine)	>3500	>1,000	<10
Dega(cold)	2,500 – 3,500	900 – 1,000	14-18
Erteb Dega (moist cold)	2,500 – 3,500	>1,000	10-14

The agro ecological zone classification method as described in table 5, on the other hand is based on combining growing periods with temperature and moisture regimes. According to the agro ecological zone classification system, Ethiopia has 18 major agro ecological zones. These AEZs are also grouped under six major categories which include the following:

1. Arid zone: This zone is less productive and pastoral, occupying 53.5 million hectares (31.5 percent of the country). (2) Semi-arid: This area is less harsh and occupies 4 million hectares (3.5 percent of the country). (3) Sub-moist: This zone occupies 22.2 million hectares (19.7 percent of the country), highly threatened by erosion. (4) Moist: This agro-ecology covers 28 million hectares (25 percent of the country) of the most important agricultural land of the country where cereals are the dominant crops. (5) Sub-humid and humid: These zones cover 17.5 million hectares (15.5 percent of the country) and 4.4 million hectares (4 percent of the country), respectively. They provide the most stable and ideal conditions for annual and perennial crops and are home to the remaining forest and wildlife, having the most biological

diversity. (6) Per-humid: This zone covers about 1 million hectares (close to 1 percent of the country) and is suited for perennial crops and forests.

Table 5 the current major agro-ecological zones of Ethiopia (Source: MoA, 2000)

No.	Code	Zone
1	A1	Hot to warm-arid lowland plains
2	A2	Tepid to cool arid mid highland
3	SA1	Hot to warm semi-arid lowlands
4	SA2	Tepid to cool semi-arid mid highlands
5	SA1	Hot to warm sub moist lowlands
6	SM 2	Tepid to cool sub moist mid highlands
7	SM 3	Cold to very cold sub-moist sub-afro alpine
8	M1	Hot to warm moist lowlands
9	M2	Tepid to cool moist mid highlands
10	M3	Cold to very cold sub-afro alpine to Afro alpine
11	SH 1	Hot to warm sub humid lowlands
12	SH 2	Tepid to cool sub humid mid highlands
13	H3	cold to very cold sub-humid sub-afro alpine to Afro alpine
14	H1	Hot to warm humid lowlands
15	H2	Tepid to cool humid mid highlands
16	H3	Cold to very cold humid sub afro alpine to afro alpine
17	Ph 1	Hot to warm per-humid lowlands
18	Ph 2	Tepid to cool per-humid highlands

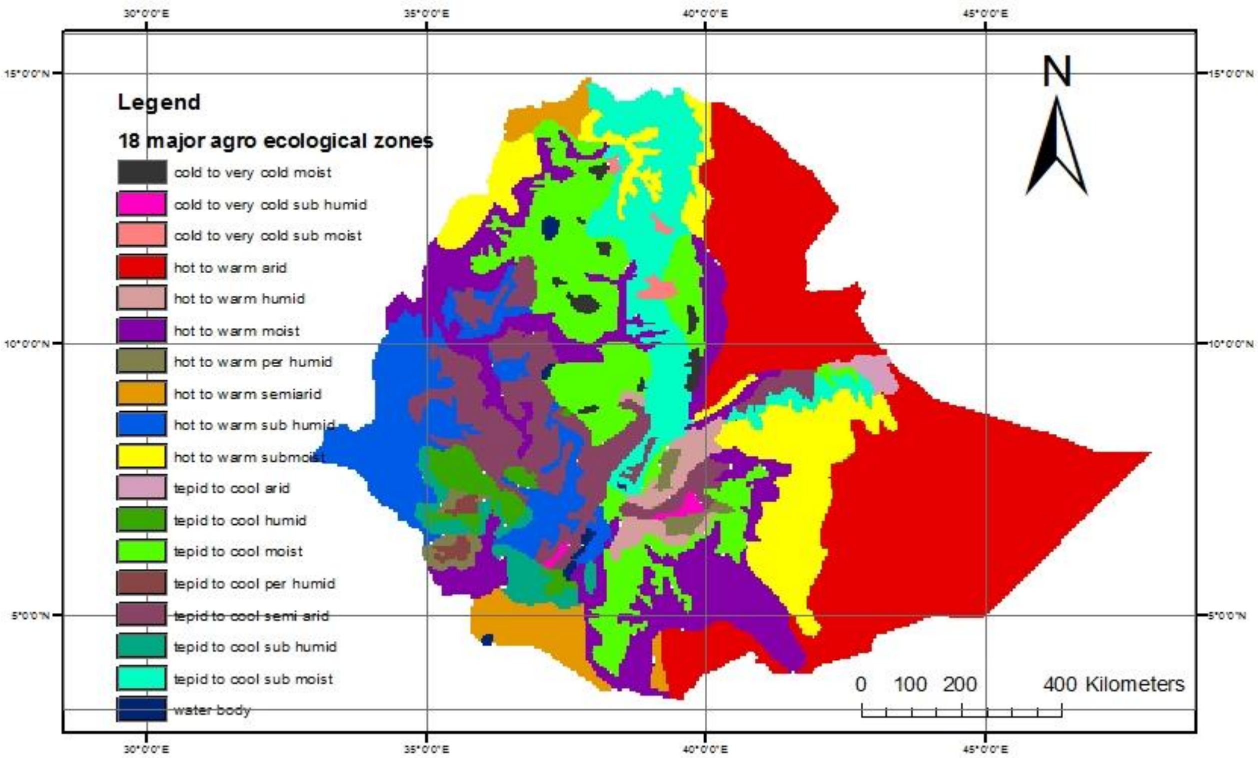


Figure 3 agro ecological zones of Ethiopia [Source: MoA, 2000 Ethiopia, re-digitized]

2.11. ROLE OF GIS

GIS is the tool for input, storage and retrieval, manipulation and analysis, and output of spatial data. GIS functionality can play a major role in spatial decision-making. The ultimate aim of GIS is to provide support for spatial decisions making process (Foote and Lynch 1996). In multi-criteria evaluation many data layers are to be handled in order to arrive at the suitability, which can be achieved conveniently using GIS.

2.12. XLSTAT

XLSTAT is the leading data analysis and satirical solution for Microsoft excel. It is a powerful, reliable, affordable, and easy to install and to use, XLSTAT has grown to be one of the most commonly used statistical software packages on the market. Since 1993, XLSTAT community includes more than 100,000 user's businesses and university, large and small in over 100 countries across the world. Also it is quantitative marketing software that includes MaxDiff, Conjoint, CBC, TURF, Parttial Least Square Structural Equation Modelling and many more.(http://www.xlstat.com)

CHAPTER THREE

3. Methodologies

3.1. Description of the Study Area

3.1.1 Location

Ethiopia is located in the horn of Africa, lies from longitudes 33°E to 48°E and latitudes from 3.5°N to 15°N, covering a land area of 1.13 million km² and including large areas of flat land and gently rolling hilly areas as well as steep mountains and ragged valleys. There is uneven distribution among regions, mainly varies with regional altitude changes from slightly below sea level to more than 4,000 m above sea level. In Ethiopia, the basins those are located in an area where water resources development for various purposes is identified to be a key element for achieving local and national development goals (MoFED, 2006).

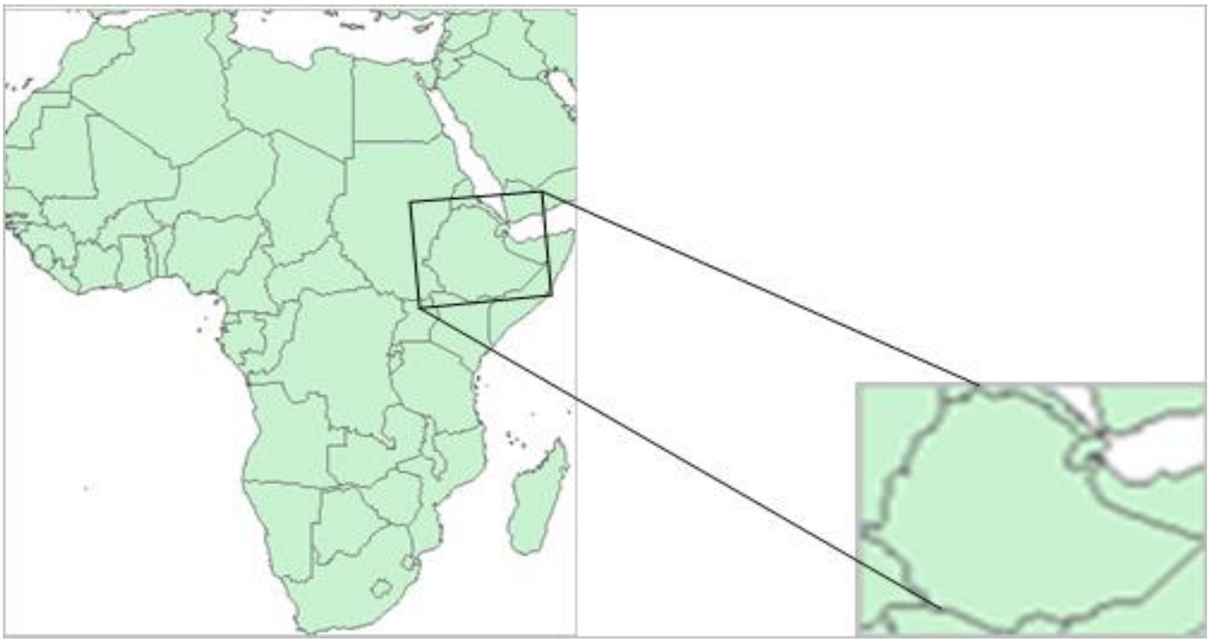


Figure 4 the location of the study area

3.1.2 Relief

Ethiopia has a high relief with altitudes ranging between 120 metres below sea level at Lake Assale (Danakil Depression) and 4550 metres above sea level at Ras Dashen (Siemen Mountains). The country may broadly be divided into three major physiographic regions (a) the Western Highlands and associated lowlands, (b) the Eastern Highlands and associated lowlands, and (c) the Rift Valley in between, running north-south in the middle of the country and dividing the Western Highlands from the Eastern Highlands. (Tesfaye.Chernet. 1993)

3.1.3 Climate

Ethiopia is located in East Africa where the common climatic feature is relatively low rainfall with complicated distribution pattern showing a general increase from north to south (McGregor and Nieuwolt, 1998). Rainfall in most of Africa and Ethiopia is highly seasonal as it is dominantly controlled by the migrating inter-tropical convergence zone (ITCZ) (Hulme, 1996). The climate of Ethiopia is quite variable across the country. Ethiopia's climate is mainly tropical steppe climate and subtropical forest climate, the annual average temperature is from 10 to 27°C and the tropical zone receives less than 510 mm rain per annum, while the subtropical zone, which includes most of the highlands, receives 510 to 1,530 mm of rain annually **(Mati, 2006).**

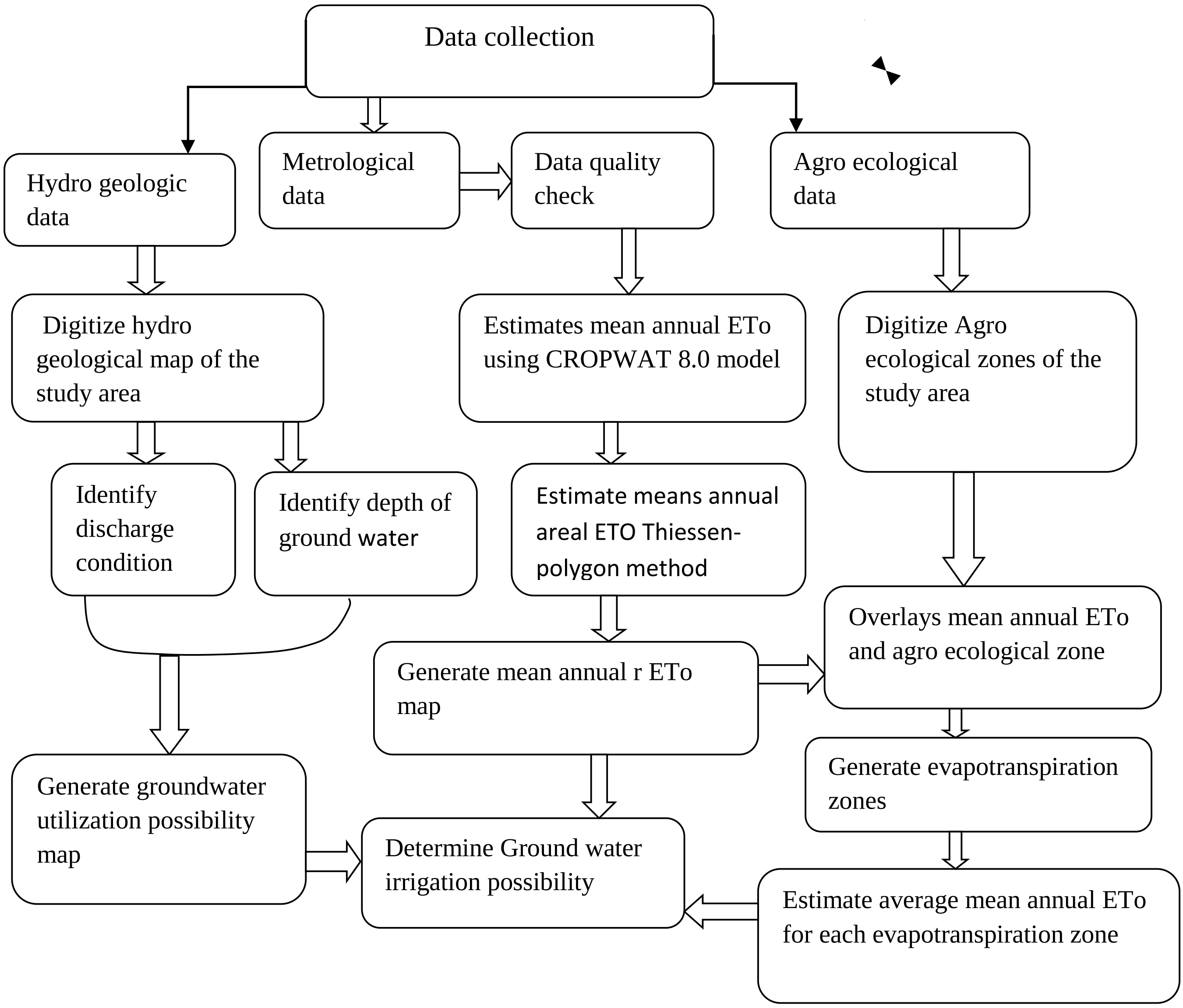
Based on the amount of rainfall, three seasons are recognized in Ethiopia and they are locally called *Kiremt* (June-September), *Bega* (October-January) and *Belg* (February-May). Different regional and global weather systems control the climate of each season (NMSA, 1996). Moreover, orographic and convective factors shape the spatial and temporal patterns of rainfall in Ethiopian highlands (Korecha and Barnston, 2006). The *Bega* season is the dry, windy and sunny season of Ethiopia due to the influence of the dry northeast monsoons that originate in the Saharan and/or Siberian anticyclones. However, a low pressure air that moves from western to Eastern Europe, very occasionally, passes over Ethiopia and interacts with warm and humid air from the tropics creating unseasonal rainfall in Ethiopia during this season (Kassahun, 1999). The climate of Ethiopia is mainly influenced by altitude and the main climatic regions are the following

- ✓ Dega (cool to cold temperature): This is typical of the cool highlands where average temperature falls between10^0c and 16^0c the altitude is above 2500 meters above sea level.
- ✓ Weina dega (warm to cool climate): Average annual temperature ranges between 16^0c and 20^0c and comprises much of the highlands between 1500 to 2500 meters above sea level.
- ✓ Kolla (warm to hot climate): This is the climate of the hot lowlands and the average temperature between 20^0c to 30^0c the altitude ranges from 500 to 1500 meters above sea level.
- ✓ Bereha (hot to arid climate): This cover the area of the desert lowlands below 500 meters above sea level- average annual temperature is over 30^0c.

3.2. Methods and Approaches

Different methodologies can be used to achieve the stated objectives. The methodology adopted in this research is as shown in flow chart below. At first relevant data were collected form secondary and primary sources. Analyses of meteorological data involved checking of data quality, gap filling and their characterization in space and time. The specific techniques for each of these activities are presented in the relevant sections.

Framework of the research



3.2.1. Data collection and analysis

This study involved the use of Arc GIS software that requires meteorological, agro ecological and Hydro-geological data. This is including:

- Meteorological data: temperature, relative humidity, and wind speed, short wave solar radiation and long wave solar radiation.
- Hydro-geological data: depth and discharge condition of ground water
- Agro ecological zones data: Tepid to cool moist, Tepid to cool sub moist, Hot to warm moist, Hot to warm sub moist, tepid to cool arid, tepid to cool semi-arid, hot to warm-arid, Hot to warm semi-arid, tepid to cool humid, Tepid to cool sub humid, Hot to warm humid, Hot to warm per-humid, Hot to warm sub humid, Cold to very cold humid, Tepid to cool per-humid, Tepid to cool moist, Cold to very cold sub-moist, cold to very cold sub-humid and Cold to very cold sub-afro alpine to Afro alpine.

This chapter presents the quality, filling data gaps and characteristics of the major datasets that could be obtained from different sources.

Class 1 meteorological data over the time period 1996 – 2015 were collected from Ethiopia National Metrological Services Agency (NMSA). To perform meteorological data using long time series and filling in missing data is very important. The source of meteorological data is the National Meteorological Agency of Ethiopia (NMA) which recognizes four station classes based on the type of observations made (NMSA, 2001).

Class 1: These are principal stations where meteorological observations are made for climatologically purposes every three hours from 03:00 to 15:00 GMT hours. There are more than 150 principal stations in Ethiopia. Observed climatologically variables include rainfall, maximum and minimum temperatures, sunshine hour, relative humidity, wind speed, pitch evaporation and soil temperature.

Class 2: These are synoptic stations at which meteorological observations are made for synoptic meteorology purpose every hour for 24 hours a day at full GMT hours. There are 22 Synoptic stations in Ethiopia.

Class 3: These are ordinary stations at which only minimum and maximum air temperatures of the day and total rainfall amount in 24 hours are observed. Minimum temperature observation is taken at 06:00 and maximum temperature is observed at 15:00 hours.

Class 4: These are stations at which only total daily rainfall is observed.

The distribution of meteorological stations in the study area is indicated in Figure 5.

Detailed information on the stations is presented in Annex A.

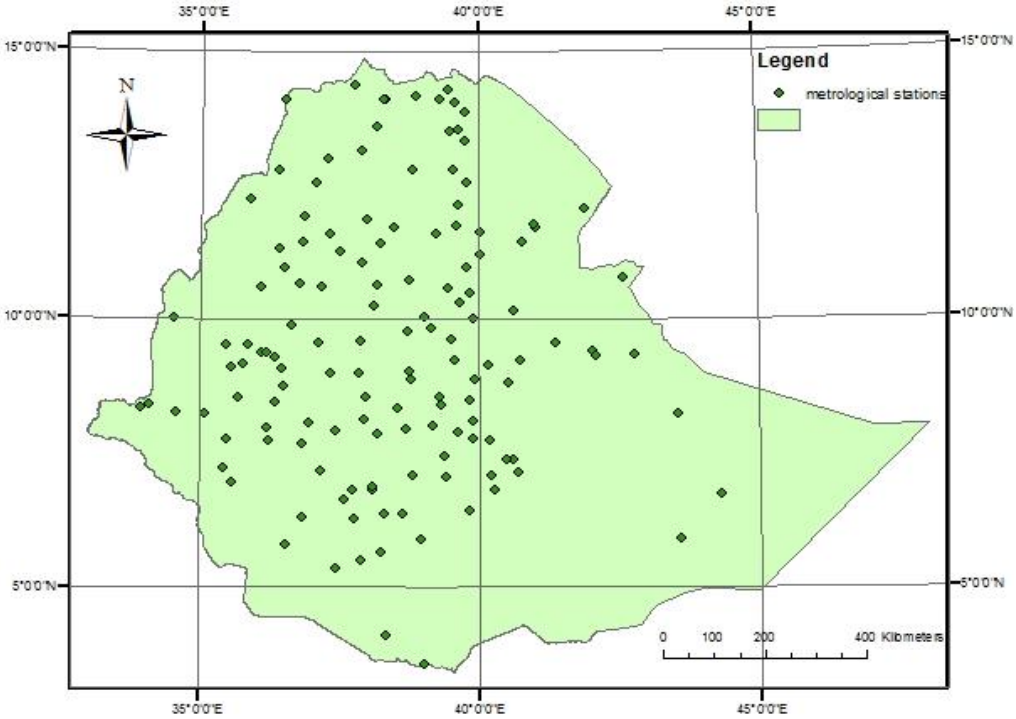


Figure 5 meteorological stations distribution in the Ethiopia

3.2.1.1. Meteorological data

The analysis involved data quality assessment, data gap filling, and characterization of the meteorological elements. Data quality of the different meteorological elements was assessed based on daily records of stations for which data could be obtained.

3.2.1.2. Temperature

Monthly temperature data of one hundred forty stations starting from 1996 to 2015 is used in this thesis paper. Some meteorological stations were not directly used from the collected class one meteorological data because they have long missing records. The minimum and maximum temperatures of the study area were assessed using observed data of one hundred forty class one station.

The analysis involved check for validity of the datasets and create continuous temperature series by filling missing data. The collected monthly maximum and minimum temperature data were subjected to quality control to identify invalid records. The invalid data was considered as missing. Identification of incorrect data was done considering the method discussed in Leung *et al* (2007) and Agizew Nigussie Engida, (2010) as follow.

- ✓ Checking whether the maximum temperature is greater than the minimum: this check was done to ensure that the minimum temperature is always less than the maximum.

- ✓ Checking existence of constant temperatures for ten or above successive days, which is impossible or unrealistic.

Filling of missing daily records temperature was done using, -for short missing gap length (one up to two months) the mean value of data in available years was simply taken, for longer missing gap length (more than two months) the inverse distance method with adjustment of elevation difference (equation 3.1) used. The relationship between average temperature and elevation was done and the temperature lapse rate computed in section was used to compute the elevation adjustment factor. The result indicated a general decrease in temperature with increase in elevation as shown in Figure 8 in section four. The lapse rate was found to be -0.007 °C per 1m increase in elevation. The use of similar spatial interpolation method for filling gaps in temperature data series could be found in the literature (Stahl *et al.,* 2006; Snell *et al.,* 2000).

$$T_m = \sum_{i=1}^{n} . \frac{(T_i + LPR(y_i - y_m))}{\sum_{i=1}^{n} d_{im}^{2}} d_{im}^{2} \quad \text{... Equation 3.1}$$

Where, T_m = estimated temperature at station m with missing data, °C; T_i = observed temperature at surrounding station i, °C; y_i = altitude of station i in meters; y_m = altitude of the station with missing data in meters; d_{im} = horizontal distance between stations with known and missing data in meters; *LPR* = temperature lapse rate, °C/m; (=-0.007 °C per 1 m). *n* = number of surrounding stations with observed temperature data.

3.2.1.3. Wind speed

Wind speed data was involved in the computation of reference evaporation transpiration using the Penman-Monteith approach/CROPWAT 8.0 model. Analysis was based on monthly data obtained for the period 1996-2015. The wind speed data was visually examined carefully for obvious errors. To fill the missing meteorological data, the following methods were followed: For short missing gap length (one up to two months) the mean value of data in available years was simply taken. For or longer missing gap length (more than two months) and XLSTAT version 2015.4.01.20059 model was used. XLSTAT is the data analysis and statistical software which is the fast and reliable.

3.2.1.4. Relative humidity

Relative humidity values are involved in the computation of the convective part of the Penman-Monteith evapotranspiration equation/CROPWAT model. The simple check was made to check the quality of the relative humidity data. This was done to check either the recorded data is within a valid range or not. According to (Ahrens, C.D, 1991) the changing air temperature that primarily regulates the daily variation in relative humidity, and its total vapour content varies only slightly during the entire day in many places. Considering the general climatology of the study region, the valid range for relative humidity was assumed to be 7-100 %. Relative humidity records that are less than 7% and greater than 100% were considered as missing data. As complete relative humidity data series is required for the estimation of reference evapotranspiration, gaps in the records were filled using the inverse distance square method. The stations with recorded relative humidity data were used in the interpolation/extrapolation without setting a limit to distance.

3.2.1.5. Sunshine hours

Sunshine hour data analysis was limited to some stations because most stations have adequate data coverage. According to general observation of the whole region the valid sunshine hour range for the study area was set to vary from 0 to 13 hours. The minimum sunshine hour limited to a day with cloud through a day and the maximum sunshine hour due to maximum day length. Any data outside of this valid range was considered as missing. During analysis period no recorded data was outside of this range. Gaps in the records were filled using, for short missing gap length (one up to two months) the mean value of data in available years was simply taken and for longer missing gap length (more than two months) interpolation/extrapolation was used.

3.3. Thiessen polygon method

Thiessen polygon method was used to determine average areal reference evapotranspiration over sub-catchments in this paper. Thiessen polygons method was used to estimate ETc for five agricultural sites in Cyprus. (G. Papadavid et al. 2011), In order to determine the suitability of the meteorological stations for estimating ETc, a spatial analysis called Thiessen polygons was applied (Burrough and McDonnell, 1998). Thiessen polygon is a local interpolation technique where the interpolated meteorological data (value) equals the nearest observation value. The technique gives all the estimations the values at the point observations and no new values are added (E.G. Beek, 1991). Thiessen polygons Created from point input features. Each Thiessen polygon contains only a single point input feature.

3.4. Hydro Geological Setting of Ethiopia

This study involved the use of different data to identify groundwater irrigation possibility in Ethiopia. 1:2,000,000 hydro-geological Map that was obtained from Geological survey of Ethiopia was digitized and used in this study. Ground water depth and discharge conditions were the main hydro-geological maps that were used to determine the possibility of groundwater utilization in Ethiopia.

3.5. Mean annual reference evapotranspiration (ETo)

CROPWAT 8.0 model was used to calculate reference evapotranspiration at 140 Ethiopian stations in this research, which required different meteorological data including temperature (minimum & maximum), wind speed, relative humidity, and solar radiation, which allows CROPWAT to calculate ETo using the Penman-Monteith formulae. Penman method provides the most reasonable estimation of reference evapotranspiration and it is one of the most reliable methods which consider the atmospheric changes comprehensively (Allen *et al.*, 1998, 2006). Reliability over a broad climatic region of these methods has been tested in different parts of the world and found to estimate reference evapotranspiration very close to field observation (walter et al.2000). Penman-Monteith method is now the sole recommended method for calculating reference evapotranspiration (ETo) (FAO, 1998): Penman- Moteinth equation provides the best method and considered to offer the best results with minimum possible error in relation to a living grass reference.

Reference evapotranspiration varies as rainfall, temperature, humidity, sunshine hour and wind speed are varying from place to place. Hence the Reference evapotranspiration computed for each station should be weighted according to the area it is expected to represent. In this thesis paper Thiessen polygon method is used to determine the average areal reference evapotranspiration over sub-catchments. The results of reference evapotranspiration calculated from each station by CROPWAT 8.0 within its X (longitude), Y (Latitude) and meteorological data were added to the map as a layer in arc map and it was then converted to Thiessen polygon, later summarized into a single value for the smallest unit of each sub-catchments division on annual level.

3.6. Classification of Agro-ecological zones of Ethiopia

According to the agro ecological zone classification system, Ethiopia has 18 major agro ecological zones and these agro ecological zones are also grouped under six major categories (MoA, 2000) which are discussed in section-2. This agro ecological zone map of Ethiopia that could be obtained from Ministry of Agricultural was re-digitized and used. To calculate average, mean annual reference evapotranspiration of each agro ecological zone figure 3 (Agro ecological zones map which is presented in section2) and Reference evapotranspiration map (which is present in section 4) are overlaid. This ultimately describes the reference evapotranspiration all over the 18 major agro ecological zones.

3.7. Classification of groundwater utilization possibility

Groundwater utilization map was generated from the overlaid figure1-a (depths of ground water) and figure1-b (groundwater discharge conditions) which are presented in literature review section of this thesis paper. Degree one, two, three, four and five suitable groundwater utilization was classified. The classification was done using map algebra raster calculator. These classified groundwater utilizations and the reference evapotranspiration map were then used to determined ground water irrigation possibility in Ethiopia.

3.8. Determination of ground water irrigation possibility

Ethiopia's agro ecology zones, groundwater utilization suitability and mean annual reference evapotranspiration of Ethiopian was used to determine groundwater Irrigation possibility in Ethiopia. Ground water irrigation suitability map was generated by overlaying ground water utilization map; evapotranspiration zones and average mean annual reference evapotranspiration. Degree one, Degree two, Degree three and Degree four suitability of groundwater irrigation can be determined from such map. The activity was done using Arc view GIS software.

CHAPTER FOUR

4. Result and Discussion

This section presents and discusses the main findings of the study. Groundwater constraints can be overcome by proper arranging system that addresses specifically ground water use for irrigation crop production. Attempt has been made to determine groundwater irrigation possibility in Ethiopia giving emphasis to the main factors that can be determine the use of groundwater resources. Reference evapotranspiration (ETo), agro ecological zones, groundwater discharge and access depth of the study area are the main focal point to achieve the objective of this research in which the results and detail information for each of these activities are presented in this section.

4.1 Mean Annual Reference Evapotranspiration (ETo)

The calculated value of mean annual reference evapotranspiration (ETo) using CROPWAT 8.0 model at 140 class one Ethiopian stations over 1996_2015 is shown in Annex-B. Manually computing reference evapotranspiration at 140 stations is very difficult and time consuming by using Penman Montieth equation consequently CROPWAT 8.0 model was used. Reference evaporation was first calculated at monthly time step and then aggregated to annual periods. Input data for CROPWAT 8.0 model was mean monthly minimum temperature; mean monthly maximum temperature, humidity, and wind speed, length of sunshine hour, altitude, longitude and latitude. For all stations the results show that as temperature, wind speed and sunshine hour increase reference evapotranspiration increases; however, as humidity increase reference evapotranspiration was found to decrease. The result shows reference evapotranspiration of the study area ranges between 1051.2 $mmyear^{-1}$to 2489.3 $mmyear^{-1}$. The maximum average annual reference evapotranspiration (2489.3mm) is obtained at Elidar station in Afar region, its average maximum temperature is 37.6 ^{O}C. The minimum value of mean annual reference (1050.2mm) is obtained at Adet, its average maximum temperature 26.4^{O}C. From the result the minimum values of reference evapotranspiration are observed that the area where low values of temperature, wind speed, sunshine hour and high values of relative humidity, which is a good information to determine ground water irrigation possibility in this research. From the result computed average reference evapotranspiration of class one metrological data high values of monthly reference evapotranspiration are observed at March, April and May. On the other hand, the lowest reference evapotranspiration values are observed in the months of July and August. Because of the minimum temperature observed months.

Estimated reference evapotranspiration at each station is weighted according to the area it is assumed to represent and is shown in annex c.

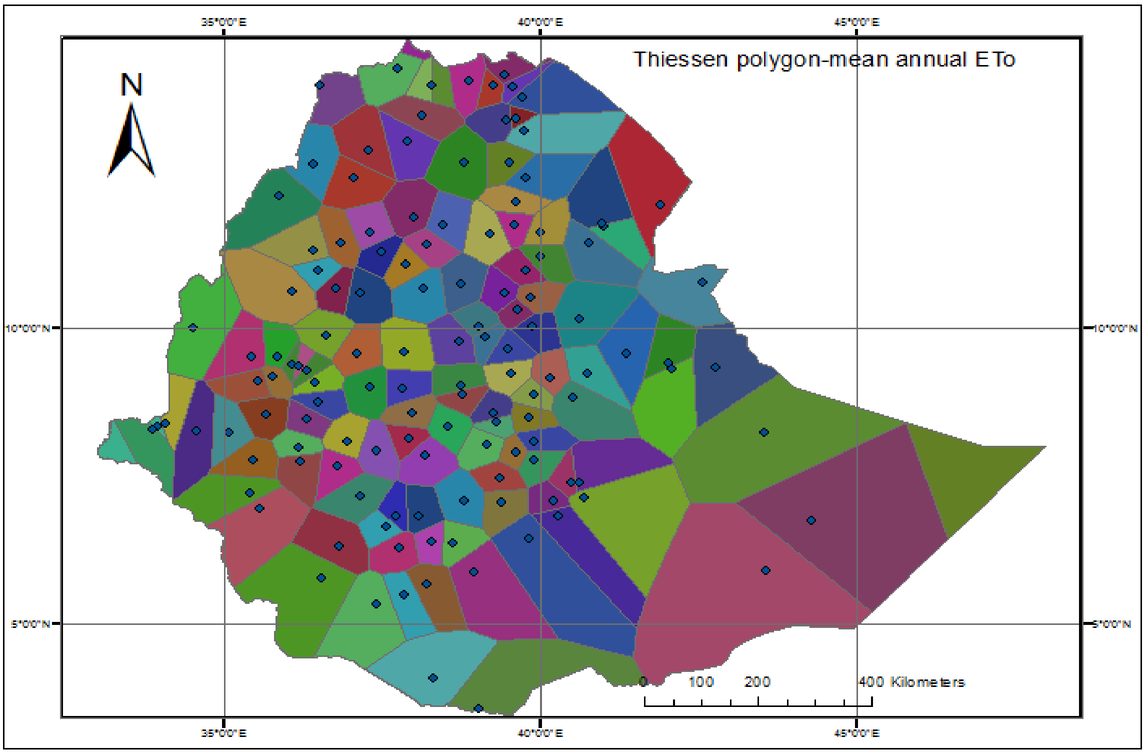


Figure 6 Thiessen Polygon developed for stations of sub-catchments

Total area coverage of the study area, Ethiopia is about 1,132,538Km^2. Among 140 stations Gode station has maximum area coverage 6.8% of the total.

Mean annual (ETo) map of Ethiopia

Reference evapotranspiration rates are controlled by several variables. A warmer atmosphere can hold more water; the actual changes in evapotranspiration will depend on the humidity levels, wind patterns, length of sunshine hour and temperature. One major contributor in deciding groundwater irrigation possibility in Ethiopia is the reference evapotranspiration. The estimated mean annual reference evapotranspiration (ETo) map using Thiessen polygon method based on data of 1996 to 2015 is shown in Figure-7.

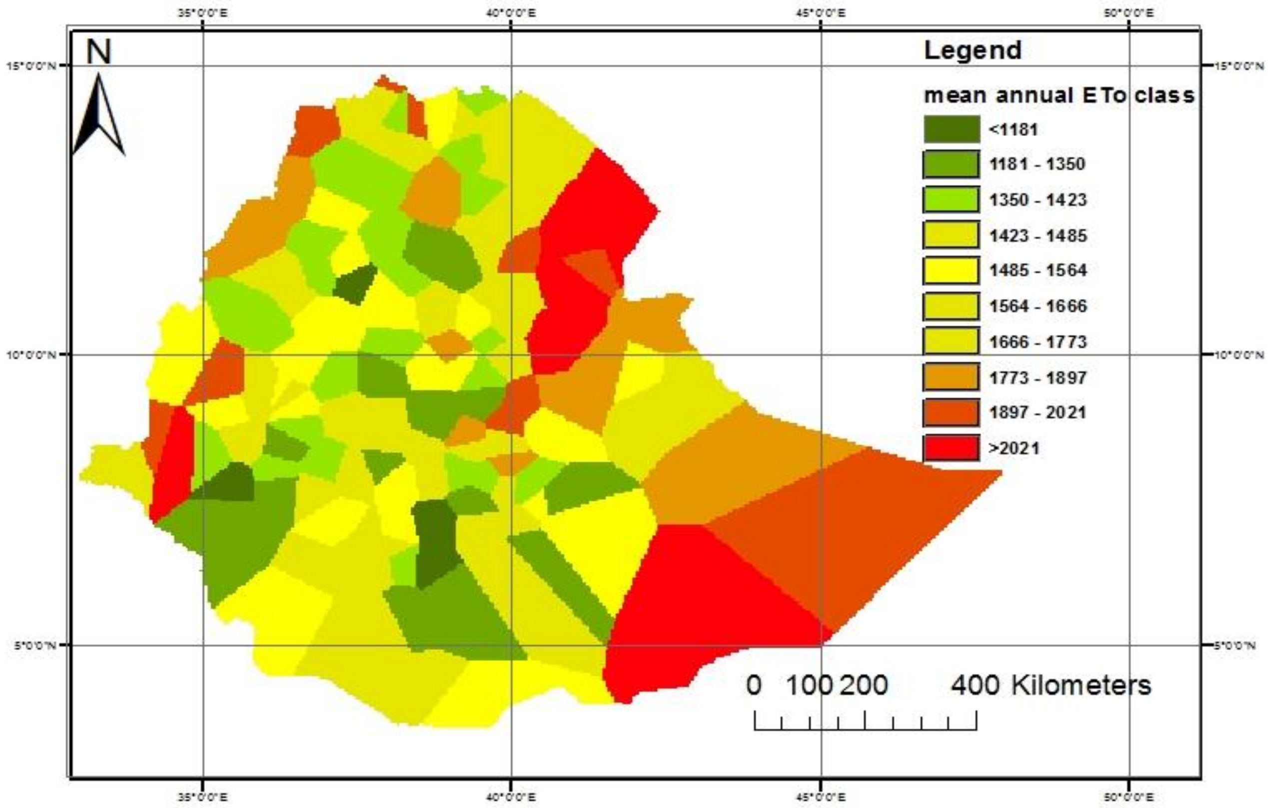


Figure 7 mean annual reference evapotranspiration of Ethiopia

4.1. Temperature Lapse Rate

Temperature laps rate was computed as it is required to estimated temperature at station m (T_m) with missing data in section three. The mean annual temperature of the whole basin and its relationship with altitude were determined. Stations that are located at higher altitude generally show lower temperature. The result indicated a general decrease in temperature with increase in elevation as shown in Figure 8. The lapse rate was found to be -0.007 °C per 1m increase in elevation

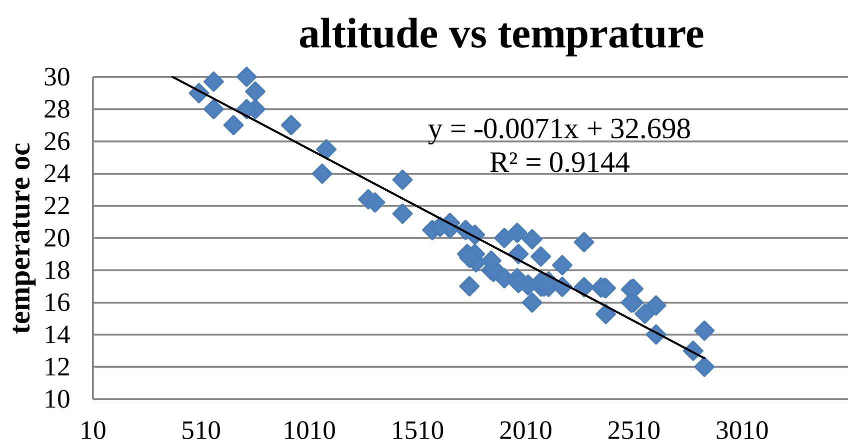


Figure 8 Temperature-Altitude relationship

4.2. Agro ecological zone and average reference evapotranspiration

Evapotranspiration was also computed on the basis of the agro ecological zones of Ethiopia as defined in MOA (2000). This is basically done to create ranges for evapotranspiration zonation of the country. Different agro ecological zones have different annual reference evapotranspiration due to uneven distribution of climate and other factors as shown in table 7. Mean annual reference evapotranspiration for each agro ecological zones was determined in order to identify regions that have sound reference evapotranspiration. The results show that highest value of reference evapotranspiration is obtained at hot arid agro ecological zones and the lowest values of reference evapotranspiration are obtained at humid and moist of agro ecological zones, these are due to climatic conditions.

The result clearly shows that it is possible to classify Ethiopia in to six evapotranspiration zones as shown in Table 8 and Figure 10.

Table 6 agro ecological zones and mean annual reference evapotranspiration

Agro ecological zone*	Average annual reference evapotranspiration(ETo-mm)	Range
Cold to very cold sub humid	1412.7	1168_1609.7
Cold to very cold moist	1433.8	1168-1522.1
Cold to very cold humid	1418.0	1168_1558.6
Cold to very cold sub moist	1435.3	1131.5_1638.9
Hot to warm arid	1877.7	1664.4-2489.3
Hot to warm semiarid	1805.8	1725_1923.6
Hot to warm humid	1610.4	1259.3_1803.1
Hot to warm sub humid	1621.1	1273.9_2007.5
Hot to warm moist	1631.9	1314_2014.8
Hot to warm sub moist	1663.9	1332.3_2295.9
Tepid to cool moist	1437.6	1051.2_1635.2
Tepid to cool sub moist	1440.8	1252_1715.5
Tepid to cool arid	1454.5	1252_1609.7
Tepid to cool semiarid	1450.5	1131.5_1638.9
Tepid to cool humid	1415.9	1168_1638.9
Tepid to cool sub humid	1411.9	1051.2_1558.6

*source MOA, (2000)

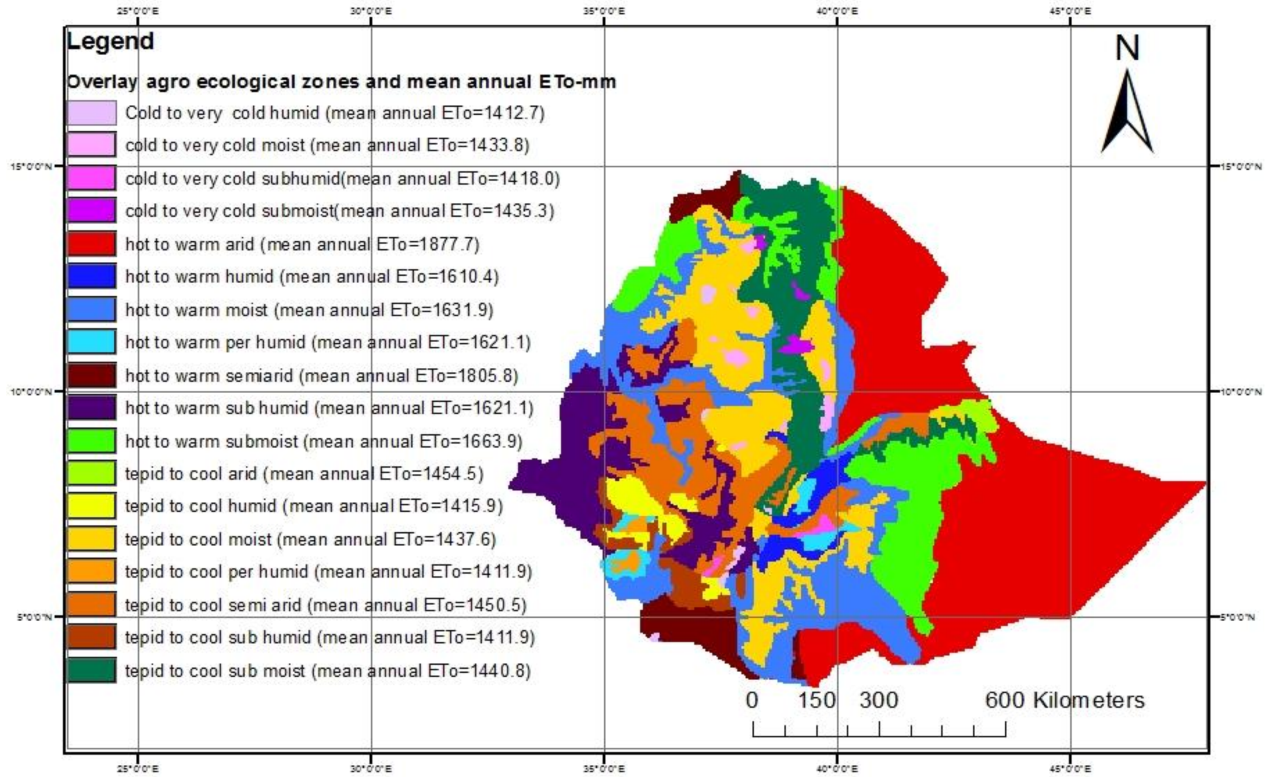


Figure 9 overlay agro ecological zones and mean annual ETo

The overlay agro ecological zones and average mean annual reference evapotranspiration (ETo) was grouped in to six major categories of Evapotranspiration zones in order to simplify the classification of ground water irrigation possibility. Zone1, zone2, zone3, zone4, zone5, and zone6 of six evapotranspiration zones were grouped as shown in table-8. These grouped agro ecological zones were based on the values of mean annual reference evapotranspiration (ETo). Agro ecological zones that have nearly the same or slightly difference values of mean annual reference evapotranspiration were grouped together. As discussed above differentiating the agro ecological zones is very important for the determination of groundwater irrigation possibility. Zone1, zone2 and zone3 are highly likely suitable for groundwater irrigation because of the lowest values of ETo than other zones, but zone6 evapotranspiration zones have little chance for groundwater irrigation on condition that it requires larger water for irrigation than other which in turn has expensive pumping and drilling requirements.

The average annual reference evapotranspiration of zone1 is 1414.6mm which is the minimum value obtained among the other regions. Consequently, it is the region that can be possible for groundwater irrigation. Whereas the average annual reference evapotranspiration of zone6 is 1841.75mm which is the maximum value obtained among the other regions. As a result, ground water irrigation is uneconomical because of unsuitable climatic conditions at this region. The average annual reference evapotranspiration of zone4 and zone5 are 1614.6mm and 1647.9mm respectively as shown in table 8 and Figure 10. These regions were considered as the region of moderately/averagely suitable ground water irrigation with respects to others.

Table 7 six evapotranspiration zones

Evapotranspiration zones	Agro ecological zones	Average annual ETo (mm)	Range
Zone1	Cold to very cold humid, cool to very cold sub humid, tepid to cool humid, Tepid to cool sub humid	1414.6	1411.9-1418.0
Zone2	Cold to very cold moist, cold to very cold sub moist, tepid to cool moist, tepid to sub moist	1436.9	1433.8-1440.8
Zone3	Tepid to cool arid, tepid to cool semi arid	1452.5	1454.5-1450.5
Zone4	Hot to warm humid, Hot to warm sub humid	1614.6	1610.4-1621.1
Zone5	Hot to warm moist, Hot to warm sub moist	1647.9	1631.9-1663.9
Zone6	Hot to warm arid, Hot to warm semi arid	1841.75	1805.8-1877.7

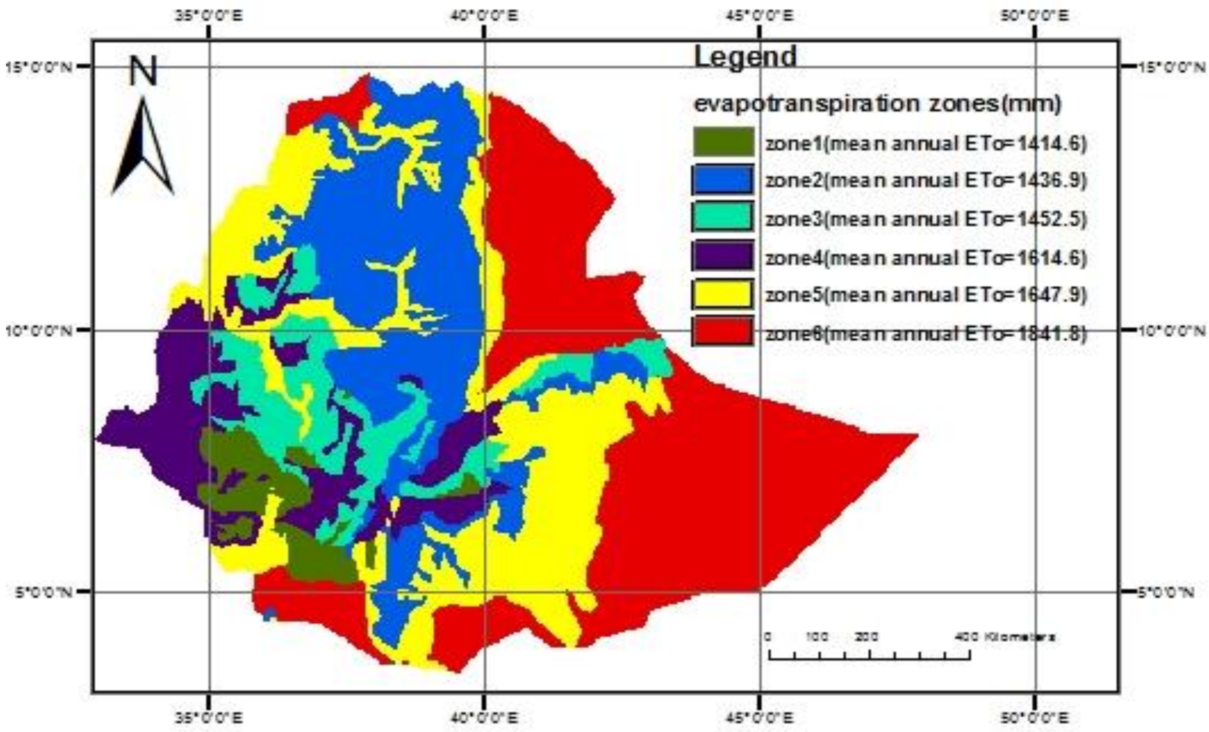


Figure 10 six Evapotranspiration zones and the corresponding average annual ETo

4.3. Classification of Groundwater Utilization for irrigation

In addition to agro ecological zones and reference evapotranspiration, hydro geological information was the main parameters to determine ground water irrigation in Ethiopia in this research. Based on ground water depth and discharge condition; Degree one, Degree two, Degree three, Degree four and Degree five suitable groundwater utilization was classified as shown in Table-9 and Figure-11. The classification was made from cost of groundwater abstraction view point. If the depths of groundwater increase obviously borehole drilling cost, pump cost, operational cost, construction cost, installation cost and maintenance cost increase.

in accordance with MOWAE, updated version, (2013) in this research, ground water zero to thirty-meter depth is considered as very shallow groundwater, groundwater thirty to one-hundred-meter depth is considered as shallow groundwater, groundwater hundred to two hundred fifty-meter depth is considered as deep groundwater and above two hundred fifty meter is considered as very deep groundwater. The same was considered in Hailemichael, (2003).

The definitions behind such classification are indicated below: The suitability of ground water utilization is decrease from degree one to degrees five. The input data is describing the discharge condition as high, moderate or high, low or moderate or high discharge which means the amount of discharge is available in the form of map and.

Degree one suitable ground water utilization; Zero to hundred-meter ground water depth within high discharge condition was classified as degree one suitable ground water utilization zone. It is the best suitable zone than other. Shallow depth of ground water with high discharge condition is obviously highly suitable because it require minimum cost than deep groundwater with low or moderate discharge conditions and as such degree one suitable groundwater utilization was determined.

Degree two suitable ground water utilization; Zero to hundred-meter ground water depth within moderate or high discharge condition was classified as degree two suitable ground water utilization zones. Ground water depth and discharge condition that was collected from geological survey of Ethiopia is not well defined. High, moderate or high, low or moderate or high discharge condition and zero to hundred, zero to one hundred fifty, zero to two hundred seventy and zero to three-hundred-meter groundwater are available as input data. Zero ground water depth is most probably found at river but the left major parts are greater than zero depth of groundwater. This region includes moderate discharge condition and it is less suitable than degree one as such depth of groundwater zero to one hundred meter with moderate or high discharge condition is determined as degree two suitable ground water utilization.

Degree three suitable ground water utilization; Zero to hundred-meter ground water depth within low or moderate or high discharge condition and zero to one hundred fifty-meter groundwater depth with high or moderate discharge condition was classified as degree three suitable groundwater utilization zones. Since the depth of groundwater is increase and the discharge condition decrease than degree one and degree two groundwater utilization it is less suitable than the above listed two conditions.

Degree four suitable ground water utilization_ Zero to one hundred fifty-meter ground water depth with low or moderate or high discharge condition and zero to three-hundred-meter ground water depth with moderate or high discharge condition were classified as degree four suitable ground water utilization zones.

Degree five suitable ground water utilization zones; zero to three-hundred-meter ground water depth with low or moderate or high discharge condition was classified as Degree five suitable groundwater utilization zones. In this zone utilization of ground water is not suitable than other zone because it is the deepest groundwater zone and the lowest discharge condition than other region. These classified groundwater utilizations and the reference evapotranspiration map were then used to determined groundwater irrigation possibility in Ethiopia.

Table 8 classification of ground water utilization

Groundwater situation		Suitability of groundwater utilization
Discharge condition	Depth (m)	
High	(0 to 100)	Degree one suitable
Moderate or high	(0 to 100)	Degree two suitable
Low or moderate or high	(0 to 100)	Degree three suitable
High	(0 to 150)	-
Moderate or high	(0 to 150)	Degree three suitable
Low or moderate or high	(0 to 150)	Degree four suitable
High	(0 to 300)	-
Moderate or high	(0 to 300)	Degree four suitable
Low or moderate or high	(0 to 300)	Degree five suitable

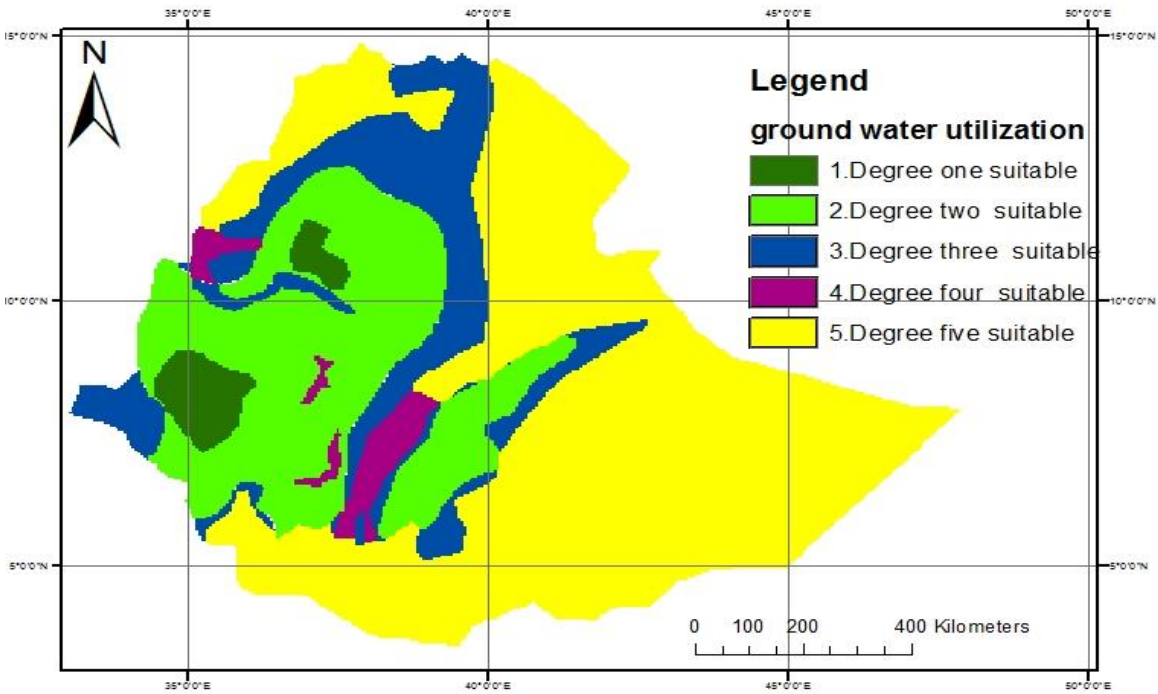


Figure 11 ground water utilization map of Ethiopian

Groundwater utilization possibility was determined to identify the location where groundwater can be used for irrigation purpose. Besides such classification, may serve for identifying the possibility of ground water for other purposes in Ethiopia. Generally shallow and very shallow groundwater depths with high discharge conditions were determined as degree one suitable groundwater utilization because it requires low cost to extract. The deepest groundwater depths with low discharge conditions were determined as degree five ground water utilization zones.

4.4. Groundwater Irrigation Possibility in Ethiopia

There were certain threats that could be emerging during the classification period. Minimum Cost, shallow depth and good discharge condition of ground water, minimum ETo, were the main parameters that taken in to account to determine most effective ground water irrigation possibility. Cost is the main constraints to develop ground water for irrigation in Ethiopia. Ethiopia's agro ecology zones, mean annual reference evapotranspiration and ground water utilization were the main variable or information that used to classify groundwater Irrigation possibility. Accordingly, Degree one, Degree two, Degree three and Degree four suitable ground water irrigation in Ethiopia were classified. The corresponding results are shown in table-10 and figure-12. These determinations were done using Arc view GIS software and the definitions behind such classification are:

Degree one suitable groundwater irrigation: The location where minimum average annual reference evapotranspiration, shallow and/or very shallow depth of groundwater and high discharge condition, was determined as degree one suitable groundwater irrigation. Because these regions are the most effective, the minimum crop water requirement, the minimum costs require to extracts, the smallest ETo, humid and the moist region. In the moist regions crop can receive moisture from surrounding and these zones are preferred than arid.

Degree two suitable groundwater irrigation: It was determined from degree three suitable ground water utilization with zone1, zone2 and zone3 evapotranspiration zones: degree one and degree two suitable ground water utilization with zone4 and zone5 evapotranspiration zone. It is the best suitable region than degree three and degree four.

Degree three suitable groundwater irrigation; It was determined from degree four and five suitable groundwater utilization zones with zone1, zone2 and zone3 evapotranspiration zones: degree three and degree four suitable ground water utilization zones with zone4 and zone5 evapotranspiration zone and degree one and degree two suitable groundwater utilization with zone6 evapotranspiration zone. In the available data of groundwater depth that was collected (0-100, 0-150 and 0-300meter) the specific location of groundwater depth is not well-defined.

The depth of 0-300 was used for the determination of degree four suitable groundater utilization zones but in reality it will include depths which were defined in the above classifications. As such degree three suitable was determined.

Degree four groundwater irrigation suitable: In this group arid agro ecological zone (zone6) with degree three, four and five groundwater utilization zones were determined as degree four suitable ground water irrigation zones. Because it is a region of high amounts ETo and large groundwater depth. The determination of degree four groundwater irrigation in this research means developing ground water irrigation in these regions is unsuitable than other region. This finding is helps to identify the location where groundwater can be used for irrigation purpose.

Table 9 classification of ground water irrigation suitability

Evapotranspiration zone	Average annual ETo (mm)	Suitability Ground water Utilization	Ground water irrigation possibility
Zone1	1414.6	Degree one suitable	Degree one
		Degree two suitable	
		Degree three suitable	-
		Degree four suitable	-
		Degree five suitable	Degree three suitable
Zone2	1436.9	Degree one suitable	Degree one
		Degree two suitable	
		Degree three suitable	Degree two suitable
		Degree four suitable	Degree three suitable
		Degree five suitable	
Zone3	1452.5	Degree one suitable	Degree one
		Degree two suitable	
		Degree three suitable	Degree two suitable
		Degree four suitable	Degree three suitable
		Degree five suitable	-
Zone4	1614.6	Degree one suitable	Degree two suitable
		Degree two suitable	
		Degree three suitable	Degree three suitable
		Degree four suitable	
		Degree five suitable	-
Zone5	1647.9	Degree one suitable	-

		Degree two suitable	Degree two suitable
		Degree three suitable	Degree three suitable
		Degree four suitable	
		Degree five suitable	-
Zone6	1841.75	Degree one suitable	Degree three suitable
		Degree two suitable	
		Degree three suitable	Degree four suitable
		Degree four suitable	
		Degree five suitable	

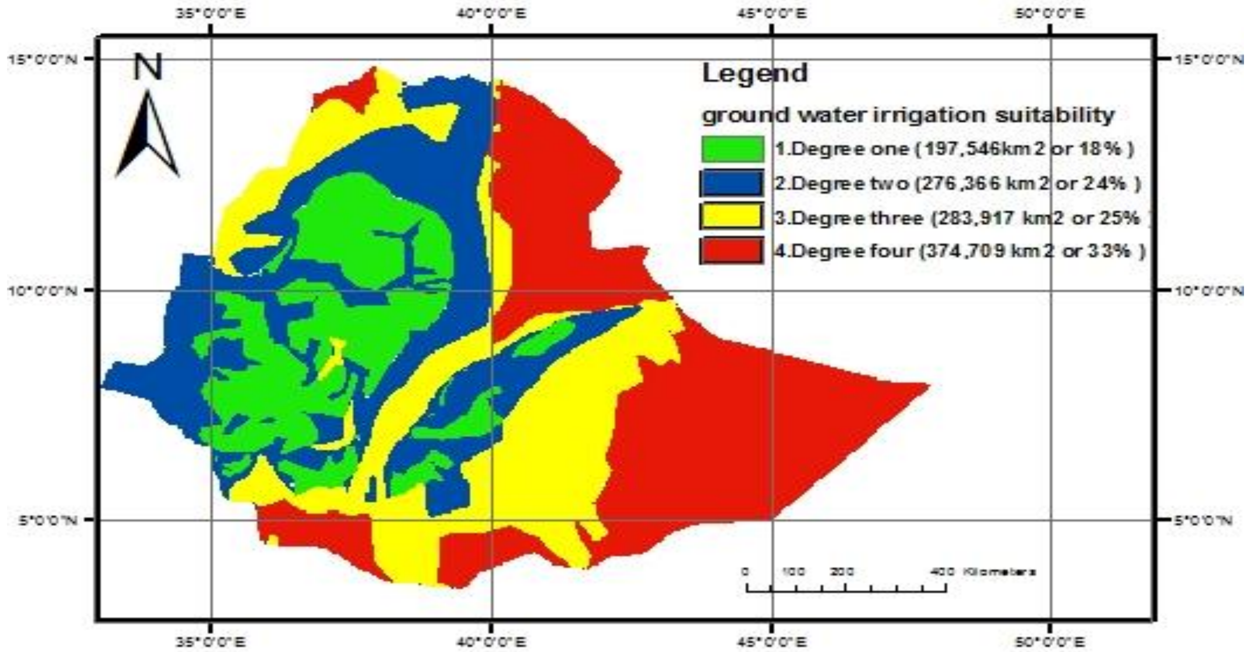


Figure 12 ground water irrigation suitability map of EthiopiA

Table 10 classification of groundwater irrigation suitability and its area

NO	Groundwater irrigation suitability	Area (km^2)	%
1	Degree one suitable	197,546	18
2	Degree two suitable	276,366	24
3	Degree three suitable	283,917	25
4	Degree four suitable	374,709	33
Total		1,132,538	100

4.5. General discussion

Surface irrigation (furrow, basin, and border) method is not recommended for groundwater irrigation. Water application efficiency is generally higher with drip and sprinkler irrigation than surface irrigation. To develop effective groundwater irrigation, minimizing cost, increasing water application efficiency and increasing benefits are expected. As it has been discussed above groundwater irrigation require high cost, so that using most efficient irrigation method such as sprinkler and drip irrigation methods within high value cash crop (vegetables and fruit) is the best and economical to develop effective groundwater irrigation.

In Ethiopia rainfall is the major source for crop production and in some area crops are failing due to erratic rain fall pattern and distribution. To reduce the failure of the crop, supplemental irrigation using groundwater resource during shortage of rain fall (early sowing and/or before crops matured) are very essential, consequently, this research is helpful to overcome this problem. ggroundwater quality, depletion and recharge rates haven't been considered in this research due to mere availability of such data all over Ethiopia. As such further research is expected to include groundwater quality for better understanding and evaluation of groundwater utilization in Ethiopia.

CHAPTER FIVE

5. Conclusion and Recommendation

5.1. Conclusion

With the objective of mapping the groundwater irrigation possibility in Ethiopia, this research has shown that the largest amount of reference evaporation transpiration is obtained at hot arid regions. From these results, it can be concluded that developing groundwater irrigation at humid and moist agro ecological zone is economical. Besides very shallow, shallow groundwater depth, high discharge condition, and minimum reference evapotranspiration are highly suitable for ground water irrigation than other region.

Degree four suitable of ground water irrigation in this research doesn't mean that groundwater irrigation is absolutely impossible rather developing groundwater irrigation in these regions is less suitable than other region.

The minimum values of reference evapotranspiration is observed at the areas where low values of temperature, wind speed, sunshine hour and high values of relative humidity, which is a good suitable groundwater irrigation region. From the result computed average reference evapotranspiration of class one metrological data high values of monthly reference evapotranspiration are observed at March, April and May. On the other hand, the lowest reference evapotranspiration values are observed in the months of July and August.

According to the results obtained the countries have in general 197,546 km^2, 276,366 km^2, 283,917 km^2 and 374,709 km^2 area degree one suitable, degree two suitable, degree three suitable and degree four suitable groundwater irrigation regions respectively, were identified and mapped.

Different agro ecological zones have different annual reference evapotranspiration due to uneven distribution of climate conditions and other factors**,** thus Agro ecological zones with minimum average annual reference evapotranspiration can be an effective ground water irrigation zones. Supplemental irrigation can be applied at Degree one suitable ground water utilization zone or at shallow, very shallow and high discharge conditions of groundwater region to reduce the failure of crop production. Besides since groundwater irrigation requires high cost, most efficient irrigation method, sprinkler and drip irrigation methods within high value cash crop (vegetables and fruit) are highly suitable than surface irrigation.

5.1. Recommendation

Ethiopia is a country with high population in sub-Saharan Africa being with poor food self-sufficiency. Therefore, groundwater irrigation should be expanded to increase agricultural production and to mitigate the existing challenging problem. Utilizing groundwater resource for irrigation purpose should be a key alternative to improve the country's deteriorating food supply.

This study is not the end of determination of groundwater irrigation possibility rather it is a good starting work for detail study in the future. With additional data, further determination of the suitability of groundwater irrigation in Ethiopia is possible, which is expected to improve the accuracy of the results.

The results of groundwater utilization map in this research can also be used for domestic water supply purposes.

To increase the profit of groundwater irrigation, efficient irrigation method (drip and sprinkler) and high value cash crop should be selected.

This study does not look for the quality of groundwater. In order to assure the effective use of groundwater resource for irrigation, a further study which integrates groundwater quality, this research should be undertaken by using recent ground water data.

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Annex A: Class One Meteorological Stations Distributions

Station	LONG	LAT.	altitude	Station	LONG	LAT.	Altitude
Abala	39.76	13.34	1441	Dedessa	36.1	9.38	1310
Abomsa	39.83	8.47	1630	Degahabur	43.55	8.22	1070
Addis Ababa Obs	38.75	9.02	2386	Dello Mena	39.83	6.42	1313
Adele	39.9	7.75	2466	Dilla	38.3	6.37	1579
Adet	37.49	11.27	2179	Dinkiti	40.62	7.38	2374
Adigrat	39.45	14.28	2497	Dubity Met	41.01	11.72	376
Adwa	38.88	14.18	1911	Ejaji	37.32	8.99	1732
Aisha	42.58	10.76	721	Elidar	41.92	12.07	660
AKAKI	38.79	8.87	2057	Eneware	39.15	9.83	2561
Alem Ketema	39.03	10.03	2280	Erer	41.38	9.56	2561
Alemaya	42.03	9.4	2020	Fiche	38.73	9.77	2784
Alge	35.67	8.53	1880	Gambela	34.58	8.25	500
Aman	35.57	6.95	1192	Gatira	36.2	7.98	2358
Ambo Agriculture	37.84	8.98	2068	Gelemso	40.53	8.81	1739
Anger	36.33	9.27	1350	Gewane	40.63	10.15	568
Arjo	36.5	8.75	2565	Gidayana	36.62	9.87	1850
Assosa	34.52	10	1600	Gimbi	35.78	9.17	1970
Atsebi	39.74	13.88	2711	Ginir	40.7	7.13	1750
Awash Arba	40.16	9.14	826	Gode	43.58	5.9	295
Ayehu	36.79	10.66	1771	Gologcha	40.49	7.37	2040
Ayira	35.55	9.1	1555	Hagere Maria)	38.23	5.65	1861
Bahir Dar (Airport	37.32	11.6	1827	Harar Indicativ	42.08	9.3	1977
Bati	40.02	11.2	1660	Humera	36.52	14.1	760
Bedele	36.33	8.45	2011	Hunte	39.4	7.05	1380
Belle Chakata	40.29	6.82	1234	Ilaila	39.63	13.53	2080
Billate	38.08	6.82	1361	Imdibir	37.94	8.12	2082
Bore	38.62	6.35	2712	Jijiga	42.78	9.33	1775
Bui	38.55	8.33	2054	Jikawo (Lare)	33.885	8.269	419
Bullen	36.08	10.6	1659	Jimma	36.82	7.67	1718
Bure	35.1	8.23	1750	Jinka	36.55	5.77	1373
Burji	37.87	5.48	1815	Kachis e(Rs)	37.86	9.58	2520
Chagni	36.5	10.97	1614	Kamashe	35.86	9.51	1317
Cheffa SF	39.77	10.98	1400	Kebri Dehar	44.3	6.73	505
Chercher	39.77	12.54	1718	Kebri Dehar	47.96	7.96	505
Chifra	40.02	11.61	926	Kebri Dehar	34.101	8.382	505
Chira	36.23	7.73	2095	Kibre Mengist	38.97	5.87	1680
Dangila	36.85	11.43	2116	Kobbo (IAR)	39.63	12.13	1470
Danna_13	37.57	6.64	1282	Kofele	38.8	7.07	2620
Debark	37.9	13.14	2836	Konso	37.43	5.33	1431
Debre Berhan	39.5	9.63	2750	Debre Work	38.16	10.65	2508

Debre Tabor	38	11.87	2612	Lay_Birr(SF)	37.17	10.59	1707
Limu Genet	36.95	8.07	1766	Soge (Belogig)	36.2	9.36	1394
Maichew	39.53	12.78	2432	Pawe	36.41	11.31	1119
Majete	39.85	10.5	2000	Quara	35.89	12.23	648
Masha	35.47	7.75	2282	Robe	39.62	7.88	2441
May_Tsebri	38.15	13.59	1349	Sawula	36.84	6.3	1348
Maygaba	38.3	14.1	1902	Sekoru	37.42	7.92	1928
Mega	38.32	4.07	1820	Semera	41	11.76	590
Mehal Meda (RS)	39.66	10.31	3084	Senkata	39.57	14.06	2437
Meiso AVA	40.75	9.23	1400	Shambu	37.12	9.57	2460
Meiso Mission	40.75	9.23	1332	Shewa Robit	39.89	10.01	1277
Mekane Selam	38.76	10.74	2605	Shiraro	37.76	14.39	1033
Mekele Observa	39.47	13.52	2000	Shire Endasila	38.29	14.1	1897
Melkasa (IAR)	39.32	8.4	1540	Shola Gebeya	39.55	9.22	2500
Meraro	39.37	7.45	2940	Simada	38.23	11.41	2584
Metehara (NMSA)	39.92	8.86	944	Sinana	40.22	7.07	2400
Metema	36.41	12.77	790	Sirinka	39.61	11.75	1861
Mille	40.77	11.43	487	Tepi	35.43	7.2	1205
Mirab AbayaBer B	37.77	6.28	1221	Tercha	37.17	7.15	1335
Motta	37.89	11.07	2417	Tsitsika	38.8	12.78	1469
Moyale	39.03	3.55	1166	Wegel Tena	39.22	11.59	2952
Nazeret	39.28	8.55	1622	Werabe	38.19	7.85	2057
Nebelet	39.28	14.1	1988	Wereilu	39.44	10.58	2708
Nedjo	35.45	9.5	1800	Wolaita	37.73	6.81	1854
Nefas Mewcha	38.47	11.73	3098	Woliso Giyon	37.98	8.55	2058
NEKEMT	36.46	9.08	2080	Yabello	38.1	6.88	1729
Nuraera (SF)	39.9	8.08	1140	Yetnora	38.11	10.24	2420
Kulumsa	39.16	8.01	2211	Ziway	38.7	7.93	1640

Annex B: Estimated Mean Annual of Reference Evapotranspiration

Station	altitude	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo	ETo
	M	°C	°C	%	m/s	hours	MJ/m² /day	mm/day	mm/year
Abala	1441	16.9	30.4	65	2.7	6.8	18.7	4.8	1733.8
Abomsa	1630	15.6	28.4	60	1.4	9.2	22.5	4.7	1715.5
Addis Ababa Obs	2386	10	23.6	64	0.7	7.1	19.4	3.58	1306.7
Adele	2466	8.8	23.2	69	1.5	8.4	21.4	4.0	1449.1
Adet	2179	10.3	26.4	68	0.7	7.5	15.9	2.9	1051.2
Adigrat	2497	8.1	23.9	52	1.1	7.4	19.5	3.8	1376.1
Adwa	1911	11.9	28.1	59	1.3	7.7	19.9	4.2	1522.1
Aisha	721	21.6	34	70	1.3	8.9	21.9	5.0	1810.4
AKAKI	2057	9.4	23.5	47	1	6.7	18.7	3.6	1328.6
Alem Ketema	2280	13.8	25.7	20	1.6	7.9	20.5	4.9	1773.9
Alemaya	2020	9.8	24.3	71	1.5	9.1	22.3	4.1	1500.2
Alge	1880	14.6	26	22	1	6.1	18.0	4.0	1474.6
Aman	1192	15.2	27.8	79	1.4	8.3	16.3	4.5	1643.0
Ambo Agric	2068	12.3	25.6	66	1.4	7.3	19.7	4.1	1478.3
Anger	1350	14.7	27.9	71	1.4	8.9	22.1	4.4	1602.4
Arjo	2565	11.3	21.3	72	1.6	8.1	20.8	3.8	1379.7
Assosa	1600	15	25.5	65	1.8	7.1	19.3	4.1	1507.5
Atsebi	2711	9.3	19.9	57	2.2	8.3	20.7	4.0	1471.0
Awash Arba	826	18.9	35	70	2.2	9.3	22.6	5.5	2014.8
Ayehu	1771	13.2	29.4	68	0.8	7.8	20.3	4.1	1489.2
Ayira	1555	14.8	27.4	70	1.8	7	19.2	4.2	1525.7
Ayisha	721	21.6	34	70	1.3	8.9	21.9	5.0	1810.4
Aykel	2254	13.7	25	71	2.4	7.7	19.9	4.2	1518.4
Bahir Dar-Airpor	1827	11.1	29.1	60	0.9	8.6	21.4	4.3	1551.3
Bati	1660	13.8	29.5	71	0.9	9.3	22.5	4.4	1602.4
Bedele	2011	12.9	25.3	72	0.5	7.4	19.8	3.7	1335.9
Belle Chakata	1234	14.6	30	63	0.5	6.3	18.3	4.1	1503.8
Billate	1361	16.1	30.3	23	1	7.7	20.4	4.5	1638.9
Bore	2712	8.6	18.7	79	1.4	6	17.9	3.1	1131.5
Bui	2054	9.4	26.3	65	1.6	9	22.3	4.4	1609.7
Bullen	1659	14.7	27.2	66	0.7	8	20.5	3.9	1408.9
Bure	1750	15.3	26.1	68	0.7	6.8	19	3.7	1350.5
Burji	1815	15.3	25.5	67	1.3	7.2	19.8	4.0	1463.7
Chagni	1614	13	28.4	71	0.7	8.2	20.8	4.0	1463.7
Cheffa SF	1400	13.8	30.7	62	1.3	6.8	18.9	4.3	1565.9
Chercher	1718	16.1	27.3	66	2.4	8	20.4	4.6	1668.1
Chifra	926	19.9	35	55	1.6	8.6	21.4	5.4	1985.6
Chira	2095	12.3	24.1	75	1	7.2	19.6	3.6	1328.6
Dangila	2116	9.4	25.2	71	0.9	8.5	21.3	3.9	1416.2
Danna_13	1282	13.3	29.5	76	0.9	7.4	20	4.0	1463.7
Debark	2836	8.6	19.9	64	1.8	8.3	20.8	3.8	1368.8
Debre Berhan	2750	6.3	20	70	2.2	8.2	20.9	3.8	1379.7
Debre Tabor	2612	9.4	22.2	66	1.1	8.2	20.7	3.8	1376.1
Debre Work	2508	10.1	23.6	63	1.4	9.2	22.5	4.2	1536.7
Dedessa	1310	14.8	31.1	72	1.8	7	19.3	4.4	1602.4
Degahabur	1070	16.7	31.6	70	2.1	8.9	22.1	5.0	1821.4

Dello Mena	1313	15.7	29.2	71	0.9	7.4	20	4.0	1471.0
Dilla	1579	13.1	27.8	74	0.4	7.2	19.7	3.7	1357.8
Dinkiti	2374	8.8	22	75	2	4.9	16.2	3.3	1186.3
Dubity Met	376	22.5	36.7	59	1.5	9.1	22.2	5.5	2007.5
Ejaji	1732	13.8	28.1	69	0.9	7.6	20.1	4.0	1460.0
Elidar	660	24	37.6	61	3.6	9.1	22.1	6.8	2489.3
Eneware	2561	9.3	21.2	66	2.9	8.2	21	4.2	1529.4
Erer	2561	17.7	33.3	66	1.6	8.8	21.9	5.1	1843.3
Fiche	2784	8.3	20.5	15	1.3	7.5	19.9	4.1	1511.1
Gambela	500	21.9	36	68	1.5	9.8	23.4	5.6	2025.8
Gatira	2358	11.6	22.2	71	1.5	7.9	20.7	3.8	1401.6
Gelemso	1739	13.3	26.8	69	1.4	8.3	21.1	4.2	1540.3
Gewane	568	22.2	37.1	56	2.1	8.7	21.7	6.1	2226.5
Gidayana	1850	13.8	24.1	66	1.5	8.5	21.4	4.1	1503.8
Gimbi	1970	13.9	26.7	69	1.3	6.8	19	3.9	1423.5
Ginir	1750	13.2	24.4	70	1.8	8.5	21.6	4.1	1503.8
Gode	295	21.7	35.4	48	2.4	9.8	23.6	6.6	2401.7
Gologcha	2040	12.5	27.4	67	1.2	8.4	21.5	4.3	1554.9
Hagere mar	1861	11.2	25	74	0.8	7.4	20	3.7	1346.9
Harar Indi	1977	13.2	24.9	69	1	8.1	21	4.0	1445.4
Humera	760	20.6	37.5	55	1	9.7	22.9	5.3	1916.3
Hunte	1380	6.5	24.1	56	1.6	9.7	23.4	4.5	1631.6
Ilaila	2080	12	25.7	69	2.6	7.8	20.1	4.3	1573.2
Imdibir	2082	10	24.6	80	0.9	6.4	18.4	3.4	1252.0
Jijiga	1775	12.2	28.1	68	1.5	9.8	23.4	4.6	1690.0
Jikawo (Lare)	419	16.9	35.1	62	1.1	7.9	20.6	4.8	1748.4
Jimma	1718	11.3	27.2	75	1.5	7.4	19.8	4.0	1449.1
Jinka	1373	16.5	27.8	67	1.6	6.7	19	4.2	1522.1
Kachis e(Rs)	2520	10.2	21.2	69	1.2	7.8	20.4	3.7	1343.2
Kamashe	1317	16.6	30.6	72	0.9	7.3	19.7	4.1	1481.9
Kebri Dehar	505	21.2	33.5	65	2.2	8.6	21.7	5.4	1974.7
Kibre Mengist	1680	12.8	26.3	76	0.5	6.9	19.3	3.6	1314.0
Kobbo (IAR)	1470	15.5	30.3	62	1.6	8.5	21.3	4.7	1730.1
Kofele	2620	5.8	19.6	80	1.1	6.8	19	3.2	1168.0
Konso	1431	17.3	28.1	68	1.5	8.3	21.3	4.5	1635.2
Kulumsa	2211	9.6	23.2	68	1.5	7.8	20.5	3.9	1408.9
Lay_Birr(SF)	1707	12.6	28.7	60	0.9	8.1	20.7	4.2	1536.7
Limu Genet	1766	13.7	27	71	0.5	7.8	20.5	3.8	1401.6
Maichew	2432	10.7	22.2	65	1.2	8.3	20.9	3.8	1401.6
Majete	2000	14.7	28.6	64	1.1	9.2	22.4	4.5	1638.9
Masha	2282	11.4	22.6	79	0.6	5.8	17.6	3.2	1168.0
May_Tsebri	1349	18.3	32.6	60	1.2	8.3	20.7	4.7	1730.1
Maygaba	1902	20.5	35.7	56	1.5	8.6	21.2	5.3	1923.6
Mega	1820	13.7	24.7	70	3.1	7.4	20.1	4.3	1584.1
Mehal Meda (RS)	3084	7.2	18.6	65	2.1	8.4	21.2	3.8	1372.4
Meiso AVA	1400	14.8	31.5	60	1.8	8.6	21.6	5.0	1821.4
Meiso Mission	1332	14.8	30.9	60	1.4	8.6	21.6	4.8	1733.8
Mekane Selam	2605	11.1	22.3	60	0.9	8	20.5	3.8	1376.1
Mekele Observa	2000	11.9	27.3	65	1.8	8.7	21.4	4.5	1649.8
Melkasa (IAR)	1540	13.4	28.9	67	4.8	9.8	23.4	5.8	2102.4
Melkasa (IAR)	1540	13.3	28.9	68	4.3	9.8	23.4	5.6	2044.0
Meraro	2940	6.3	18.4	68	2.1	7.8	20.5	3.6	1321.3
Metehara -NMSA	944	18.2	34	59	1.6	8.5	21.5	5.2	1901.7

Metema	790	19.2	35.7	60	1.2	9	21.8	5.1	1846.9
Mille	487	25	37.4	52	2.1	8.8	21.8	6.3	2295.9
Mirab Abaya Ber	1221	17.7	30.2	68	1.3	8.4	21.5	4.5	1649.8
Motta	2417	10	23.9	66	1.4	9.6	22.8	4.2	1536.7
Moyale	1166	16.5	27.5	73	1.7	7.4	20.1	4.2	1529.4
Nazeret	1622	15.2	28	62	2.5	8.8	21.9	5.0	1817.7
Nebelet	1988	16.2	27.9	57	1.5	8.3	20.7	4.5	1657.1
Nedjo	1800	11.4	26.1	69	6.5	7.3	19.6	5.4	1960.1
Nefas Mewcha	3098	8	18.7	70	1.5	8.7	21.5	3.6	1321.3
NEKEMT	2080	13.1	24.5	73	4.4	6.5	18.5	4.2	1518.4
Nuraera (SF)	1140	16.7	31.9	62	1.8	8.7	21.5	5.0	1817.7
Pawe	1119	17	31.7	73	0.5	9	22.1	4.4	1591.4
Quara	648	19.7	36.3	59	1.2	7.8	20.1	4.9	1784.9
Robe	2441	8.4	22.6	73	1.6	7.9	20.7	3.8	1379.7
Sanja	1003	18.1	34.3	58	1.2	8.8	21.6	4.9	1803.1
Sawula	1348	17.5	30	69	0.5	7.5	20.1	4.0	1467.3
Sekoru	1928	13.1	25.4	68	0.7	8.3	21.2	3.9	1423.5
Semera	590	23.4	37.9	55	2.6	8.7	21.6	6.6	2409.0
Senkata	2437	10.8	24	57	2.1	9.2	22	4.5	1646.2
Seru	2468	8.4	20.6	72	1.2	7.2	19.5	3.4	1248.3
Shahura	2205	14.2	24.6	60	1.9	8.9	21.8	4.5	1638.9
Shambu	2460	11.8	23.2	71	1	7.7	20.3	3.8	1368.8
Shewa Robit	1277	13.7	31.5	60	1.4	7.7	20.1	4.6	1664.4
Shiraro	1033	18.5	34.8	56	1.4	9.6	22.5	5.3	1927.2
Shire Endasilasse	1897	14.3	27.9	59	1.8	8.8	17.2	3.7	1361.5
Shola Gebeya	2500	9.3	20	69	2	7.2	19.5	3.6	1317.7
Simada	2584	9.5	23.5	81	2.3	8.1	20.9	3.8	1401.6
Sinana	2400	6.8	22	68	2.3	8	20.8	3.9	1430.8
Sirinka	1861	13.6	26	73	1.3	8.2	20.7	4.0	1456.4
Soge -Belogiganf	1394	15.6	32.3	80	0.6	8.2	21	4.3	1558.6
Tepi	1205	14.7	29.7	78	0.4	5.8	17.6	3.5	1273.9
Tercha	1335	16.9	28.6	77	0.9	8.1	21	4.2	1522.1
Tsitsika	1469	18.9	33.4	53	1.5	8.6	21.2	5.1	1868.8
Wegel Tena	2952	6.8	19.6	71	1.9	8.2	20.7	3.7	1343.2
Werabe	2057	11.7	25	75	2.4	8.2	21.1	4.2	1540.3
Wereilu	2708	10.2	21.4	62	2.5	7.5	19.9	4.1	1500.2
Wolaita	1854	14.7	25.6	74	1.6	7.3	19.9	4.0	1456.4
Woliso Giyon	2058	13.7	25.5	65	1.1	7.7	20.2	4.0	1452.7
Yabello	1729	14.3	25.9	69	1.6	7.5	20	4.1	1496.5
Yetnora	2420	9.7	22.8	65	1.2	8.1	20.8	3.8	1390.7
Ziway	1640	14.3	28.1	64	1.8	9.3	22.7	4.8	1741.1

Annex-C Thiessen mean annual ETo weights for study area sub-catchments

Station Name	AreaWeight-(km^2)	Thiessen weight (%)	Annual ETo-mm	Station Name	Area Weight-km^2	Thiessen weight (%)	Annual ETo-mm
Abala	12558	1.1	1733.8	Belle Chakata	13700	1.2	1503.8
Abomsa	3078	0.3	1715.5	Billate	1471	0.1	1638.9
Addis Ababa Ob	4617	0.4	1306.7	Bore	4794	0.4	1131.5
Adele	2260	0.2	1449.1	Bui	3804	0.3	1609.7
Adet	3711	0.3	1051.2	Bullen	15353	1.4	1408.9
Adigrat	2759	0.2	1376.1	Bure	6034	0.5	1350.5
Adwa	4906	0.4	1522.1	Burji	6410	0.6	1463.7
Aisha	12759	1.1	1810.4	Chagni	2863	0.3	1463.7
AKAKI	2939	0.3	1328.6	Cheffa SF	3570	0.3	1565.9
Alem Ketema	3227	0.3	1773.9	Chercher	8600	0.8	1668.1
Alemaya	6502	0.6	1500.2	Chifra	5092	0.3	1985.6
Alge	5219	0.6	1474.6	Chira	5722	0.5	1328.6
Aman	16683	1.5	1642.5	Dangila	3539	0.3	1416.2
Ambo Agric	4358	0.4	1478.3	Danna_13	3138	0.3	1463.7
Anger	1713	0.2	1602.4	Debark	7666	0.7	1368.8
Arjo	3602	0.3	1379.7	Debre Berhan	3223	0.3	1379.7
Assosa	16668	1.5	1507.5	Debre Tabor	7507	0.7	1376.1
Atsebi	10606	0.9	1471.0	Debre Work	3972	0.4	1536.7
Awash Arba	4207	0.4	2014.8	Dedessa	1218	0.1	1602.4
Ayehu	3910	0.8	1489.2	Degahabur	49737	4.4	1821.4
Ayira	4710	0.4	1525.7	Dello Mena	29955	2.6	1471.0
Ayisha	2122	0.1	1810.4	Dilla	3124	0.3	1357.8
Aykel	6203	0.5	1518.4	Dinkiti	10691	0.9	1186.3
Bahir Dar-Airp	3965	0.4	1551.3	Dubity Met	4841	0.4	2007.5
Bati	4345	0.4	1602.4	Ejaji	6072	0.5	1460.0
Bedele	3545	0.3	1335.9	Elidar	17954	1.6	2489.3
Eneware	2481	0.2	1529.4	Meraro	3779	0.3	1321.3
Erer	11538	1.0	1843.3	Metehara –NMS	2754	0.2	1901.7
Fiche	5073	0.4	1511.1	Metema	7655	0.7	1846.9
Gambela	10805	1.0	2025.8	Mille	9787	0.9	2295.9
Gatira	3367	0.3	1401.6	Mirab Abaya Ber	5077	0.4	1649.8
Gelemso	10638	0.9	1540.3	Motta	3609	0.3	1536.7
Gewane	12672	1.1	2226.5	Moyale	24683	2.2	1529.4
Gidayana	6284	0.6	1503.8	Nazeret	2957	0.3	1817.7
Gimbi	2275	0.2	1423.5	Nebelet	2246	0.2	1657.1
Ginir	28420	2.5	1503.8	Nedjo	8359	0.7	1960.1
Gode	76995	6.8	2401.7	Nefas Mewcha	5858	0.5	1321.3
Gologcha	1528	0.1	1554.9	NEKEMT	2845	0.3	1518.4
Hagere mar	7910	0.7	1346.9	Nuraera (SF)	2717	0.2	1817.7
Harar Indi	14879	1.3	1445.4	Pawe	7125	0.6	1591.4
Humera	6711	0.6	1916.3	Quara	13262	1.2	1784.9
Hunte	5332	0.5	1631.6	Robe	2160	0.2	1379.7
Ilaila	1021	0.1	1573.2	Sanja	2210	0.1	1803.1
Imdibir	3072	0.3	1252.0	Sawula	10145	0.9	1467.3
Jijiga	17085	1.5	1690.0	Sekoru	5641	0.5	1423.5
Jikawo (Lare)	2672	0.7	1748.4	Semera	10459	0.9	2409.0
Jimma	4693	0.4	1449.1	Senkata	2049	0.2	1646.2
Jinka	24550	2.2	1522.1	Seru	5211	0.2	1248.3
Kachis e(Rs)	6602	0.6	1343.2	Shahura	2152	0.1	1638.9

Kamashe	3797	0.3	1481.9	Shambu	6097	0.5	1368.8
Kebri Dehar	68663	6.1	1974.7	Shewa Robit	4508	0.4	1664.4
Kibre Mengist	27880	2.5	1314.0	Shiraro	6873	0.6	1927.2
Kobbo (IAR)	4658	0.4	1730.1	Shire Endasilasse	2262	0.2	1361.5
Kofele	6228	0.5	1168.0	Shola Gebeya	3521	0.1	1317.7
Konso	16497	1.5	1635.2	Simada	8520	0.3	1401.6
Kulumsa	3032	0.3	1408.9	Sinana	3652	0.6	1430.8
Lay_Birr(SF)	6549	0.6	1536.7	Sirinka	6598	0.3	1456.4
Limu Genet	4749	0.4	1401.6	Soge Belogiganfo	3256	0.2	1558.6
Maichew	4428	0.4	1401.6	Tepi	10023	0.9	1273.9
Majete	3613	0.3	1638.9	Tercha	7367	0.7	1522.1
Masha	6007	0.5	1168.0	Tsitsika	10564	0.9	1868.8
May_Tsebri	7003	0.6	1730.1	Wegel Tena	6494	0.6	1343.2
Maygaba	2461	0.2	1923.6	Werabe	5153	0.5	1540.3
Mega	19489	1.7	1584.1	Wereilu	3769	0.3	1500.2
Mehal Meda	2061	0.2	1372.4	Wolaita	2950	0.3	1456.4
Meiso AVA	6896	0.6	1821.4	Woliso Giyon	4156	0.4	1452.7
Meiso Mission	6530	0.6	1733.8	Yabello	3752	0.3	1496.5
Mekane Selam	6530	0.6	1376.1	Yetnora	4521	0.2	1390.7
Mekele Observa	4441	0.4	1649.8	Ziway	6897	0.4	1741.1
Melkasa (IAR)	1979	0.2	2102.4	Melkasa (IAR)	1979	0.2	2044.0