

**GIS- BASED SURFACE IRRIGATION POTENTIAL ASSESSMENT OF  
RIVER CATCHMENTS FOR IRRIGATION DEVELOPMENT IN DALE  
WOREDA, SIDAMA ZONE, SNNP**

**M.Sc Thesis**

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Haramaya University**

**GIS- BASED SURFACE IRRIGATION POTENTIAL ASSESSMENT OF  
RIVER CATCHMENTS FOR IRRIGATION DEVELOPMENT IN DALE  
WOREDA, SIDAMA ZONE, SNNP**

**A Thesis Submitted to the Institute of Technology,  
School of Natural Resource and Environmental Engineering  
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**In Partial Fulfillment of the Requirements for the Degree of  
MASTER OF SCIENCE IN IRRIGATION ENGINEERING**

**By  
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**June 2010  
Haramaya University**

**SCHOOL OF GRADUATE STUDIES  
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## **DEDICATION**

I dedicate this thesis manuscript to my father GANOLE TIRO, and to my late mother FAYO LAGIDE, for nursing me with affection, love and for their dedicated partnership in the success of my life.

## STATEMENT OF AUTHOR

First, I declare that this thesis is my bonafide work and that all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for an advanced M.Sc degree at Haramaya University and is deposited at the University Library to be made available under rules of the Library. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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## LIST OF ABBREVIATIONS

CA	Comprehensive Assessment of water management for agriculture
CNES	Centre National d'Études Spatiales
DEM	Digital Elevation Model
DFID	Department for International Development
EMA	Ethiopian Mapping Agency
ENVI	Environment for Visualizing Images
ESRI	Environmental Systems Research Institute
ETc	Crop Evapo-transpiration
ETo	Reference Crop Evapo-transpiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
GLCN	Global Land Cover Network
GPS	Global Positioning System
IFAD	International Fund for Agricultural Development
ILRI	International Livestock Research Institute
IWR	Irrigation Water Requirement
MoA	Ministry of Agriculture
MoWR	Ministry of Water Resources
NASA	National Aeronautics and Space Administration
NGA	National Geospatial intelligence Agency
NMSA	National Meteorological Services Agency
SPOT	Système Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
UNESCO	United Nations Scientific and Cultural Organization

## **BIOGRAPHICAL SKETCH**

The author was born in Arbegona Woreda, Sidama Zone, on September 24<sup>th</sup>, 1983. He attended his elementary and junior schools from 1992 -1999 at Arbegona (Yaye) and Aleta Wondo towns, and Yirgalem Comprehensive Secondary school from 2000 - 2003.

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Soon after graduation, the author was employed by the Ministry of Agriculture and Rural Development in Dale Woreda, Sidama Zone. Since then, he has been working as a Soil and Water Conservation expert and Irrigation Engineer.

In 2008, he joined the Graduate School of the Haramaya University as a candidate for Master of Science Degree in Soil and Water Engineering (Irrigation Engineering).

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## TABLE OF CONTENTS

<b>STATEMENT OF AUTHOR</b>	<b>iv</b>
<b>LIST OF ABBREVIATIONS</b>	<b>v</b>
<b>BIOGRAPHICAL SKETCH</b>	<b>vi</b>
<b>ACKNOWLEDGMENTS</b>	<b>vii</b>
<b>LIST OF TABLES</b>	<b>xi</b>
<b>LIST OF FIGURES</b>	<b>xii</b>
<b>LIST OF FIGURES IN THE APPENDIX</b>	<b>xiv</b>
<b>ABSTRACT</b>	<b>xv</b>
<b>2. LITERATURE REVIEW</b>	<b>5</b>
2.1. Definition of Irrigation Potential	5
2.2. Irrigation Potential in Ethiopia	5
2.3. Irrigation Land Suitability Evaluation Factors	7
2.3.1. Slope	8
2.3.3. Land cover or land use	9
2.3.4. Water availability	9
2.4. Overview of GIS Application	10
2.4.1. Mapping	10
2.4.2. Weighted overlay analysis	11
2.4.3. Watershed delineation	11
2.4.4. GIS as a tool for irrigation potential assessment	11
2.5. Application of Remote Sensing	13

## TABLE OF CONTENTS (*CONTINUED*)

2.6. Review of Commonly Used GIS and Remote Sensing Data.	14
2.6.1. Spatially interpolated climate data on grids	14
2.6.2. Satellite imagery	14
2.6.3. Digital elevation model (DEM)	16
<b>3. MATERIALS AND METHODS</b>	<b>19</b>
3.1. Description of the Study Area	19
3.1.1 Location	19
3.1.2. Agro-ecology	20
3.1.3. Drainage system	21
3.2. Materials Used	22
3.3.1. Data pre-processing and checking	24
3.3.2. Watershed delineation	25
<b>3.3.3. Identification of potential irrigable sites</b>	<b>28</b>
3.3.3.1. Slope suitability analysis	28
3.3.3.2. Soil suitability assessment	29
3.3.3.3. Land cover/use	30
3.3.3.4. Distance from water supply (source)	34
3.3.3.5. Weighing of irrigation suitability factors to find potential irrigable sites	34
3.3.4. Computing irrigation water requirements	35
3.3.5. Estimating surface water resources potential of river catchments	37
3.3.5.1. Estimating discharges at un-gauged sites from gauged sites	38
3.3.5.2. Transferring discharges of gauged rivers to the site of interest	39
3.3.6. Ranking of the potential irrigable sites among the river catchments	40
<b>4. RESULTS AND DISCUSSIONS</b>	<b>41</b>
4.1. Testing Stream Flow and Rainfall Data for Consistency	41
4.2. Watershed Delineation	42
4.3. Irrigation Suitability Evaluation	46
4.3.1. Suitable slope	46

## **TABLE OF CONTENTS (*CONTINUED*)**

4.3.2. Soil suitability	47
4.3.3. Land cover/use evaluation	50
4.5. Gross Irrigation Water Requirements of the Identified Command Areas	57
4.6. Water Resources Assessment	59
4.6.1. Gauged and un-gauged watersheds similarities	59
4.6.2. Mean areal rainfall of sub-watersheds	63
4.6.4. Transferring discharges to sites of interest	68
4.7. Irrigation Potential of River Catchments	69
<b>5. SUMMARY AND CONCLUSIONS</b>	<b>73</b>
5.1. Summary and Conclusions	73
5.2. Recommendations	74
<b>6. REFERENCES</b>	<b>76</b>
<b>7. APPENDICES</b>	<b>84</b>
7.1 Summary of Hydro Meteorological Data	85
7.1.1 Hydrological data	85
7.2. Meteorological Data	89
7.2.1. Rainfall data	89
7.2.2. Summary of other climatic data	94
7.2.3. Crop water requirement tables	97
7.3. Double Mass Curve Analysis Result	101

## LIST OF TABLES

Table	Page
1: Irrigation potential in the river basins of Ethiopia. ....	6
2. Slope suitability classification for surface irrigation .....	29
3. Soil suitability factor rating.....	29
4. Hydrometric stations inside and around the study woreda .....	38
5. Summary of missing rainfall data for the stations .....	42
6. Slope suitability range of the study area for surface irrigation .....	47
7. Soil suitability classification result for surface irrigation .....	49
8. Confusion matrix of SPOT 2006 LUC classification .....	51
9. Area coverage of land cover/use classes of the study are .....	52
10. Suitable land for surface irrigation in the study area .....	56
11. Gross monthly irrigation water requirements (Mm <sup>3</sup> ) for growing banana .....	58
12. Gross monthly irrigation water requirements (Mm <sup>3</sup> ) for growing sugarcane.....	58
13. Characteristics of watersheds above the gauged and un-gauged sites .....	60
14. Average monthly areal rainfall of the sub-watersheds.....	67
15. Mean monthly stream flows of un-gauged river catchments estimated from gauged	68
16. Mean monthly discharges (m <sup>3</sup> /s) at the sites of interest.....	69
17. Comparing of irrigation demands and available flows of river catchments for banana ...	70
18. Comparing of irrigation demands and available flows of river catchments for the sugarcane.....	71
19. Summary of irrigation potential of the river catchments and their ranking.....	72

## LIST OF FIGURES

Figure	Page
1. Location map of the study area .....	19
2. Agro-ecological map of the study area .....	20
3. Drainage systems inside and outside the study area .....	21
4. Digital elevation model showing drainage system of the study area .....	26
5 .Flow direction and streams network .....	27
6 . Watershed outlets definition .....	27
7. SPOT5 satellite image of the study area showing true color composite (321) .....	31
8. Irrigation suitability model.....	35
9. Thiessen polygons showing area of influence of climatic stations in the study area.....	36
10. Double mass curve of Bilate station .....	41
11. Gidawo watershed.....	43
12. Bilate watershed .....	43
13. Raro sub-watershed .....	44
14. Woyima sub-watershed.....	44
15. Wamole sub-watershed .....	45
16. Dama sub-watershed .....	45
17. Slope suitability map of the study area for surface irrigation .....	46
18 . Study area soil classification.....	47
19. Soil suitability map of the study area.....	50
20. Land cover/use map of the study area.....	52
21. Suitable sites for surface irrigation development.....	55
22. Land cover/ use map of Gidawo Watershed .....	61
23. Soil map of Gidawo watershed .....	62
24. Slope map of Gidawo watershed.....	63
26. Theissen polygon map of Gidawo gauge site at Aposto .....	64
25. Theissen polygon map of kola sub watershed gauge site near Aleta Wondo .....	64
27. Theissen polygon map of Dama sub watershed .....	65
28. Theissen polygon map of Raro sub-watershed .....	65
29. Theissen polygon map of Woyima sub-watershed .....	66
30. Theissen polygon map of Wamole sub watershed.....	66

## LIST OF TABLES IN THE APPENDIX

<b>Appendix Table</b>	<b>Page</b>
1. Kola tributary near Aleta Wondo monthly flow.....	85
2. Bilate river monthly flow at Tena .....	86
3. Gidawo river monthly flow at Aposto .....	87
4. Gidawo monthly flow at Miesso.....	88
5. Corrected monthly rainfall data at Bilate Agri.....	89
6. Corrected monthly rainfall data at Dilla Mission.....	90
7. Monthly rainfall at Hawassa .....	91
8. Corrected monthly rainfall at Yirgalem.....	92
9. Grid interpolated long-term mean monthly rainfall data around study area.....	93
10. Summary of other climatic data in and around study area.....	94
11. ET <sub>O</sub> and climatic data for Bilate meteorological station.....	95
12. ET <sub>O</sub> and climatic data for Dila meteorological station.....	95
13. ET <sub>O</sub> and climatic data for Yirgalem meteorological station.....	96
14. ET <sub>O</sub> and climatic data for Aleta Wondo meteorological station.....	96
15. Sugarcane monthly irrigation water requirements at Yirgalem stations.....	97
16. Banana monthly irrigation water requirements at Yirgalem stations.....	97
17. Sugarcane monthly irrigation water requirements at Aleta Wondo station.....	98
18. Banana monthly irrigation water requirements at Aleta Wondo station.....	98
19. Sugarcane monthly irrigation water requirements at Dila station.....	99
20. Banana monthly irrigation water requirements at Dilla station.....	99
21. Sugarcane monthly irrigation water requirements at Bilate station.....	100
22. Banana monthly irrigation water requirements at Bilate station.....	100

## LIST OF FIGURES IN THE APPENDIX

<b>Appendix Figures</b>	<b>Page</b>
1. Double mass curve for the consistency of Gidawo river at Meissa gauging station....	101
2. Double mass curve for the consistency of Kola river gauging station.....	101
3. Double mass curve for the consistence of Gidawo river at Aposto gauging station.....	102
4. Double mass curve for the consistency of Dilla meteorological station rainfall data....	102
5. Double mass curve for the consistency of Yirgalem meteorological station rainfall data.....	103
6. Double mass curve for the consistency of Bilate meteorological station rainfall data...	103
7. Double mass curve for the consistency of Hawassa meteorological station rainfall data.....	104

# **GIS- BASED SURFACE IRRIGATION POTENTIAL ASSESSMENT OF RIVER CATCHMENTS FOR IRRIGATION DEVELOPMENT IN DALE WOREDA, SIDAMA ZONE, SNNP**

## **ABSTRACT**

*Assessing available land and water resources for irrigation is important for planning their use. This study was initiated with the objective of assessing the water and land resources potential of river catchments in Dale Woreda of Sidama Zone for irrigation development and generating geo-referenced map of these resources by using Geographic Information System. Watershed delineation, identification of potential irrigable land, and estimation of irrigation water requirement and surface water resources of river catchments were the steps followed to assess this irrigation potential. Results of the watershed delineation lead to gave two main watersheds (Bilate and Gidawo) and four sub-watersheds on Gidawo (Dama, Raro, Wamole and Woyima). To identify potential irrigable land, irrigation suitability factors such as soil type, slope, land cover/use, and distance from water supply (sources) were taken into account. The irrigation suitability analysis of these factors indicate that 86 % of soil and 58.5 % slope in the study area are in the range of highly suitable to marginally suitable for surface irrigation system. In terms of land cover/use, 87.1% of land cover/use are highly suitable where as 12.9% were restricted from irrigation development. Overall, the weighted overlay analysis of these factors gave potential irrigable land among river catchments as Bilate (3,621.6 ha), Dama (552.7 ha), Gidawo (7,265.6 ha), Raro (693.35 ha), Wamole (1,511.3 ha) and Woyima (805.66 ha). To grow on these identified irrigable areas, two crops such as banana and sugarcane were selected and their gross irrigation demand calculated by using nearby climatic stations. The result revealed that irrigation requirements of identified command area varies according to nearby climatic station and type of crops selected. The discharges at un-gauged sites were estimated from gauged sites by applying runoff coefficient method and results were obtained on monthly bases. By comparing gross irrigation demand of irrigable land with available flow in rivers, total surface irrigation potential of the study area was obtained as 14089.55 ha. In conclusion, irrigation potential from this figure can be increased by using sprinkler and drip irrigation methods.*

## **1. INTRODUCTION**

Ethiopia depends on the rainfed agriculture with limited use of irrigation for agricultural production. It is estimated that more than 90% of the food supply in the country comes from low productivity rainfed smallholder agriculture and hence rainfall is the single most important determinant of food supply and the country's economy (Belete, 2006). The major problem associated with the rainfall-dependent agriculture in the country is the high degree of rainfall variability and unreliability. Due to this variability, crop failures due to dry spells and droughts are frequent. As a consequence, food insecurity often turns into famine with the slightest adverse climatic incident, particularly, affecting the livelihoods of the rural poor.

With declining productivity in rain fed agriculture and with the need to double food production over the next two decades, water has been recognized as the most important factor for the transformation of low productive rain-fed agriculture into most effective and efficient irrigated agriculture (FAO, 1994). It is obvious that the utilization of water resources in irrigated agriculture provide supplementary and full season irrigation to overcome the effects of rainfall variability and unreliability. Hence, the solution for food insecurity could be provided by irrigation development that can lead to security by reducing variation in harvest, as well as intensification of cropping by producing more than one crop per year.

In this regard, sustainable food production that can be expected through an optimal development of water resources, in conjunction with development of land depends on the method of irrigation considered (FAO, 2003). These methods, however, can be broadly classified into three categories: surface (basin, border, and furrows), sprinkler, and drip /micro-irrigation/ methods. Surface irrigation is the application of water by gravity flow to the surface of the field, either the entire field is flooded (basin irrigation) or the water is fed into small channel (furrow) or strip of land (borders). It is the oldest and still the most widely used method of water application to agricultural lands.

Surface irrigation offers a number benefits for the less skilled and poor farmers. Under such circumstances, more than 90% of the world uses surface irrigation, even if local irrigators have

least knowledge of how to operate and maintain the system (Saymen, 2005). Furthermore, these systems can be developed at the farm level with minimal capital investment. The major capital investment on surface system is mainly associated with land grading, but if the topography is not too undulating, these costs are not high. Hence, surface irrigation development requires favorable topography and information on land and water resources for proper planning (FAO, 1995).

Therefore, planning process for surface irrigation has to integrate information about the suitability of the land, water resources availability and water requirements of irrigable areas in time and place (FAO, 1997). Determining the suitability of land for surface irrigation requires thorough evaluation of soil properties and topography (slope) of the land within field (Fasin *et al*, 2008). Since all kinds of rural land are involved by different land cover/use types, its suitability evaluation for surface irrigation also provides guidance in cases of conflict between rural land use and urban or industrial expansion, by indicating which areas of land covers /uses are most suitable for irrigation (FAO, 1993). The suitability of the land must also be evaluated on condition that water can be supplied to it. The volume of water obtainable for irrigation will depend on the outcome of hydrological studies of surface water (FAO, 1985). The amount of runoff in river catchments with limited stream flow data can be determined from runoff coefficient of gauged river basin (Goldsmith, 2000; DFID, 2004; Sikka, 2005). After the amount of river discharges both gauged and un-gauged are quantified, an important part of the evaluation is the matching of water supplies and water demand (requirement) (FAO, 1977b). Irrigation water supplies and their requirements are therefore, important physical factors in matching the available supply to the requirements.

However, these factors should be assessed in an integrated manner, geo-referenced and mapped for surface irrigation development possibilities. With an adequate database, Geographic Information Systems (GIS) can serve as a powerful analytic and decision-making tool for irrigation development (Aguilar-Manjarrez and Ross, 1995). Large area extent of GIS as well as its ability to collect store and manipulate various types of data in a unique spatial database, helps performing various kinds of analysis and thus, extracting information about spatially distributed phenomena. In this kind of situation, the factors that are involved for

irrigation potential assessment such soil, land cover/use, land slope and distance between water supply and suitable command area should be weighted and evaluated by the use of GIS according to their suitability for irrigation.

In Dale *Woreda*, there are six perennial rivers: Gidawo, Bilate, Raro, Wamole, Dama, and Woyima rivers. Despite this large number of rivers, exploitation of their water resources for irrigated agriculture has remained low in the *Woreda*. The water resources of these rivers have been serving as sources of water for industrial use (coffee processing industries) and domestic water supply. The efforts to establish small and large-scale irrigation schemes in the *Woreda* are constrained by a number of uncertainties. Firstly, stream flows from some of the rivers are not known. Secondly, potential irrigable areas in the *Woreda* have not been identified and matched with the water requirements of some crops commonly grown in the *Woreda*.

Therefore, to overcome these uncertainties, this study was carried out by using GIS as a tool for assessing irrigation potential in Dale *Woreda* using input data from soil, digital elevation model (DEM), and satellite image (SPOT5) and geo-referencing and mapping of the assessment result in the context of surface irrigation development in the study area. Furthermore, the study attempted to estimate water resource potential of the river catchments in the *Woreda* and the irrigation water requirements of the identified irrigable areas for cultivating some selected crops in the area.

The main objective of this study was to assess the water and land resources potential of river catchments for surface irrigation in Dale *Woreda*, ranking as well as providing geo-referenced map of these resources, by using Geographic Information System (GIS).

The specific objectives of the study include:

- i. to delineate main river catchments, and sub catchments using GIS from digital elevation model (DEM), and estimating their surface water potential,
- ii. to identify available irrigable land in the area and estimate total irrigation water requirement for surface irrigation method from each delineated river catchments, and

- iii. to provide geo-referenced map of two resources (water and land resources) and rank the identified irrigable areas among the river catchments for future planning and development possibilities.

## **2. LITERATURE REVIEW**

### **2.1. Definition of Irrigation Potential**

The definition of irrigation potential is not straightforward and implies a series of assumptions about irrigation techniques, investment capacity, national and regional policies, social, health and environmental aspects, and international relationships, notably regarding the sharing of waters. However, to assess the information on land and water resources at the river basin level, knowledge of physical irrigation potential is necessary. The area which can potentially be irrigated depends on the physical resources 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate. Therefore, physical irrigation potential represents a combination of information on gross irrigation water requirements, area of soils suitable for irrigation and available water resources by basin (FAO, 1997).

### **2.2. Irrigation Potential in Ethiopia**

The estimates of the irrigation potential of Ethiopia vary from one source to the other, due to lack of standard or agreed criteria for estimating irrigation potential in the country. The earlier report, for example from the World Bank (1973), showed the irrigation potential at a lowest of 1.0 and 1.5 million hectares, and a highest of 4.3 million hectares. There have also been different estimates of the irrigation potential in Ethiopia. According to the Ministry of Agriculture (1986), the total irrigable land in the country measures 2.3 million hectares. The International Fund for Agricultural Development (IFAD, 1987), on the other hand gives a figure 2.8 million ha. A total of 3.7 million ha had been identified as potentially irrigable land by MoWR (2002). Most of these figures are derived by adding up the irrigation potential of the country's twelve river basins (Silesh *et al*, 2007) as shown in Table.1 below.

Table 1: Irrigation potential in the river basins of Ethiopia.

Basin	Catchment Area (Km2)	Irrigation potentials (Ha) (Respective recent master plan studies)				Irrigation Potential (WAPCOS 1995)		
		Small-scale	Medium-scale	Large-scale	Total	Total Drainage Area (km2)	Irrigable Area (Ha)	Percent Irrigable Area of the Country
Abbay	198,890.70	45,856	130,395	639,330	815,581	201,346	1,001,000	27
Tekeze	83,475.94	N/A	N/A	83,368	83,368	90,001	3,17,000	8.5
Baro-Akobo	76,203.12	N/A	N/A	1,019,523	1,019,523	74,102	9,85,000	26.5
Omo-Ghibe	79,000	N/A	10,028	57,900	67,928	78,213	4,45,000	12
Rift Valley	52,739	N/A	4000	45,700	139,300	52,739	1,39,000	3.7
Awash	110,439.30	30,556	24,500	79,065	134,121	112,697	2,05,000	5.5
Genale Dawa	172,133	1,805	28,415	1,044,500	1,074,720	117,042	4,23,000	11.4
WabiShebele	202,219.50	10,755	55,950	171,200	237,905	102,697	200,000	5.4
Denakil	63,852.97	2,309	45,656	110,811	158,776	74,102		
Ogaden	77,121					77,121		
Ayisha (Gulf of Aden)	2,000					2,000		
<b>Total</b>	<b>1,118,074.53</b>				<b>3,731,222</b>	<b>982,060</b>	<b>3,715,000</b>	<b>100</b>

Source: IWMI Working paper 123: Water resources and Irrigation Development in Ethiopia

Ethiopia, indeed, has significant irrigation potential assessed both from available land and water resources potential, irrespective of the lack of accurate estimates of potentially irrigable land and developed area under irrigation.

### **2.3. Irrigation Land Suitability Evaluation Factors**

Land suitability is the fitness of a given type of land for a defined use. The land may be classified in its present condition or after improvements for its specified use. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976).

Land evaluation is primarily the analysis of data about the land –its soils, climate, vegetation, and etc in terms of realistic alternatives for improving the use of that land. For irrigation, land suitability analysis, particular attention is given to the physical properties of the soil, to the distance from available water sources and to the terrain conditions in relation to methods of irrigation considered (FAO, 2007). In addition to these factors, land cover/land use types are considered as limiting factors in evaluating suitability of land for irrigation (Haile Gebrie, 2007; Meron, 2007). As extensively discussed in FAO land evaluation guidelines (FAO, 1976, 1983, 1985), the suitability of these factors for surface irrigation method and for the given land utilization types can be expressed corresponding to the following suitability classes.

#### **Order S - suitability. The classes under this order are:**

- S1 (highly suitable) - land having no significant limitation to sustained application of a given use.
- S2 (moderately suitable) - land having limitation which in aggregate are moderately severe for a sustained application of a given use.

- S3 (marginally suitable) - land having limitation which in aggregate are severe for a sustained application of a given use and will reduce productivity or benefits.

#### **Order N suitability classification**

- N1 (temporarily not suitable) - land having limitations which may be surmountable in time but which cannot be corrected with existing knowledge at currently acceptable cost.
- N2 (Permanently not suitable) - land having limitations which appear as severe as to preclude any possibilities of successful sustained use of the land of a given land use.

The factors considered for surface irrigation land suitability evaluation are narrated separately in subsequent sub-sections.

#### **2.3.1. Slope**

Slope is the incline or gradient of a surface and is commonly expressed as a percent. Slope is important for soil formation and management because of its influence on runoff, drainage, erosion and choice of irrigation types. The slope gradient of the land has great influence on selection of the irrigation methods. According to FAO standard guidelines for the evaluation of slope gradient, slopes which are less than 2%, are very suitable for surface irrigation. But slopes, which are greater than 8%, are not generally recommended (FAO, 1999)

#### **2.3.2. Soils**

The assessment of soils for irrigation involves using properties that are permanent in nature that cannot be changed or modified. Such properties include drainage, texture, depth, salinity, and alkalinity (Fasina *et al*, 2008). Even though salinity and alkalinity hazards possibly improved by soil amendments or management practices, they could be considered as limiting factors in evaluating the soils for irrigation (FAO, 1997). Accordingly, some soils considered

not suitable for surface irrigation could be suitable for sprinkler irrigation or micro-irrigation and selected land utilization types.

### **2.3.3. Land cover or land use**

Land cover and land use are often used interchangeably. However, they are actually quite different. The GLCN (2006) defines land cover as the observed (bio) physical cover, as seen from the ground or through remote sensing, including vegetation (natural or planted) and human construction (buildings, roads, etc.) which cover the earth's surface. Water, ice, bare rock or sand surfaces also count as land cover. However, the definition of land use establishes a direct link between land cover and the actions of people in their environment. Thus, a land use can be defined as a series of activities undertaken to produce one or more goods or services. A given land use may take place on one, or more than one, pieces of land and several land uses may occur on the same piece of land. Definitions of land cover or land use in this way provide a basis for identifying the possible land suitability for irrigation with precise and quantitative economic evaluation. Therefore, matching of existing land cover/use with topographic and soil characteristics to evaluate land suitability for irrigation with land suitability classes, present possible lands for new agricultural production (Jaruntorn, *et al.*, 2004).

### **2.3.4. Water availability**

It is important to make sure that there will be no lack of irrigation water. If water is in short supply during some part of the irrigation season, crop production will suffer, returns will decline and part of the scheme's investment will lay idle (FAO, 2001). Therefore, water supply (water quantity and seasonality) is the important factor to evaluate the land suitability for irrigation according to the volume of water during the period of year which it is available (FAO, 1985). Quantifying the amount of water available for irrigation and determining the exact locations to which water can be economically transported are important in the decision to expand its use. Where possible, the water source preferred to be located above the command area so that the entire field can be irrigated by gravity. It is also desirable that the water source be near the center of the irrigated area to minimize the size of the delivery

channels and pipelines. Therefore, distance from water sources to command area, nearness to rivers, is useful to reduce the conveyance system (irrigation canal length) and thereby develop the irrigation system economical (Silesh, 2000).

## **2.4. Overview of GIS Application**

A Geographic Information System (GIS) is computer software used for capturing, storing, querying, analyzing, and displaying geographically referenced data (Goodchild, 2000). Geographically referenced data are data that describe both the locations and characteristics of spatial features such as roads, land parcels, and vegetation stands on the Earth's surface. The ability of a GIS to handle and process geographically referenced data distinguishes GIS from other information systems which are the other information system. It also establishes GIS as a technology important to a wide variety of applications. Clearly, the increased availability of large, geographically referenced data sets and improved capabilities for visualization, rapid retrieval, and manipulation inside and outside of GIS will demand new methods of exploratory spatial data analysis that are specifically tailored to this data-rich environment (Wilkinson, 1996; Gahegan, 1999). Using GIS databases, more up- to-date information can be obtained or information that was unavailable before can be estimated and complex analyses can be performed. This information can result in a better understanding of a place, can help to make the best choices, or prepare for future events and conditions. The most common geographic analyses that can be done with a GIS are narrated separately in the subsequent sub-sections.

### **2.4.1. Mapping**

The main application in GIS is mapping where things are and editing tasks as well as for map-based query and analysis (Campbell, 1984). A map is the most common view for users to work with geographic information. It's the primary application in any GIS to work with geographic information. The map represents geographic information as a collection of layers and other elements in a map view. Common map elements include the data frame containing map layers for a given extent plus a scale bar, north arrow, title, descriptive text, and a symbol legend.

#### **2.4.2. Weighted overlay analysis**

Weighted overlay is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis. Geographic problems often require the analysis of many different factors using GIS. For instance, finding optimal site for irrigation requires weighting of factors such as land cover, slope, soil and distance from water supply (Yang Yi, 2003). To prioritize the influence of these factor values, weighted overlay analysis uses evaluation scale from 1 to 9 by 1. For example, a value of 1 represents the least suitable factor in evaluation while, a value of 9 represents the most suitable factor in evaluation. Weighted overlay only accepts integer rasters as input, such as a raster of land cover/use, soil types, slope, and Euclidean distance output to find suitable land for irrigation (Janssen and Rietveld, 1990). Euclidean distance is the straight-line from the center of the source cell to the center of each of the surrounding cells.

#### **2.4.3. Watershed delineation**

A watershed can be defined as the catchment area or a drainage basin that drains into a common outlet. Simply, watershed of a particular outlet is defined as an area, which collects the rainwater and drains through gullies, to a single outlet. Delineation of a watershed means determining the boundary of the watershed i.e. ridgeline. GIS uses DEMs data as input to delineate watersheds with integration of Arc SWAT or by hydrology tool in Arc GIS spatial analysis (Winchell *et al.*, 2008).

#### **2.4.4. GIS as a tool for irrigation potential assessment**

In the past, several studies have been made to assess the irrigation potential and water resources by using GIS tool (FAO, 1987; FAO, 1995; FAO, 1997; Melaku, 2003; Negash, 2004; Hailegebriel, 2007; Meron, 2007).

FAO (1987) conducted a study to assess land and water resources potential for irrigation in Africa on the basis of river basins of countries. It was one of the first GIS based studies of its kind at a continental level. It proposed natural resource-based approach to assess irrigation

potential. Its main limitations were in the sensitivity of criteria for defining land suitability for irrigation and in water allocation scenarios needed for computation of irrigation potential.

Another study was conducted by FAO (1995), as part of the AQUASTAT programme, which is a program for country wise collection of secondary information on water resources and irrigation. A survey was carried out in all African countries, where information on irrigation potential was systematically collected from master plans and sectoral studies. Such an approach integrates many more considerations than a simple physical approach to assessing irrigation potential. However, it cannot account for the possible double counting of water resources shared by several countries.

FAO (1997) has studied the irrigation potential of Africa taking into consideration the above limitations. It concentrated mainly on quantitative assessment based on physical criteria (land and water), but relied heavily on information collected from the countries. A river basin approach had been used to insure consistency at river and basin level. Geographic Information System (GIS) facilities were extensively used for this purpose. In this study, a physical approach to irrigation potential was understood as setting the global limit for irrigation development.

Melaku (2003) carried out study on assessment of irrigation potential at Raxo dam area (Portugal) for the strategic planning by using Remote Sensing (RS) and Geographic Information System (GIS). This study considered only the amount of available water in dam and topographic factor (slope) in identifying potential irrigable sites in downstream side of the dam.

Negash (2004) conducted a study on irrigation suitability analysis in Ethiopia a case of Abaya-Chamo lake basin. It was a Geographical Information System (GIS) based and had taken into consideration soil, slope, land use and water resource availability in perennial rivers in the basin to identify potential irrigable land.

Hailegebriel (2007) conducted a study on Irrigation potential evaluation and crop suitability analysis using GIS and Remote sensing techniques in Beles sub basin, Beneshangul Gumuz Region. The study considered slope, soil, land cover/use, water resources and climate factors in evaluating surface irrigation suitability.

Meron (2007) carried out similar work on surface irrigation suitability analysis of southern Abay basin by implementing GIS techniques. This study, considered soil, slope and land cover /use factors to find suitable land for irrigation with respect to location of available water resource and to determine the combined influence of these factors for irrigation suitability analysis, weighted overlay analysis was used in Arc GIS.

## **2.5. Application of Remote Sensing**

Remote Sensing refers to the technique of obtaining information about an object or feature through the analysis of data acquired by a device that is not in contact with the object or feature under investigation (Lille sand and Kiefer, 1994). This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information. In much of remote sensing, the process involves an interaction between incident radiation and the targets of interest. Remote Sensing technology produces an authentic source of information for surveying, identifying, classifying, mapping, monitoring, and planning of natural resources and disasters mitigation, preparedness and management as a whole. Remote sensing is a technology that has close tie to GIS. Remote sensing can provide timely data at scales appropriate to a variety of applications. As such many researchers feel that the use of GIS and RS can lead to important advances in research and operational applications. Merging these two technologies can result in a tremendous increase in information for many kinds of users. Land cover/use mapping is one of the most important and typical applications of remote sensing (Lillesand, 200). Land cover corresponds to the physical condition of the ground surface, for example, forest, grassland, concrete pavement etc. Land use reflects human activities such as the use of the land, for example, industrial zones, residential zones, agricultural fields etc.

## **2.6. Review of Commonly Used GIS and Remote Sensing Data.**

Geographic Information System (GIS) can integrate Remote Sensing and different data sets to create a broad overview of potential irrigable area. While the remotely sensed image of an area gives a true representation of an area based on land cover / use, grid interpolated climate data can serve many purposes and used as climatic data base where meteorological data from gauging networks are not adequate. The topographic and hydrologic attributes of land and landscape such as slope, aspect and watershed modeling can be derived directly from the DEM. They are point elevation data stored in digital computer files. The detailed review of these data is provided in the following sections.

### **2.6.1. Spatially interpolated climate data on grids**

These data are referred to as the 'WorldClim' database. The WorldClim dataset created by (Hijmans *et al.*, 2003; Jones and Gladkov, 2003; Parra *et al.*, 2004) are used in many applications, particularly in environmental, agricultural and biological sciences (Hijmans *et al.*, 2005). With this dataset, several analyses by means of GIS can be performed. These data were compiled based on monthly averages of climate as measured at weather stations from a large number of global, regional, national, and local sources, mostly for the 1950–2000 periods with spatial resolution of 30 arc-seconds or 1 km resolution. WorldClim provides high resolution monthly maximum ( $t_{\max}$ ), minimum ( $t_{\min}$ ), and mean temperatures ( $t_{\text{mean}}$ ), and monthly precipitation (prec).

### **2.6.2. Satellite imagery**

Remotely sensed satellite data are familiar to GIS users. The utility of different remote sensing data from different satellites have been demonstrated in many fields such as agriculture, cartography, civil engineering, environmental monitoring, forestry, geography, water resources management, land resources analysis and land use planning.

The use of satellite images in any of fields mentioned above, demands the knowledge of the different bands that each sensor system onboard satellites use to take the imagery and how

these bands of the electromagnetic spectrum interact with land surface features and with that of the atmosphere (Lemlem, 2007). All types of satellites vary with their sensors, flight height, bands, and spatial resolution, spectral resolution, etc. The spatial resolution of a satellite image relates to the ground pixel size. For example, a spatial resolution of 30 meters means that each pixel in the satellite image corresponds to a ground pixel of 900 square meters. The pixel value, also called the brightness value, represents light energy reflected or emitted from the Earth's surface (Jensen 1996; Lillesand and Kiefer, 2000). The measurement of light energy is based on spectral bands from a continuum of wavelengths known as the electromagnetic spectrum. Panchromatic images are comprised of a single spectral band, whereas multispectral images are comprised of multiple bands.

As there are many satellites in the space providing remote sensing data, their application will vary with their way of data acquisition. The most popular satellites are the land sat and SPOT. Land sat operated by the National Aeronautics and Space Administration (NASA) with the cooperation of the U.S. Geological Survey (USGS) since early 1970s till 2003, have produced the most widely used imagery worldwide with 60,30 and 15m spatial resolutions (Blundell and Opitz, 2006).

SPOT (Système Pour l'Observation de la Terre) is a series of Earth observation imaging satellites designed and launched by CNES (Centre National d'Études Spatiales) of France, with support from Sweden and Belgium. SPOT-1 was launched in 1986, with successors following every three or four years. SPOT was designed to be a commercial provider of Earth observation data, and it is available with different resolutions such as 10m, 5m and 2.5m on the market. SPOT has a number of benefits over other spaceborne optical sensors. Its fine spatial resolution and point able sensors are the primary reasons for its popularity (Zhang, 2002). The three band multispectral data are well suited to displaying as false-colour images and the panchromatic band can also be used to "sharpen" the spatial detail in the multispectral data. SPOT allows applications requiring fine spatial detail (such as urban mapping) to be addressed while retaining the cost and timeliness advantage of satellite data. The potential applications of SPOT5 data are numerous. Applications requiring frequent monitoring (agriculture, forestry) are well served by the SPOT5 sensors. The acquisition of stereoscopic

imagery from SPOT5 has played an important role in mapping applications and in the derivation of topographic information (Digital Elevation Models - DEMs) from satellite data (Kakiuchi *et al.*, 2003).

### **2.6.3. Digital elevation model (DEM)**

DEMs are point elevation data stored in digital computer files. These data consists of x, y grid locations and point elevation or z variables. They are generated in a variety of ways for a different map resolutions or scales. Under an agreement with the National Aeronautics and Space Administration (NASA) and the Department of Defense's National Geospatial intelligence Agency (NGA), the US Geological Survey (USGS) distribute elevation data from the Shuttle Radar Topographic Mission (SRTM). Shuttle Radar Topography Mission (SRTM) obtains elevation data on a near-global scale with a radar system that flew onboard a space shuttle. For most parts of the world, this data set provides a dramatic improvement in the availability of high-quality and high-resolution elevation data (Jarvis *et al.*, 2004). Digital Elevation Models (DEM) is a commonly used digital elevation source and an important part of using for watershed characterization. Many agencies provide DEM data with 90-m, 30-m and 10-m resolutions. The point elevation data are very useful as an input to the GIS. This data is used to yield important derivative products such as slope, aspect, flow accumulation, flow direction and curvature in process of watershed delineation.

## **2.7. Assessment of Water Resources**

Assessment of water resources can only be done at basin level (FAO, 1997). According to the CA (2007), "river basins are the geographic area contained within the watershed limits of a system of streams and rivers converging toward the same terminus, generally the sea or sometimes an inland water body. Tributary sub-basins or basins more limited in size (typically from tens of square kilometers to 1,000 square kilometers) are often called watersheds (in American English), while catchment is frequently used in British English as a synonym for river basins, watershed being more narrowly defined as the line separating two river basins.

An important consideration in water resource assessment is to estimate how much flow is available at the outlet of river catchment. The volume of water reliably available on an annual or seasonal basis can be determined from the available data in case of gauged rivers and for completely ungauged rivers the runoff coefficient method can be employed (Goldsmith, 2000). According to DFID (2004), when this is the case, then data from the gauging site should be used to estimate mean annual runoff (MAR) at ungauged site, provided that the requirements set out below are met

- i. Catchment characteristics should be similar,
- ii. The distance between the centroids of the catchments should be less than 50 km,
- iii. At least ten years of mean monthly flows should be available.

Otherwise, the simplest method of estimating mean annual runoff in un-gauged site was established in applying a runoff coefficient to the mean annual rainfall as shown below in the following steps.

- a. Determine the mean annual runoff (mm) at the gauged site as

$$\text{MAR}_g = K * \text{MAP} \quad 2.1$$

Where:

$\text{MAR}_g$  = Mean annual runoff at gauged site (mm)

MAP = Mean annual precipitation at gauged site (mm)

$$K = \frac{\text{MAR}_g}{\text{MAP}} \quad 2.2$$

K = Runoff coefficient at gauged site

- b. Determine the MAR at ungauged site as

$$\text{MAR}_u = K * \text{MAP}_g$$

2.3

$\text{MAR}_u$  = Mean annual runoff at un-gauged site (mm)

The mean annual or monthly runoff depth obtained from equation (2.3) at un-gauged site can be converted to mean monthly runoff considering, average areal monthly rainfall and catchment area of both gauged and ungauged sites (Jamshid, 2003). Estimation of areal rainfall over a given catchment is therefore, useful for estimating the total runoff generated from the entire catchment. There are several methods of determining the spatial distribution of rainfall, and all of them yield slightly different variations of rainfall patterns across an area. The Thiessen method is a widely recognized scheme proven to be reasonably accurate for estimating areal precipitation distributions. The primary assumption in the Thiessen method is that areas closest to a precipitation station are most likely to experience similar rainfall conditions to those measured at the station location (Chow *et al.*, 1988). Thiessen polygons can be constructed using the GIS to determine the spatial distribution of storms for computation of spatially variable excess rainfall. Grids of rainfall can also be computed and mapped for selected storm events (Melesse, 2002).

### 3. MATERIALS AND METHODS

#### 3.1. Description of the Study Area

##### 3.1.1 Location

The study was conducted in Dale *Woreda* which is located between 6°27'00" - 6° 51'00" N latitude and 38°00'00" -38°37'00"E longitude in Sidama Zone, Southern Region of Ethiopia. This *Woreda* is one of the 21 *Woredas* in the Zone covering a total area of 1,494.63 km<sup>2</sup> with the altitude range of 1100 m to 2650 m (from low lands in the west to the highlands in the east).

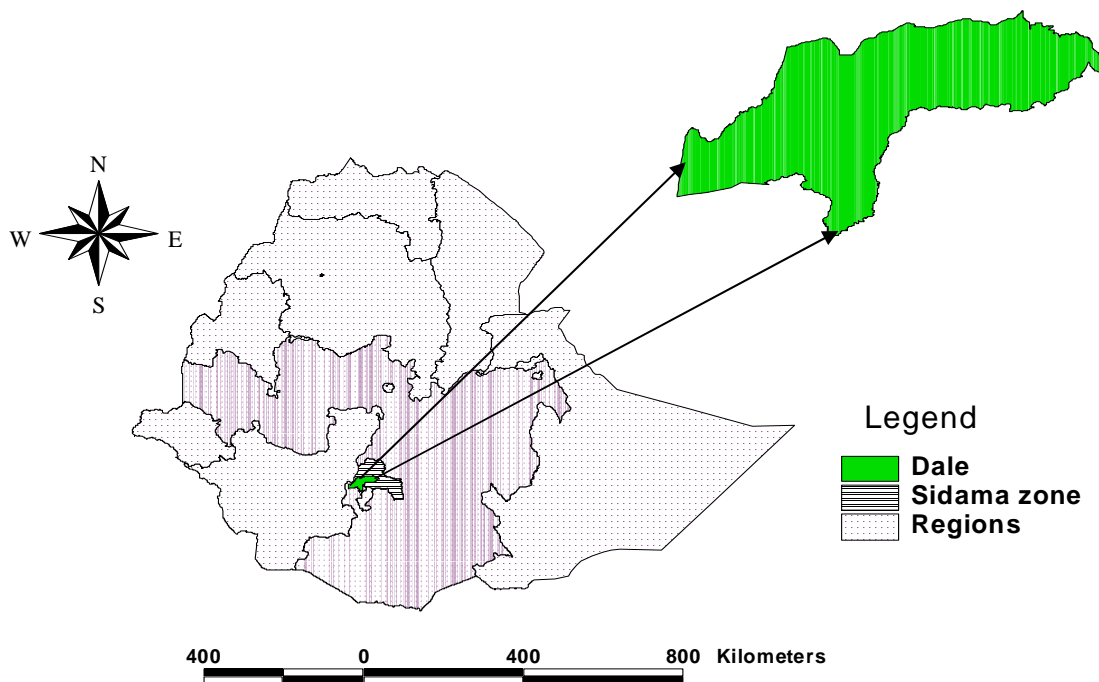


Figure 1 Location map of the study area

### 3.1.2. Agro-ecology

According to MoA (2000) classification, agro-ecology of Ethiopia is classified as: *Wurch*, *Dega*, *Weina-dega*, *Kolla*, and *Bereha*. Similarly, the landform in Dale *Woreda* also shows variations in agro-ecology as *Dega*, *Woina-dega* (dry and moist *Woina-dega*), *Kola* and wet moist *Bereha*. Generally, *Dega*, dry *Woina-dega*, moist *Woina deg*, *Kola* and moist *Bereha* constitute 2.4%, 15%, 37%, 39.4%, and 6.2% of the total area of the Dale *Woreda*, respectively, as shown in Figure 2. This agro-ecological variation in landforms has had a significant influence on climatic condition of the *Woreda*. Minimum and maximum rainfall and temperature range from 1041 mm -1448 mm and 11 C° - 22C°, respectively.

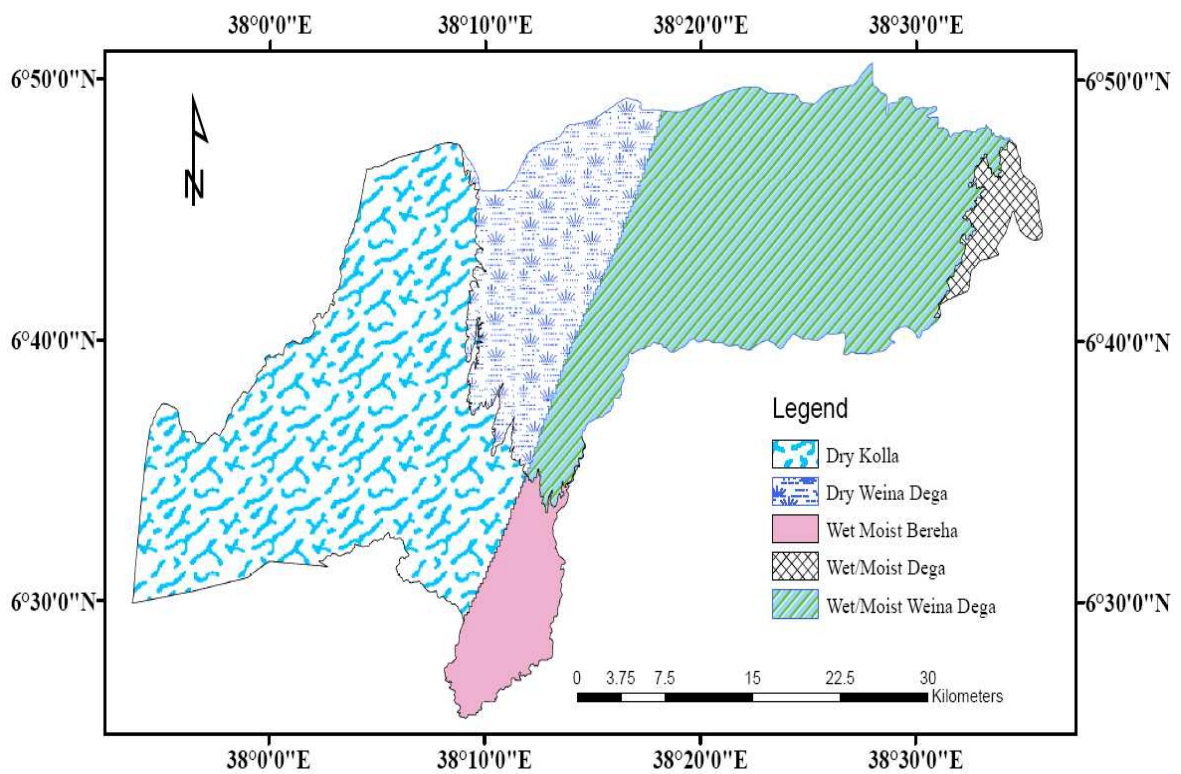


Figure 2 Agro-ecological map of the study area

### 3.1.3. Drainage system

The origin of the rivers that flow towards the *Wareda* start from the Rift valley lakes sub river basin that covers Sidama zone. The zone falls in the two sub river basins, namely: Ganale Dawa and Rift valley lakes, as shown in Figure 3. There are seven rivers (Bilate, Gidawo, Dara, Ererete, Logita, Gambeltu, Hamile) and one trans boundary river (Genale) in the zone. Bilate and Gidawo rivers are found in the Rift valley lakes sub- river basin flowing towards Lake Abaya. In the Rift valley lakes sub-river basin, there are two lakes such as Abaya and Hawassa. Lake Hawassa is found in the zone covering a total area of 129.5 km<sup>2</sup> while some part of Lake Abaya is also found in the zone. As shown in the Figure 3, the study area falls under Rift valley lakes sub-river basin. All the rivers flow through the *Woreda* until they feed Lake Abaya, except few which feed Lake Hawassa.

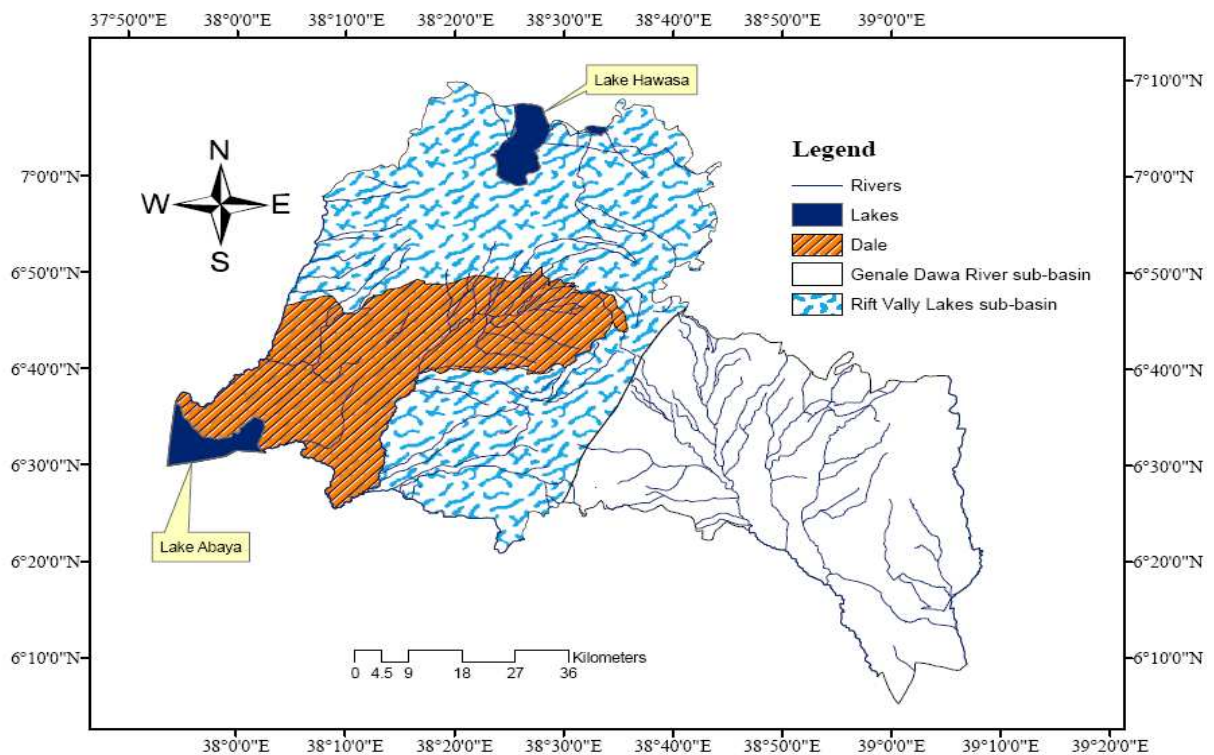


Figure 3 Drainage systems inside and outside the study area

### **3.2. Materials Used**

The materials and data used to assess the irrigation potential of this study area were:

#### **GPS and Digital Camera**

GPS and digital camera were used to collect geographic-coordinate values in (UTM, Lat-Long) and field photographs, respectively. The geographic-coordinate values were used as ground control points to locate field photographs on SPOT5 image for supervised classification. The field photographs were used as signature of land cover class which helped as region of interest in supervised image classification.

#### **Satellite images**

SPOT5 satellite images, with acquisition dates between November 2005 and December 2006 that included three bands (1, 2 & 3) and with spatial resolution of 5m, were obtained from Ethiopian Mapping Agency. They were used to classify land cover of the study area.

#### **Topographic maps**

Topographic maps of the study area, with a scale of 1:50,000 and map sheet numbers of 0638A2, 0638A3, 0638A4, 0638B3 and with a scale of 1: 250,000 and map sheet number of NB 37<sup>6</sup> obtained from the Ethiopian Mapping Agency, were used as a background for the GPS to locate the samples of ground truth data and to use the data during the satellite image classification.

#### **Stream flow data**

Discharges of four gauging stations such as Aposto and Meissa (both on Gidawo river), Aleta Wond (on Kolla River) and Tena (on Bilate River) were obtained from Hydrology Department

of the Ministry of Water Resources. The streamflow data were used to assess both water resources potential of the gauged and un-gauged sites for irrigation purpose.

### **Meteorological data**

Meteorological data of Yirgalem, Dilla, Bilate and Hawassa stations were collected from NMSA and grid interpolated rainfall data of Aleta Wondo, Arbegona, Leku, Hagereselam, Hayissa Wita and Morocho stations were obtained from ILRI GIS database. These data were used to estimate irrigation water requirements of some selected crops using CROPWAT4.3. In addition, the rainfall data were used to calculate average areal rainfall using Thiessen polygon extension in ArcGIS. The areal rainfall was used in the estimation of streamflow at un-gauged sites from gauged sites.

### **Soil data**

FAO/UNESCO- Soil Map of East Africa (1997), available in Arc/Info format with scale of 1:1000000, and soil laboratory results of Rift valley lakes river basin were obtained from GIS and Remote Sensing Department, Ministry of Water Resources. These data were used for soil suitability analysis for irrigation.

### **DEM (Digital Elevation Model)**

DEM data were obtained from ILRI GIS database and were used as input data in ArcGIS to delineate watersheds and to derive slope maps of the study area for irrigation suitability analysis.

### **Softwares**

The softwares used to prepare and analyze data were ArcGIS9.2, ArcSWAT9.2, ENVI4.3, CROPWAT4.3, and Global Mapper7.

### **3.3. Methodology**

#### **3.3.1. Data pre-processing and checking**

Collected data can contain errors due to failures of measuring device or the recorder. So, before using the data for specific purpose, the data have to be checked and errors have to be removed. The analysis was extended to hydrological and meteorological data to prepare input data for water resources assessment and irrigation water requirement estimation using the CROPWAT model.

##### **1. Consistency of stream flow and rainfall data**

To prepare the stream flow and rainfall data for further application, their consistency was checked using double mass curve analysis. A plot of accumulated discharge/rainfall data at site of interest against the accumulated average at the surrounding stations is generally used to check consistency of stream flow /rainfall data. To check the degree of consistency, Nemec (1973) provided the value of coefficient of correlation as follows:

$r = 1$ : direct linear correlation

$0.6 \leq r < 1$ : good direct correlation

$-0.6 < r < 0$ : insufficient – reciprocal correlation

$-1 < r < 0.6$ : good reciprocal correlation

$r = -1$ : reciprocal linear correlation

For the grid interpolated rainfall data, no analysis was done and they were used in further analysis directly.

The stream flow and rainfall data are relatively consistent if the periodic data are proportional to an appropriate simultaneous period, and of these data, which are inconsistent, can be adjusted by proportioning, using correlation coefficient, between the stations (selesh, 2000, Moutaz, 2001 and Yarahmad, 2003).

## 2. Filling missing rainfall data

Missing records of the rainfall stations were estimated by using normal ratio method which is recommended to estimate missing data in regions where annual rainfall among stations differ by more than 10% (Dingman, 2002). This approach enables an estimation of missing rainfall data by weighting the observation at N gauges by their respective annual average rainfall values as expressed by equation 3.1 (Yemane, 2004).

$$P_x = \frac{1}{N} \left( \sum \frac{P_x}{P_i} * P_g \right) \quad 3.1$$

Where:

$P_x$  = missing data,

$P_x$  = the annual average precipitation at the gauge with the missing data,

$P_i$  = annual average values of neighboring stations

$P_g$  = monthly rain fall data in station for the same month of missing station

N = the total number of gages under consideration

The monthly maximum and minimum temperature values at Bilate, Dilla and Yirgalem stations have been averaged into maximum and minimum long term monthly values. These values were used as input data for evapotranspiration computations. Other climatic data such as sunshine duration, relative humidity and wind speed data of Bilate and Dilla stations have been also averaged into long term mean monthly values and used for evapotranspiration calculation.

### 3.3.2. Watershed delineation

Following drainage boundaries on the DEM, masking the Digital Elevation Model (DEM) with Rift valley Lakes sub basin coverage of the Sidama Zone was started. This was done because drainage boundaries exceed the *Woreda* boundary. The delineation process requires a Digital

Elevation Model (DEM) in ESRI grid format. To delineate watershed using Arc SWAT the following steps were used.

#### a. Importing DEM data

The DEM of sub basin was projected to UTM Coordinate system using Arc Catalog in Arc GIS and imported to Arc SWAT to start automatic watershed delineation. Figure 4 shows imported DEM into SWAT session.

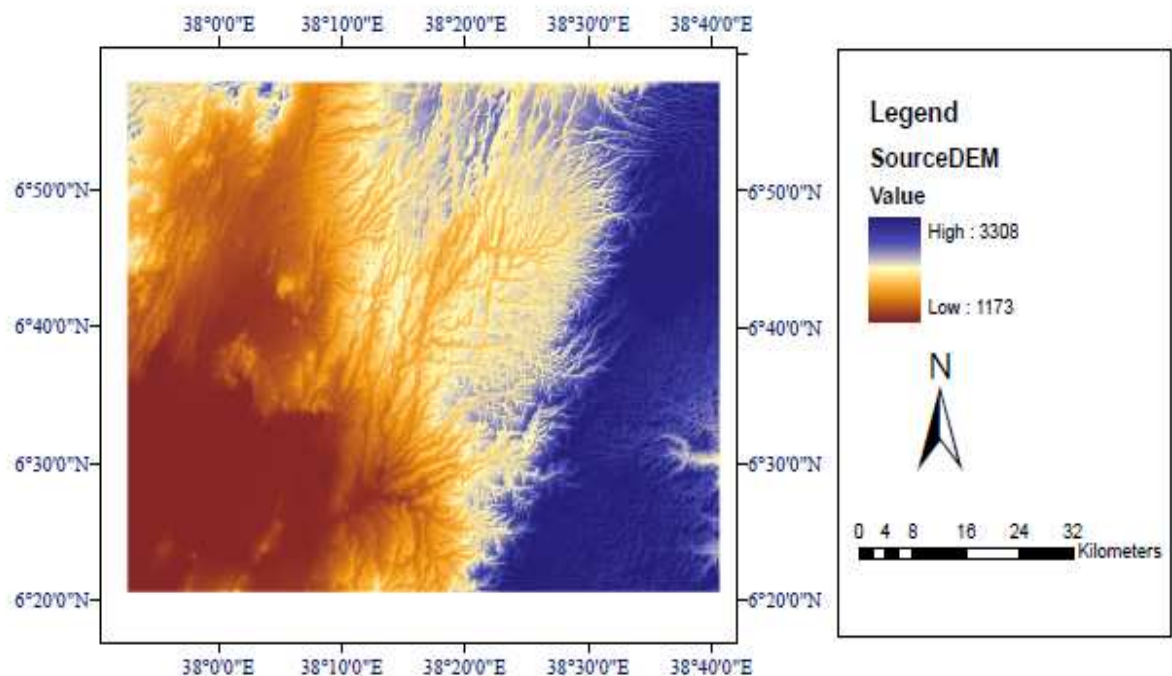


Figure 4 Digital elevation model showing drainage system of the study area

#### b. Computing flow direction

Flow directions for individual DEM cells were created using flow direction and accumulation tool in Arc SWAT. SWAT computes flow direction for individual DEM cells and uses stream threshold area in hectares to create streams based on these directions. Figure5 shows flow direction and the networks of streams on top of the DEM.

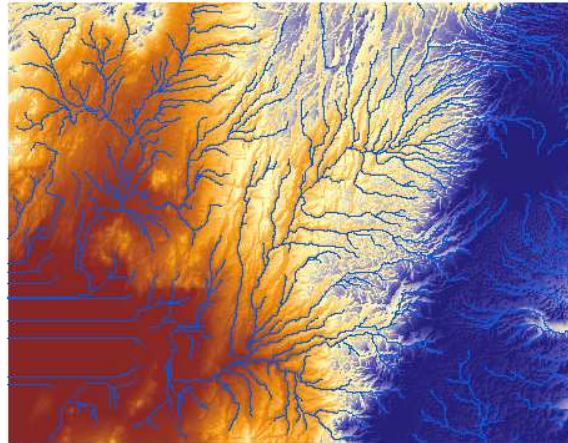


Figure 5 Flow direction and streams network

### c. Creating watershed outlets

An outlet, or pour point, is the point at which water flows out of an area. This is the lowest point along the boundary of the watershed. The cells in the source raster are used as pour points above which the contributing area is determined. By using outlet selection tool in SWAT, the watershed outlets are defined as shown in Figure 6.

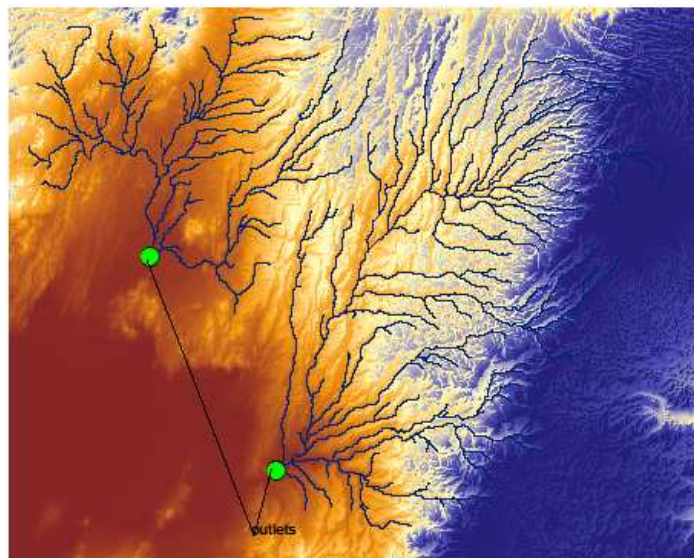


Figure 6 Watershed outlets definition

#### **d. Delineation of main and sub-watersheds**

The main watershed was delineated by using watershed delineator tool in Arc SWAT based on an automatic procedure using the watershed outlets created in step 3 above. In order to create sub-watersheds, additional drainage outlets need to be defined. After several nodes or vertices are defined into drainage outlets along the stream arcs, the same method defining watershed outlets in step 3 was used again to delineate sub-watershed.

#### **3.3.3. Identification of potential irrigable sites**

Identification of suitable sites for irrigation was carried out by considering the slope, soil, land cover/use and distance between water supply and the potential command area as factors. The individual suitability of each factors were first analyzed and finally weighted to get potential irrigable sites. This procedure is discussed as follows.

##### **3.3.3.1. Slope suitability analysis**

Land slope is the most important topographical factor influencing land suitability for irrigation. To derive slope suitability map of the study area, digital elevation model of the area was clipped from SRTM of NASA satellite with 90 meters resolution by masking layer of *Woreda* boundary using Global mapper7 software. Then slope maps of the *Woreda* and watersheds were derived using the “Spatial Analysis Slope” tool in ArcGIS. The Slope derived from the DEM was classified based on the classification system of FAO (1996) using the “Reclassification” tool, which is an attribute generalization technique in ArcGIS. The four suitability ranges (S1, S2, S3 and N) were classified for surface irrigation as shown in Table 2.

Table 2. Slope suitability classification for surface irrigation

Legend	Slope (%)	Factor rating
1	0-2	S1
2	2-5	S2
3	5-8	S3
4	>8	N

Source: FAO (1996).

The classified raster data layers were then converted to feature (vector) data layers for the overlaying analysis. Using data management tools in Arc Tool box, generalization of the feature (vector) data layers was performed to make a clearer slope suitability map.

### 3.3.3.2. Soil suitability assessment

To assess soil suitability for irrigation, FAO/UNESCO- soil map of east Africa (1997) was used. It is available in ARC/ INFO format with scale of 1: 1000000. The major soil groups classified in the study area were: Chromic Luvisols, Eutric Vertisols, Haplic Luvisols, Humic Nitosols and Lithic Leptosols. Chemical and physical properties of these soil groups were used for irrigation suitability analysis. The following soil suitability rating was used based on the FAO guidelines for land evaluation (FAO, 1976, 1979, 1990, 1991) and FAO (1997) land and water bulletin.

Table 3. Soil suitability factor rating

Factors	Factor rating			
	S1	S2	S3	N
Drainage class	well	Imperfect	poor	Very poor
Soil depth (cm)	>100	80-100	50-80	<50
Soil texture	L-SiCL, C	SL	-	-
Salinity	<8 mmhos/cm	8-16 mmhos/cm		
Alkalinity	<15 ESP	15-30 ESP		

Source: FAO guideline for land evaluation, (1976, 1979 and 1991)

Further, the soil vector layer was converted into raster layer using conversion tool “To Raster or Feature to Raster module”. The rasterized soil map of the study area was then reclassified based on their soil type name, texture, depth and drainage class. Using overlay tool in Arc GIS 9.2 Spatial analyst, weighted overlay analysis of these factors were performed to determine their suitability for surface irrigation. Then, the new values were reassigned for each soil factor in order of their irrigation suitability rating based on common evaluation scale from 1-9 available in weighted overlay analysis. A value 1 represents the least suitable factor in evaluation while, value 9 represents highly suitable factor in evaluation. Soil factor that is highly suitable was given a value 9, for moderately suitable factor was given a value 6, for marginal suitable factor was given a value 3 and for least suitable factor was given a value 1. When scale values from 1-9 is not assigned for soil factors in evaluation, that cell value restricted for surface irrigation and it should be excluded from evaluation. For example a soil factor with soil depth 10cm is restricted for surface irrigation development and the cell value representing this value is assigned as ‘restricted scale’ so that it will be excluded from the evaluation.

### **3.3.3.3. Land cover/use**

Land cover/use of the study area is also the factor, which was used to evaluate the land suitability for irrigation. In this research, land cover classification was done using SPOT5 (Système Pour l'Observation de la Terre) satellite image for identifying land cover types to estimate potential irrigable land. The classification was carried out using ENVI4.3 software in the following steps.

#### **I. Image pre-processing**

Successful identification of land cover usually requires multi-temporal images. Unfortunately, the SPOT image for the study area was available only from November 2005 to December 2006. The format of this image was IMAGIN Image, which could be imported into ENVI4.3 directly. The SPOT images were geo-referenced by ancillary data such as topographic maps and geographic coordinates of the study area. Then true color composite images were created by combining the spectral bands that most closely resemble the range of vision of the human

eye which in the SPOT images are normally used for land cover analysis. A true-color composite uses the visible red (band 3), visible green (band 2), and visible blue (band 1) channels to create an image that is very close to what a person would expect to see in a photograph of the same scene as shown in Figure 7. The bands to color mapping for a 321 Composite are:

Band 3 (Visible red) = red

Band 2 (Visible green) = green

Band 1 (Visible blue-green) = blue

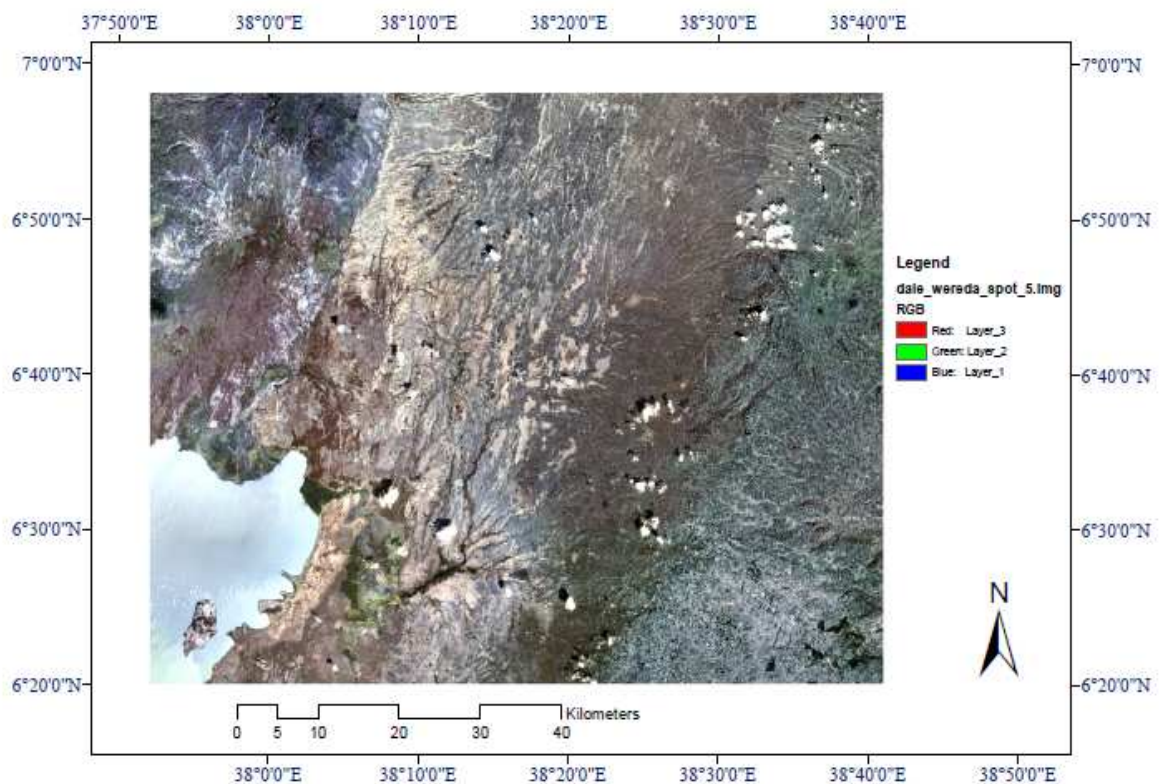


Figure 7 SPOT5 satellite image of the study area showing true color composite (321)

The other image pre-processing steps, such as image rectification and restoration and image enhancement, were also performed.

## **II. Image classification**

There are two approaches to extract spectral information: the supervised and unsupervised classification (Richards, 1986). Unsupervised classification is the method in which image pixels are assigned to spectral classes without the user having previous knowledge about the study area whereas, supervised classification is a method that involves selection of areas in the image, which statistically characterize the categories of interest. Prior to the field work, unsupervised classification from the SPOT image was conducted to understand the general land cover classes of the study area. Based on results from unsupervised classification and information from topographic map of the study area, sample training sites were selected to collect geographic coordinates and field photographs during the field work. The geographic coordinate values of field photographs were then added to the SPOT image by Ground Control Points Selection dialog box in ENVI 4.3. This process, therefore, establishes the framework of the GCPs positions of the pixels for output image. The problem then is to decide how best to examine the different land cover signatures at pixels in the image and comparing field photographs of the same GCPs locations with the unclassified image. This information was then used in the selection region of interest for the supervised classification. By using supervised classification with maximum Likelihood method, seven land cover classes were classified for the study area except towns, which were not separable and they were classified by masking using their polygon layers.

## **III. Accuracy assessment**

To validate and crosscheck the result of the SPOT classification with known ground truth data, accuracy assessment was checked for the signature values of the classified images by calculating the confusion matrix in ENVI 4.3 software. The confusion matrix is a table with the columns representing the reference (observed) classes and the row the classified (mapped) classes (Rossiter, 2001). The ground truth data were used in the maximum likelihood report as the independent dataset from which the classification accuracy was compared. The accuracy is essentially a measure of how many pixels in the ground truth region of interests (ROIs) were classified correctly.

Items calculated include; overall accuracy, kappa coefficient and confusion matrix. The overall accuracy was calculated by summing the number of pixels classified correctly and dividing by the total number of pixels.

Kappa coefficient represents strong agreement between classified land cover classes and observed land cover/use (Ephrem, 2007). It lies between 0 and 1, where 0 represents weak agreement and 1 represents strong agreement. According to Rahman *et.al* (2006), kappa values can be classified into three: the value greater than 0.8 represents strong agreement, between 0.4 and 0.8 represents moderate agreement and a value below 0.4 represents poor agreement. Equation 3.2 gives mathematical relationship for calculating kappa coefficient in ENVI4.3 software.

$$\text{Kappa(K)} = \frac{P_o - P_e}{1 - P_e} \quad 3.2$$

Where,

$P_o$  = is the proportion of correctly classified classes

$P_e$  = is the proportion of correctly classified classes expected by chance

#### **IV. Compilation of final land cover/use map**

Classified images require post-processing to generalize classes for export to image-maps and vector GIS. In ENVI4.3 post classification tool, majority analysis was applied to generalize image classification. Then classification to vector tool was used to convert classification results to ENVI polygon vector layers (.evf files) and then exported to shape files, Arc GIS 9.2 - compatible file set. The classification images will have a vector layer for each selected class. Due to higher spatial resolution of SPOT image, a countless of very small polygons were created in classified image. To produce land cover map by 1:250,000 scale (a common rule of thumb for thematic mapping), it was therefore necessary to filter these polygons so that no polygons were smaller than 50 ha. This processing was performed within Arc Map software using 'Select by attribute tool' and 'Generalization tool' in the Arc tool box.

The aim of this processing is to generalize the classification by removing small polygons. In this case, polygons were removed if they are less than 50 Ha. The final clearer map with a scale of 1:250,000 was produced

#### **3.3.3.4. Distance from water supply (source)**

To identify irrigable land close to the water supply (rivers), straight-line (Euclidean) distance from watershed outlets was calculated using DEM of 90m×90m cell size and reclassified as shown in Figure 8. Then, reclassified distance was used for weighted overlay analysis together with other factors.

#### **3.3.3.5. Weighing of irrigation suitability factors to find potential irrigable sites**

To find suitable site for surface irrigation, a suitability model was created using model builder in Arc tools box and tools from spatial analysis tool sets. Then, after their individual suitability was assessed, the irrigation suitability factors which were considered in this study, such as slope factor, soil factor, land cover /use factor and distance factor were used as the input for irrigation suitability model to find the most suitable land for surface irrigation as shown in Figure 8.

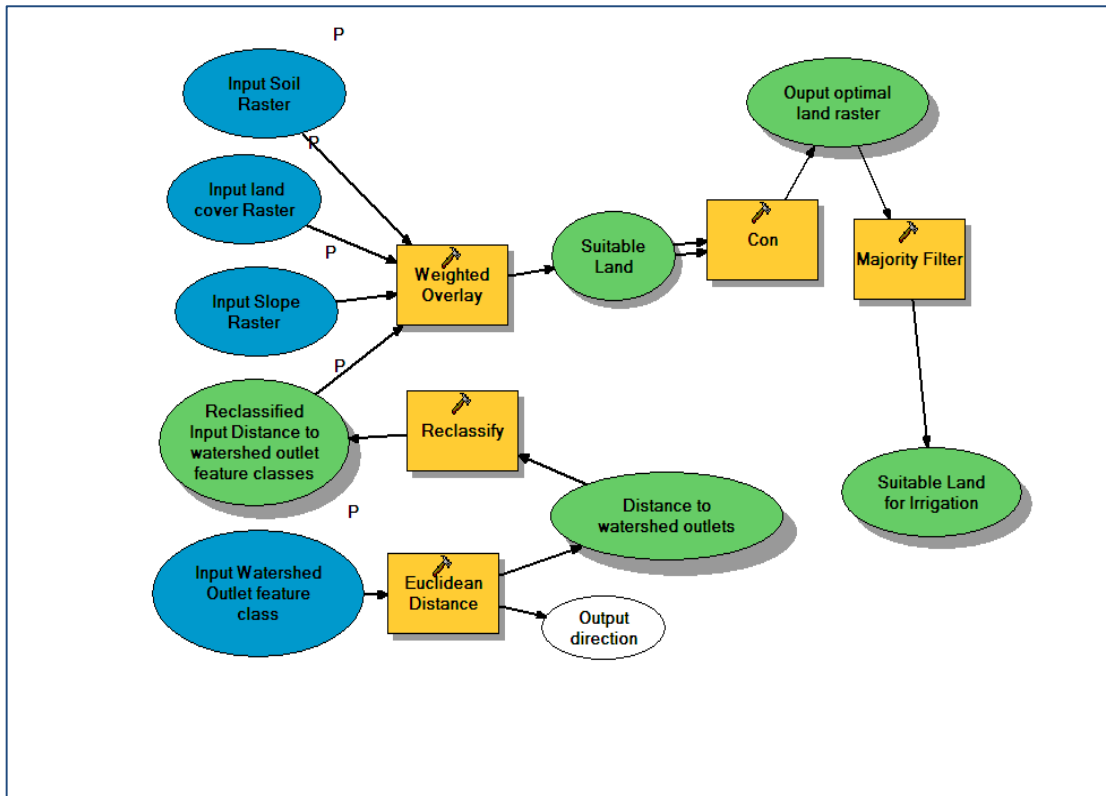


Figure 8 Irrigation suitability model

### 3.3.4. Computing irrigation water requirements

In order to estimate irrigation water requirements of some selected crops in the potential irrigable sites, definition of area of influence of the climatic stations using Arc GIS inside and around the *Woreda* were performed. To obtain a spatial coverage of climate data over the study area, each station was assigned to an area of influence using the Thiessen polygons method (FAO, 1997). This method assigns an area of 'nearest vicinity' to each climate station. Figure 9 gives an indication of the density of the stations over the study area.

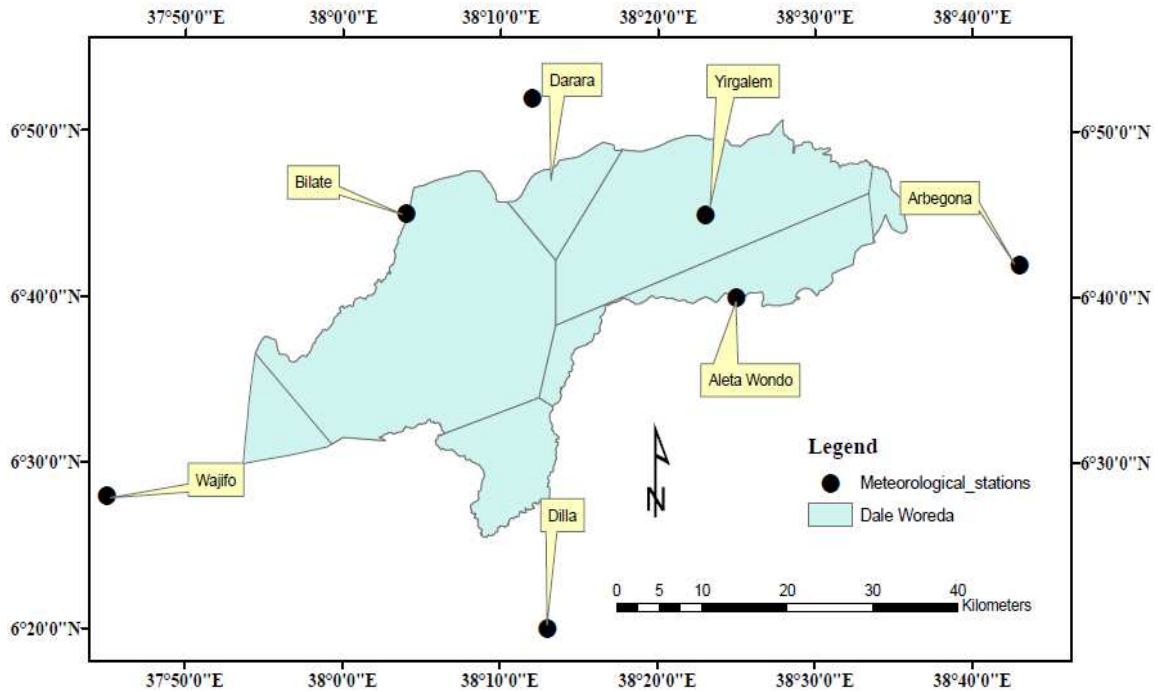


Figure 9 Thiessen polygons showing area of influence of climatic stations in the study area

From Figure 9, four climatic stations such as Aleta Wondo, Bilate, Dila and Yirgalem were taken to calculate irrigation water requirement of the identified irrigable area. Except Bilate and Dilla stations, other stations do not have complete climatic records. Therefore, recorded data of these stations from the FAOCLIM has taken for creation of data base. Then based on cropping pattern of the study area, obtained from Dale *Woreda* agricultural office, two crops such as banana and sugarcane, were selected to estimate the water demand on monthly basis. Planting dates for banana and sugarcane were chosen in such a way that the planting dates coincided with the local cropping calendar at the nearby meteorological stations. Then,  $ET_O$  and other climatic data were derived from the computation for crop water requirement estimation. The respective crop coefficients for these crops were selected based on FAO (1998). Then, gross irrigation water requirements of the crops at the identified potential irrigable sites were estimated by considering application efficiency of 65% for surface irrigation according to FAO (2001) and assuming 75% of water conveyance efficiency from the source to identified command area as follows:

$$ET_c = ET_o * K_c \quad 3.3$$

$ET_c$  = crop evapotranspiration (mm/day)

$$IWR = ET_c - P_{ef} \quad 3.4$$

IWR = Irrigation water requirement (mm)

$P_{ef}$  = effect rainfall (mm)

$$GIWR = \frac{1}{E} (FWS * A_{crop}) \quad 3.5$$

Where:

E = water conveyance efficiency

GIWR = Gross irrigation requirements ( $m^3$ /month)

FWS = Field Water Supply (l/s/ha)

$A_{crop}$  = the potential irrigable area to be cultivated with selected crop (ha)

### 3.3.5. Estimating surface water resources potential of river catchments

The available surface water of the catchments was estimated using stream flow discharges (obtained from the Ministry of Water Resources) and rainfall data (obtained from NMSA and ILRI GIS database). The stream flows that were used as input to determine discharges at ungauged sites were measured at the four gauging stations inside and around the study area as presented in Table 4.

Table 4. Hydrometric stations inside and around the study woreda

N°	River	Site	Start Date	End date	Latitude	Longitude	Drainage area (Km <sup>2</sup> )
1	Bilate	at Bilate tena	1980	2006	6°56'	38°08'	5518
2	Gidawo	near Aposto	1977	2006	6°45'	38°23'	646
3	Gidabo	near Miessa	1997	2005	6°26'	38°26'	2532
4	Kola	near Aleta Wondo	1980	2006	6°38'	38°24'	206

### 3.3.5.1. Estimating discharges at un-gauged sites from gauged sites

The rainfall data analysis results, together with discharges from gauged sites, were used to estimate the stream-flow at the ungauged sites in the study area. Since only irrigation potential of perennial rivers were considered in this study, a long term average of stream-flow at gauged sites and mean monthly areal rainfall of the sites were used to estimate the discharges at ungauged sites. This was performed by applying runoff coefficient of the gauged sites to ungauged sites (FAO, 1997; Goldsmith, 2000 and DFID, 2004). According to Goldsmith (2000) and DFID (2004), to estimate mean monthly runoff volume of un-gauged sites from gauged sites, catchment characteristics such as land cover, soil type, and catchment slope ranges should be similar, and distances between the gauged and un-gauged river catchments should not be more than 50km and a minimum 10 years mean monthly river flow at the gauged sites should be available. Based on these criteria, the gauged and un-gauged river catchments soil, slope and land cover maps were derived using FAO (1997) digital soil map of East Africa, DEM and SPOT5 satellite image, respectively. Then runoff volume per month at the ungauged site was estimated using the following steps:

1. Both gauged and un-gauged catchment areas were calculated
2. Point rainfall data of stations both in and around gauged and un-gauged catchments were converted to areal or average rainfall over an area of river catchments using Thiessen polygon method in Arc GIS.

3. Both un-gauged and gauged river catchments in terms of their land cover/use, soil type and slope range were compared to determine their similarities.
4. Runoff coefficient from the ratio of mean monthly discharge to mean monthly areal rainfall of gauged catchments was determined.
5. Above steps were followed to estimate monthly average runoff of the un-gauged river catchments from gauged river catchments using the following equation (5) (Jamshid, 2003).

$$Q_{\text{ungauged}} = \left( \frac{A_{\text{ungauged}}}{A_{\text{gauged}}} \right) * Q_{\text{gauged}} * \frac{P_{\text{ungauged}}}{P_{\text{gauged}}} \quad 3.6$$

Where,

$Q_{\text{ungauged}}$  = discharge at ungauged site ( $\text{m}^3/\text{s}$ )

$A_{\text{ungauged}}$  = drainage area of ungauged site ( $\text{km}^2$ )

$P_{\text{un gauged}}$  = areal rainfall at the ungauged site (mm)

$Q_{\text{gauged}}$  = discharge at gauged site ( $\text{m}^3/\text{s}$ )

$A_{\text{gauged}}$  = drainage area at gauged site ( $\text{km}^2$ )

$P_{\text{gauged}}$  = areal rainfall at the gauged site (mm)

The stream flow calculated using above procedure for ungauged sites were used to estimate their adequacy for the potential irrigable sites.

### 3.3.5.2. Transferring discharges of gauged rivers to the site of interest

For gauged rivers, the discharges from gauge sites were transferred to the site of interest using the following formula.

$$Q_{\text{site}} = \left( \frac{DA_{\text{site}}}{DA_{\text{gauge}}} \right)^n * Q_{\text{gauge}} \quad 3.7$$

Where:

$Q_{\text{site}}$  = discharge at site of interest

$Q_{\text{gauge}}$  = discharge at gauge site

$DA_{\text{gauge}}$  = drainage area at gauge site

$DA_{\text{site}}$  = drainage area at site of interest

The exponent  $n$  varies between 0.6 and 1.2. If the  $DA_{\text{site}}$  is within 20% of the  $DA_{\text{gauge}}$  ( $0.6 \leq DA_{\text{site}} / DA_{\text{gauge}} \leq 1.2$ ),  $n$  value equal to 1 is used, otherwise the value 0.6 is used.

### **3.3.6. Ranking of the potential irrigable sites among the river catchments**

The identified irrigable area, water resources (the mean monthly runoff calculated by runoff coefficient method for un-gauged rivers and the mean monthly flows transferred to site of interest on gauged rivers) and monthly irrigation water requirements were compared to estimate irrigation potential of the river catchments. After identifying irrigation potential of each river catchments, the sites were ranked according to their irrigation potential for irrigation development possibilities. The catchment with the highest irrigation potential was ranked first and so on.

## 4. RESULTS AND DISCUSSIONS

### 4.1. Testing Stream Flow and Rainfall Data for Consistency

The double-mass curve analysis revealed that there is good direct correlation between the cumulative stream flow records at Bilate gauging station with the cumulative average stream flows at the three stations ( $r = 0.996$ ). This indicates that the stream flow data at Bilate gauging station is consistent. For the other three stations, the consistencies of their stream flow records were checked using similar procedure and it was found that no significant shift of slope was observed on their respective plots. As presented in Appendix Figure (1, 2, 3), the correlation coefficients of the three stations indicated that there is good direct correlation between the stations' records and their corresponding base stations. Therefore, it was concluded that the stream flow data from all stations can be used for further application.

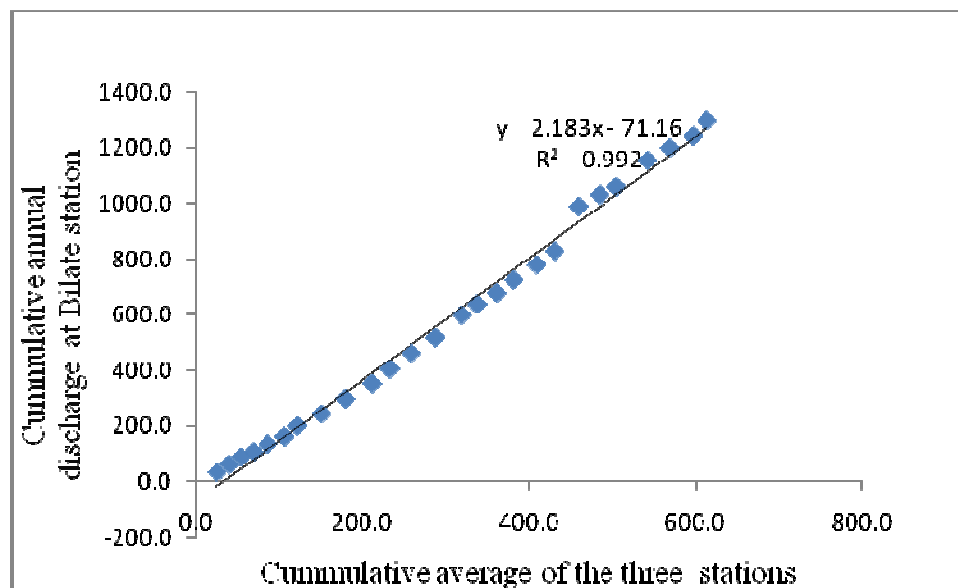


Figure 10 Double mass curve of Bilate station

The rainfall analysis result showed that there were missing rainfall records at stations as presented in Table 5. Therefore, to use these data for further application, missing values were filled and results summarized in Appendix Tables 5, 6, and 8. The rainfall data at Hawassa station, as presented in Appendix Table 7, this station have no missing records and with data of other stations, they were used to fill missing values for these rainfall stations. Similarly, results of the double-mass curve analysis of the rainfall stations revealed that the rainfall recorded at the four gauging stations (Bilate, Dilla, Hawassa and Yirgalem) are consistent with no significant change of slope on their respective plots as presented in Appendix Figures (4, 5, 6 and 7). This also suggests that the rainfall data recorded at these four stations can be used directly for further analysis.

Table 5. Summary of missing rainfall data for the stations

Rainfall stations	Year ( months ) with missed records
Bilate Agri	(Jan, 1984), (June, 1986), (Jul, 1989), (May, 1992) and (Aug, 1996)
Dilla	( Jan, may, June and Jul, 1991)
Yirgalem	(Dec, 1997), (June, 2002), (Mar, 2003), and (Sep, 2004)

#### 4.2. Watershed Delineation

The watershed delineation showed that there were two main watersheds and four sub-watersheds in the study area. Gidawo and Bilate watersheds are the major ones. The others such as Dama, Raro, Wamole and Woyima are sub-watersheds of Gidawo watershed each covering area of 8,170.56 ha, 5,580.72 ha, 16,938.72 ha and 4,678.11 ha, respectively. Gidawo is the largest watershed in and around the study area covering a total area of 216,817.74 ha and comprising of the above four sub-watersheds. Bilate watershed is the second largest watershed in and around the study area. It covers a total area of 116,010.27 ha. Figures 11 to 16 show these main and sub-watersheds in the study area.

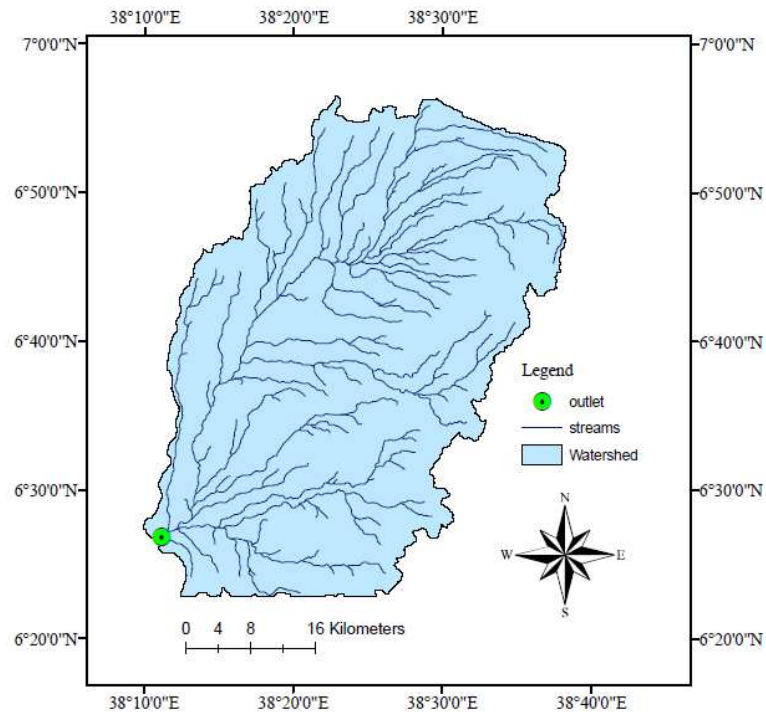


Figure 11 Gidawo watershed

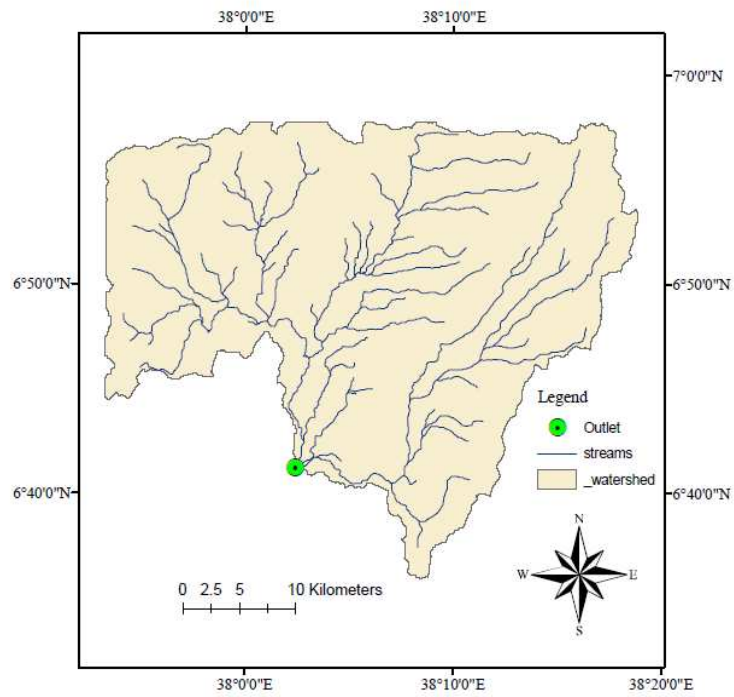


Figure 12 Bilate watershed

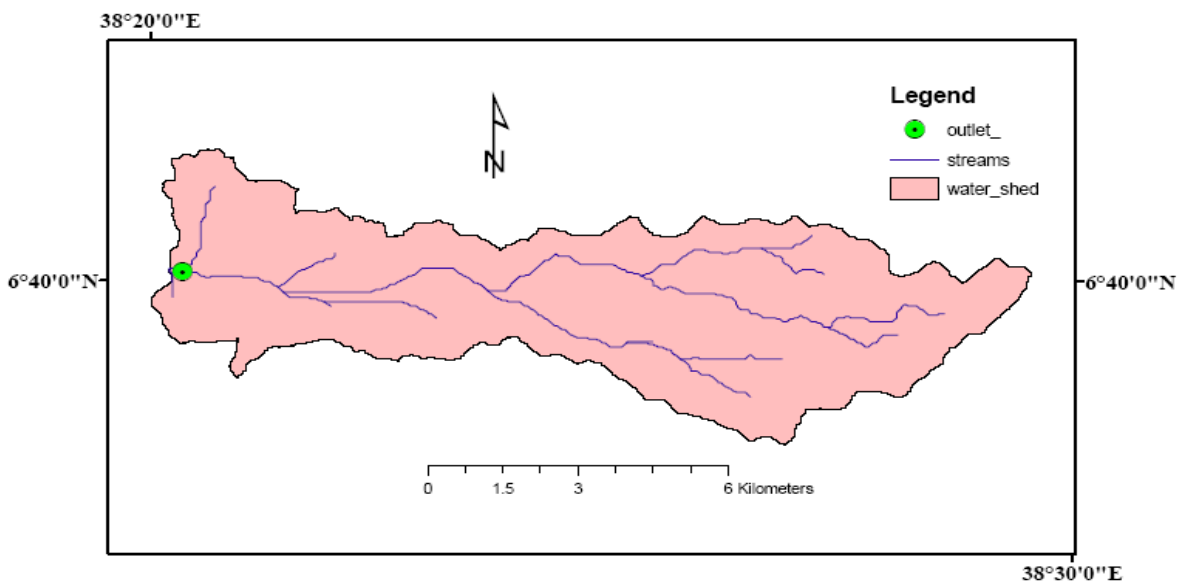


Figure 13 Raro sub-watershed

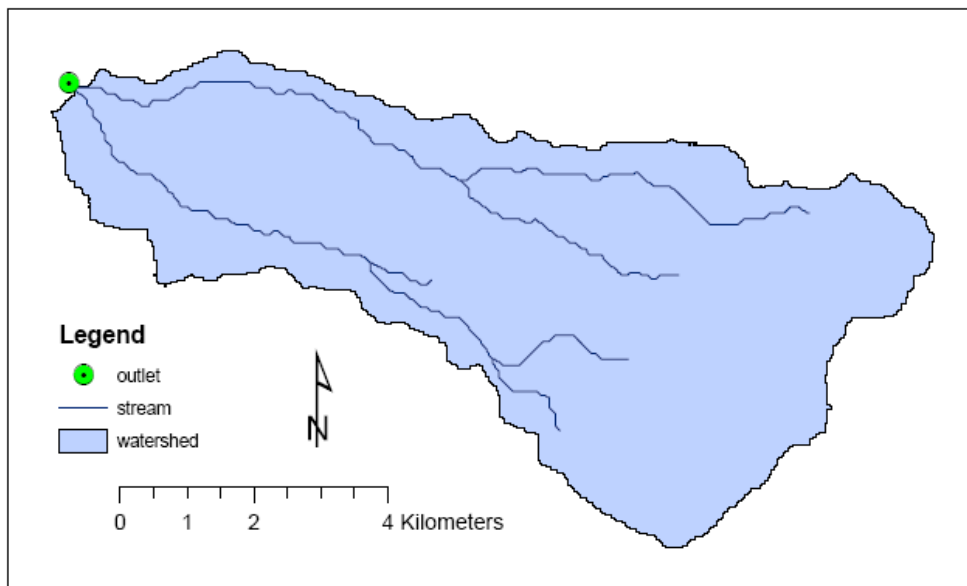


Figure 14 Woyima sub-watershed

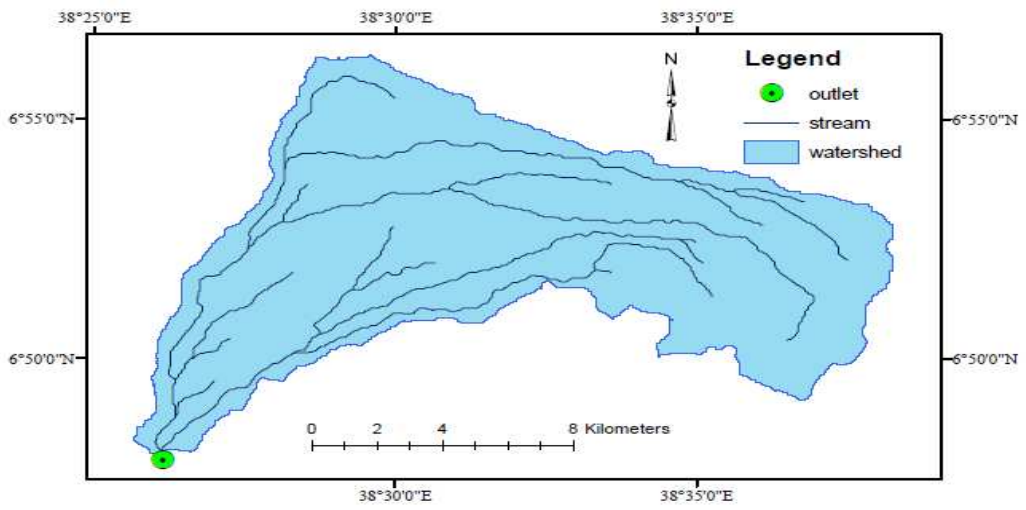


Figure 15 Wamole sub-watershed

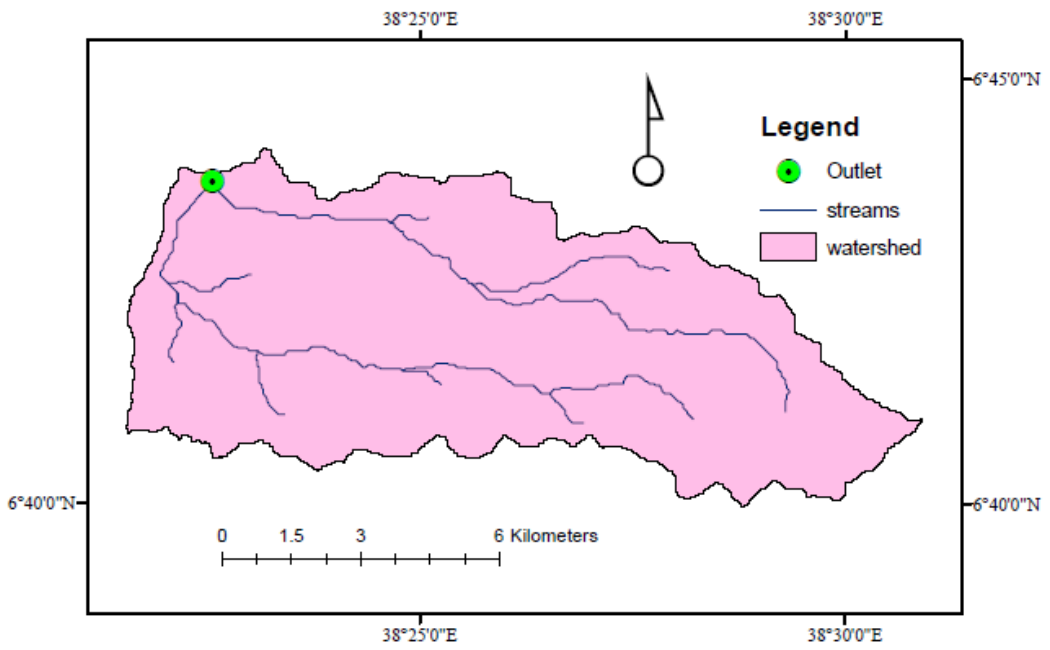


Figure 16 Dama sub-watershed

### 4.3. Irrigation Suitability Evaluation

The analysis results of surface irrigation suitability evaluation factors are presented as the following sections.

#### 4.3.1. Suitable slope

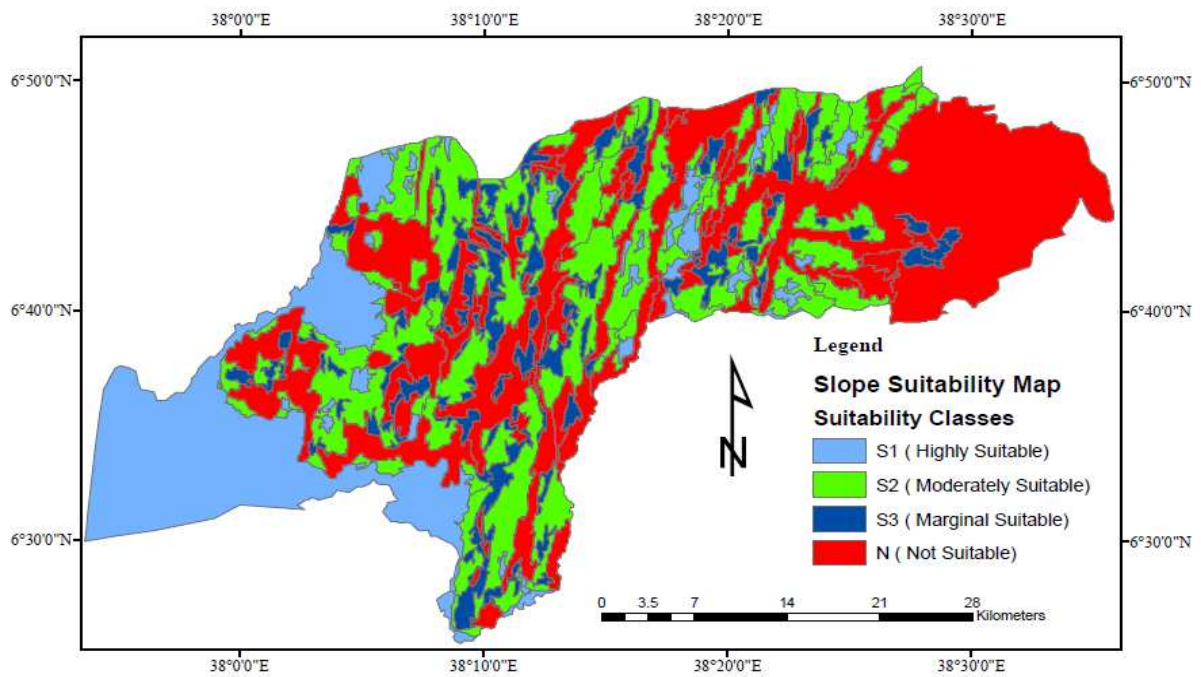


Figure 17 Slope suitability map of the study area for surface irrigation

Slope has been considered as one of the evaluation parameters in irrigation suitability analysis. Based on the four slope classes (S1, S2, S3 and N), the suitability of the study area for the development of surface irrigation system is shown in Figure 17 and the area coverage of the suitability classes are presented in Table 6.

Table 6. Slope suitability range of the study area for surface irrigation

Slope range (%)	Area coverage (ha)	% of total area	Suitability classes
0-2	30,182.4	20.2	S1
2-5	41,869.2	28.0	S2
5-8	15,384.4	10.3	S3
8-86.6	62,007.6	41.5	N
Total	149,443.6	100	

The results in Table 6 revealed that 58.5% of the total area of the *Woreda* (covering an area of 87,436.0 ha) is in the range of highly suitable to marginal suitable for surface irrigation system with respect to slope whereas the remaining 41.5% of the area (covering an area of 62,007.6 ha) is not suitable. Hence, the majority of the study area is highly to marginally suitable for surface irrigation in terms of slope suitability.

#### 4.3.2. Soil suitability

The major soil groups identified in the study area are: Chromic Luvisols, Eutric Vertisols, Haplic Luvisols, Humic Nitosols and Lithic Leptosols as shown in Figure 18. Summary of soil suitability classification results are given in Table 7.

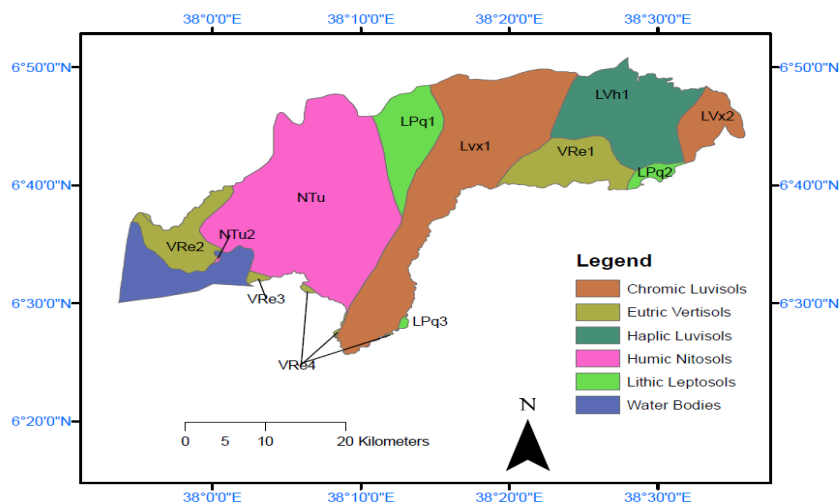


Figure 18 study area soil classification

Results of this analysis indicate that the study area can be generally classified into three irrigation suitability classes based on soil suitability as a factor: S1 (highly suitable), S2 (moderately suitable) and N (not suitable). Humic Nitosols, covering an area of 48,233 ha which accounts 32.3% of the total area, was classified as highly suitable (S1) for surface irrigation. This soil is characterized by deep soil, clay texture, well drainage condition and no salinity and alkalinity hazards. Haplic luvisols, Chromic Luvisols and Eutric vertisols were classified as S2 (moderately suitable class). Haplic Luvisols and Chromic luvisols are characterized by optimum conditions for surface irrigation system in terms of all factors except that both are limited by sandy loam texture. Similarly, EutricVertisols are limited by their imperfect drainage condition while the other factors are optimum for surface irrigation. In general, about 54.2% of the land in the study area (81,090 ha) can be categorized as moderately suitable (S2 class) for surface irrigation. These soils are classified as S2 because of the presence of the factors limiting the land for the specified use (FAO, 1979). However, S2 can be transferred to S1 using the most appropriate irrigation methods such as sprinkler and drip irrigation on these soils.

Table 7. Soil suitability classification result for surface irrigation

Soil type	Soil map unit	Texture	Depth (Cm)	Drainage	Salinity (ds/m)	Alkalinity (ESP)	Irrigation suitability	Area in	
								ha	%
Haplic Luvisols	LVh	SL	125	W	0.1	4.83	S2	18,673	12.5
Lithic Leptosols	LPq	CL	10	W			N	10,954	7.3
Chromic Luvisols	LVx	SL	130	W	0.1	0.7	S2	43,840	29.3
Eutric Vertisols	VRe	C	200	I	0.1	4.93	S2	18,557	12.4
Humic Nitosols	NTu	C	200	W	0	0.43	S1	48,233	32.3
Water body	WBD						N	9,183.8	6.2
<b>Total</b>								<b>149,441</b>	<b>100</b>

C= Clay, CL= Clay Loam, SL = Sandy Loam

S1= highly suitable, S2 = moderately suitable, N= Not suitable

W= Well, I = Imperfect

However, the study established that there is no land in the study area with soil types that can be categorized as S3 (marginal suitable) for surface irrigation. Lithic Leptosol is limited by shallow soil depth (10 cm) which is unfavorable for crop growth and surface irrigation method. Therefore, areas covered by this soil and the lake (water body) were classified as N (not suitable class). In general, land classified under N class accounts for 13.4% of the total study area (20,137 ha). Figure 19 shows soil suitability map of the study area.

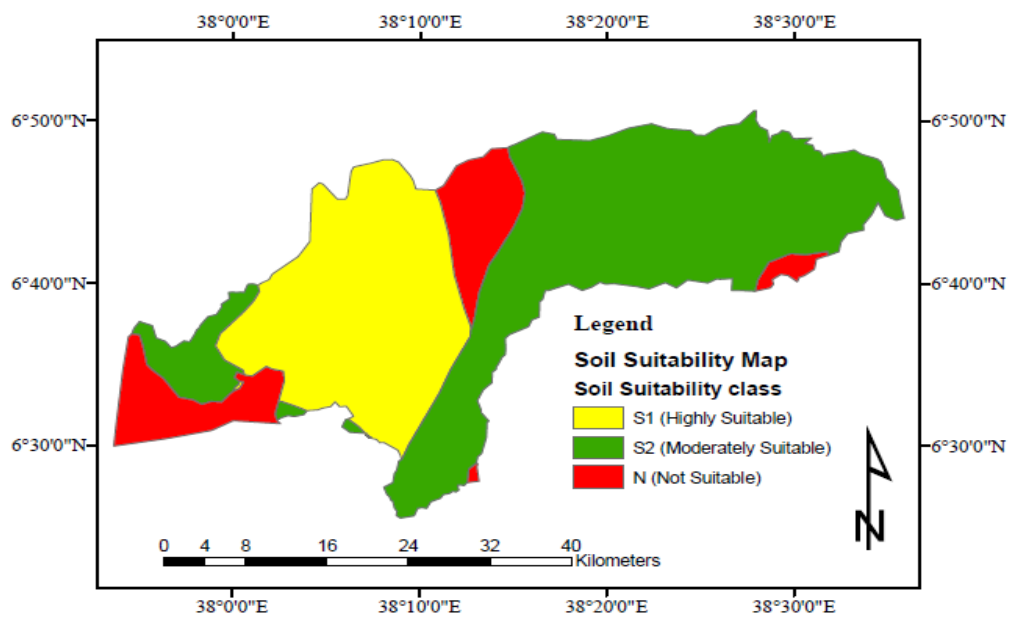


Figure 19 Soil suitability map of the study area

#### 4.3.3. Land cover/use evaluation

From SPOT5 satellite image supervised classification, eight land cover/use classes were identified. These classes include: degraded shrub land, cultivated land, shrub grassland, forest, grass land, wetland, settlements and water body, as shown in Figure 20. As presented in Table 8, all land cover/use classes were classified with high accuracy except shrub grass land which interfered with cultivated and forest lands. Of all land cover classification, water body was classified with 100% accuracy level. The land cover/use of the study area was classified with over all accuracy of 94.65% and Kappa coefficient of 0.94. The Kappa coefficient of 0.94 of the land cover classification in the study area represents a strong agreement according to Rahman et.al (2006).

Table 8. Confusion matrix of SPOT 2006 LUC classification

Class	Ground truth (Percent)							Total
	Degraded shrub land	Grass land	Cultivated land	Forest	Shrub grassland	Wet land	Water body	
Unclassified	0	0	0	0	0	0	0	0
Degraded shrub land	99.59	0.01	0.04	0.02	0	0	0	8.36
Grass land	0	97.76	0.06	0	8.27	0	0	11.89
Cultivated Land	0.2	0.01	95.25	0.53	4.45	1.18	0	24.2
Forest	0	0	0.64	99.44	0	0	0	9.47
Shrub grassland	0.21	2.22	3.44	0	77.21	0	0	13.85
Wet land	0	0	0.57	0	0.02	98.82	0	10.01
Water body	0	0	0	0.05	0	0	100	22.21
Total	100	100	100	100	100	100	100	100

Overall Accuracy = (517001/546203) 94.6536%

Kappa Coefficient = 0.9357

Settlement land cover class was not included in Table 8 because trees in urban areas resemble cultivated and forest land covers and was not distinguishable. Hence, settlement land cover was classified by masking from image using polygon layer of urban areas.

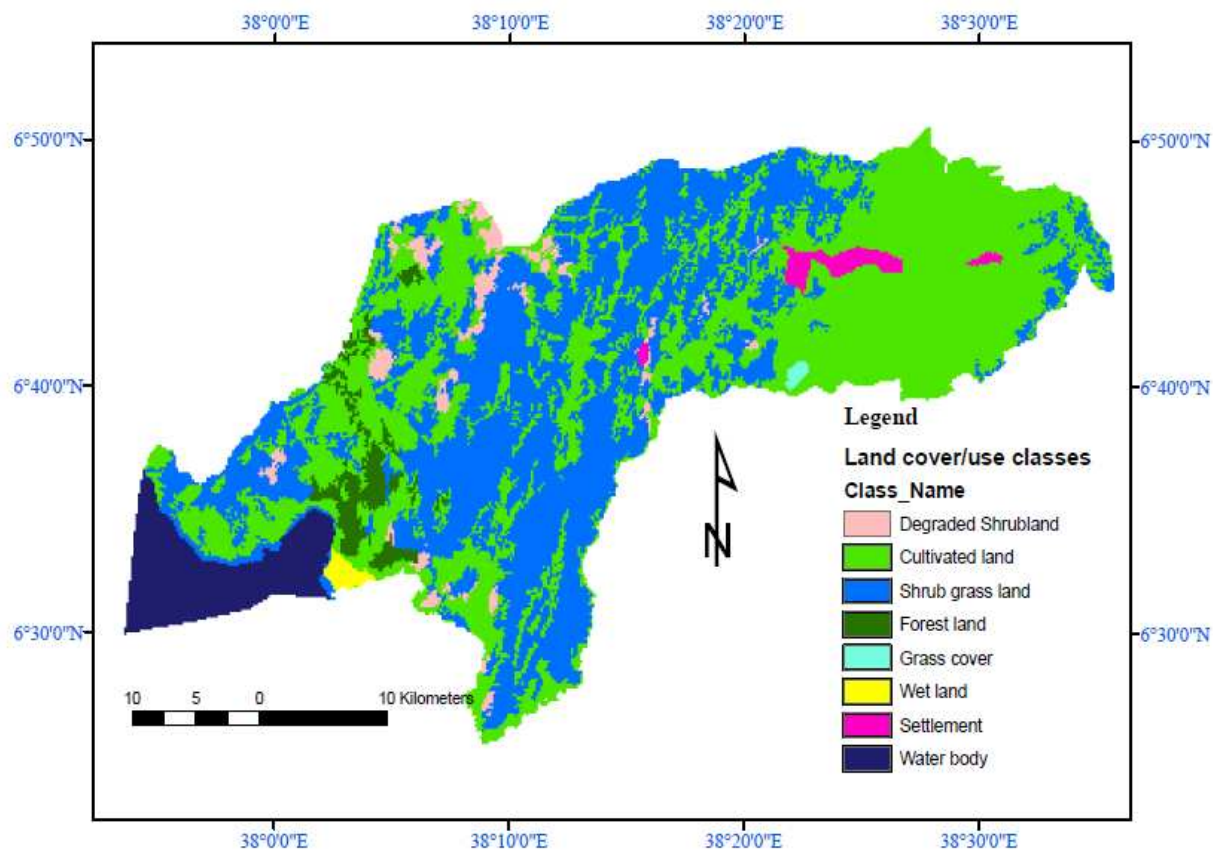


Figure 20 Land cover/use map of the study area

Table 9. Area coverage of land cover/use classes of the study are

	Area in (ha)	Percentage (%)
Cultivated land	70301.6	47.0
Degraded Shrub land	3939.9	2.6
Grazing land	245.2	0.2
Forest cover	3731.6	2.5
Lake/ water body	9000.8	6.0
Settlement	1700.7	1.1
Shrub grass land	59898.4	40.1
Wet land	637.4	0.4
Total	149455.5	1.00

Referring to Figure 20 and Table 9, discussions of results for the land cover/use classification are presented under the following headings.

### **Degraded shrub land**

Degraded shrub land is characterized by degraded land areas and small trees with no grass cover. This land unit is mainly found at the lower part of the Gidawo river and near inlet of Bilate river to Dale *Woreda* and lake Abaya. This land cover/use covers an area of 2.6% of the study area.

### **Cultivated land**

This land cover type is dominant as compared to the other land cover types in the study area. It covers 47% of the total area of the *Woreda*. As described in section 3.2, *Dale Woreda* is classified into three agro-ecological zones such as *Dega*, *Woinadega* and *Kola*. The cultivated land cover type is therefore found in these three agro-ecological zones. The crops commonly grown in the the *Dega* part of the study area are apple, barely, beans, onion, wheat, *enset* etc. In *Woinadega* agro-ecological zone, the crops most commonly grown include *enset*, vegetables and fruits, banana, coffee, maize and sugarcane whereas *Teff*, *enset*, banana, sugarcane and maize are the most dominant crops grown in *Kola* agro-ecological zone.

### **Forest cover**

This unit of land mainly lies around lake Abaya and at the periphery of Bilate river covering an area of 2.5% of the total area of the *Woreda*.

### **Grass cover**

This land cover type is characterized by an area covered by open grassland. It is mostly used for grazing purpose. The grass cover occupies an area of about 0.2% of the study area and found in the eastern side of the *Woreda*.

## **Settlement**

This land cover class covers urban areas such as Bokaso, Hantate and Yirgalem towns covering an area of 1.1% of the total area of the study *Woreda*.

.

## **Shrub grass land**

This land unit is the second dominant land cover in the study *Woreda* covering an area of 40% of the total area. It is mixed with cultivated land and dominantly found at *Kola* agro ecological zone of Dale *Woreda*. It is characterized by short stem trees with dense grass cover.

## **Water body**

This land unit covers some part of Lake Abaya in the study area occupying 6% of the *Woreda's* land area.

## **Wet land**

This land unit mostly consists of wetlands (swampy areas). It is found near the Inlet of Gidawo River to Lake Abaya at south eastern side of the *Woreda*. It covers an area of 0.4% of the total area of the *Woreda*.

Land cover/use classes such as cultivated and shrub grass land were classified as highly suitable for irrigation with the assumption that these land cover classes can be irrigated without limitations. They cover 87.1% of the study area. Other land units such as grazing and forest lands were classified as lands not suitable for irrigation. This is because according to the local culture land use reserved for these purposes can't be put under cultivation. It is obvious that land cover classes such as degraded shrub land, settlement/urban areas, water body or lake and wet land cover classes are restricted to use for irrigation. Therefore, the land cover that was not suitable for surface irrigation accounts for 12.9%.

#### 4.4. Suitable Land for Irrigation

Potential irrigable land was obtained by creating irrigation suitability model analysis which involved weighting of values of all data sets such as soil, slope, land cover and distance from the water supply. Figure 21 shows the identified potential irrigable lands below the reservoir or diversion sites among the main and tributary perennial rivers. The main and tributary rivers are referring to the main and sub-watersheds obtained by watershed delineation in section 4.2. Attempts were made to identify potential reservoir or diversion sites above the identified irrigable areas since the suitability was assessed for surface irrigation methods. Table 10 presents the identified irrigable land areas in hectares along rivers in different reservoir sites. Gidawo River at Argada has the highest irrigable land potential as compared to the other sites Table 10. Bilate River at Abaya Zuria has the highest irrigable land potential next to Gidawo.

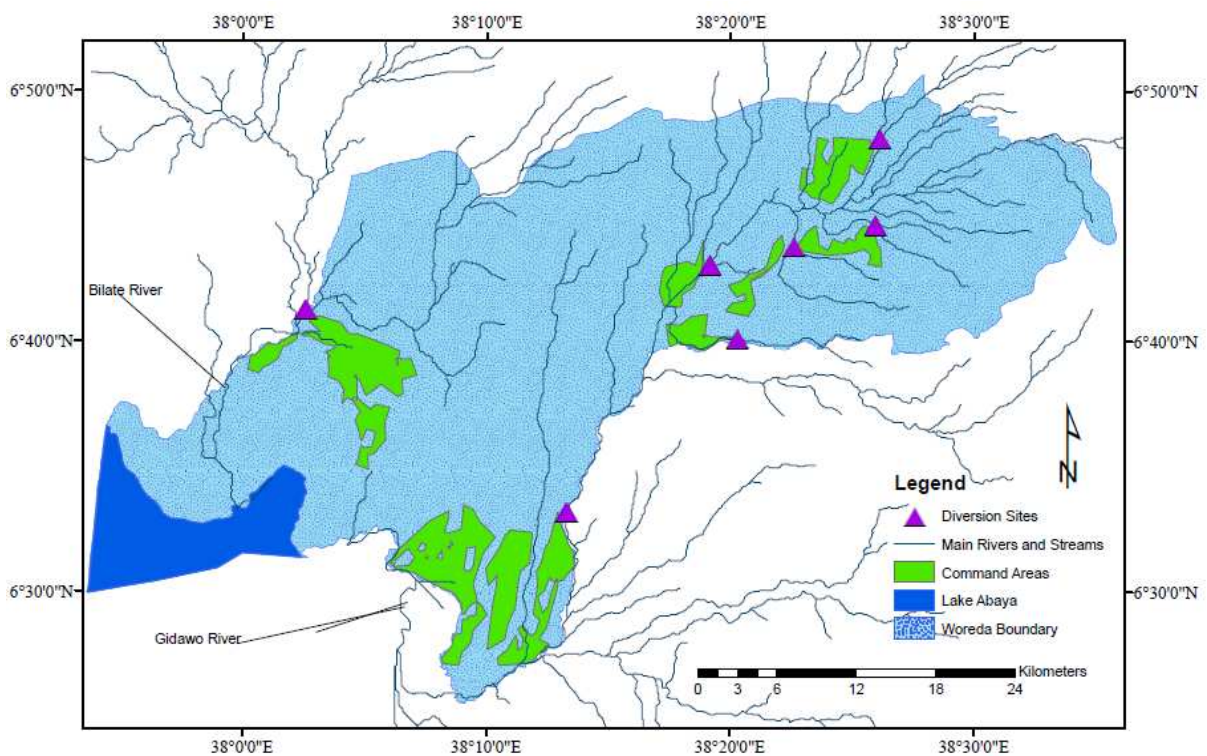


Figure 21 Suitable sites for surface irrigation development

Table 10. Suitable land for surface irrigation in the study area

No	River (water supply)	Reservoir site location			Command area (location & size)	
		<i>Kebele</i>	Latitude	Longitude	<i>Kebele</i>	Hectares
1	Bilate River	Abaya Zuria	6.69	38.04	Abaya Zuria and lower Falka towards Abaya Zuria part	3621.64
2	Dama River	Bera chale	6.73	38.38	Wenanata and Magara	552.68
3	Gidawo River at Desse	Desse	6.72	38.32	Desse, small parts of Chalbessa and Sodo simita	760.16
4	Gidawo at lower Argada	Lower Argada	6.55	38.22	Lower parts of Argada and Falka	6505.4
5	Raro River	Aleta sodo	6.67	38.34	Aleta Sodo	693.35
6	Wamole River	Motto	6.8	38.43	Ajawa, Gane, Motto and small parts of Tula	1511.31
7	Woyima River	Masincho	6.74	38.43	Awada, Masincho and small parts of Goyida	805.66

#### **4.5. Gross Irrigation Water Requirements of the Identified Command Areas**

Gross irrigation water requirements of banana and sugarcane at the identified seven potential irrigable sites (Table 10) under surface irrigation methods were estimated using ETO and other climatic data which were derived from the computation as presented in Appendix Tables 11-14 and 15-22. Tables 11 and 12 present monthly gross irrigation water requirements that must be met from the rivers. These results give a general overview of monthly water demands of the crops that should be abstracted from the rivers by assuming a single cultivation in a year during the local cropping period (mono-cropping). Results revealed that the gross irrigation requirements of the crops at the identified potential irrigable areas are affected by the type of crop selected and the nearby meteorological stations.

Table 11. Gross monthly irrigation water requirements (Mm<sup>3</sup>) for growing banana

N <sub>o</sub>	Command area name	Meteorological station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bilate River	Bilate Agri	3.9	2.8	1.6	1.1	0.9	0.5	0.5	1.0	2.0	2.5	2.9	4.0
2	Dama River	Yirgalem	0.88	0.72	0.56	0.44	0.35	0.21	0.15	0.19	0.35	0.49	0.63	0.88
3	Gidawo River at Dese	Yirgalem	1.2	1	0.8	0.6	0.5	0.3	0.2	0.3	0.5	0.7	0.9	1.2
4	Gidawo River at lower Argada	Dila	8.1	5.8	3.6	2.3	1.3	0.0	0.0	0.0	1.6	3.1	4.9	7.6
5	Raro River	Aleta Wondo	0.81	0.53	0.24	0.09	0.00	0.00	0.00	0.09	0.39	0.63	0.87	1.03
6	Wamole River	Yirgalem	2.4	2.0	1.5	1.2	0.9	0.6	0.4	0.5	0.9	1.4	1.7	2.4
7	Woyima River	Yirgalem	1.3	1.1	0.8	0.6	0.5	0.3	0.2	0.3	0.5	0.7	0.9	1.3

Table 12. Gross monthly irrigation water requirements (Mm<sup>3</sup>) for growing sugarcane

N <sub>o</sub>	Command area name	Meteorological station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bilate River	Bilate Agri	7.1	6.9	6.1	5.1	4.1	3.6	3.0	2.4	2.1	2.0	2.1	5.6
2	Dama River	Yirgalem	0.3	0.8	0.9	0.7	0.4	0.3	0.2	0.3	0.3	0.3	0.4	0.4
3	Gidawo River at Dese	Yirgalem	0.4	1.1	1.2	0.9	0.6	0.4	0.3	0.3	0.4	0.5	0.5	0.6
4	Gidawo River at lower Argada	Dila	2.5	6.5	7.2	4.5	2.0	0.7	0.0	0.7	1.3	1.8	2.5	2.9
5	Raro River	Aleta Wondo	0.9	1.0	0.7	0.3	0.1	0.0	0.0	0.1	0.1	0.2	0.0	0.4
6	Wamole River	Yirgalem	1.0	2.3	2.6	1.9	1.2	0.8	0.6	0.7	0.9	1.0	1.2	1.2
7	Woyima River	Yirgalem	0.5	1.1	1.3	0.9	0.6	0.4	0.3	0.4	0.4	0.5	0.6	0.6

## **4.6. Water Resources Assessment**

Prior to estimating stream-flows at the un-gauged sites from gauged sites, watersheds above both gauged and un-gauged sites were characterized. Taking the watershed similarities into account, stream flows at un-gauged sites were estimated from the gauged sites by applying runoff coefficient method. In case of gauged sites, discharges from gauge site transferred to site of interest. These results are discussed under the following sub-sections:

### **4.6.1. Gauged and un-gauged watersheds similarities**

Referring to Figures 22, 23, and 24, the sub-watersheds in Gidawo watershed with similar land cover, soil type, and slope range are identified and the results are presented in Table 13. Un-gauged sub-watersheds such as Dama, Raro, Wamole and Woyima are similar with gauged sub-watersheds such as Kola and Gidawo at Aleta Wondo and Aposto sites, respectively

Table 13. Characteristics of watersheds above the gauged and un-gauged sites

	Gauged sub-watersheds	Un-gauged sub-watersheds
1	Kola river	Dama and Raro rivers
	Land cover /use	
	Cultivated land	Cultivated land
	Shrub grass land	Shrub grass land
	Soil type	
	Eutric Vertisols	Eutric Vertisols
	Lithic leptosols	Lithic leptosols
	Slope range	
	0 - 8% (dominant)	0 -8% (dominant)
	8- 16%	8- 16%
	16 - 30 %	16 - 30%
2	Gidawo river at Aposto	Wamole and Woyima rivers
	Land cover /use	
	Cultivated land	Cultivated land
	Shrub grass land	Shrub grass land
	Settlements	Settlements
	Soil type	
	Haplic luvisols	Haplic luvisols
	Chromic luvisols	Chromic luvisols
	Slope range	
	0 - 8%	0 - 8%
	8 - 16%	8 - 16%
	16 - 30%	16 - 30%
	30 -87%	30 -87%

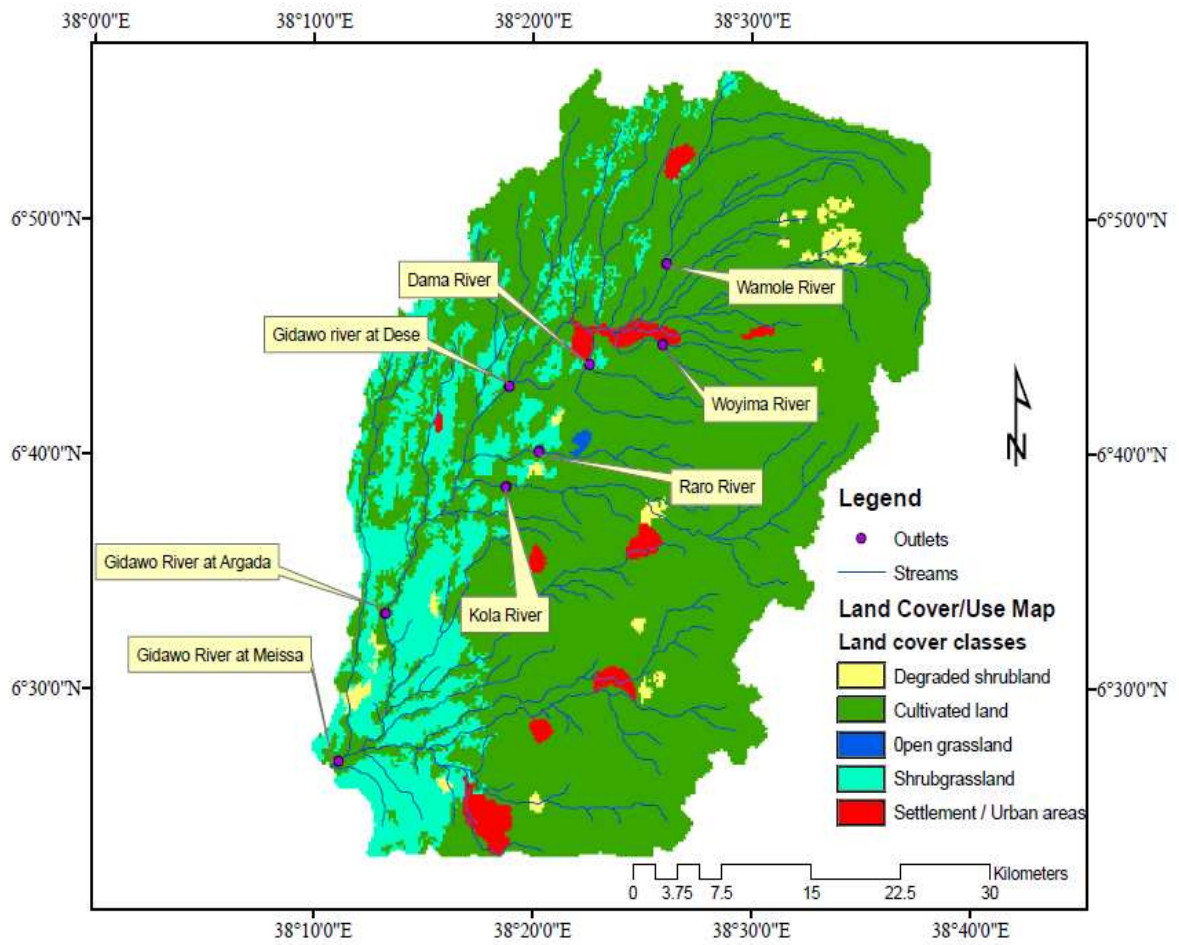


Figure 22 Land cover/ use map of Gidawo Watershed

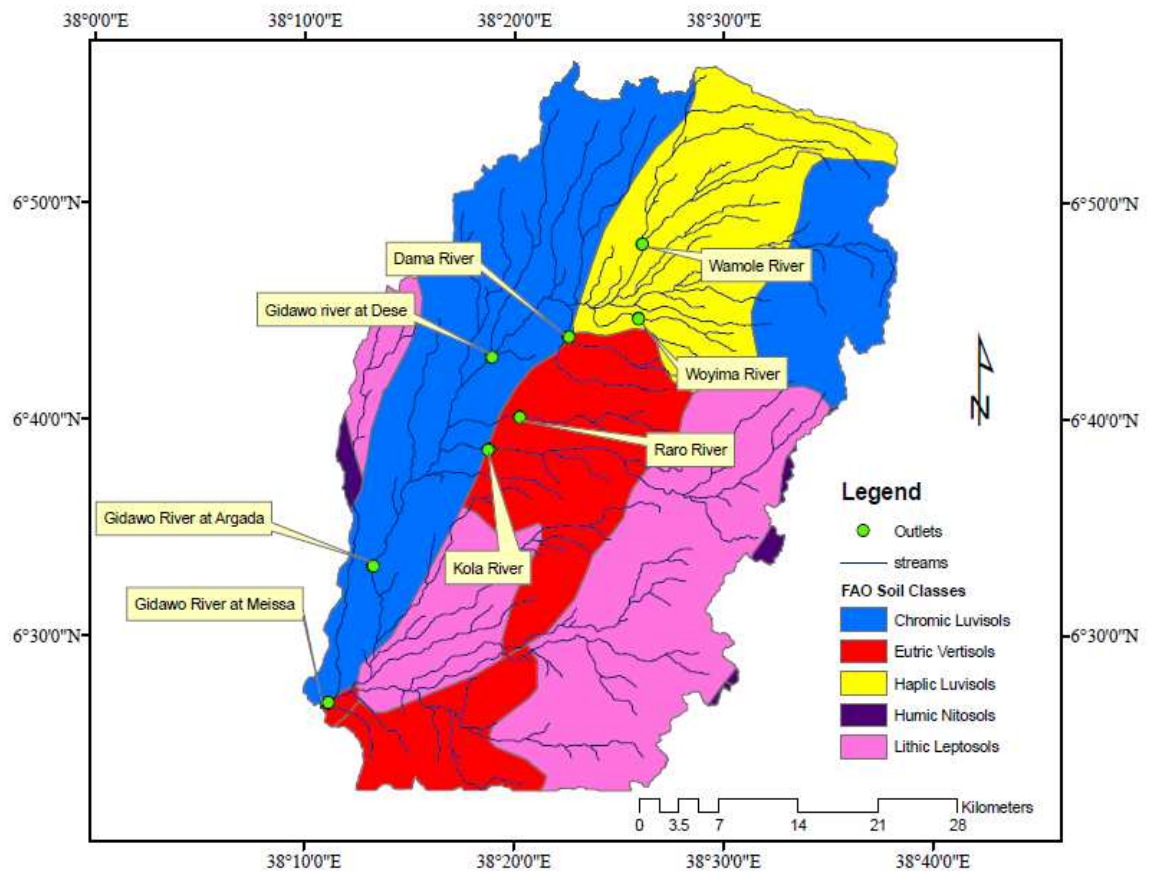


Figure 23 Soil map of Gidawo watershed

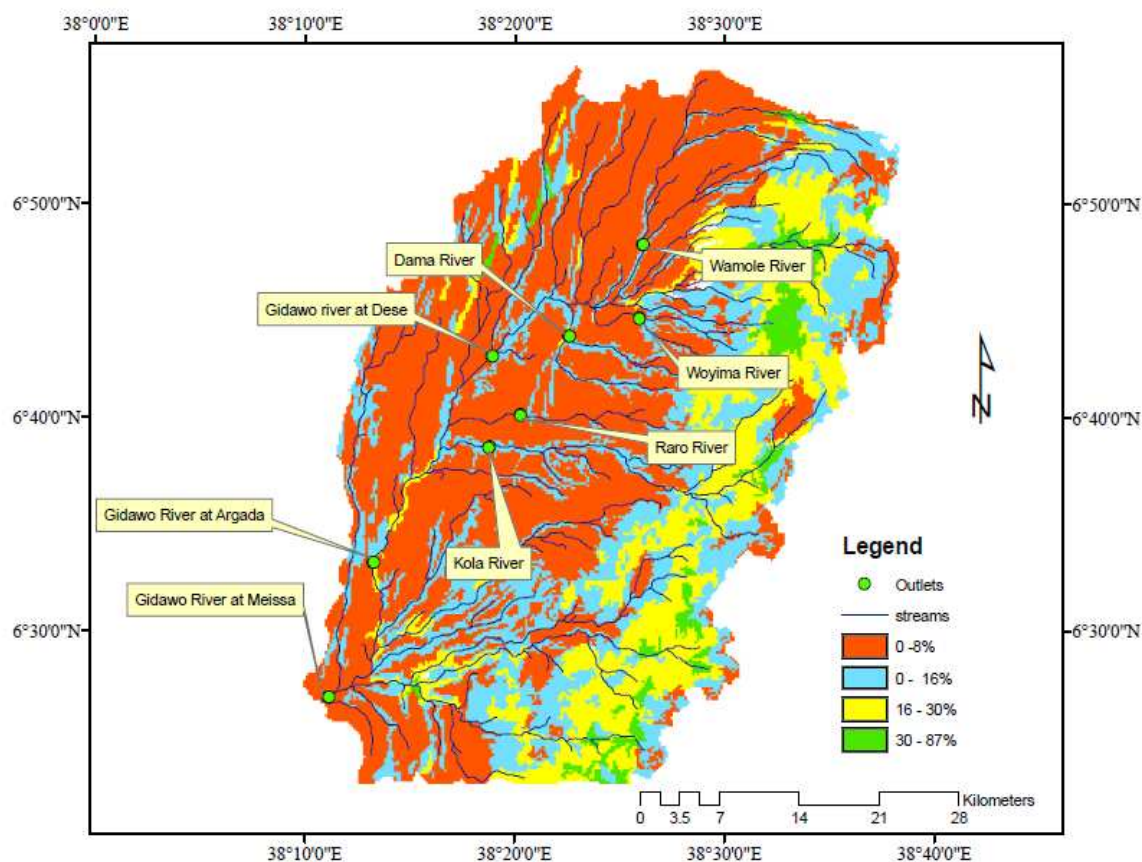


Figure 24 Slope map of Gidawo watershed

#### 4.6.2. Mean areal rainfall of sub-watersheds

Mean areal rainfall of sub-watersheds, which were used as input data to estimate stream flows in un-gauged sites, were calculated by by Thiessen polygon method using Arc GIS. Figures 25 to 30 show Thiessen polygon maps of each sub-watershed inside and around the study area. All sub-watersheds, except Woyima sub-watershed (Figure 29), are influenced by more than one rain gauge stations. Table 14 presents the stations, areas within the watersheds, stations' area fraction, and stations mean monthly rainfall contribution (calculated by multiplying stations area fraction by long term mean monthly rainfall data from Appendix Tables 5, 6, 8 and 9)

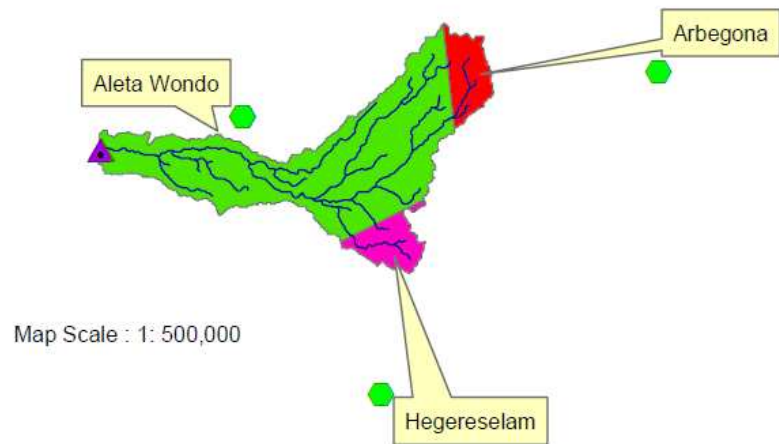


Figure 25 Theissen polygon map of kola sub watershed gauge site near Aleta Wondo

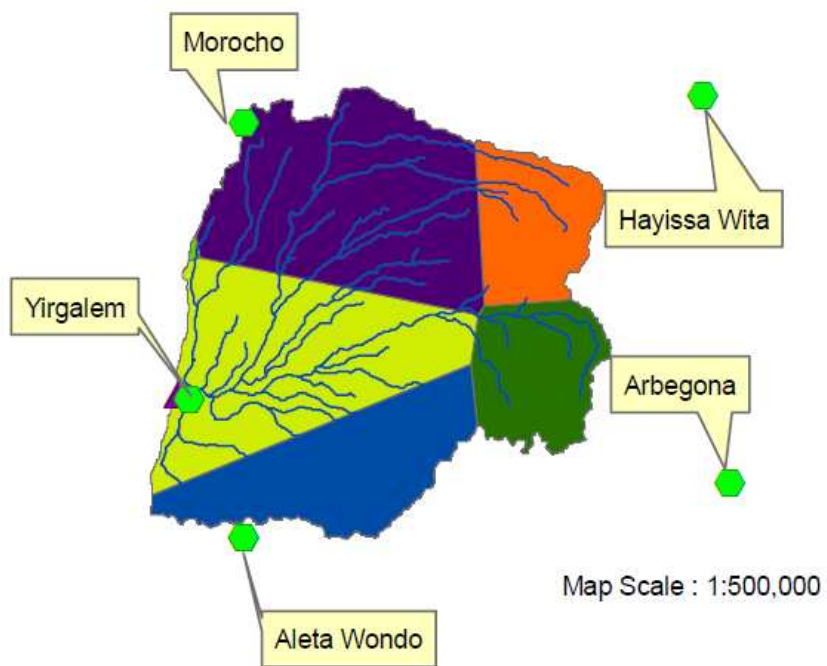


Figure 26 Theissen polygon map of Gidawo gauge site at Aposto

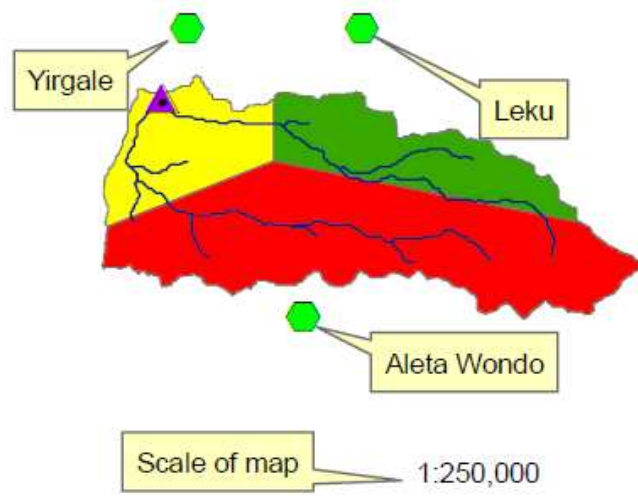


Figure 27 Theissen polygon map of Dama sub watershed

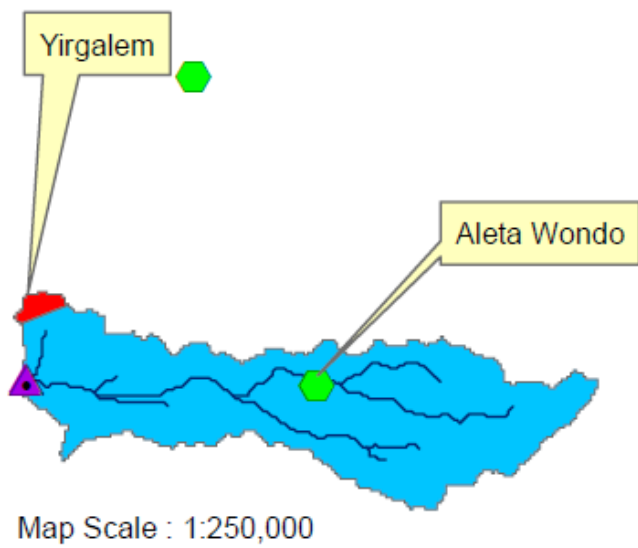


Figure 28 Theissen polygon map of Raro sub-watershed

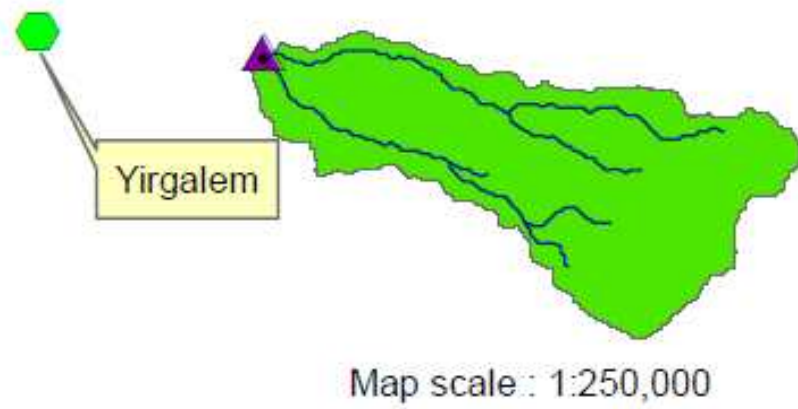


Figure 29 Theissen polygon map of Woyima sub-watershed

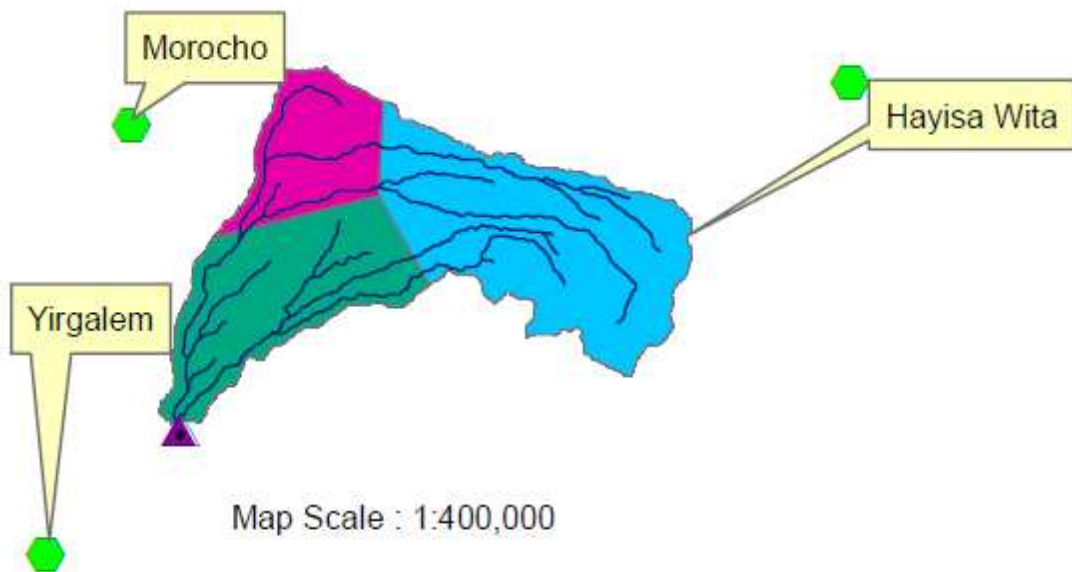


Figure 30 Theissen polygon map of Wamole sub watershed

Table 14. Average monthly areal rainfall of the sub-watersheds.

1 Dama sub-watershed															
Stations	Stations area in Catchments (km <sup>2</sup> )	Stations Area fraction (%)	Stations monthly rainfall contribution in (mm)												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Yirgalem	15.40	19.00	4.9	8.6	20.9	31.7	31.3	18.9	19.8	24.2	29.4	32.7	7.1	6.6	
Leku	18.38	22.00	7.7	11.7	20.5	31.5	29.0	23.8	30.8	30.6	35.4	25.3	11.0	4.8	
Aleta Wondo	47.93	59.00	21.2	31.3	56.1	89.7	92.6	66.7	82.6	81.4	97.9	79.1	34.2	13.0	
Total	81.71	100.00	33.8	51.5	97.4	152.9	153.0	109.3	133.2	136.2	162.7	137.1	52.3	24.4	
2 Kola sub-watershed															
Arbegona	20.54	10.00	3.7	5.5	9.3	15	13.7	11.9	16.4	16.1	17.1	12.9	5.7	2.9	
Aleta Wondo	175.48	82.00	29.5	43.5	77.9	124.6	128.7	92.7	114.8	113.2	136.1	109.9	47.6	18.0	
Hagere Selam	18.26	9.00	3.87	5.58	10.08	17.28	17.19	12.51	14.49	14.4	17.64	15.75	6.93	2.61	
Total	214.28	100.00	37.09	54.54	97.28	156.92	159.6	117.07	145.7	143.7	170.86	138.53	60.19	23.55	
3 Raro sub-watershed															
Aleta Wondo	53.57	98.00	35.3	51.9	93.1	149.0	153.9	110.7	137.2	135.2	162.7	131.3	56.8	21.6	
Yirgalem	0.86	2.00	0.514	0.902	2.204	3.34	3.296	1.99	2.082	2.55	3.092	3.444	0.744	0.69	
Total	54.43	100	35.8	52.8	95.3	152.3	157.2	112.7	139.3	137.8	165.8	134.8	57.6	22.3	
4 Woyima sub-watershed															
Yirgalem	46.78	100	25.7	45.1	110.2	167	164.8	99.5	104.1	127.5	154.6	172.2	37.2	34.5	
5 Wamole sub-watershed															
Hayisa Wita	84.26	50.00	21.5	31	56	96	95.5	69.5	80.5	80	98	87.5	38.5	14.5	
Morocho	30.86	18.00	6.3	9.4	16.6	23.4	24.3	18.9	25.9	25.7	27.0	18.5	8.1	3.8	
Yirgalem	54.27	32.00	8.2	14.4	35.3	53.4	52.7	31.8	33.3	40.8	49.5	55.1	11.9	11.0	
Total	169.39	1.00	36.0	54.8	107.8	172.8	172.5	120.2	139.7	146.5	174.5	161.1	58.5	29.3	
6 Gidawo at Aposto															
Arbegona	75.1	0.11	4.1	6.1	10.2	16.5	15.1	13.1	18.0	17.7	18.8	14.2	6.3	3.2	
Hayisa wita	71.5	0.11	4.7	6.8	12.3	21.1	21.0	15.3	17.7	17.6	21.6	19.3	8.5	3.2	
Yirgalem	191.2	0.29	7.5	13.1	32.0	48.4	47.8	28.9	30.2	37.0	44.8	49.9	10.8	10.0	
Aleta Wondo	121.8	0.18	6.5	9.5	17.1	27.4	28.3	20.3	25.2	24.8	29.9	24.1	10.4	4.0	
Morocho	207.4	0.31	10.9	16.1	28.5	40.3	41.9	32.6	44.6	44.3	46.5	31.9	14.0	6.5	
Total	667.0	1.00	33.6	51.6	100.1	153.7	154.0	110.1	135.8	141.5	161.6	139.4	49.9	26.9	

#### 4.6.3. Stream flows at un-gauged sites

Referring to Table 13, the characteristics of watershed above the un-gauged sites on Dama, Raro, Wamole and Woyima rivers are similar with the watersheds above the gauged sites on Kola river (near Aleta Wondo) and Gidawo river (at Aposto). Similarly, the distances between these gauged and un-gauged sites were found to be less than 10 kilometers and the length of records of streamflow data near Aleta Wondo and Aposto gauging sites were about 30 and 26 years, respectively, (Appendix Tables 1 and 3). Hence, the requirements suggested by Goldsmith (2000) and DFID (2004) to use the runoff coefficient method were met and thus estimated mean monthly discharges at the un-gauged sites from gauged sites are presented in Table 15.

Table 15. Mean monthly stream flows of un-gauged river catchments estimated from gauged sites

River catchments name		Mean monthly flows in ( m <sup>3</sup> /s)											
Gauged Rivers	Ungauged Rivers	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kola River	Dama	0.6	0.5	0.6	1.2	2.7	3.0	3.2	5.3	5.0	6.1	2.6	1.8
	Raro River	0.4	0.3	0.4	0.8	1.8	2.0	2.2	3.6	3.3	4.0	1.9	1.1
Gidawo River at Aposto	Wamole	1.6	1.3	1.8	3.7	6.3	5.0	4.8	7.0	8.0	10.2	4.3	2.3
	Woyima	0.3	0.3	0.5	1.0	1.7	1.2	1.0	1.7	2.0	3.1	0.8	0.8

#### 4.6.4. Transferring discharges to sites of interest

The discharges at site of the interest were obtained by transferring the river discharges at the gauged site to the site of interest on the same river. The site of interest, in this case, is referring to a site closer to and above the identified potential irrigable land (command area). All drainage areas of the sites of interest were found within 20% of the drainage areas of the gauged sites. Hence, the area ratio method suggested by Silesh (2000) was adopted and the results are presented in Table 16.

Table 16. Mean monthly discharges (m<sup>3</sup>/s) at the sites of interest

Site of interest	Mean Monthly Discharges at site of interest in m <sup>3</sup> /s											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bilate at Abaya Zuria	13.9	12	28.1	42	55.9	66.7	79.2	120	143	118	42	13.3
Gidawo at Dese	7.3	6.2	8.4	16.4	28	22.6	23.3	33.6	36.9	43.9	18.2	10.3
Gidawo at Argada	19	17.7	20	28.4	40.4	35.1	34.4	43.4	46.1	52.9	29.3	21.5

#### 4.7. Irrigation Potential of River Catchments

Irrigation potential of the river catchments in the study area was obtained by comparing irrigation requirements of the identified land suitable for surface irrigation and the available mean monthly flows in the river catchments based on the method suggested by FAO (1997). Tables 17 and 18 present gross irrigation demand of the two crops commonly grown in the study area (banana and sugarcane) and the available mean monthly flows of the corresponding river catchments. Results of these analyses revealed that monthly irrigation requirements of both banana and sugarcane are less than the available mean monthly flows of Bilate at (Abaya Zuria) and Gidawo rivers (at both Argada and Dese sites) while the mean monthly flows of Dama, and Wamole rivers are slightly greater than the irrigation water requirements of both crops at their corresponding command area. But in Woyima sub-watersheds, the irrigation requirement of banana is more than the available flow in the month of January and February and irrigation requirement of sugarcane exceeds the available flow in the month of February. Similarly, irrigation requirement of sugarcane in Raro sub-watershed exceeds the available flow in month of February. As a result, the critical command areas were calculated according to (Micheal, 2008) to grow these crops. From Table 17 the minimum available flow in the month of February is 0.31 m<sup>3</sup>/s whereas the water requirement of banana in the month of January is 0.61 l/s/ha (0.00061m<sup>3</sup>/s /ha) giving a critical command area (that can be reliably irrigated using the available flows in Woyima river) of 505.71 ha.

Table 17. Comparing of irrigation demands and available flows of river catchments in the study area for banana

River Name	Command area in (ha)	Monthly flows available in each river and gross irrigation demand m <sup>3</sup> /s												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1 Bilate	3621.64	Available flows (m <sup>3</sup> /s)	13.9	12	28	42	55.9	67	79	120	143	118	42	13
		Gross.irr.Req (m <sup>3</sup> /s)	1.5	1.1	0.7	0.4	0.4	0.1	0.1	0.4	0.8	0.9	1.1	1.6
2 Dama	552.68	Available flows (m <sup>3</sup> /s)	0.62	0.47	0.61	1.22	2.66	2.95	3.2	5.33	4.96	6.13	2.61	1.81
		Gross.irr.Req (m <sup>3</sup> /s)	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3
3 Gidawo river at Dese	760.16	Available flows(m <sup>3</sup> /s)	7.3	6.2	8.4	16	28	23	23	33.6	36.9	43.9	18.2	10
		Gross.irr.Req (m <sup>3</sup> /s)	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.2	0.3	0.3	0.5
4 Gidawo river at Argada	6505.4	Available flows (m <sup>3</sup> /s)	19	17.7	20	28	40.4	35	34	43.4	46.1	52.9	29.3	22
		Gross.irr.Req (m <sup>3</sup> /s)	3.1	2.3	1.3	0.9	0.5	0.0	0.0	0.0	0.7	1.2	1.9	2.9
5 Raro	693.35	Available flows (m <sup>3</sup> /s)	0.43	0.31	0.39	0.8	1.8	2	2.2	3.55	3.32	3.96	1.89	1.09
		Gross.irr.Req (m <sup>3</sup> /s)	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.4
6 Wamole	1511.31	Available flows (m <sup>3</sup> /s)	1.58	1.33	1.8	3.71	6.33	4.97	4.84	7.02	8.04	10.23	4.31	2.27
		Gross.irr.Req (m <sup>3</sup> /s)	0.9	0.8	0.6	0.5	0.4	0.2	0.2	0.2	0.4	0.5	0.7	0.9
7 Woyima	805.66	Available flows (m <sup>3</sup> /s)	0.32	0.31	0.52	1	1.69	1.15	1.01	1.71	2	3.06	0.77	0.75
		Gross.irr.Req (m <sup>3</sup> /s)	0.5	0.4	0.3	0.3	0.2	0.1	0.1	0.1	0.2	0.3	0.4	0.5

Table 18. Comparing of irrigation demands and available flows of river catchments in the study area for sugarcane

River Name	Command area (ha)		Monthly flows available in each river and gross irrigation demand m <sup>3</sup> /s											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 Bilate	3621.64	Available flows (m <sup>3</sup> /s)	13.9	12	28.1	42	55.9	66.7	79.2	120	143	118	42	13.3
		Gross.irr.req (m <sup>3</sup> /s)	2.8	2.7	2.4	2.0	1.6	1.5	1.2	0.9	0.8	0.8	0.8	0.8
2 Dama	552.68	Available flows (m <sup>3</sup> /s)	0.62	0.47	0.61	1.22	2.66	2.95	3.2	5.33	4.96	6.1	2.6	1.81
		Gross.irr.req (m <sup>3</sup> /s)	0.1	0.3	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2
3 Gidawo river at Dese	760.16	Available flows (m <sup>3</sup> /s)	7.3	6.2	8.4	16.4	28	22.6	23.3	34	37	44	18	10.3
		Gross.irr.req (m <sup>3</sup> /s)	0.2	0.4	0.5	0.3	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2
4 Gidawo river at Argada	6505.4	Available flows (m <sup>3</sup> /s)	19	17.7	20	28.4	40.4	35.1	34.4	43	46	53	29	21.5
		Gross.irr.req (m <sup>3</sup> /s)	1.0	2.5	2.8	1.7	0.8	0.3	0.0	0.3	0.5	0.7	1.0	1.1
5 Raro	693.35	Available flows (m <sup>3</sup> /s)	0.43	0.31	0.39	0.8	1.8	2	2.2	3.55	3.32	4	1.9	1.09
		Gross.irr.req (m <sup>3</sup> /s)	0.3	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3
6 Wamole	1511.31	Available flows (m <sup>3</sup> /s)	1.58	1.33	1.8	3.71	6.33	4.97	4.84	7.02	8.04	10	4.3	2.27
		Gross.irr.req (m <sup>3</sup> /s)	0.3	0.8	0.9	0.7	0.4	0.3	0.2	0.3	0.3	0.4	0.4	0.4
7 Woyima	805.66	Available flows (m <sup>3</sup> /s)	0.32	0.31	0.52	1	1.69	1.15	1.01	1.71	2	3.1	0.8	0.75
		Gross.irr.req (m <sup>3</sup> /s)	0.2	0.4	0.5	0.4	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2

Similarly, the critical command area for Roro sub-watershed was found 632.65ha. As a result, the irrigation potential of the Raro and Woyima sub-watersheds are 632.65 ha and 505.71 ha, respectively. However, for the other watersheds, since their monthly flows are greater than the irrigation requirements of the two crops, the identified potential irrigable area was taken as their irrigation potential (IFAD, 1987; MoWR, 2002). Therefore, the irrigation potential of the river catchments in the study area are obtained and ranked (Table 19).

Table 19. Summary of irrigation potential of the river catchments and their ranking for development possibilities

River Name	Irrigation potential in (ha)	Rank
Bilate at Abaya zuria	3621.64	2
Dama	552.68	7
Gidawo river at Dese	760.16	4
Gidawo river at Argada	6505.4	1
Raro	632.65	5
Wamole	1511.31	3
Woyima	505.71	7
Total	14089.55	

Therefore, the total irrigation potential of Dale *Woreda* (the study area) is found to be 14089.55 ha which accounts for 10 % of the total land area of the *Woreda*

## 5. SUMMARY AND CONCLUSIONS

### 5.1. Summary and Conclusions

This study assessed the irrigation potential of perennial rivers in the study area such as Bilate, Dama, Gidawo, Raro, Wamole, and Woyima Rivers. The watershed areas obtained through watershed delineation of these Rivers were: 116,010.27 ha, 8,170.56 ha, 216,817.74 ha, 5,580.72 ha, 16,938.72ha and 4,678.11ha, respectively.

Surface irrigation land suitability analysis indicate that 86 % of soil and 58 .5 % slope in the study area are in the range of highly suitable to marginal suitable for surface irrigation system whereas the remaining 14% (soil) and 41.5% (slope) in the area are not suitable. In terms of land cover/use, land covered by settlement, degraded shrub land, forest, wetland, water body and grazing land covering 12.9% of the study area were restricted from irrigation development. When these factors were weighted using weighted overlay in Arc GIS, the potential irrigable land for surface irrigation was reduced to 10%. This implies that, if more factors are considered in the evaluation process and weighted, the total irrigable land is expected to reduce more thereby giving accurate estimate of the land potential for surface irrigation.

Gross irrigation requirement calculation result indicated that irrigation water demand of the banana and sugarcane at identified command areas vary according to nearby meteorological stations

The water resource assessment was carried out using runoff coefficient method at ungauged sites and results are presented on monthly basis. This implies that the estimated amount of flow is available for each month and varies from month to month.

By comparing gross monthly irrigation demand of identified irrigable land under river catchments with corresponding available mean monthly flows, their surface irrigation potential was obtained as: Bilate (3,621.6 ha), Dama (552.7 ha), Gidawo (7,265.6 ha), Raro (632.65 ha), Wamole (1511.3 ha) and Woyima (505.71 ha). Except in Dama, Raro and

Woyima rivers, the available monthly flows in Bilate, Gidawo and Wamole rivers are much larger than their command area monthly irrigation demand. This implies that surface irrigation potential of these rivers limited by the land area to be irrigated along them.

## **5.2. Recommendations**

Irrigation is considered as an important investment for improving rural income through increased agricultural production. However this can be achieved, by assessing available land and water resources for irrigation .Therefore, identified surface irrigation potential of river catchments in the study area can assist in policy decisions during a development of irrigation projects in Dale Woreda.

The data generated for the purpose of the this research work such as estimated discharges at ungauged sites, evapotranspiration data close to identified potential irrigable sites, land cover/use, soil, and slope maps of river catchments can assist local or regional planners to facilitate preliminary surveys and prepare irrigation projects in the study area.

**Future research:** this study needs to be continued to include the following points for the future.

The surface irrigation potential was carried out in this research by considering only distance from water sources, soil, slope, and land cover/use factors. But the effects of other factors such as water quality, environmental, economic and social terms should be assessed to get sound and reliable result.

Surface irrigation land suitability analysis result indicates that only 10% of the study area is suitable for surface irrigation. Land suitability analysis for sprinkler and drip irrigation should be carried out to increase the land area to be irrigated from this figure.

Stream flows at un-gauged sites were estimated using runoff coefficient method. However, future research should test other methods such as regional regression analysis, base flow

correlation and development of unit hydrograph to estimate discharges at ungauged sites from gauged sites.

In this research, estimation of irrigation water requirement of identified command areas was carried out by selecting two crops only. But the future research should select several crops to calculate gross irrigation requirements of identified potential irrigable land among river catchments.

Furthermore, application of remote sensing and GIS was found helpful in assessing surface irrigation potential in this study. It is therefore hoped that future irrigation development activities will exploit these resources more than the present study for better assessment of land and water resources in the study area and elsewhere

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## **7. APPENDICES**

## 7.1 Summary of Hydro Meteorological Data

### 7.1.1 Hydrological data

Appendix Table 1 Kola tributary near Aleta Wondo monthly flow (m<sup>3</sup>/s)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1981	1.3	1.4	2.5	8.7	11.5	4.6	6.7	18.7	15.5	9.2	5.7	2.7	88.5
1982	2.3	1.7	1.4	3.8	8.7	12.1	12.7	22.5	9.6	10.1	6.0	5.1	96.1
1983	2.6	2.0	1.8	2.8	6.9	6.9	7.9	27.5	20.5	27.0	6.3	1.9	114.2
1984	0.7	0.3	0.2	1.8	3.2	7.5	6.0	8.8	18.2	10.2	4.7	3.1	64.6
1985	2.3	1.3	1.6	4.5	8.6	7.2	7.6	10.5	7.7	9.4	4.0	2.5	67.1
1986	1.4	1.7	1.4	3.4	6.2	22.1	7.6	10.5	18.1	13.7	4.3	2.5	92.9
1987	1.4	1.2	1.8	2.2	9.4	9.8	5.6	6.5	10.5	18.5	9.2	3.2	79.5
1988	2.0	1.3	1.3	2.4	5.1	8.8	27.0	32.6	13.0	22.0	6.7	3.0	125.1
1989	1.9	1.4	1.5	3.6	4.8	6.7	10.3	6.6	13.2	14.6	5.9	5.4	75.7
1990	2.5	3.2	4.1	4.1	9.2	9.0	5.9	7.7	7.2	5.5	3.2	2.3	63.6
1991	1.8	1.4	2.0	3.0	3.2	2.7	9.3	4.9	11.2	5.2	2.7	1.7	49.2
1992	1.3	1.5	1.2	3.4	3.8	5.7	6.8	24.3	13.3	30.5	7.8	3.5	103.1
1993	2.3	2.5	1.9	3.6	19.9	13.5	7.6	6.3	7.2	13.5	6.6	2.8	87.6
1994	1.8	1.2	1.6	2.2	4.9	4.6	23.4	18.9	9.9	9.1	5.7	2.7	86.0
1995	0.9	0.8	1.0	3.9	4.1	1.7	2.5	8.8	15.6	16.3	3.4	1.6	60.5
1996	1.0	0.4	1.4	3.1	7.5	28.3	9.6	18.9	18.8	12.5	2.8	1.2	105.5
1997	0.7	0.3	0.3	3.0	7.0	4.6	10.0	16.2	3.9	15.3	16.8	6.8	84.8
1998	5.4	3.0	2.3	3.6	7.1	9.8	12.1	31.5	12.6	24.9	6.5	2.6	121.6
1999	1.7	1.0	1.8	2.3	5.2	4.0	7.9	8.7	7.5	12.6	7.7	2.9	63.3
2000	1.4	0.8	0.8	1.6	4.1	3.3	4.8	20.4	9.1	23.3	7.7	2.9	80.1
2001	1.6	1.1	1.5	3.7	12.8	11.4	6.0	24.3	18.2	15.7	4.9	2.3	103.3
2002	1.9	1.0	1.6	2.2	6.4	5.6	3.5	5.5	5.3	5.4	4.0	2.6	44.9
2003	1.9	0.9	1.0	2.3	2.6	2.1	4.3	5.4	5.2	5.2	3.8	2.3	36.8
2004	2.0	1.2	1.5	3.2	5.3	5.8	3.5	5.2	6.4	10.5	3.6	2.2	50.2
2005	1.6	0.8	1.3	3.0	9.9	8.9	12.6	18.7	68.2	72.9	58.3	42.7	298.9

2006	1.9	1.5	2.7	5.5	12.1	9.4	17.5	15.8	11.4	10.5	7.4	6.7	102.3
Mean	1.8	1.3	1.6	3.3	7.3	8.3	9.2	14.8	13.7	16.3	7.9	4.6	90.2
STDEV	0.9	0.7	0.8	1.4	3.8	5.9	5.8	8.6	12.1	13.4	10.7	7.9	48.7

Appendix Table 2 Bilate river monthly flow at Tena in (m<sup>3</sup>/s)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANNUAL
1980	2.5	3.4	6.0	17.7	62.5	114.6	47.6	117.5	146.8	88.7	30.5	2.1	639.8
1981	1.5	2.0	79.4	74.9	21.4	13.7	40.4	36.5	166.3	76.8	3.8	1.5	518.2
1982	2.0	2.7	42.7	46.3	41.9	64.1	44.0	77.0	156.5	82.8	17.2	1.8	579.0
1983	3.0	6.3	29.2	82.1	111.4	116.8	55.6	206.6	297.2	191.1	39.2	4.5	1143.1
1984	2.6	1.6	1.6	1.7	15.7	18.7	42.6	98.6	125.9	23.5	4.9	3.9	341.3
1985	4.2	1.4	2.8	42.9	88.8	65.6	46.0	86.7	63.3	92.6	19.1	2.7	516.1
1986	2.7	9.3	29.1	56.8	104.2	150.8	354.4	366.3	374.7	255.2	203.8	18.4	1925.6
1987	5.4	2.8	7.1	41.2	55.6	127.3	122.4	50.9	42.4	99.3	36.3	3.6	594.3
1988	3.0	3.7	24.7	45.4	62.7	83.9	94.1	130.0	171.6	113.8	44.3	4.8	782.2
1989	2.2	24.1	7.1	65.9	39.2	23.1	32.5	54.8	161.4	113.8	44.3	4.8	573.1
1990	2.9	5.7	23.0	47.5	60.3	77.9	88.0	122.5	58.9	52.5	18.9	14.4	572.5
1991	7.2	13.3	51.8	17.8	59.3	68.6	58.7	68.7	68.9	17.7	20.7	19.2	472.0
1992	67.8	41.6	40.0	32.7	32.7	69.1	60.0	124.6	233.2	232.4	19.8	16.8	970.6
1993	37.5	27.4	45.9	25.3	46.0	68.8	59.4	96.7	130.6	100.9	19.8	16.8	675.0
1994	28.9	10.3	10.4	27.9	42.7	57.3	75.9	81.8	116.9	157.0	110.1	37.3	756.6
1995	24.4	20.4	29.7	36.2	46.7	60.8	62.4	91.5	128.3	112.4	38.9	18.2	670.0
1996	26.6	15.4	20.0	32.0	44.7	59.0	69.2	86.7	122.6	134.7	74.5	27.8	713.3
1997	13.2	11.3	26.5	40.8	55.1	72.9	79.6	111.6	150.9	114.4	43.9	11.7	731.9
1998	8.1	7.0	17.2	23.4	30.6	20.0	35.7	187.4	86.7	80.5	19.4	7.2	523.2
1999	5.2	3.0	10.1	6.4	10.2	17.3	48.6	51.2	80.6	189.8	31.2	7.0	460.6
2000	4.4	3.0	2.6	14.5	48.1	15.3	23.5	53.4	44.7	76.8	21.9	12.9	320.9
2001	8.5	5.9	28.0	14.8	31.1	31.6	44.9	41.0	62.8	41.5	12.8	7.0	329.8
2002	5.9	9.9	33.5	20.3	15.7	14.8	16.6	40.3	30.6	14.6	9.1	15.0	226.4
2003	18.1	12.0	12.7	30.4	16.0	21.3	23.2	34.3	46.2	80.6	18.9	9.8	323.7

2004	12.0	10.1	8.9	26.6	18.5	19.7	63.5	68.3	47.2	50.7	9.3	7.6	342.4
2005	9.0	7.3	13.8	39.1	68.9	20.9	51.6	65.4	50.4	33.3	17.8	8.3	385.8
2006	5.3	8.5	28.3	35.2	26.9	27.7	42.6	148.9	60.1	27.0	14.1	14.9	439.5
Mean	11.6	10.0	23.4	35.0	46.6	55.6	66.0	100.0	119.5	98.3	35.0	11.1	612.1
STDEV	14.7	9.2	17.9	19.4	26.0	38.7	62.1	68.9	81.6	63.0	40.5	8.5	334.8

Appendix Table 3 Gidawo river monthly flow at Aposto (m<sup>3</sup>/s)

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1977	11.7	8.5	7.9	10.4	17.1	17.4	20.4	30.8	37.1	63.8	39.4	12.9	277.4
1978	7.2	6.3	15.9	19.4	30.1	16.0	48.9	52.0	32.5	39.1	13.4	10.0	290.7
1979	10.1	9.6	10.8	12.2	19.1	22.8	16.1	32.2	31.9	36.0	17.6	14.0	232.4
1980	3.4	3.3	3.9	11.9	19.0	7.9	4.7	4.7	34.1	20.3	8.0	5.9	127.1
1981	3.9	3.7	7.7	23.9	26.4	10.7	14.3	34.2	57.9	35.5	14.1	7.1	239.2
1982	7.2	5.4	5.1	8.7	20.5	25.8	20.8	34.7	39.3	34.9	17.5	12.9	232.9
1983	7.4	5.9	7.2	21.2	42.6	30.3	23.0	62.0	45.2	55.0	28.1	14.5	342.3
1984	9.0	6.4	6.3	7.2	10.4	17.0	12.4	14.6	37.9	18.6	11.7	6.8	158.3
1985	5.7	4.0	5.0	14.2	45.4	19.9	18.9	20.7	37.3	29.9	9.2	7.0	217.3
1986	4.3	4.2	6.0	11.5	24.2	67.2	30.4	20.5	47.9	32.9	9.5	7.3	265.9
1987	5.3	4.7	8.0	12.7	36.8	26.9	13.4	11.7	18.2	31.9	0.1	0.3	169.9
1988	0.5	1.6	3.7	11.8	7.1	12.0	18.9	27.4	29.7	35.0	15.3	5.9	169.0
1989	6.9	5.6	5.3	12.8	10.7	15.2	15.4	9.6	30.2	33.3	11.9	11.4	168.4
1990	6.5	9.2	16.2	26.2	28.3	16.2	16.1	16.1	17.7	18.6	9.7	8.5	189.3
1991	8.5	8.3	10.0	11.9	12.5	8.7	12.9	11.6	26.8	14.6	5.5	4.7	136.2
1992	3.1	3.9	3.2	17.2	17.4	13.1	19.1	61.1	50.5	73.6	27.8	12.0	302.0
1993	7.8	10.4	6.2	14.4	43.7	42.9	20.7	14.6	24.1	44.1	19.5	7.2	255.9
1994	4.8	3.5	4.6	8.1	26.2	17.8	42.9	47.4	32.6	17.1	13.8	6.5	225.3
1995	4.4	4.0	5.0	24.6	24.3	11.0	12.8	17.5	22.4	33.4	9.9	7.9	177.1
1996	7.7	4.7	16.0	29.3	39.7	26.3	42.6	48.8	48.7	51.5	10.7	7.0	332.9
1997	5.7	3.7	4.2	13.9	21.7	15.0	27.1	34.7	21.2	57.3	43.5	15.6	263.5
1998	5.5	2.5	3.2	8.6	27.1	11.6	20.3	62.0	28.3	79.7	15.8	7.3	272.0

1999	5.8	4.2	5.1	4.9	9.8	6.4	6.6	8.2	10.2	18.3	7.8	5.1	92.5
2000	3.8	3.3	3.4	5.1	13.2	7.8	6.7	21.0	18.7	49.5	16.3	6.6	155.2
2001	6.0	4.4	5.1	7.2	15.1	21.7	10.5	23.6	25.7	26.3	10.7	6.6	163.0
2002	5.4	3.8	5.5	7.6	10.6	13.7	7.3	9.8	12.7	9.4	5.7	6.0	97.3
2003	4.9	3.6	4.6	10.4	8.0	6.2	8.1	17.6	12.5	35.5	14.7	8.5	134.6
2004	5.0	5.0	5.0	10.0	18.3	8.4	7.5	10.8	16.1	21.3	6.8	5.8	119.8
2005	4.8	3.3	4.6	7.4	28.2	17.5	14.9	16.1	22.8	16.8	9.5	5.4	151.2
2006	4.4	4.0	7.4	11.8	24.8	13.7	29.4	37.3	23.0	29.4	16.5	12.1	213.8
Mean	5.9	5.0	6.7	13.2	22.6	18.2	18.8	27.1	29.8	35.4	14.7	8.3	382.4
STDV	2.2	2.2	3.7	6.3	10.9	12.3	11.1	17.1	12.2	17.5	9.4	3.5	68.5

Appendix Table 4 Gidawo monthly flow at Mieso in (m<sup>3</sup>/s)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1997	27.6	22.8	23.7	44.8	59.1	47.7	67.0	75.7	58.1	107.1	92.5	30.7	656.7
1998	26.9	19.6	21.0	33.6	67.4	40.9	55.4	114.1	70.7	138.5	48.8	48.0	684.8
1999	27.9	24.1	26.2	25.8	37.0	29.4	29.9	33.5	37.5	53.5	32.4	31.5	388.7
2000	22.6	21.5	21.6	26.1	43.9	32.5	30.1	57.6	53.1	101.8	49.9	29.7	490.4
2001	27.5	23.9	25.3	30.2	48.6	64.2	37.9	68.8	73.9	75.2	38.4	28.8	542.6
2002	25.9	22.5	26.1	31.1	37.9	45.4	30.3	36.1	43.0	35.3	26.7	27.4	387.8
2003	24.9	22.0	24.1	37.7	32.0	28.0	32.1	54.5	42.6	16.1	16.1	16.1	346.1
2004	16.1	16.1	16.1	16.1	16.1	33.0	30.7	38.4	51.1	63.3	29.2	26.9	352.9
2005	25.1	22.3	24.8	30.0	69.5	49.8	44.3	46.6	59.2	47.9	34.1	16.1	469.5
Mean	24.9	21.6	23.2	30.6	45.7	41.2	39.7	58.4	54.4	71.0	40.9	28.4	570.9
STDEV	5.1	5.0	8.1	13.4	22.9	26.6	21.0	34.0	27.5	33.9	19.0	8.9	147.7

## 7.2. Meteorological Data

### 7.2.1. Rainfall data

Appendix Table 5 Corrected monthly rainfall data at Bilate Agri (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1984	6.0	31.2	29.5	18.4	77.0	59.6	91.7	53.7	81.6	27.4	54.3	24.5	554.9
1985	12.0	4.3	59.0	134.4	69.2	86.5	59.6	48.5	49.5	66.9	29.2	4.8	623.9
1986	0.0	60.0	0.0	78.0	129.0	98.4	108.7	105.3	119.2	44.1	23.5	68.1	834.3
1987	5.4	48.1	127.4	0.0	250.5	60.9	21.2	98.2	29.8	70.7	11.9	6.1	730.2
1988	20.3	43.0	52.3	133.5	108.0	72.0	208.4	141.4	80.8	105.9	0.0	11.2	976.8
1989	41.0	39.0	64.6	119.1	30.0	73.4	24.1	18.8	59.8	44.8	65.5	9.5	589.6
1990	8.7	134.3	77.0	97.1	90.1	74.8	75.0	30.1	22.5	26.3	22.1	7.8	665.8
1991	29.7	64.4	81.3	52.8	76.0	64.8	71.9	125.1	55.3	32.5	0.0	43.2	697.0
1992	24.2	94.5	73.9	141.7	70.2	54.7	60.9	75.9	84.2	138.9	92.5	25.3	936.9
1993	88.1	71.2	10.9	117.0	160.6	103.7	32.3	36.8	57.7	93.5	21.5	2.9	796.2
1994	0.0	14.5	45.8	179.4	50.2	88.1	263.1	26.3	36.3	42.1	40.8	35.0	821.6
1995	0.0	11.0	101.1	133.9	44.8	42.8	64.4	21.8	92.0	51.7	15.7	38.0	617.2
1996	118.3	1.3	96.8	126.5	80.9	252.5	133.0	106.7	76.3	49.4	18.7	25.4	1085.8
1997	11.3	0.0	8.5	146.5	76.2	57.4	72.0	97.3	89.2	164.3	150.0	41.3	914.0
1998	87.4	38.2	41.5	66.1	84.4	59.6	61.6	87.8	33.2	70.0	1.8	0.0	631.6
1999	8.6	0.0	37.0	37.5	48.7	32.5	67.3	84.9	42.1	76.1	19.8	7.3	461.8
2000	0.0	0.0	7.4	58.7	117.8	69.4	74.0	51.9	99.7	76.8	50.1	10.6	616.4
2001	10.9	17.4	34.9	39.4	101.3	80.0	53.5	45.9	48.7	91.3	4.6	9.0	536.9
2002	47.1	1.2	52.7	72.5	49.0	17.2	33.3	47.6	27.9	48.6	0.0	123.5	520.6
2003	12.0	16.0	39.3	276.6	58.7	75.9	66.7	112.2	72.8	53.1	45.1	19.3	847.7
2004	99.0	8.6	15.9	212.5	91.9	27.2	71.1	71.2	50.4	50.9	38.3	13.4	750.4
Mean	30.0	33.2	50.3	106.7	88.8	73.9	81.6	70.8	62.3	67.9	33.6	25.1	724.3

Appendix Table 6 Corrected monthly rainfall data at Dilla Mission (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0	101.3	65.8	257.9	223.6	141.4	140.6	54.4	155.0	111.4	47.5	9.2	1308.1
1987	28.3	69.7	224.9	194.0	314.3	138.7	22.2	47.7	141.6	320.0	43.0	63.3	1607.7
1988	52.3	71.0	68.9	167.2	247.9	69.9	262.8	207.3	153.3	194.6	60.0	6.6	1561.8
1989	50.8	26.2	102.0	108.9	78.5	133.8	98.3	59.0	150.2	158.4	90.8	143.3	1200.2
1990	13.2	198.8	159.9	161.4	158.9	53.7	71.9	109.1	132.8	94.1	59.3	25.3	1238.4
1991	27.7	49.9	123.6	195.0	169.4	105.3	109.5	109.6	143.6	101.8	9.0	44.7	1189.1
1992	14.2	37.8	44.8	199.9	179.9	156.9	100.9	97.4	186.1	250.0	54.2	46.4	1368.5
1993	132.7	20.2	1.3	153.7	340.8	162.1	34.5	72.7	114.9	163.2	50.5	17.6	1264.2
1994	1.3	10.2	132.4	384.2	147.6	105.5	257.4	164.0	142.6	92.1	38.4	0.4	1476.1
1995	0.5	55.4	73.9	262.9	190.3	67.0	151.8	105.4	200.0	174.0	42.4	18.4	1342
1996	87.6	33.2	165.8	280.1	252.9	232.8	80.6	151.6	237.8	86.0	27.9	12.4	1648.7
1997	13.5	5.3	20.9	256.8	272.3	161.3	111.5	93.1	149.0	220.3	203.5	85.2	1592.7
1998	58.4	45.6	108.4	232.9	210.4	67.9	124.7	146.2	107.8	155.2	82.3	7.2	1347
1999	20.7	14.1	116.9	148.0	241.5	75.5	46.6	39.2	144.4	148.3	35.1	13.8	1044.1
2000	0	0.0	19.2	188.8	312.9	19.7	98.7	113.3	83.6	133.1	69.8	13.1	1052.2
2001	14.7	24.3	105.6	226.7	194.8	144.4	72.2	145.3	153.6	197.1	52.4	28.8	1359.9
2002	35.6	18.7	208.0	136.6	137.9	104.7	69.6	108.6	88.2	57.4	70.1	115.2	1150.6
2003	71.9	7.4	81.1	146.7	100.3	102.9	55.5	120.7	67.3	128.0	95.4	22.2	999.4
2004	87.3	32.1	63.3	275.5	113	40.2	73.7	63.4	136	70	112.2	45.4	1112.1
2005	44.6	9.3	77	273.2	246.2	63.7	76.9	95.9	144.5	183.4	58.6	4	1277.3
2006	15.5	51.4	151.1	206.2	158.4	151.4	53.7	159.5	130.3	292.1	82	39.4	1491
Mean	36.7	42.0	100.7	212.2	204.4	109.5	100.6	107.8	141.1	158.6	65.9	36.3	1315.8

Appendix Table 7 Monthly rainfall at Hawassa (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.0	34.7	69.6	109.8	167.2	193.0	153.3	194.2	171.8	57.3	22.8	18.4	1192.1
1987	0.1	11.8	151.4	127.8	230.8	58.0	97.3	108.1	68.8	100.1	0.4	4.1	958.7
1988	25.8	68.5	17.5	80.9	100.1	110.9	117.7	138.8	205.0	83.9	1.3	6.6	957.0
1989	38.8	49.9	62.8	191.8	95.2	123.8	78.1	86.4	166.3	44.7	22.3	50.2	1010.3
1990	10.5	93.7	121.1	89.9	85.3	44.4	139.5	39.5	94.1	27.3	7.6	3.8	756.7
1991	12.3	90.6	87.4	48.0	129.5	116.7	109.2	90.6	104.0	21.6	12.2	44.8	866.9
1992	23.4	83.2	73.0	109.0	60.5	83.0	92.8	123.6	74.5	142.3	80.1	16.6	962.0
1993	101.6	109.1	22.3	104.9	165.3	46.7	54.7	130.8	47.8	130.8	10.5	3.9	928.4
1994	0.0	4.7	56.8	108.7	80.8	146.2	195.7	118.9	68.9	58.8	19.1	2.9	861.5
1995	0.8	21.4	61.8	156.1	43.6	118.7	175.7	134.7	166.8	22.3	18.3	84.2	1004.4
1996	78.4	36.9	89.6	113.8	161.5	243.3	121.2	108.7	145.0	69.6	19.7	1.4	1189.1
1997	23.4	1.7	75.1	125.0	73.0	111.2	98.6	113.9	118.9	157.1	132.2	24.0	1054.1
1998	92.0	140.0	90.8	86.4	88.4	56.0	172.9	108.3	109.6	193.3	10.6	0.0	1148.3
1999	19.8	0.4	105.5	27.1	64.7	99.8	135.1	83.8	115.4	120.4	20.1	16.8	808.9
2000	1.1	0.0	11.0	132.0	145.1	36.4	80.0	179.3	87.6	110.7	29.0	9.3	821.5
2001	1.8	39.9	122.7	67.0	233.7	137.5	93.5	131.7	89.7	80.2	2.6	21.3	1021.6
2002	52.5	2.4	127.7	119.6	85.2	118.4	76.6	190.4	82.2	37.2	0.0	51.5	943.7
2003	30.4	2.0	78.2	179.1	40.4	110.5	74.5	76.1	85.7	56.4	6.2	51.8	791.3
2004	46.2	94.2	42.0	83.1	81.5	75.7	75.4	182.8	113.0	57.1	26.8	15.2	893.0
2005	81.1	7.7	120.9	156	144.5	73.2	150.9	61.3	122.2	28.4	46	10.4	1002.6
2006	1.7	9	139.2	145.9	74.4	108	171.1	169.3	194.9	56.9	79.2	48.3	1197.9
Mean	30.6	42.9	82.2	112.5	111.9	105.3	117.3	122.4	115.8	78.9	27.0	23.1	970.0

Appendix Table 8 Corrected monthly rainfall at Yirgalem (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1986	0.0	107.8	70.7	210.3	172.0	162.8	59.5	137.7	182.6	77.2	14.1	47.6	1242.3
1987	0.0	15.1	190.9	71.1	263.0	105.6	20.1	85.8	83.1	182.3	13.1	91.0	1121.1
1988	14.9	49.3	61.0	167.4	104.8	78.8	201.5	196.1	140.9	126.8	7.1	1.1	1149.7
1989	20.3	77.8	192.1	235.0	144.6	91.7	83.6	34.8	267.4	185.6	44.6	73.6	1451.1
1990	13.3	214.9	148.8	228.1	111.3	104.5	96.3	115.8	118.9	75.2	30.4	12.9	1270.4
1991	6.2	32.0	74.5	153.0	176.7	126.1	85.1	185.1	274.2	77.6	0.0	37.2	1227.7
1992	26.1	36.9	64.3	126.8	164.2	95.8	130.0	147.4	170.2	260.0	61.4	22.2	1305.3
1993	27.2	76.7	32.5	148.7	298.2	138.0	29.3	48.6	127.8	290.4	23.3	2.5	1243.2
1994	2.9	13.5	77.3	215.6	192.2	149.9	175.1	147.7	130.4	75.2	47.8	17.0	1244.6
1995	0.0	26.0	75.1	328.9	148.6	48.2	84.6	98.9	181.2	42.9	32.2	54.1	1120.7
1996	86.3	77.4	195.5	248.8	159.9	175.3	123.5	91.9	291.7	85.3	6.6	2.4	1544.6
1997	22.6	5.4	31.7	59.9	56.2	98.7	156.7	151.0	202.8	370.5	193.6	51.8	1400.9
1998	68.1	59.0	99.4	227.7	164.8	84.9	190.2	200.3	108.0	442.5	21.4	0.0	1666.3
1999	16.5	24.1	98.5	108.4	163.3	62.2	105.0	184.6	107.4	183.1	13.7	8.7	1075.5
2000	3.0	0.0	170.9	170.9	265.9	100.0	115.0	90.7	90.9	119.3	55.1	47.1	1228.8
2001	16.1	38.7	126.9	101.7	277.4	104.6	65.3	228.3	224.9	356.9	9.6	23.5	1573.9
2002	47.1	6.2	216.5	106.9	109.2	81.7	37.9	101.0	89.7	64.1	0.0	86.8	947.1
2003	52.5	12.9	88.5	177.0	25.8	52.6	61.7	76.9	101.3	109.9	61.7	60.0	880.8
2004	79.6	35.6	54.5	75.0	65.9	55.7	108.3	90.5	106.7	102.9	37.8	1.3	813.8
2005	34.4	1.1	81.3	134.0	243.5	80.1	129.7	67.4	130.1	105.9	64.6	0.0	1072.1
2006	2.9	36.8	162.9	212.2	153.9	91.4	128.7	197.4	116.0	282.3	42.3	84.5	1511.3
Mean	25.7	45.1	110.2	167.0	164.8	99.5	104.1	127.5	154.6	172.2	37.2	34.5	1242.4

Appendix Table 9 Grid interpolated long-term mean monthly rainfall data around study area (mm)

No	Stations name	Stations code	Latitude (Northing)	Longitude (Easting)	Elevation (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nove	Dec
1	Arbegona	516	6.7	38.71	2709	37	55	93	150	137	119	164	161	171	129	57	29
2	Aleta wondo	550	6.66	38.41	1805	36	53	95	152	157	113	140	138	166	134	58	22
3	Leku	592	6.75	38.43	1775	35	53	93	143	132	108	140	139	161	115	50	22
4	Hagereselam	536	6.46	38.51	2747	43	62	112	192	191	139	161	160	196	175	77	29
5	Hayissa witto	535	6.93	38.7	2747	43	62	112	192	191	139	161	160	196	175	77	29
6	Morocho	595	6.91	38.41	1886	35	52	92	130	135	105	144	143	150	103	45	21

## 7.2.2. Summary of other climatic data

Appendix Table 10 Summary of other climatic data in and around study area

No	Stations/recording	Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bilate Agri													
	1983-2004	Sunshine	8.4	7.6	7.8	6.3	7.4	6.0	4.8	5.0	6.1	9.5	7.6	6.8
	1983-2005	Tmax ( °C )	32.3	33.0	33.3	31.7	29.8	28.2	27.0	27.6	29.1	30.0	31.2	31.5
	1983-2005	Tmin ( °C )	15.5	15.8	15.5	15.2	15.5	15.4	15.4	15.4	15.1	14.2	13.5	14.0
	1983-2005	Wind (m/s)	1.4	1.5	1.3	1.0	1.1	1.2	1.1	0.9	0.8	0.7	0.9	1.4
	1983-2005	RH-06	69.4	73.8	84.9	91.1	93.4	92.1	92.4	91.6	93.5	89.4	71.5	66.9
	1983-2005	RH-12	41.4	42.8	45.0	57.3	61.1	62.2	64.9	60.4	55.4	50.4	46.8	41.0
	1983-2005	RH-18	39.6	39.9	49.8	61.5	63.3	60.6	64.4	59.9	64.7	62.6	53.7	46.3
		Average	50.1	52.1	59.9	70.0	72.6	71.6	73.9	70.7	71.2	67.5	57.3	51.4
2	Dilla													
	1974-2007	Tmax ( °C )	29.7	30.4	30.5	28.3	27.2	26.6	25.7	26.0	26.5	26.9	28.0	28.8
	1974-2007	Tmin ( °C )	10.2	10.4	11.5	12.4	12.4	12.1	12.5	12.8	12.3	12.3	11.0	10.5
	1988-2007	Sunshine	7.7	7.1	6.6	5.9	6.2	4.9	3.3	4.6	4.7	5.5	7.5	7.9
	1989-2005	Wind (m/s)	0.6	0.7	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.5
	1997-2005	RH-06	82.3	78.7	83.3	89.7	91.0	89.5	91.1	91.1	93.0	92.1	90.7	89.1
	1989-2005	RH-12	46.6	43.6	49.2	59.7	65.5	66.0	68.6	66.2	66.2	62.0	59.1	52.3
	1989-2005	RH-18	56.7	51.9	58.5	73.9	78.0	74.4	76.3	75.0	80.6	79.6	71.6	66.5
		Average	61.9	58.0	63.7	74.4	78.2	76.6	78.7	77.4	80.0	77.9	73.8	69.3
3	Yirgalem													
	1981-2006	T max ( °C )	28.1	28.7	28.3	27.0	25.7	25.0	23.5	24.0	24.6	25.6	26.7	27.3
	1981-2006	T min ( °C )	11.0	10.8	12.1	12.1	11.8	11.7	11.9	12.0	11.6	12.0	11.4	10.7

Appendix Table 11 ET<sub>O</sub> and climatic data for Bilate meteorological station

Climate Data Table							
Country	Ethiopia		Station	Bilate Agri		Altitude	1281 (m)
Month	Max Temp. (C)	Min Temp. (C)	Humidity (%)	WindSpeed (km/d)	SunShine (hours)	Solar Radiation (MJ/m2/d)	ET <sub>O</sub> (mm/d)
January	32.3	15.5	50.1	1.4	8.4	20.4	3.3
February	33.0	15.8	52.1	1.5	7.6	20.3	3.5
March	33.3	15.5	59.9	1.3	7.8	21.5	3.9
April	31.7	15.2	70.0	1.0	6.3	19.2	3.6
May	29.8	15.5	72.6	1.1	7.4	20.2	3.7
June	28.2	15.4	71.6	1.2	6.0	17.7	3.2
July	27.0	15.4	73.9	1.1	4.8	16.0	2.9
August	27.6	15.4	70.7	0.9	5.0	16.8	3.1
September	29.1	15.1	71.2	0.8	6.1	18.7	3.4
October	30.0	14.2	67.5	0.7	9.5	23.4	4.0
November	31.2	13.5	57.3	0.9	7.6	19.4	3.2
December	31.5	14.0	51.4	1.4	6.8	17.7	2.9
Average	30.4	15.0	64.0	1.1	6.9	19.3	3.4

Appendix Table 12 ET<sub>O</sub> and climatic data for Dila meteorological station

Climate Data Table							
Country	Ethiopia		Station	Dila		Altitude	1723 (m)
Month	Max Temp. (C)	Min Temp. (C)	Humidity (%)	WindSpeed (km/d)	SunShine (hours)	Solar Radiation (MJ/m2/d)	ET <sub>O</sub> (mm/d)
January	29.7	10.2	61.9	51.8	7.7	19.5	3.6
February	30.4	10.4	58.0	60.5	7.1	19.6	3.9
March	30.5	11.5	63.7	60.5	6.6	19.7	4.0
April	28.3	12.4	74.4	51.8	5.9	18.6	3.7
May	27.2	12.4	78.2	43.2	6.2	18.4	3.5
June	26.6	12.1	76.6	0.5	4.9	16.0	2.9
July	25.7	12.5	78.7	34.6	3.3	13.8	2.7
August	26.0	12.8	77.4	34.6	4.6	16.2	3.1
September	26.5	12.3	80.0	0.4	4.7	16.6	3.0
October	26.9	12.3	77.9	0.0	5.5	17.4	3.1
November	28.0	11.0	73.8	0.5	7.5	19.4	3.2
December	28.8	10.5	69.3	0.5	7.9	19.3	3.1
Average	27.9	11.7	72.5	28.2	6.0	17.9	3.3

Appendix Table 13 ET<sub>0</sub> and climatic data for Yirgalem meteorological station

Climate Data Table							
Country	Ethiopia		Station	YIRGALEM		Altitude	1835 (m)
Month	Max Temp. (C)	Min Temp. (C)	Humidity (%)	WindSpeed (km/d)	SunShine (hours)	Solar Radiation (MJ/m2/d)	ET <sub>0</sub> (mm/d)
January	28.5	8.9	76.0	112.0	8.9	21.2	4.1
February	29.0	9.5	73.0	112.0	8.4	21.6	4.4
March	29.0	10.6	77.0	130.0	7.5	21.0	4.5
April	27.2	11.1	86.0	112.0	7.7	21.3	4.1
May	26.8	11.1	88.0	112.0	7.4	20.2	3.9
June	25.3	11.1	89.0	138.0	6.8	18.8	3.6
July	23.7	12.2	86.0	112.0	4.5	15.6	3.0
August	24.1	12.9	82.0	104.0	4.6	16.2	3.2
September	24.6	12.2	88.0	78.0	6.0	18.6	3.4
October	25.8	11.7	79.0	69.0	8.1	21.3	3.8
November	26.4	10.2	80.0	86.0	9.0	21.5	3.8
December	27.5	10.2	68.0	95.0	8.7	20.4	3.9
Average	26.5	11.0	81.0	105.0	7.3	19.8	3.8

Appendix Table 14.E T<sub>0</sub> and climatic data for Aleta Wondo meteorological station

Climate Data Table							
Country	Ethiopia		Station	WENDO (ALETA)		Altitude	1860 (m)
Month	Max Temp. (C)	Min Temp. (C)	Humidity (%)	WindSpeed (km/d)	SunShine (hours)	Solar Radiation (MJ/m2/d)	ET <sub>0</sub> (mm/d)
January	28.5	4.1	85.0	112.0	8.7	20.9	4.1
February	28.5	6.8	77.0	112.0	8.4	21.6	4.3
March	26.2	8.6	77.0	130.0	7.5	21.1	4.2
April	26.9	10.2	87.0	112.0	7.8	21.5	4.1
May	27.3	8.9	92.0	112.0	7.4	20.2	3.9
June	25.5	9.2	93.0	138.0	6.3	18.0	3.5
July	24.9	9.5	91.0	112.0	4.4	15.4	3.0
August	25.8	9.1	90.0	104.0	4.5	16.1	3.2
September	24.9	9.4	93.0	78.0	6.0	18.6	3.4
October	25.9	8.3	84.0	69.0	7.1	19.8	3.6
November	25.7	6.9	85.0	86.0	9.0	21.5	3.8
December	26.7	4.7	75.0	95.0	8.7	20.4	3.8
Average	26.4	8.0	85.8	105.0	7.1	19.6	3.7

## 7.2.3. Crop water requirement tables

Appendix Table 15 Sugarcane monthly irrigation water requirements at Yirgalem stations

\*\*\*\*\*  
Crop Water Requirements Report  
\*\*\*\*\*

- Crop # 1 : Sugarcane (Ratoon)  
- Block # : tAll blocksý  
- Planting date : 9/12  
- Calculation time step = 30 Day(s)  
- Irrigation Efficiency = 65%  
Climatic station = yirgalem

Date	ETo (mm/period)	Planted Area (%)	Crop Kc	CWR (ETm)	Total Rain (mm/period)	Effect. Rain (mm/period)	Irr. Req. mm	FWS (l/s/ha)
9/12	122.55	100.00	0.40	49.02	50.60	45.27	3.74	0.02
8/1	129.38	100.00	0.62	80.38	59.02	51.71	28.67	0.17
7/2	132.31	100.00	1.04	138.19	81.57	68.28	69.91	0.41
9/3	128.86	100.00	1.25	161.07	101.77	82.85	78.22	0.46
8/4	120.81	100.00	1.25	151.02	117.65	94.11	56.91	0.34
8/5	111.14	100.00	1.25	138.93	128.42	101.58	37.35	0.22
7/6	102.86	100.00	1.25	128.58	133.78	105.17	23.41	0.14
7/7	98.23	100.00	1.25	122.79	133.57	104.85	17.94	0.11
6/8	98.27	100.00	1.25	122.83	127.62	100.52	22.32	0.13
5/9	102.58	100.00	1.17	119.77	115.81	92.08	27.70	0.16
5/10	109.51	100.00	1.01	110.57	98.42	79.65	30.91	0.18
4/11	116.67	100.00	0.85	99.39	76.63	64.04	35.35	0.21
4/12	20.02	100.00	0.76	15.22	10.49	9.03	6.19	0.22
Total	1393.19			1437.77	1235.35	999.14	438.63	0.21ý

\* ETo data is distributed using polynomial curve fitting.  
\* Rainfall data is distributed using polynomial curve fitting.

Appendix Table 16 Banana monthly irrigation water requirements at Yirgalem stations

\*\*\*\*\*  
Crop Water Requirements Report  
\*\*\*\*\*

- Crop # 1 : BANANA (second year, Mediterranean, 15 Nov dormancy)  
- Block # : tAll blocksý  
- Planting date : 8/11  
- Calculation time step = 30 Day(s)  
- Irrigation Efficiency = 65%  
Meteorological station = Yirgalem

Date	ETo (mm/period)	Planted Area (%)	Crop Kc	CWR (ETm)	Total Rain (mm/period)	Effect. Rain (mm/period)	Irr. Req.	FWS (l/s/ha)
8/11	117.50	100.00	1.00	117.50	73.52	61.80	55.70	0.33
8/12	122.37	100.00	1.00	122.37	51.07	45.61	76.77	0.46
7/1	129.17	100.00	1.00	129.17	58.27	51.15	78.02	0.46
6/2	132.32	100.00	1.00	132.32	80.84	67.74	64.57	0.38
8/3	129.06	100.00	1.01	130.75	101.15	82.42	48.34	0.29
7/4	121.13	100.00	1.10	133.36	117.20	93.79	39.57	0.23
7/5	111.46	100.00	1.19	132.41	128.15	101.39	31.02	0.18
6/6	103.09	100.00	1.20	123.71	133.69	105.11	18.60	0.11
6/7	98.31	100.00	1.20	117.98	133.67	104.92	13.05	0.08
5/8	98.19	100.00	1.20	117.83	127.92	100.73	17.10	0.10
4/9	102.38	100.00	1.20	122.85	116.30	92.42	30.43	0.18
4/10	109.27	100.00	1.13	123.11	99.08	80.13	42.98	0.26
3/11	18.94	100.00	1.01	19.19	14.50	11.91	7.28	0.26
Total	1393.19			1522.56	1235.35	999.14	523.42	0.26ý

Appendix Table 17 Sugarcane monthly irrigation water requirements at Aleta Wondo station

```

*****
Crop Water Requirements Report
*****
- Crop # 1 : Sugarcane (Ratoon)
- Block # : tAll blocksy
- Planting date : 1/12
- Calculation time step = 30 Day(s)
- Irrigation Efficiency = 65%
Meteorological station = Aleta Wondo
-----
Date      ETo      Planted  Crop    CWR    Total  Effect.  Irr.    FWS
          (mm/period)  Area    Kc      (ETm)  Rain   Rain    Req.    (l/s/ha)
                               (%)
-----
1/12      118.31   100.00   0.40    47.32   70.48   57.96   0.00   0.00
31/12     124.25   100.00   0.62    77.22   60.18   52.33   24.89   0.15
30/1      128.37   100.00   1.04    134.14  90.05   71.89   62.25   0.37
1/2       127.08   100.00   1.25    158.86  119.26  90.60   68.26   0.41
31/3      121.27   100.00   1.25    151.58  144.14  106.15  45.44   0.27
30/4      113.09   100.00   1.25    141.37  162.89  117.47  23.90   0.14
30/5      105.10   100.00   1.25    131.37  174.49  124.07   7.30   0.04
29/6      99.45    100.00   1.25    124.31  178.27  125.68   0.00   0.00
29/7      97.50    100.00   1.25    121.87  173.62  122.10   0.00   0.00
28/8      99.51    100.00   1.17    116.22  160.15  113.22   3.00   0.02
27/9      104.68   100.00   1.01    105.70  138.05  99.28   6.42   0.04
27/10     111.35   100.00   0.85    94.85   108.74  81.20   13.65   0.08
26/11     19.20    100.00   0.76    14.60   14.94   11.59   3.01
-----
Total     1369.16                                1419.42  1595.26  1173.53  258.11  t0.13y
-----

```

\*| ETo data is distributed using polynomial curve fitting.

Appendix Table 18 Banana monthly irrigation water requirements at Aleta Wondo station

```

*****
Crop Water Requirements Report
*****
- Crop # 1 : BANANA (second year, Mediterranean, 15 Nov dormancy)
- Block # : tAll blocksy
- Planting date : 1/12
- Calculation time step = 30 Day(s)
- Irrigation Efficiency = 65%
Meteorological station = Aleta Wondo
-----
Date      ETo      Planted  Crop    CWR    Total  Effect.  Irr.    FWS
          (mm/period)  Area    Kc      (ETm)  Rain   Rain    Req.    (l/s/ha)
                               (%)
-----
1/12      118.31   100.00   1.00    118.31   70.48   57.96   60.36   0.36
31/12     124.25   100.00   1.00    124.25   60.18   52.33   71.92   0.43
30/1      128.37   100.00   1.00    128.37   90.05   71.89   56.48   0.34
1/3       127.08   100.00   1.00    127.08   119.26  90.60   36.48   0.22
31/3      121.27   100.00   1.01    122.85   144.14  106.15  16.70   0.10
30/4      113.09   100.00   1.10    124.52   162.89  117.47   7.05   0.04
30/5      105.10   100.00   1.19    124.86   174.49  124.07   0.79   0.00
29/6      99.45    100.00   1.20    119.34   178.27  125.68   0.00   0.00
29/7      97.50    100.00   1.20    17.00    173.62  122.10   0.00   0.00
28/8      99.51    100.00   1.20    119.42   160.15  113.22   6.19   0.04
27/9      104.68   100.00   1.20    125.62   138.05  99.28   26.34   0.16
27/10     111.35   100.00   1.13    125.47   108.74  81.20   44.27   0.26
26/11     19.20    100.00   1.01    19.45   14.94   11.59   7.86   0.28
-----
Total     1369.16                                1496.54  1595.26  1173.53  334.45  t0.16y
-----

```

\* ETo data is distributed using polynomial curve fitting.

\* Rainfall data is distributed using polynomial curve fitting.

\*\*\*\*\*

Appendix Table 19 Sugarcane monthly irrigation water requirements at Dilla station

```

*****
|
|                               Crop Water Requirements Report
|
*****
- Crop # 1                      : Sugarcane (Ratoon)
- Block #                       : tAll blocksý
- Planting date                 : 9/12
- Calculation time step = 30 Day(s)
- Irrigation Efficiency = 65%
- Meteorological station = Dilla
-----
Date      ETo      Planted   Crop      CWR      Total   Effect.   Irr.      FWS
      (mm/period)  Area      Kc      (ETm)   Rain   Rain   Req.      (l/s/ha)
-----
9/12     103.36    100.00    0.40     41.34    51.03    44.96    0.00     0.00
8/1      111.49    100.00    0.62     69.36    62.14    51.09    18.27    0.11
7/2      116.30    100.00    1.04    121.54    96.03    72.61    48.93    0.29
9/3      114.82    100.00    1.25    143.53    123.30    90.40    53.13    0.32
8/4      108.52    100.00    1.25    135.65    140.93    102.66    32.99    0.20
8/5      99.98     100.00    1.25    124.97    148.82    109.22    15.76    0.09
7/6      91.95     100.00    1.25    114.94    148.39    110.72    4.22     0.03
7/7      86.62     100.00    1.25    108.27    141.54    108.00    0.27     0.00
6/8      85.10     100.00    1.25    106.38    129.94    101.70    4.68     0.03
5/9      87.35     100.00    1.17    102.02    114.74    92.17    9.85     0.06
5/10     92.22     100.00    1.01     93.12    96.64    79.61    13.51    0.08
4/11     97.86     100.00    0.85     83.37    76.32    64.45    18.92    0.11
4/12     16.80     100.00    0.76     12.78    10.65    9.15     3.63     0.13
-----
Total    1212.37                                1257.26  1340.48  1036.73  224.14  t0.11ý
-----
* ETo data is distributed using polynomial curve fitting.

```

Appendix Table 20 Banana monthly irrigation water requirements at Dilla station

```

*****
|                               Crop Water Requirements Report
|
*****
- Crop # 1                      : BANANA (second year, Mediterranean, 15 Nov dormancy)
- Block #                       : tAll blocksý
- Planting date                 : 8/11
- Calculation time step = 30 Day(s)
- Irrigation Efficiency = 65%
- Meteorological station = Dilla
-----
Date      ETo      Planted   Crop      CWR      Total   Effect.   Irr.      FWS
      (mm/period)  Area      Kc      (ETm)   Rain   Rain   Req.      (l/s/ha)
-----
8/11     98.56     100.00    1.00     98.56    73.50    62.29    36.27    0.22
8/12    103.16    100.00    1.00    103.16    51.64    45.43    57.74    0.34
7/1      111.22    100.00    1.00    111.22    60.97    50.35    60.87    0.36
6/2      116.24    100.00    1.00    116.24    94.98    71.93    44.31    0.26
8/3      114.96    100.00    1.01    116.48    122.54    89.89    26.58    0.16
7/4      108.78    100.00    1.10    119.77    140.50    102.34    17.43    0.10
7/5      100.27    100.00    1.19    119.12    148.70    109.08    10.03    0.06
6/6      92.19     100.00    1.20    110.62    148.52    110.74    0.00     0.00
6/7      86.74     100.00    1.20    104.08    141.86    108.15    0.00     0.00
5/8      85.09     100.00    1.20    102.11    130.39    101.97    0.14     0.00
4/9      87.23     100.00    1.20    104.67    115.30    92.54    12.14    0.07
4/10     92.04     100.00    1.13    103.71    97.29    80.07    23.64    0.14
3/11     15.90     100.00    1.01     16.11    14.29    11.94     4.17     0.15
-----
Total    1212.37                                1325.86  1340.48  1036.73  293.32  t0.14ý
-----
* ETo data is distributed using polynomial curve fitting.

```

Appendix Table 21 Sugarcane monthly irrigation water requirements at Bilate station

```

*****
Crop Water Requirements Report
*****
- Crop # 1 : Sugarcane (Ratoon)
- Block # : tAll blocksy
- Planting date : 6/10
- Calculation time step = 30 Day(s)
- Irrigation Efficiency = 65%
Meteorological station = Bilate
-----
Date ETo Planted Crop CWR Total Effect. Irr. FWS
(mm/period) Area Kc (ETm) Rain Rain Req. (l/s/ha)
(%)
-----
6/10 101.30 100.00 0.40 40.52 47.12 43.30 0.00 0.00
5/11 101.74 100.00 0.62 63.00 36.48 34.34 28.66 0.17
5/12 99.23 100.00 1.04 103.50 29.61 28.29 75.21 0.45
4/1 101.67 100.00 1.25 127.08 33.11 30.94 96.15 0.57
3/2 108.40 100.00 1.25 135.50 47.74 42.80 92.70 0.55
5/3 109.92 100.00 1.25 137.40 62.96 55.14 82.27 0.49
4/4 107.34 100.00 1.25 134.17 75.75 65.57 68.60 0.41
4/5 102.84 100.00 1.25 128.55 83.91 72.34 56.21 0.33
3/6 98.68 100.00 1.25 123.34 86.22 74.44 48.90 0.29
3/7 96.43 100.00 1.17 112.69 82.56 71.75 40.94 0.24
2/8 96.64 100.00 1.01 97.64 73.87 64.95 32.69 0.19
1/9 98.66 100.00 0.85 84.09 61.94 55.40 28.68 0.17
1/10 16.69 100.00 0.76 12.69 9.07 8.21 4.48 0.16
-----
Total 1239.53 1300.17 730.33 647.48 655.47 t0.32y
-----

```

\* ETo data is distributed using polynomial curve fitting.

Appendix Table 22 Banana monthly irrigation water requirements at Bilate station

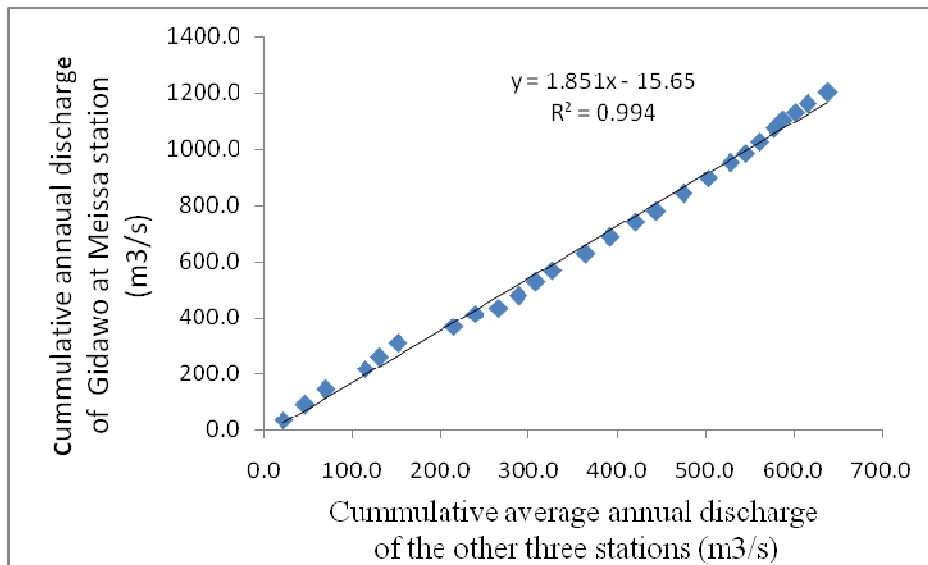
```

*****
Crop Water Requirements Report
*****
- Crop # 1 : BANANA (second year, Mediterranean, 15 Nov dormancy)
- Block # : tAll blocksy
- Planting date : 6/10
- Calculation time step = 30 Day(s)
- Irrigation Efficiency = 65%
Meteorological station = Bilate
-----
Date ETo Planted Crop CWR Total Effect. Irr. FWS
(mm/period) Area Kc (ETm) Rain Rain Req. (l/s/ha)
(%)
-----
6/10 101.30 100.00 1.00 101.30 47.12 43.30 58.00 0.34
5/11 101.74 100.00 1.00 101.74 36.48 34.34 67.39 0.40
5/12 99.23 100.00 1.00 99.23 29.61 28.29 70.94 0.42
4/1 101.67 100.00 1.00 101.67 33.11 30.94 70.73 0.42
3/2 108.40 100.00 1.01 109.86 47.74 42.80 67.06 0.40
5/3 109.92 100.00 1.10 121.09 62.96 55.14 65.95 0.39
4/4 107.34 100.00 1.19 127.54 75.75 65.57 61.96 0.37
4/5 102.84 100.00 1.20 123.41 83.91 72.34 51.07 0.30
3/6 98.68 100.00 1.20 118.41 86.22 74.44 43.97 0.26
3/7 96.43 100.00 1.20 115.72 82.56 71.75 43.97 0.26
2/8 96.64 100.00 1.20 115.96 73.87 64.95 51.02 0.30
1/9 98.66 100.00 1.13 111.23 61.94 55.40 55.82 0.33
1/10 16.69 100.00 1.01 16.91 9.07 8.21 8.70 0.31
-----
Total 1239.53 1364.06 730.33 647.48 716.58 t0.35y
-----

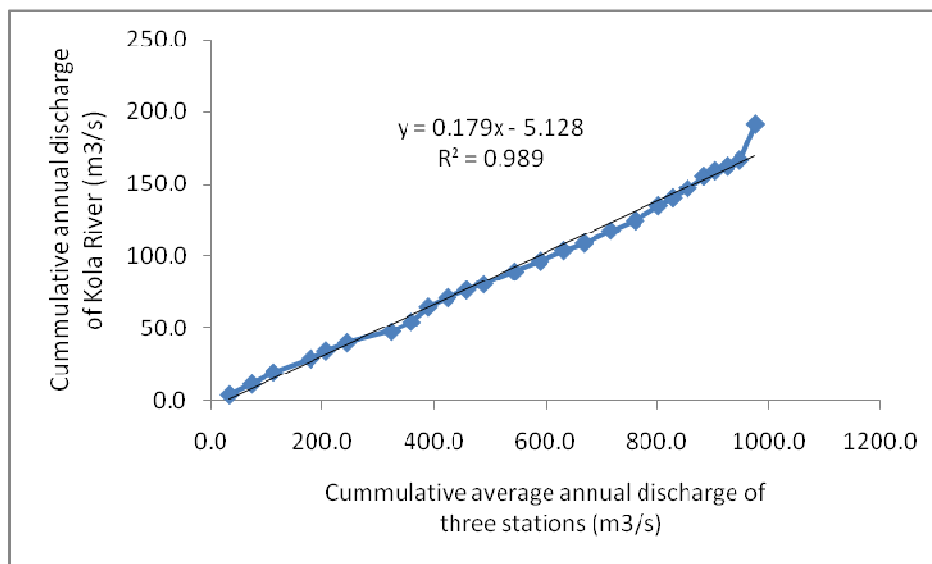
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\* ETo data is distributed using polynomial curve fitting.

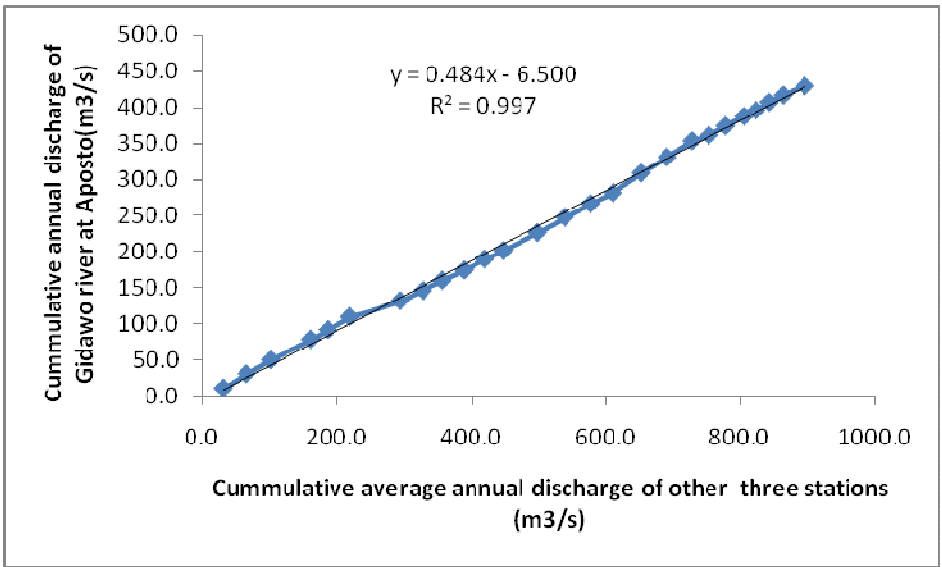
### 7.3. Double Mass Curve Analysis Result



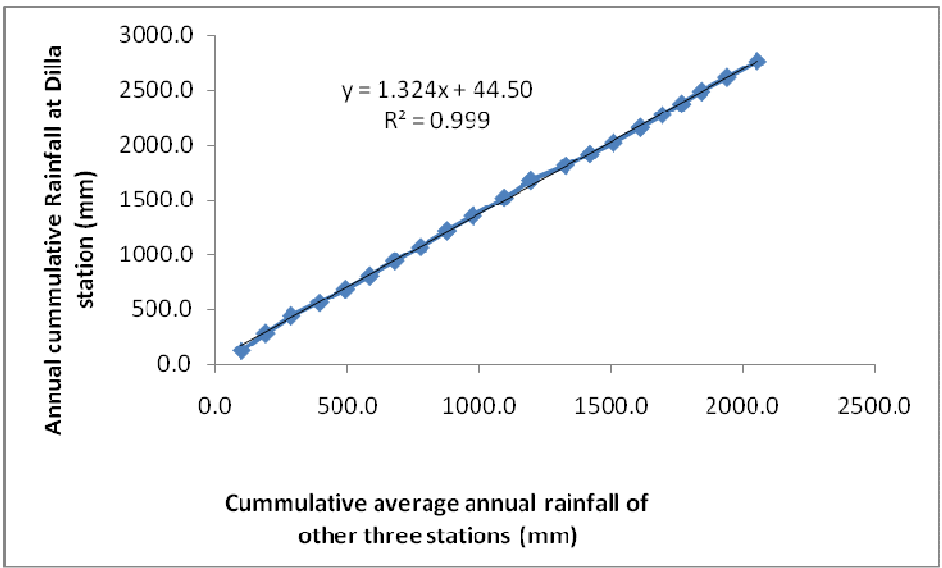
Appendix Figure 1 Double mass curve for the consistency of Gidawo river at Meissa gauging station



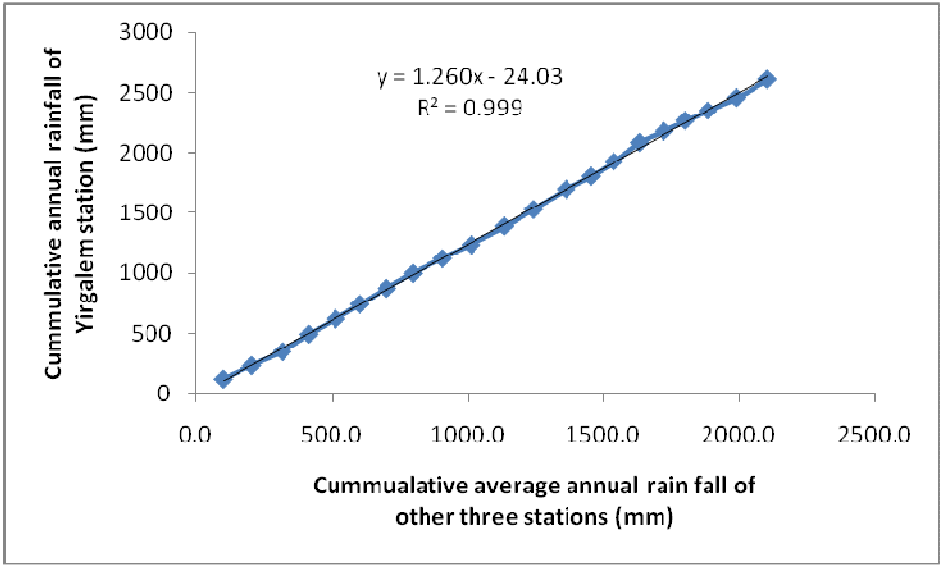
Appendix Figure 2 Double mass curve for the consistency of Kola river gauging station



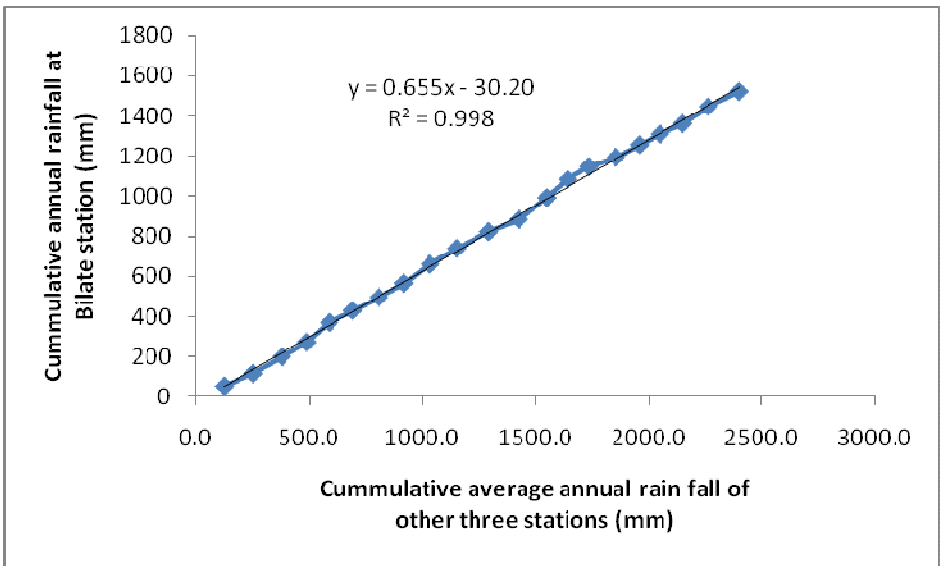
Appendix Figure 3 Double mass curve for the consistence of Gidawo river at Aposto gauging station.



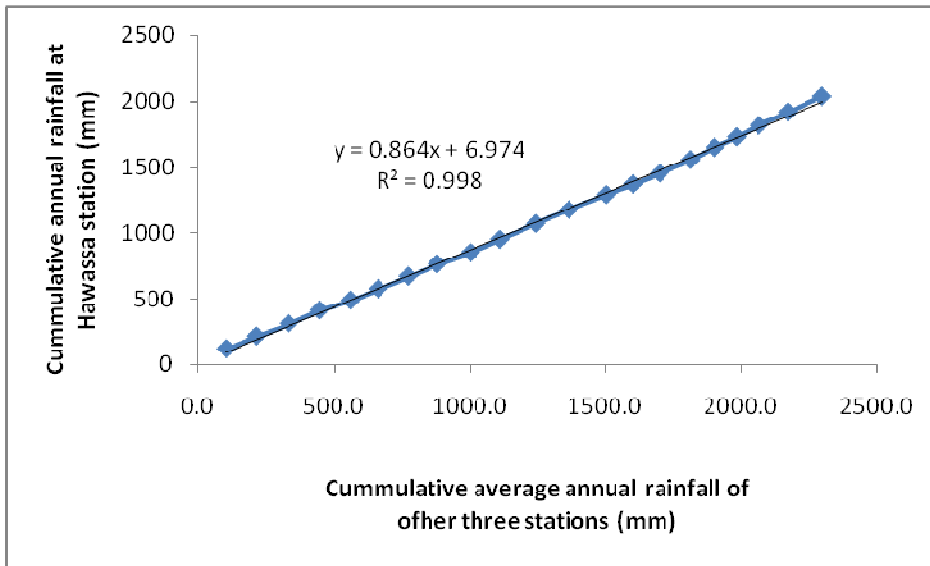
Appendix Figure 4 Double mass curve for the consistency of Dilla meteorological station rainfall data



Appendix Figure 5 Double mass curve for the consistency of Yirgalem meteorological station rainfall data



Appendix Figure 6 Double mass curve for the consistency of Bilate meteorological station rainfall data



Appendix Figure 7 Double mass curve for the consistency Hawassa meteorological station rainfall data