HAWASSA UNIVERSITY

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FACULTY OF BIO-SYSTEMS AND WATER RESOURCES ENGINEERING

DEPARTMENT OF WATER RESOURCES AND IRRIGATION ENGINEERING

GIS-BASED SURFACE IRRIGATION POTENTIAL ASSESSMENT: A CASE STUDY IN MUGA WATERSHED EAST GOJAM ZONE, AMHARA REGION, ETHIOPIA

MSC IN IRRIGATION AND DRAINAGE ENGINEERING

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HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

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THESIS SUBMITTED TO THE DEPARTMENT OF WATER RESOURCES AND IRRIGATION ENGINEERING, HAWASSA INSTITUTE OF TECHNOLOGY, SCHOOL OF GRADUATE STUDIES, HAWASSA UNIVERSITY

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FEBRUARY, 2021

DECLARATION

I hereby declare that this MSc thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged. I solemnly declare that this thesis is not submitted and presented to any other institution anywhere for the award of any academic degree, diploma, or certificate.

Name: Zelalem Abeza   Signature: _______________

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This is to certify that the MSc Thesis entitled "GIS-BASED SURFACE IRRIGATION POTENTIAL ASSESSMENT: A CASE STUDY IN MUGA WATERSHED, EAST GOJAM ZONE, AMHARA REGION, ETHIOPIA" submitted in partial fulfillment of the requirements for the degree of Master's with specialization in Irrigation and Drainage Engineering, the Graduate Program of the Department of Water resources and Irrigation Engineering, and has been carried out by Zelalem Abeza (ID NO. PGIrDrR/0016/2011), under my supervision. Therefore I recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

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We, the undersigned, members of the Board of Examiners of the final open defense by Zelalem Abeza have read and evaluated his thesis entitled "GIS-BASED SURFACE IRRIGATION POTENTIAL ASSESSMENT: A CASE STUDY IN MUGA WATERSHED, EAST GOJAM ZONE, AMHARA REGION, ETHIOPIA", and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree.

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TABLE OF CONTENTS **PAGES**

LIST OF TABLES

LIST OF FIGURES

LIST OF TABLES/FIGURES IN THE APPENDIXES

LIST OF ACRONYEMS AND ABRBEATIONS

AHP	Analytical Hierarchy Process
CWR	Crop Water Requirement
CROPWAT	Crop Water Assessment Tool
DEM	Digital Elevation Model
ERDAS	Earth Resource Data Analysis
ESCO	Soil Evaporation Compensation Factor
ESRI	Environmental System Research Institute
ETc	Crop Evapotranspiration
ETM	Enhanced Thematic Mapper
FDRE	Federal Democratic Republic of Ethiopia
ET_O	Reference Crop Evapotranspiration
FAO	Food and Agricultural Organization
GIS	Geographic Information System
GIR	Gross Irrigation Requirement
GLCN	Global Land Cover Network
HRU	Hydrological Response Unit
IFAD	International Fund for Agricultural Development
IWMI	International Water Management Institute
Kc	Crop Coefficient
LULC	Land Use/Land Cover
MADM	Multi-Attribute Design Method
MCDM	Multi-Criteria Decision Making

MoA	Ministry of Agriculture
MODM	Multi-Objective Decision Method
MoWR	Ministry of Water Resource
Mha	Million hectares
NMSA	National Meteorological Services Agency
OWA	Ordered Weighted Averages
RWH	Rain Water Harvesting
SAW	Simple Additive Weighting
SRTM	Shuttle Radar Topographic Mission
SWAT	Soil Water Assessment Tool
UNESCO	United Nations Educational Scientific and Cultural Organization
USGS	Unite State Geological Survey
UTM	Universal Transverse Mercator
WXGEN	Weather Generator

ABSTRACT

Assessing available water and land for surface irrigation is important for planning their use. The high dependency on rain-fed farming and erratic rainfall require alternative ways of improving agricultural production. The alternative to improve is through development of small scale irrigation schemes by assessing the available suitable land and water resources in sub-basin level. The objective of this study was assessing the land and water resources potential of Muga watershed in East Gojjam Zone for surface irrigation development using Geographic Information System. Identification of suitable land, estimation of available river flow, and determination of irrigation water requirement were the main steps that were followed. The land irrigation suitability factors considered were: slope, soil, land use/land cover, and river proximity. Estimation of river flow in the six manually added outlets was conducted by simulation after calibration and validation were carried out with the observed flow of gauged river using Soil and water assessment tool. The commonly cultivated crops in the area maize, onion and potato were selected, and the irrigation water requirements of these crops were determined using the CROPWAT8.0 model. Comparison between gross irrigation water requirement of the selected crops for the identified suitable land with simulated river flow at the area of the selected site was carried out. Overall, the weighted overlay analysis of these factors gave a suitable land among river sub-basin as G/muga 560ha, E/muga 3057ha, Bora 670ha, Gibstawit 404ha, and Genet 241ha. Mean monthly flow of 11.4m^3/s were determined at the watershed. A total of 3443ha (5.1%) was found to be potentially suitable for the development of surface irrigation project from a total watershed area of 67535ha. In conclusion, the irrigation potential of the area could be increased either by harvesting rainwater or using groundwater.

Keywords: Arc GIS, Irrigation Potential, Land Suitability, Muga watershed, Surface Irrigation

1. INTRODUCTION

1.1 Background

The Ethiopian economy is mostly based on traditional agricultural methods, with industry and services slightly increasing recently (FAO, 2016). Agriculture is a mainstay of the Ethiopian economy. Agriculture employs 83% of the active population of the country (MoA, 2011). The country largely depends on rain-fed and thus vulnerable to a high degree of rainfall variability and unreliability. This in turn has resulted in frequent crop failure and droughts which affect the agriculture productivity and food supply of fast-growing population in the country (Hailemariam *et al.,* 2018).

Ethiopia depends on rain fed 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 rain-fed Smallholder agriculture and hence rainfall is the single most important determinant of food supply (FDRE, 2011).

Generally, irrigation is developed to increase the productivity of land and labor, which are especially relevant for future constraints due to population growth. Also, the reduction of trust in rainfall due to climatic change is another reason for the development of irrigation infrastructure. So irrigation mitigates spatial and temporal variability in rainfall. As irrigation expands the country export opportunity and job opportunity increases alarmingly, also it promotes the economy dynamically with rural entrepreneurship (Awulachew *et al.*, 2010).

In recent years, a large number of irrigation schemes have been developed in different parts of Ethiopia by the Government and the support of different funding agencies. However, due to different environmental and management factors most of these irrigation schemes are not being utilized fully and irrigation, in general, is not contributing its share to the overall economic development of the country as needed. Hence, the irrigation sub-sector has to be given top priority in the overall development plans of the country with the ultimate objective of enhancing agricultural production and sustain crop production and alleviate food insecurity problems (MoA, 2011).

Considering the available water and land resources of the country, Ethiopia has huge potential in expanding irrigated agriculture. The country has 12 river basins that provide an estimated annual run-off of ~125 billion m^3. While much of this run-off could be used for irrigation or other purposes, Ethiopia has limited water infrastructure to use this surface water. For example, the current per capital water storage capacity is just $160m^3$ which is only 20% of South Africa's capacity (Awulachew *et al*., 2010).

Surface irrigation offers a number of advantages for the less skilled and poor farmers. Under such circumstances, more than 90% of the world uses surface irrigation, even if local irrigators have the least knowledge of how to operate and maintain the system (Saymen, 2005).

Geographical information system (GIS) is an information system capable of assembling, storing, manipulating various kinds of analysis, and displaying geographically referenced data. With an adequate database, GIS can serve as a powerful analytic and decision-making tool for irrigation development. In this kind of situation, the factors that are involved for irrigation potential assessment such as soil, land use/land cover, topography (slope), and availability of irrigation water should be weighted and evaluated by the use of GIS according to their suitability for irrigation (Aguilar-Manjarrez and Ross, 1995).

1.2 Statement of the Problem

Irrigation would provide farmers with sustained livelihoods and improve their general well-being. Thus to bring food security in the national level as well as the house hold level, improvement and expansion of irrigated agriculture must be enhanced (Negash, 2015). Soil, slope, river proximity, land use classification, and water potential criteria are the basis used to define the suitability. With this respect, the GIS facilities will be extensively used. To ensure adequate management and design of a particular irrigation system, a well-developed and suitability database is quite important (Rediet *et al.*, 2020).

Also, very few attempts have been made to assess surface water irrigation potential in Ethiopia mostly referring to master plan studies and official reports (Awulachew *et al.,* 2007; Awulachew *et al.,* 2010; FAO, 2016). Still, there is a shortage of detailed studies regarding water potentials and its developmental perspectives in the Ethiopian (Amhara region) context as it lacks agreed on reports in common consensus (Haile and Kasa, 2015).

The Amhara National Regional State is known to have a high potential of water and land resources, but people live below the poverty level because these resources are not properly used for food production except in the case where traditional methods are used (Awulachew *et al.,* 2011). So to overcome this problem with development of irrigated agriculture it is necessary to carry out GIS based surface irrigation potential assessment under particular case study area of Muga watershed Abbay sub basin.

In the study area, there is no sustainable land resources utilization and management and its agricultural system has been developed on rain fed agriculture and does not yet full beneficiary.

This is may be due to lack of updated information on available resources potential, systematic potential assessment and matching of the available water resources potential with crop water requirement of the area. Since there is no study conducted in the study area concerning irrigation potential assessment.

1.3 Objective

1.3.1 General objective

The aim of this study was to assess the surface irrigation potential of Muga Watershed using geographic information system (GIS).

1.3.2 Specific objectives

The specific objectives of the study were:-

- To identify suitable irrigable land for surface irrigation method.
- To estimate the available surface water using Arc Swat model.
- To estimate the irrigation water requirement of dominant crops
- To estimate surface irrigation potential and mapping the potential land

1.4 Research Questions

- How much monthly flow is available in sub basin level?
- Which land is suitable for surface irrigation development using the physical suitability parameters?
- How much is the irrigation water requirements of dominant crops in the watershed?
- Does available surface water flow in the river satisfies the demands of dominant crops?

1.5 Significance of the Study

This study is necessary for the community by increasing the production term of the people because irrigation is the way to cultivate more than 2 times per year. Also it is important for good utilization and efficient use of the land and water resources by enabling information on the land and water resources potential in the watershed for dominating crops. At the end of this study any one can know how much hectare of land is suitable for surface irrigation and the potential of the river with the dominating crops on the Muga watershed at sub basin level.

Ethiopia has an important opportunity in water-led development, but it needs to address critical challenges in the planning, design, delivery, and maintenance of its irrigation systems if it is to capture its full potential (Awulachew *et al.,* 2010). An irrigation project design which do not consider or taken available water and land resources data leads to insufficient water resources in the irrigation period. This study has been used to identify and quantify the water resources potential and land suitability in the study area to help the planners and decision makers for developing short term and long term plan for irrigation development. Generally, the information obtain from the research will assist the decision makers to evaluate existing irrigation schemes and plan future developments of the area so that the agricultural production sustainability will be improved.

2. LITERATURE REVIEW

2.1 Irrigation Potential

Irrigation potential is the area, which can potentially being irrigated, depends on different physical resources, slope, LULC, soil and water etc. combined with the irrigation water requirements as determined by the cropping patterns and climate. It is an important indicator to the extent of land suitable for irrigation development. This means that it is the possibilities for irrigation development. In countries like Ethiopia which has ample water resources, the concept of irrigation potential also comprises some considerations of suitability and economic feasibility of irrigated lands (FAO, 2015).

2.2 Irrigation Potential in Ethiopia

Ethiopia has a huge potential of water and land resources that could be easily used in expanding irrigation agriculture. Ethiopia has 12 river basins, 9 wet and 3 dry, annual runoff volumes from the 9 river basins is 122BM^3. Among these Abbay basins (in central and northwest Ethiopia) accounts about 53%, and Baro-Akobo 24%, Omo-Gibe 18% of this amounts. The remaining river basins contribute less than 10% (Abiti, 2011).

Water resources management in agriculture is a critical contributor to the economic and social development of Ethiopia. If successful, irrigation in Ethiopia could represent a cornerstone of the agriculture development of the country, contributing up to ETB 140 billion to the economy and potentially moving up to 6 million households into food security (Awulachew *et al.*, 2010).

2.3 Irrigation Potential of Abbay Basin

Traditional irrigation practice has long history in Abbay basin. Farmers of different locality divert water and make use for the production of vegetable and cereal crops. There is a considerable irrigation potential within the Abbay basin for the development of different scale irrigation schemes. About 230000ha of medium and large scale irrigation are recommended to be implemented over the master plane period. According to the recent master plan study, in the Abbay basin a total of 815,581ha of potentially irrigable land are estimated (IWMI, 2010).

2.4 The Need for Irrigation Development in Ethiopia

Ethiopia has vast cultivable land (30 to 70 Mha), but only about a third of this is currently cultivated, with current irrigation schemes covering about 640,000ha across the country. However, the study estimates that total irrigable land potential in Ethiopia is 5.3 Mha assuming use of existing technologies, including 1.6Mha through rain water harvesting (RWH) and ground water. This means that there are potential opportunities to vastly increase the amount of irrigated land (Awulachew *et al.,* 2010).

Irrigated agriculture represents 20% of the total cultivated land but contributes 40% of the total food produced worldwide (FAO, 2015). This indicates that, irrigation will play a significant role in the substantial increase in food production for food security enhancement and economic development of Ethiopia with the efficient use of land and water resources (Haile and Kasa, 2015; Sultan, 2013). The production function analysis shows that irrigation could change the agriculture production frontier to a higher level (Makombe *et al.,* 2007). However, its contribution the national economy is not significant when compared with rain-fed agriculture.

But global agricultural production has doubled within an area that has only increased by 12%, and a part of this gain can be attributed to an increase in irrigation (Bégué *et al.,* 2018).

Increasing irrigation has long been seen as the most direct strategy to alleviate the impact of drought and ensure food security (World Bank, 2006). The report emphasizes without increased irrigation, the unpredictability of rains in Ethiopia is an overwhelming disincentive to investments in agricultural improvements. Well-managed irrigation development is a key in helping Ethiopia overcome major challenges of population pressure, soil and land degradation, high climate variability, and low agricultural productivity (Awulachew *et al.,* 2010).

2.5 Irrigable Land Suitability Evaluation Factors

Land evaluation is the process of assessing land performance for a specified purpose. The principal factors for evaluating irrigable land suitability are soil, topography, land use land/cover and climate. However climate is different from others due to its uniformity in a particular area to be investigated (Stanhill, 2002).

Suitability is a measure of how well the qualities of a land unit match the requirements of a particular form of land use. Land suitability is the fitness of a given type of land for a defined use. The land may be considered in its present condition or after improvements. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses. The main aim of irrigable land investigation is therefore to provide information on potentials and constraints for the use of land, as abases for making decisions on its use and management (Anaman, 1994).

2.5.1 Order of land suitability

It indicates weather the land is suitable or not for a particular use. If the land is expected to yield benefits which justify the inputs, without unacceptable risk of damage to land resources it is categorized as suitable (order S). In other words land which has qualities that appears to impede sustained use of the kind under consideration is classified as non-suitable (order N) (FAO, 1996).

2.5.2 Classes of land suitability

It refers to the degree of land suitability. The suitability class are categorized as class S1 highly suitable land when it has no significant limitations to sustain application of a given use or only minor limitations that will not significantly reduces productivity and will not raise inputs above an acceptable level; Class S2 moderately suitable land has limitation which in aggregate is moderately severe for sustained application for a given use; Class S3 marginally suitable land is having limitations which in the aggregates are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified and Class N Not suitable is the land having limitation which may rehabilitate in time, but cannot be corrected with existing knowledge of current acceptable cost. It may also preclude any possibilities of successful sustained use of the land in the given manner (FAO, 1993).

2.6 Parameters Used for Evaluation of Land Suitability

2.6.1 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 type and methods. 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).

The suitability class of slope for surface irrigation includes very suitable (S1) slope less than 2%, moderately suitable (S2) with slope between 2% and 5%, marginally suitable (S3) with slope between 5% and 8% and non- suitable (N) with slope greater than 8% (FAO, 2006).

2.6.2 Soil

The assessment of soil for irrigation involves using properties that are permanent in nature that can't 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 amendment 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. Soil influences the productive capacity and system development cost. Also the soil parameters affect root growth of plant and infiltration of water to soil (Ganole, 2010).

- **Soil texture**

Based on the particle size soil are divided in to 3 textural class (clay, silt and sand). Soil texture affects the rate at which water enters in to the soil. When the infiltration capacity greatly exceeds the permeability of the subsoil, the permeability will greatly influence the basic intake rate of the soil. The infiltration rate may influence selection of irrigation type, length of irrigation run, field size, irrigation development cost and crop type selection (FAO, 1991).

Table 2.1: FAO soil texture suitability class for surface irrigation

Factor	Factor rating			
	S1	S2	S3	N
Texture	C, SiC, SC	Si-SCL	SL, LS, FS	Coarse sand

C=clay, SC sandy clay, SiC silty clay, Si silt, L loam, CL clay loam, SiCL silty clay loam, SCL sandy clay loam, SiL silty loam, SL sandy loam.

Sources: FAO, 1991 guide line for land evaluation

- **Soil depth**

Soil depth refers to the thickness of the soil material. It provides a structural support, nutrients and water for the plant. Soil depth, soil layering, and depth to an estimated water table are also major factors that must be considered when determining the amount of available water a soil profile can hold (Jamshid, 2003).

Table 2.2: FAO soil depth suitability class for surface irrigation

Factor	Factor rating			
	S1	S2	S3	N
Soil depth (cm)	>120	100-120	50-100	<50

Source: FAO, 1991 guideline for land evaluation

- **Soil drainage**

Evaluation of soil drainage requirement is a critical element in selecting land for irrigation, particularly with diversified upland crop production (FAO, 1997).

Table 2.3: FAO soil drainage suitability class for surface irrigation

Factors	Factor rating			
	S1	S2	S3	N
Soil drainage	Well drained	Imperfectly drained	Poor drained	Very poor drained

Sources: FAO, 2002 Guideline for land evaluation.

2.6.3 Land use land cover

Land use and land cover are often used interchangeably. However they are actually quite different. Land cover is the observed (bio) physical cover, as seen from the ground or through remote sensing, including vegetation and human construction which cover the earth's surface. Water, ice, bare rock or sand surfaces also count as land cover. However, land use establishes a direct link between land cover and the action of people in their environment (GLCN, 2006).

Land use or land cover provides a basis for identifying the possible land suitability form irrigation with precise and quantitative economic evaluation. Therefore matching of the existing land use/cover with topographic and soil characteristics to evaluate land suitability for irrigation with land suitability class, present lands for new agricultural production (Jaruntorn *et al*., 2004).

Table 2.4: FAO LULC suitability class for surface irrigation

Category	Suitability class	LULC description
S1	Highly suitable	Cultivated land
S2	Moderately suitable	grass land and open bush land
S3	Marginally suitable	Open forest, Woodland, dese bush land
N	Non suitable	Dense forest, urban area and water body

Source: FAO, (1996) an interactive multi criteria analysis for land resource appraisal.

2.6.4 Water availability

Quantifying the amount of water available for irrigation and determining the exact location to which water can be economically transported are important in the decision to expand its use. Where possible, the water sources preferred to be located above the command area so that the entire field can be irrigated by gravity (Ganole, 2010). It is desirable that the water sources 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, proximity to rivers, is useful to reduce the conveyance system (irrigation canal length) and thereby develop the irrigation system economical (Awulachew, 2001).

An important consideration in water resource assessment is to estimate how much adequate amount of surface water potential is available in the catchment for the intended irrigation method and crops to be grown in the identified irrigable areas. As a result availability of water both spatially and temporally is a major factor for feasibility of irrigation development (FAO, 1997).

2.7 Over-View of GIS Application

The ability of a GIS is to handle and process geographically referenced data distinguishes. 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).

The main application in GIS is mapping where things are and editing tasks as well as for map based query and analysis. A map is the most common understanding for users to analysis geographic information. It's the primary application in any GIS to work with geographic information to understand slope, land use land cover and water bodies. 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 (Campbell, 1984).

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. To prioritize the influence of these factor values, weighted overlay analysis uses evaluation scale from 1 to 4 by 1 (Yang, 2003).

2.7.1 Watershed delineation

A watershed is the catchment area or a drainage basin that drains in to a common outlet. Delineation of a watershed means determining the boundary of the watershed i.e. ridgeline. GIS uses digital elevation models (DEMs) data as input to delineate watersheds with integration of Arc SWAT or by hydrology tool in Arc GIS spatial analysis tool (Winchell *et al.*, 2008).

2.7.2 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,1997;Melaku, 2003;Negash,2004; Hailegebriel, 2007; Meron, 2007; Ganole, 2010; Abebe, 2014, Nasir *et al.,* 2019, Kassay *et al.*, 2019).

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.

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.

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.

Ganole (2010) carried out similar work on surface irrigation potential analysis of Dale woreda 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.

Abebe (2014) also conduct research on surface runoff potential and irrigation suitability assessment of an-lemo river watershed using GIS application and SWAT modeling by considering suitability factors like slope, soil, LULC and water availability.

Kassay and others in 2019 conduct study on a GIS based Multi criteria land suitability analysis for surface irrigation along the Erer watershed, eastern Hararghe zone by considering different physical parameters and soil chemical properties. Also in 2019 Nasir and others study on irrigation potential assessment on shala river sub basin in Bale zone in Oromia region.

2.8 Multi-Criteria Decision Making

Multi-Criteria Decision Making (MCDM) model are suitable for evaluating and making decision for the best alternative options in order to choose the perfect criteria. This involves a general class of operation research models, which considers problems in decision making in the presences of many decision criteria. There are two type of MCDM, which are; Multi-Objective Decision Methods (MODM) and Multi-Attribute Decision Methods (MADM) (Sorooshian, and Dodangeh, 2013).

There are many other methods which are used under MADM such as; Analytical Hierarchy Process (AHP); Simple Additive Weighting (SAW); Ordered Weighted Averages (OWA); etc. (Filianie *et al*., 2016).

2.8.1 AHP method

The analytic hierarchy process (AHP) was introduced by Saaty since 1970's. The AHP method is ranking process that is used in making group decision and widely used around the world in a variety of fields such as agriculture and others (Filianie *et al.*, 2016).

AHP method is suitable for ranking and analyzing complex decision problems. It is also regarded as one of the perfect and easiest method under MCDM because it is easy to use and make room for checking and reducing inconsistencies in options. There is therefore sufficient evidence based on the formulae, along with comprehensive literature review by the authors to strongly recommend AHP to future researchers and professionals to use the methodology process when engaged in complex decision-making problems involving many criteria, sub-criteria, and alternatives (Filianie *et al.*, 2016).

The scale of ratio and consistency index is derived from the principal Eigen vectors and Eigen value respectively. The method focuses on prioritizing the selection criteria, and distinguishing the more important criteria from the less important one. Although some researchers argue some disadvantage of AHP (Sorooshian, 2015), AHP is simple method with focus placed on peer to peer comparisons that are suitable to evaluate both qualitative and quantitative design (Zamani and Yousefi, 2013).

2.9 Description of Arc-SWAT Model

SWAT (Soil and Water Assessment Tool) is a watershed model developed to quantify the impact of land management practice in large watershed (Arnold *et al*., 1998). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods. The model simulates eight major components which are hydrology, weather, erosion, sediment transport, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Neitsch *et al*., 2005).

SWAT a basin-scale, continuous-time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in un-gauged watersheds. In SWAT, a watershed is divided in to multiple sub-watersheds, which are further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management and soil characteristics. The HRUs represent percentages of the sub watershed area and are not identified spatially within a SWAT simulation. Alternatively, a watershed can be subdivided into sub-watersheds that are characterized by dominant land use, soil type, and management (Gassman *et al*., 2007).

The review of SWAT model applicability to local situation indicated that the model is capable of simulating hydrologic processes with reasonable accuracy and can applied to large un-gauged watershed (Setegn *et al*., 2008; Alemayehu, 2012; Abebe, 2014).

Assessment of the spatial distribution of water resources and evaluation of the impacts of different land management practices on hydrologic response and soil erosion in the upper part of the Awash River basin in Ethiopia was done using SWAT model. In the catchment farming activities are changing very rapidly due to population pressure and nine scenarios were developed to understand the effects of these changes on water quality and sedimentation. The results of the study concluded that the SWAT model accurately tracked the measured flows and simulated well the monthly sediment yield (Dilnesaw *et al*., 2007).

In another study, the dynamics of Land use change in the Hare River basin located in the Southern Rift Valley Lakes Basin of Ethiopia was studied using SWAT model. The purpose of the study was to investigate the consequent impacts of land use change on stream flow. The catchment was delineated into 27 sub-basins and further divided into 160 Hydrological Response Units (HRUs) with 2 % land use cover and 5 % soil class cover. The study concluded that the SWAT model satisfactorily predicted monthly and annual flows and the model is useful to analyze the impacts of land use/land cover changes on stream flow even in basins with limited data (Tadele and Forch, 2007).

In the study of calibration and validation of SWAT model and estimation of water balance components of Shaya River Watershed, Genale-Dawa Basin, South-Eastern Ethiopia, calibrated

SWAT model was performed well for simulation of monthly stream flow. Statistical model performance measures, coefficient of determination (R2) of 0.71, the Nash-Sutcliffe simulation efficiency (ENS) of 0.71 and Percent difference (D) of 3.69, for monthly calibration and 0.76, 0.75 and 3.30 respectively for validation, indicated good to very good performance of the model simulation. Relatively weaker performance were obtained for the daily simulation with corresponding values of 0.41 for R2, 0.41 for ENS and -1.51 for D, for calibration and 0.43, 0.43 and 3.05 respectively for validation periods.

Therefore it is recommended that SWAT model can be a potential tool for simulation of stream flow and water balance components of un-gauged watershed in the highlands of Ethiopia which behave similar hydro-metrological characteristics with Shaya watershed (Alemayehu, 2012).

The study in an-lemo river watershed, in Hadiya zone indicates that the R^2 value of 0.63 and ENS of 0.98 for calibration. The validation also indicates that 0.94 of R^2 and ENS of 0.86. Therefore it is recommended that SWAT model can used for stream flow simulation for un-gauged watershed (Abebe, 2014).

2.10 Weather Generator

SWAT requires daily values of precipitation, maximum and minimum temperature, solar radiation relative humidity and wind speed. The user may choose to read these input from a file or generate the values using monthly average data summarized over a number of year. SWAT includes the WXGEN weather generator model to generate climatic data or to fill in gaps in measured records (Sharpley and Williams, 1990). The occurrence of rain on a given day has a major impact on relative humidity, temperature and solar radiation for the day. The weather generator first independently generates precipitation for the day. Once the total amount of rainfall for the day is generated, the distribution of rainfall within the day can be computed (if the Green and Ampt method is used for infiltration). Maximum temperature, minimum temperature, solar radiation and relative humidity are then generated based on the presence or absence of rain for the day. Finally, wind speed is generated independently (Neitsch *et al*., 2005).

2.11 Crop Water Requirement

Crop Water requirement is the quantity of water, regardless of its source, required by a crop or diversified patterns of crops in a given period of time for its normal growth under field conditions at a place. Water requirement includes the losses due to evapotranspiration (ET) or consumptive use (CU) plus the losses during application of irrigation water (unavoidable losses) and the quantity of water required for special operations such as land preparation, trans planting, leaching, etc. Consumptive use (CU) is the evapotranspiration from a vegetative area plus the water used directly by the plant in the metabolic process of building the plant tissues. As the water used in the metabolic process is negligibly small (usually, less than 1% of the total loss), it is the usual practice to neglect the difference between evapotranspiration and consumptive use and the two terms are generally used synonymously (Michael, 1986).

The field irrigation requirement of a crop therefore, refers to the water requirement of crops, exclusive of effective rainfall and contribution from soil profile, and given as:

IR=WR-(ER+S) where IR = irrigation water ER= effective rainfall And S=soil profile contribution including that from shallow water tables.

2.11.1 Over-view of CROPWAT

CROPWAT is a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirement and crop irrigation requirement, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rain fed conditions or deficit irrigation (FAO, 1992). In CROPWAT8.0, the calculation of crop water requirements is carried out per decade.

Calculation of the crop water requirements and irrigation requirements were carried out with inputs of climatic, crop and soil data. The model requires the following data for estimating crop water requirements (CWR).

1. Climatic Data to calculate the reference evapotranspiration, CROPWAT model use monthly maximum and minimum temperature, relative humidity, sunshine hour, and wind speed data that was collected from.

2. Monthly rainfall data

3. Cropping Pattern Data: includes planting date, crop coefficient data files (including Kc values, stage days, and root depth),yield response, critical depletion and the area planted (0-100% of the total area) a set of typical crop coefficient data files are provided in the program.

Once all the data is entered, CROPWAT 8.0 Windows automatically calculates the results as tables or plotted in graphs. The time step of the results can be any convenient time step: daily, weekly, decade or monthly.

3. MATERIAL AND METHODS

3.1 Description of the Study Area

3.1.1 Location of the study area

The study was carried out in Muga Watershed which is located in Upper Blue Nile Basin under Choke Mountains Watersheds in Amhara Region. Geographically, it lies between 10^0 6' N and 10^0 41' N latitude and 37^0 54'E and 38^0 20'E (Figure 3.1). Muga River originates from Bibugn woreda near Choke Mountain at an elevation of 4090 and drain to Abay River. The total area that the watershed covers is 675.53 km^2. The watershed covers three Woredas of East Gojjam (DibayTilatgin, Dejen and Enemay Woredas).

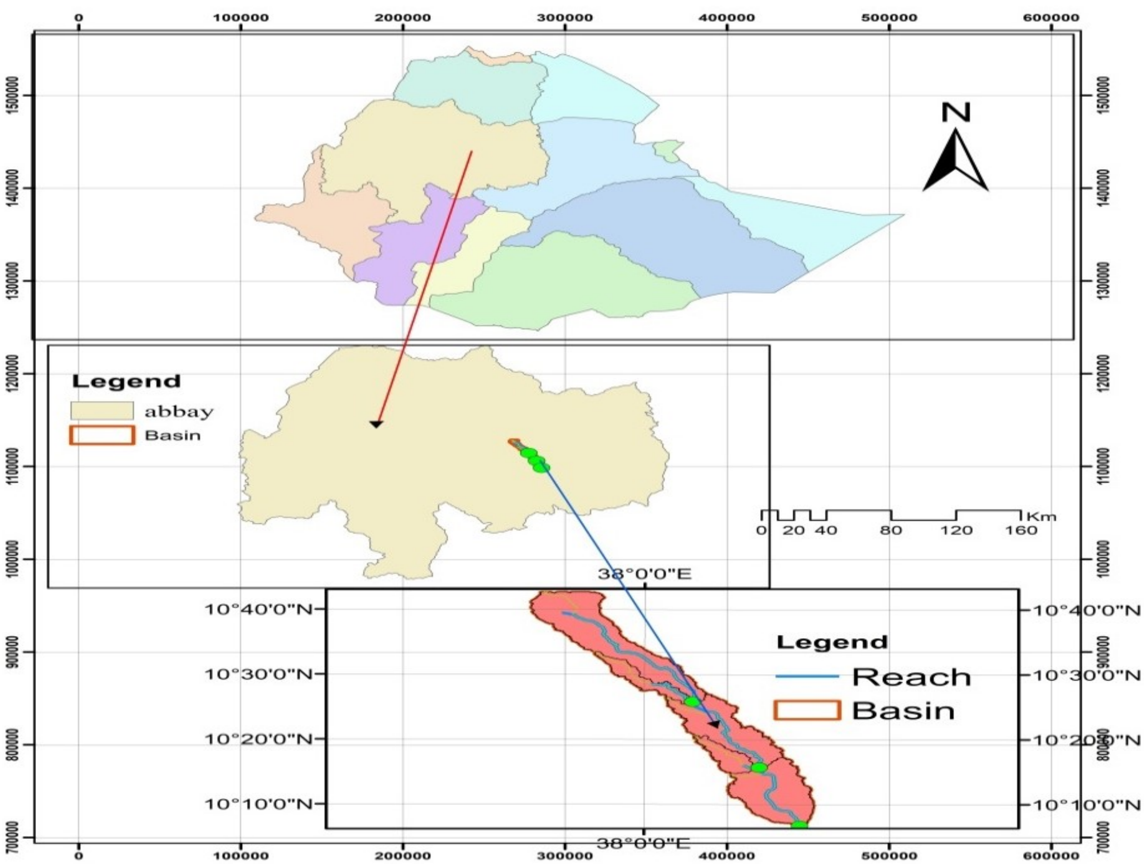

Figure 3.1: Map of the study area

3.1.2 Topography

On the southern part of the study watershed there is sloping land which is sloped towards the river feature. Also on the northern part the watershed there is complicated land with higher and lower slopes. There is somehow gently sloping topography at the mid part of the watershed towards Muga River. Generally the elevation of the land varies from 4090m to 1045m above sea level.

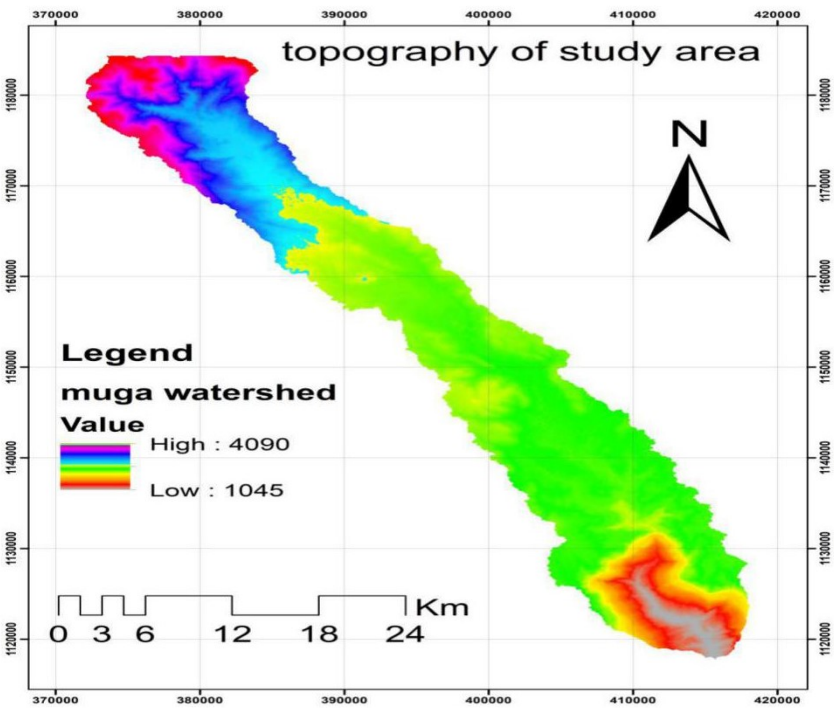

Figure 3.2: Topography of the study area

3.1.3 Climate

Locally, the climatic seasons are defined as: dry season (Bega) from January to the end of March; short rain period (Belg) from April to June; long rainy period (Kiremt) from July to September and Meher from October to December, with the greatest rainfall occurring in July and August. The mean annual rainfall of the area was 1446mm and the maximum and minimum temperature of around 25^{o}C and 5^{o}C respectively.

3.2 Data Collection and Analyses

3.2.1 Identification of suitable land for surface irrigation

Different data types were utilized to attain this objective. Land sat image with acquisition date 2018 that includes bands 1,2,3,4,5 and 7 with spatial resolution of 30m were downloaded using internet for LULC classification. The harmonized world soil database was also downloaded for the classification of soil physical parameters using GIS. FAO/UNESCO soil map of East Africa available in Arc/info format with scale of 1:5,000,000 obtained from GIS and Remote Sensing Department, ministry of water resources which is used for soil suitability analysis.

DEM data were downloaded from freely available Shuttle Radar Topography Mission (SRTM). DEM data of the study area were delineated from the downloaded DEM using the outlet point of the stream using ArcGIS and derive slope map of the study and distance of water sources from the command area for irrigation suitability estimation.

The main software used for this analysis was Arc GIS, Google earth, EARDAS IMAGINE and Arc SWAT with GIS extension. This software used for the determination of the data necessary for the whole surface irrigation potential analysis of the study area.

The identification of suitable site for surface irrigation was carried out by considering different suitability parameters. The suitability parameters considered were slope, soil (soil depth, soil drainage and soil texture), and LULC and river proximity. Each suitability parameter was first analyzed individually in GIS software and finally weighted overly analysis was done using MCDM process in spatial analysis tool by creating suitability model.

3.2.1.1 Watershed delineation

The watershed delineation was done from DEMs of 30m*30m which is developed by (USGS) the shuttle Radar Topographic Mission (SRTM). The study area DEM was downloading from internet by importing it to Global mapper and configures its coordinate system to UTM projection and WGS 1984 datum. The projected DEM were exported to Arc GIS and run automatic watershed delineation using Arc SWAT.

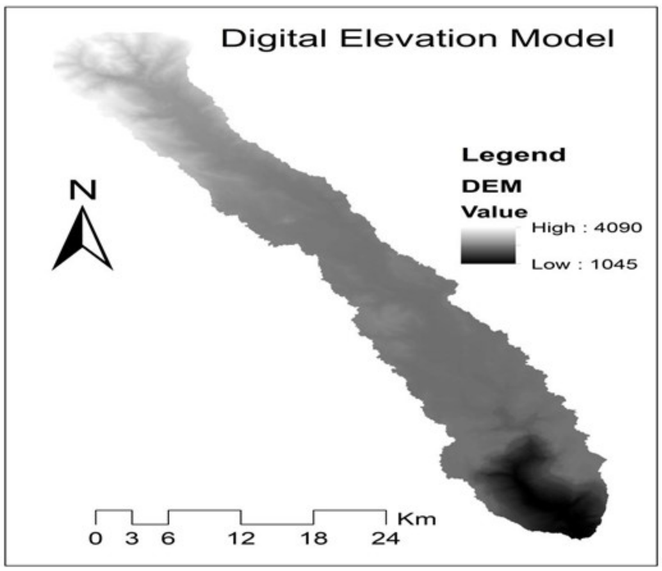

Figure 3.3: Digital elevation model of the study area

3.2.1.2 Slope suitability assessment

Slope map of Muga watershed was derived from freely available Shuttle Radar Topography Mission (SRTM)-DEM of 30m*30m spatial resolution using the “spatial analysis tool’’ in the Arc GIS. The slope derived from the DEM was classified based on the classification system of FAO 2006 using “reclassification’’ tool in to suitability class and finally slope suitability map was developed. The data layer was prepared for further overlay analysis.

Table 3.1: Slope suitability class for surface irrigation

Slope suitability classification for surface irrigation		
Slope	Slope range (%)	Factor rating
Horizontal	0-2	S_1
Very flat	2-5	S_2
Flat	5-8	S_3
Steep	>8	N

Sources: FAO, an interactive multi-criteria analysis for land resources appraisal, 2006.

3.2.1.3 Soil suitability assessment

Soil is a key factor in determining the suitability of irrigation. Also the soil data covering study area (soil depth, texture and drainage) attributes were derived from the FAO website Harmonized world soil database, in Environmental System Research Institute (ESRI) shape file format (version 1.21). The major soil groups classified in the study area were Chromic Luvisols, Eutric Vertisols, Humic Hitosols and Rendezic Leptosolos. The basic physical parameters of the soils in the watershed were used in the suitability analysis which were soil depth, soil texture and soil drainage. These soil properties were first classified individually and weight for further analysis.

Table 3.2: Soil suitability for surface irrigation

	Soil suitability factors			
Factors	S_1	S_2	S3	N
Drainage class	Well, moderate	Imperfect	Poor	Very poor
Soil depth	>120	100-120	50-100	<50
Soil texture	C	Si-CL, CL-C	SL	CS
PH	<4	4-8	8-12	>12

Source: (FAO, 1991 and 2002) Guide line for land evaluation

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 texture, depth and drainage class. Using overlay tool in Arc GIS spatial analysis, 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 1-9 available in weighted overlay analysis. For the three soil physical parameters equal weights were given.

Finally soil suitability map of each parameter was developed with the factor rating of S1, S2, S3, and N through reclassified the raster layers based on the FAO classification guideline.

3.2.1.4 LULC suitability analysis

LULC classification was generated through image classification of land sat ETM+5 satellite imagery of the study area. The Land sat image of 2018 was downloaded from internet for the study area. Which is from Land sat ETM+5 satellite having 1,2,3,4,5 and 7 bands and 30m*30m spatial resolution using ERDAS imagine software. Google earth were used for the image classification in the ERDAS imagine software. The true color composite images were created by combining the spectral bands that mostly resemble the range of the human eye which in the Landsat images are normally used for LULC analysis. The LULC classified in ERDAS imagine was opened in ArcGIS and reclassified for further analysis in the suitability assessment.

3.2.1.5 Distance from water supply (sources)

It is necessary to determine the irrigable land close to the water supply by using straight line (Euclidean) distance from water sources was calculated using DEM of 30m*30m raster and reclassify it using spatial analysis tool. The reclassified distance was used for weighted overly analysis together with other factors.

3.2.1.6 Weighted overlay analysis

The weights of the suitability parameters were developed by providing a series of pair-wise comparison of the relative importance of the suitability parameters being evaluated in the analysis. The logic developed by Saaty in 1977 was used to produce weights under the AHP process with a weighted linear combination. In pair-wise comparison each factor was compare one to one with each other, and comparison matrix was developed.

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.

3.2.2 Surface water availability assessment

Available surface waters of the sub basin were simulated in Arc SWAT model. For the simulation of Arc SWAT model the metrological data of four stations (Dejen, Yetnora, Debremarkos and Motta), LULC data, LULC code, soil data, soil code, slope and DEM of the study watershed were used. The stream flow discharges that are obtained from the Ministry of Water, Irrigation and Energy; department of hydrology was used for flow calibration and validation using SWAT CUP after sensitivity analysis was performed. The stream flow that was used as input to determine discharge at un-gauged site were measured at the gauging station inside the study area near Dejen. The Map Window SWAT was downloaded for coding and classification of soil in SWAT simulation process.

3.2.2.1 Data pre-processing and checking

The data that were collected may have errors caused by either failure of measuring device or the recorder reading error. In order to reduce this error we need to check the data consistency and homogeneity that is used for a specific purpose. For this specific research the analysis was extended for both metrological and hydrological data to prepare input data for irrigation water requirement estimation and water resources assessment respectively.

3.2.2.2 Filling missing rainfall data

Missing rainfall and flow data were estimated 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). Also some missing dates were filled with average of some data since the missing is in days. The data was presented in the appendix. Other metrological data also filled with the same method.

PX= $\frac{1}{N}(\sum \frac{px}{pi} * pg)$ ……………………………………………………3.1

Where PX= missing data

Px= the annual average precipitation at the gauge with the missing data

Pi= annual average values of neighboring station

Pg= monthly rainfall data in all stations for the same month of missing stations.

N=the total number of gauges under consideration

3.2.2.3 Homogeneity of rainfall data

Test of homogeneity is required for the purpose of validation of the recorded data. In any hydrological design the recorded rainfall data need to be homogeneous. Because of the uncertainty about possible changes graphical method was used in climatology and hydrology to obtain some insight into the homogeneity of record.

Table 3.3 Mean monthly rain fall data of metrological stations (mm)

	Mean monthly rain fall (mm)											
Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Yetnora	4.9	13.1	51.1	65.8	94.5	143.6	300.3	265.8	135.5	60.4	19.6	11.7
Markos	10.7	14.7	50.0	71.3	116.5	168.9	270.7	299.3	221.9	75.3	28.3	17.6
Motta	5.0	7.8	32.4	52.9	86.0	120.9	316.1	306.9	172.4	106.1	33.4	11.2
Dejen	7.2	11.1	59.1	69.1	98.7	149.6	334.7	335.5	180.9	77.2	32.5	8.8

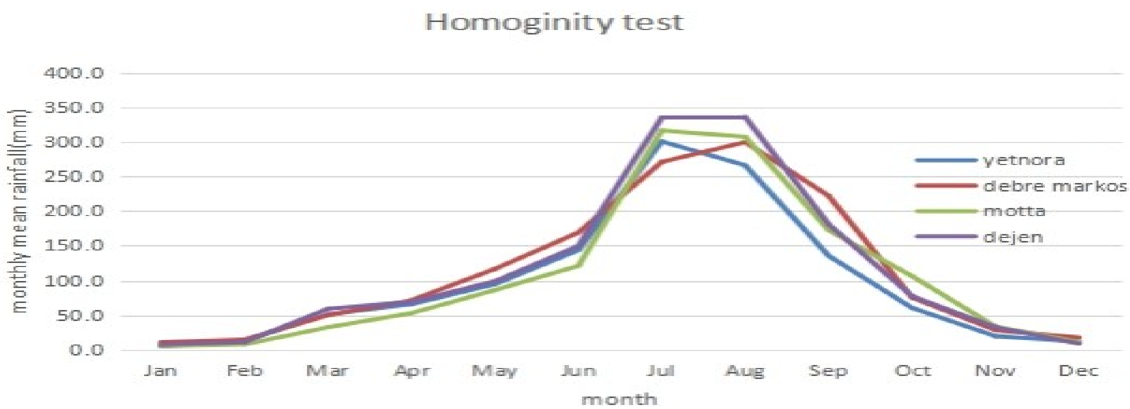

Figure 3.4 Chart of homogeneity test in the metrological station

3.2.2.4 Consistency of rainfall data

The double mass curve analysis method is used to check the consistency of rainfall data for further application. A plot of cumulated rainfall data of each station with the cumulative mean of the surrounding stations was used to check consistency of rainfall data (Nemec, 1973).

r=1, direct linear correlation,

0.6≤r, <1, good direct correlation, -0.6<r<0, insufficient-reciprocal correlation,

-1<r<0.6, good reciprocal correlation and, R= -1, reciprocal linear correlation.

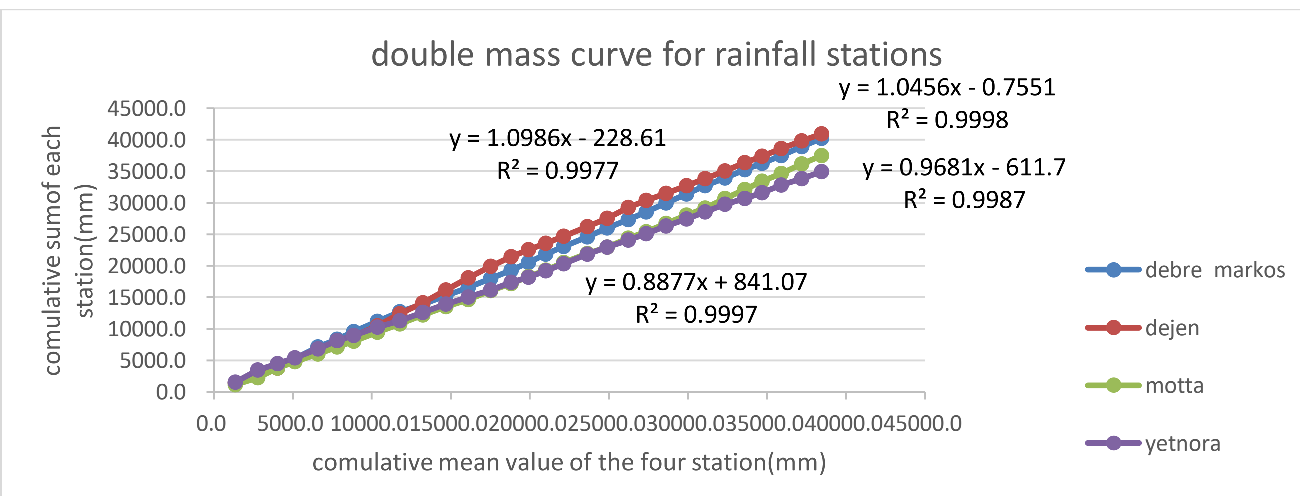

Figure 3.5 Double mass curves for consistency analysis

3.2.2.5 Weather data generation

The four meteorological stations have both temperature and precipitation data, but only Debre markos and Motta stations were synoptic stations used for generating remaining weather data for others (weather generator stations). After loading WXGEN parameter and location table, the daily meteorological data (daily precipitation, daily minimum and maximum air temperature) with the missing data filled with a missing data identifier of NA and including the corresponding location table prepared according to the SWAT format were loaded into the model .SWAT weather database VO1803 were extracted and SWAT takes data of each climatic variable from the nearest weather station measured from the meteorological stations.

3.2.2.6 SWAT model simulation

After loading all the data which are necessary for SWAT model, the model were run and read the simulated output of the stream flow. The model was adjusted to run the simulation for 25 years (1994- 2018) years of data with two warm up period. The result from the simulation cannot be directly used for further analysis. Instead, the ability of the model that sufficiently predicts the stream flow that should be evaluated through sensitivity analysis, model calibration and model validation as (White and Chaubey, 2005).

3.2.2.7 Model sensitivity analysis, calibration and validation

Sensitivity analysis was done using 10 years recorded river flow for identifying the most sensitive parameters. Global sensitivity analysis performs the sensitivity of one parameter while the value of other related parameters are also changing. Global sensitivity analysis uses t-stat and p-value to determine the sensitivity of each parameter. The t-stat provides a measure of the sensitivity (large in absolute value are more sensitive) and p-values determine the significant of the sensitivity. A p-value closer to zero has more significant. This type of sensitivity can be performed after iteration. The main problem related to global sensitivity analysis is that it needs a large number of simulations.

Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions. Calibration was done with the pre-defined parameters that have been identified as most sensitive parameters. The parameter values are then adjusted to more closely match the model behavior to that of the watershed. In this study the calibration process was done by observed stream flow data using automatic calibration. After calibration, checking the R^2, NSE and RVE values and calibrate at least until the minimum recommended values were embraced by the model that is $R^2 > 0.6$, NSE > 0.5 and RVE < ±15 (Santhi *et al*., 2001). For calibration observed flow of 1994 to 2003 with two years of warm up were used.

The validation procedure involves running a model by means of parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration. The observed flows of the stream from 2004 to 2008 were used for validation.

3.2.2.8 Model performance and efficiency

- **Nash-Sutcliffe efficiency (NSE):-**For monthly time steps that NSE values between 0.75 and 1 is very good, value between 0.65 and 0.75 is good. The efficiency, NSE proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Moriasi *et al*., 2007).

$$\text{NSE}=1-\frac{\sum_{i=1}^{n}(Qi-Pi)2}{\sum_{i=1}^{n}(Qi-Qmean)2}\text{.............................}3.2$$

Where Qi is observed flow at i^{th} period,

Pi is simulated flow at the i^{th} period and

Q_{mean} mean of the observed flow.

- **Coefficient of determination (R^2):-**The coefficient of determination the square ratio between the covariance and the multiplied standard deviation of the observed and predicted values and also defined as the squared value of correlation.

$$R^2=\left[\frac{[\sum_{i=1}^{n}(Qs-Qs\ mean)(Qo-Qo\ mean)]2}{[[\sum_{i=1}^{n}(Qs-Qs\ mean]2[\sum_{i=1}^{n}Qo-Qo\ mean]2]}\right] \ldots\ldots 3.3$$

Where: - Qo =observed discharge (m^3/s)

Qs= simulated discharge (m^3/s)

Qo mean= mean of observed discharge (m^3/s)

Qs Mean =mean of simulated discharge (m^3/s) and n is the number of observation.

R^2 indicates how the simulated data correlates the observed value of data. If R^2 is 1 the simulation is accurate. If the value of R^2 ranges from 0.75 to 1 it is categorized as very good and if it ranges between 0.5 to 0.75 categorized as good (Moriasi *et al.*,2007).

- **Relative volume error (RVE):-**The optimal value of RVE is zero which means the magnitude of RVE is small indicates more accurate simulation. The positive and negative value of RVE indicates under estimation bias and over estimation bias respectively (Gupta *et a.*, 1999).

$$VRE=\frac{\sum_{i=0}^{n}(Qob-Qsim)}{\sum_{i=0}^{n}(Qob)} * 100 \ldots\ldots 3.4$$

Where: - RVE is Relative Volume Error (%) Qob is observed flow (m^3/s),

Q_{sim} is simulated flow (m^3/s) n is number of observation

3.2.2.9 Transferring discharge of simulated rivers to site of interest

For gauged rivers the discharge was transferred to site of interest using the formula given bellow.

$$Q_{site} = \left(\frac{DA_{site}}{DA_{gauged}}\right)^n * Q_{gauged} \quad \text{………………………………………………………..3.5}$$

Where: Qsite=discharge at site of interest DAgauged=drainage area at gauged site

Q_{gauged}=discharge at gauged site DAsite=drainage area at site of interest

The exponent "n" varies between 0.6 and 1.2. If the DA_{site} is within 20% of DA_{gauged} (0.6≤ DA_{site} is divided by DA_{gauged} ≤1.2), n value equal to 1 is used, and otherwise the value 0.6 is used.

3.2.3 Computing irrigation water requirement for dominating crops

To calculate irrigation water requirement of the identified area for dominating crops the climatic data of stations were used for CROPWAT software in order to create data base. Based on the cropping pattern information of the study area obtained from East Gojjam zone agricultural office and information from the farmers three crops (onion, maize and potato) were selected to estimate the water demand.

The water requirement of crops depends on the climatic condition, the crop variety, the stage of crop and the soil type and depth. Reference crop evapo-transpiration (ETo) and other climatic data were derived from the computation for crop water requirement estimation in CROPWAT software. The crop coefficient (kc) and yield response (ky) for each crop with in different growing stage was selected based on FAO 1998. The gross irrigation water requirements of the crops for the identified potential irrigable site were estimated by considering irrigation efficiency of 60% for surface irrigation (FAO, 1992) irrigation and drainage paper number 24.

WR= IR + ER + S……………………………………………………………….3.6

The field irrigation requirement of the dominating crop is calculated as the difference of total crop water requirement and effective rain fall with contribution of moisture in the soil.

IR= WR - (ER + S) ………………………………………………………………3.7

ETc =ETo*Kc…………………………………………………………………..3.8

Where ETO=reference crop evapotranspiration in mm per day

ETc= standard evapotranspiration in mm per day

Kc = crop coefficient

IWR=ETc – Pef…………………………………………………………………3.9

Where IRW = the irrigation water requirement (mm)

Pef = effective rainfall (mm)

GIWR= $\frac{1}{E}(FWS * Acrop)$ ……………………………………………………3.10

Where GIWR=gross irrigation water requirement (m^3/month)

FWS=field water supply (l/s/ha)

Acrop=the potential irrigable area to be cultivated with selected crop (ha)

E=irrigation efficiency

GIR= $\frac{1}{E}$(NIR) where GIR is the Gross irrigation requirement of crops and E represents the Efficiency of the irrigation in percentage which was taken as 60%.

For all these units, the CROPWAT model - a computer program for crop water requirement calculations developed by FAO (FAO, 1995a) – will be uses to compute net irrigation water requirements. Inputs for the model are climatic parameters - rainfall and ETo - and crop coefficients. Output from CROPWAT includes monthly net irrigation water requirements by crop. Using the cropping pattern, and the actual and potential cropping intensity, net irrigation water requirements per year should be for a theoretical hectare of irrigated land in each area, were determined. The FAO Penman – Monteith method is recommended as the main method to determine ETo.

$$ETo = \frac{0.408\triangle(Rn-G)+\frac{900\gamma}{T+27.3}*U2(es-ea)}{\triangle+\gamma(1+0.3U2)} \quad \text{..........} 3.11$$

Where, ETO = reference evapotranspiration (mm/day)

Rn = net radiation at the crop surface (MJ/day m^2)

G = soil heat flux density (MJ/day m^2)

T = means daily air temperature at 2m height (^oC)

U2= wind speed at 2m height (m/s)

Ea =actual vapor pressure (kpa)

Es =saturation vapor pressure (kpa)

Es-es= saturation vapor pressure deficit (kpa)

$\triangle$ = slope vapor pressure curve (kpa/^OC)

γ = psychrometric constant (kpa/^OC)

3.2.4 Potential irrigable sites by the stream flows and approaches to develop potential map

After the suitable land for surface irrigation was identified, the mean monthly river flow was estimated using SWAT for un-gauged sub basin and monthly irrigation water requirements was calculated; it was necessary to compare and estimate the potential irrigable site for the watershed. After the potential of the river was identified the site should be compared according to their irrigation potential for irrigation development possibilities and give rank.

The method that was followed to address the objective of the study was presented below using chart. The chart shows the process of the whole work from data collection to final result of the study.

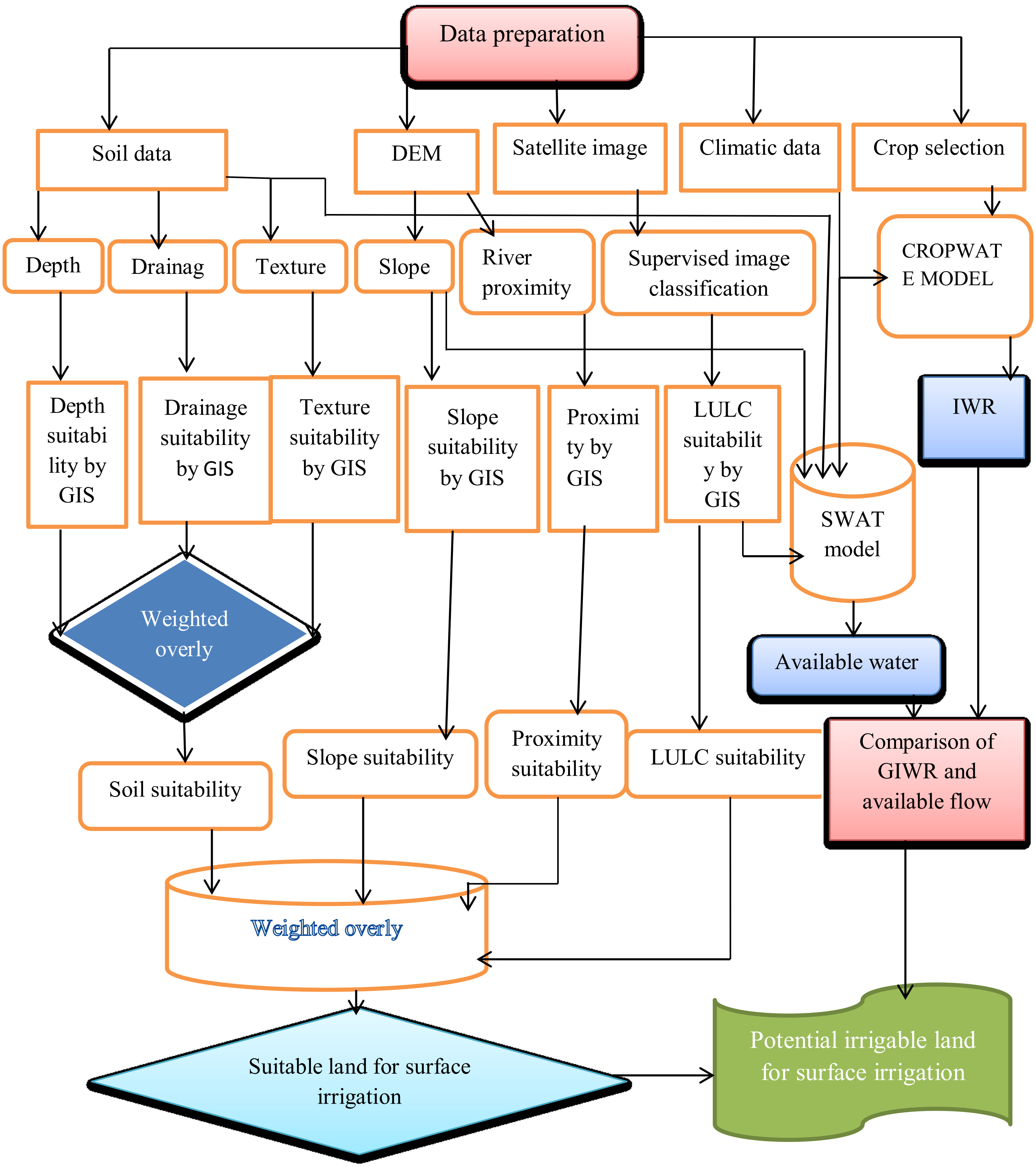

Figure 3.6: Conceptual frame work for surface irrigation potential assessment

4. RESULTS AND DISCUSSION

4.1 Land Suitability Evaluation for Surface Irrigation

The analysis of surface irrigation suitability was discussed in the following section. The suitability map of each parameter was reclassified and ready for the weighted overly process in Arc GIS.

4.1.1 Slope suitability

Since the irrigation method selected were surface, slope is the major factor. The four suitability classes of slope for the development of surface irrigation were shown in the figure 4.1 and the area coverage of the suitability classes were presented in the table 4.1.

Table 4.1: Slope suitability class of the study area

Slope range (%)	Area coverage (ha)	% coverage	Suitability classes
0-2	10940.1	16.2	Highly suitable
2-5	25121.7	37.2	Moderately suitable
5-8	13979.4	20.7	Marginally suitable
>8	17490.9	25.9	Non-suitable
Total	**67531.5**	**100**	

From the table 4.1 it was revealed that 53.4% (36061.7ha) of the total area is in range of highly suitable to moderately suitable. It is recommended for surface irrigation application process. But 47.6% (31470.3ha) of the area is from marginally suitable to not suitable for surface irrigation development.

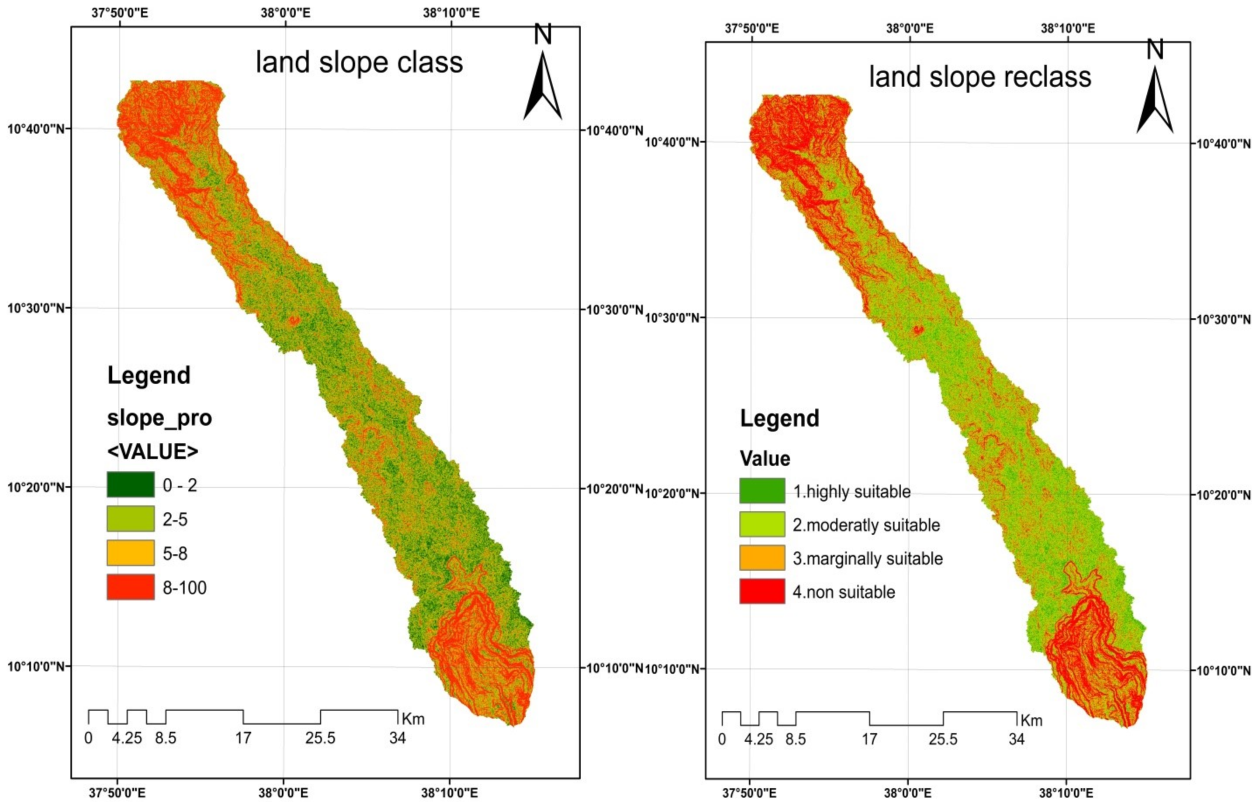

Figure 4.1: Slope class and suitability map of the study area

4.1.2 Soil type of the area

The major soil type extracted was Humic Nitosols (NTu) 4.4% (2971ha), Chromic Luvisols (LVx) 24.9% (16815ha), Eutric Vertisols (VRe) 53.9% (36399ha) and Rendezic Leptosoils (LPk) 16.8% (11345ha). Humic Nitosols soil was characterized by deep soil, light clay texture and moderately well drains condition and no salinity and alkalinity hazards. Eutric Vertisols was light clay textured with moderately well in drainage condition and deep in depth. Chromic Luvisols was characterized as sandy clay loam texture, poor drainage and deep soil. Also Rendezic Leptosoils is another soil type in the study area with property of sandy loam texture, imperfect drainage and shallow soil.

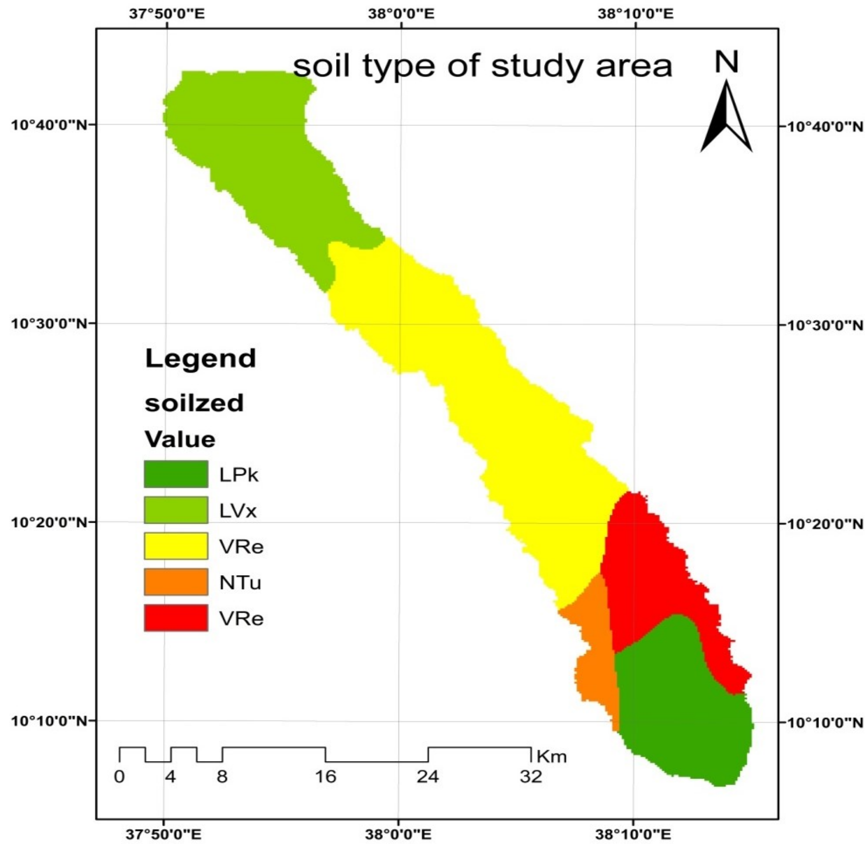

Figure 4.2: Soil type map of the study watershed

4.1.3 Soil depth suitability

The soil depth of the study area were classified in to two class which were >150cm and <40cm. Most area of the Muga watershed had a depth of greater than 150cm which is categorized as highly suitable for surface irrigation. The figure 4.3 shows the soil depth class and suitability of each area in the watershed.

From the figure 4.3 below it was conclude that except the Rendzic leptosolis soil type all soils have a depth of greater than 150cm which means they are suitable for surface irrigation. From the suitability map in Arc GIS the attribute table of reclassification indicated 56191.3ha (83.2%)

was highly suitable. The remaining 11324.4 ha (16.8%) was non suitable for the irrigation development.

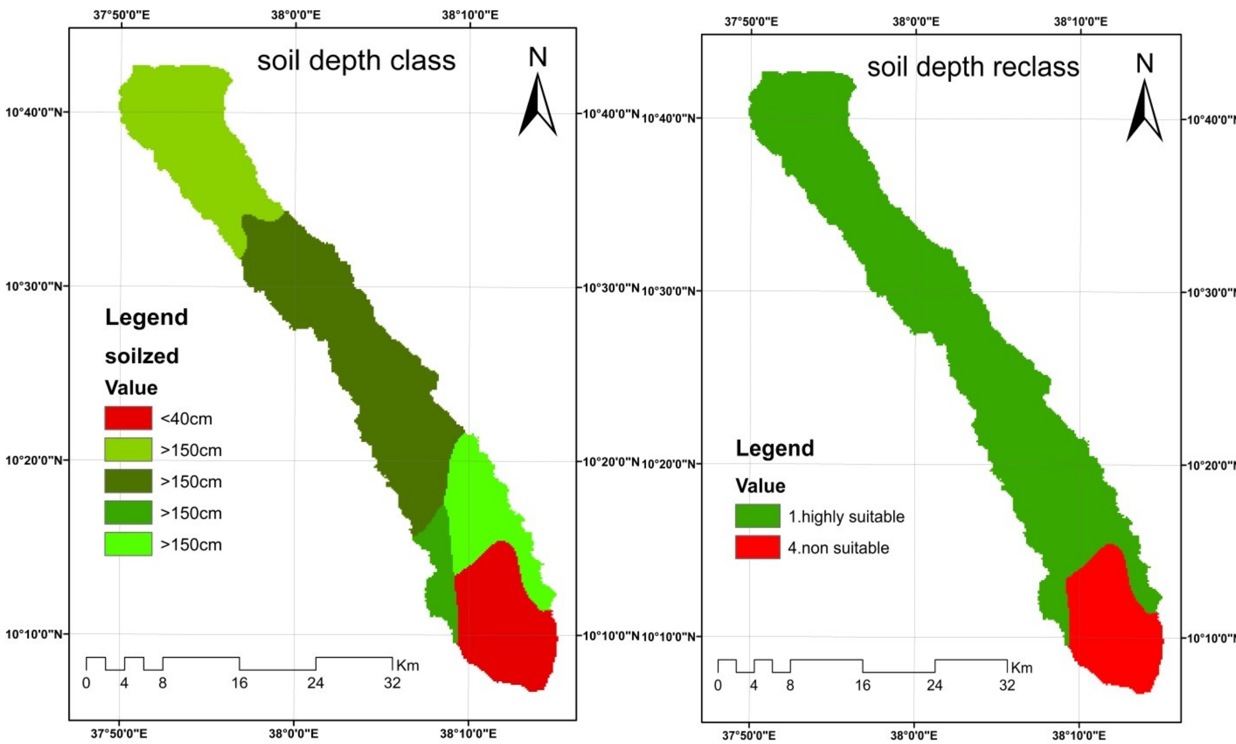

Figure 4.3: Soil depth map and suitability for surface irrigation in the study area

4.1.4 Soil drainage suitability

Well drained soils are preferred for surfaces irrigation in general. According to the FAO 2002 classification guide line the study area was divided in to four drainage classes which were well, moderately well, imperfectly well and poor drain. From the figure 4.4 the suitability class were 52471.9ha (77.7%) highly suitable, 14991.9ha (22.2%) moderately suitable and 67.53ha (0.1%) marginally suitable for surface irrigation development in the study area which is described in the table 4.2. But there were no area under non-suitable category.

Table 4.2: Soil drainage suitability class of the study area

Soil drainage	Area (ha)	Area (%)	Suitability class
Well/moderately well	52471.9	77.7	Highly suitable
Imperfectly well	14991.9	22.2	Moderately suitable
Poor drain	67.35	0.1	Marginally suitable

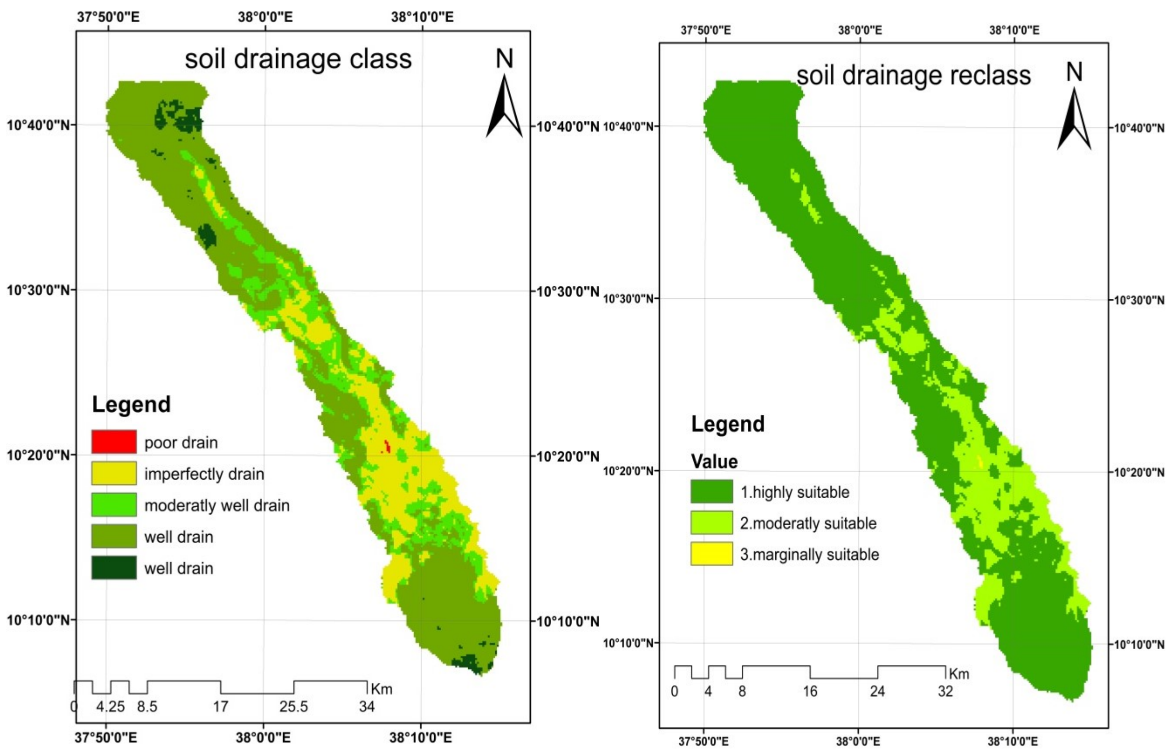

Figure 4.4: Soil drainage map and suitability class for surface irrigation

4.1.5 Soil texture suitability

Depending on this textural class the soil in the study area were classified as clay soil, sandy loam soil and sandy clay loam soil. Light clay soil is the most chemically active soil and categorized as highly suitable for surface irrigation based on FAO 2002 guide line. And sandy clay loam soil was evaluated as moderately suitable but sandy loam soil as marginally suitable for surface irrigation. Based on this classification 393.3km^2(58.2%) highly suitable, 168.8km^2(25%) moderately suitable and 113.5km^2(16.8%) marginally suitable for surface irrigation development. The result of soil texture suitability was shown below in the figure 4.5.

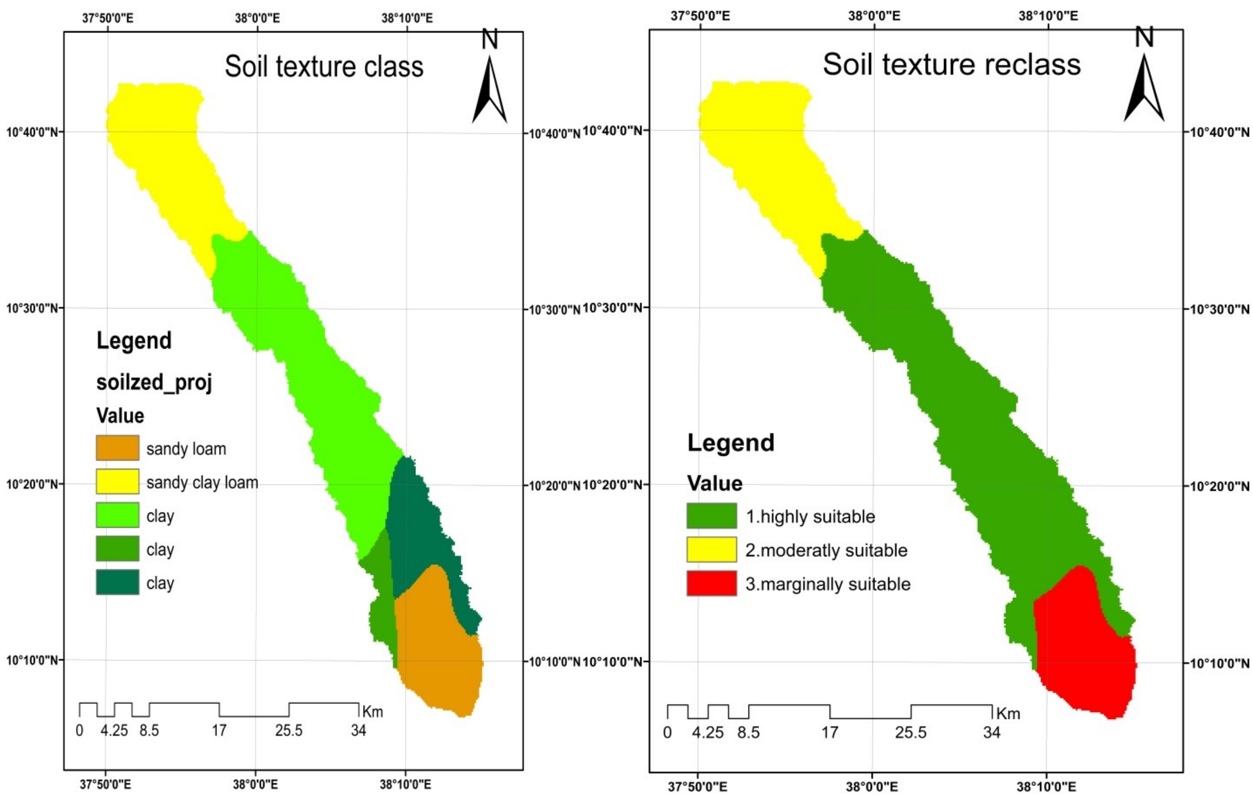

Figure 4.5: Soil textural map and suitability for surface irrigation

4.1.6 Weighted soil suitability

The overlay for soil parameter was done with equal influence in each parameter with 1 by 4 in 1 scale for the analysis. From the soil suitability evaluation the result was 82.2% highly suitable, 1% moderately suitable, 16.8% was marginally suitable but there were no area under non suitable for surface irrigation development with the combined effect of soil parameters like soil texture, soil depth and soil drainage. The result of the analysis described in the table 4.3 and figure 4.6 below.

Table 4.3: Weighted overly soil suitability classification for surface irrigation

No.	Area covered (ha)	Area covered (%)	Suitability class
1	55510.9	82.2	Highly suitable
2	675.31	1	Moderately suitable
3	11345.2	16.8	Marginally suitable

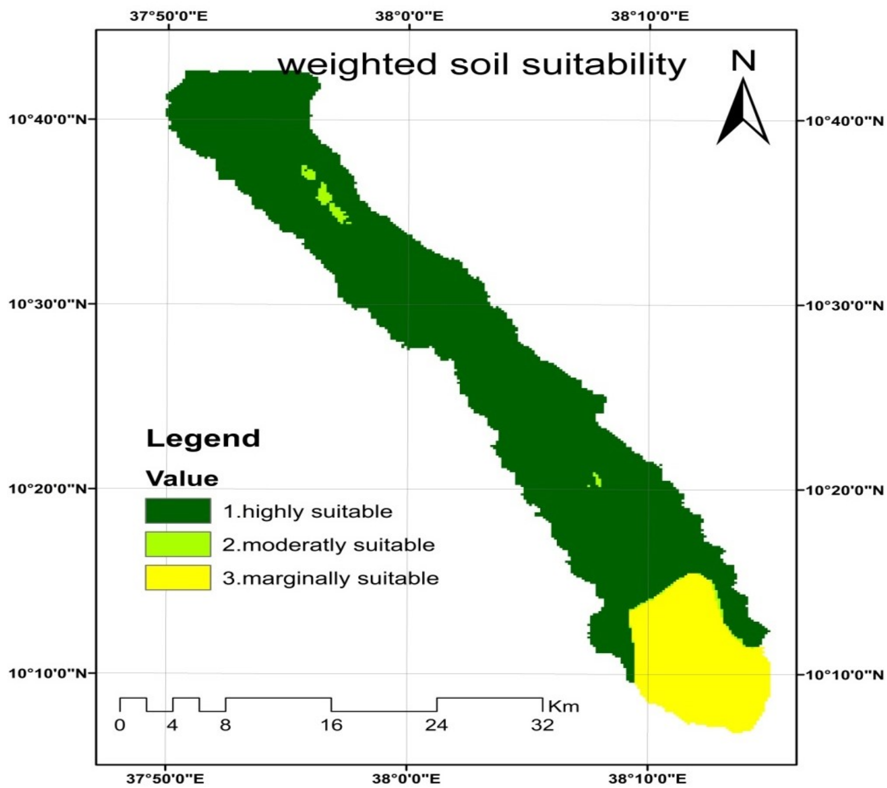

Figure 4.6: Weighted overly soil suitability map for surface irrigation

4.1.7 Land use/land cover suitability

From Land sat image supervised classification, six land cover/ land use classes were identified in the study area. The class was cultivated land, grass land, forest land, shrub land, water body and built up area.

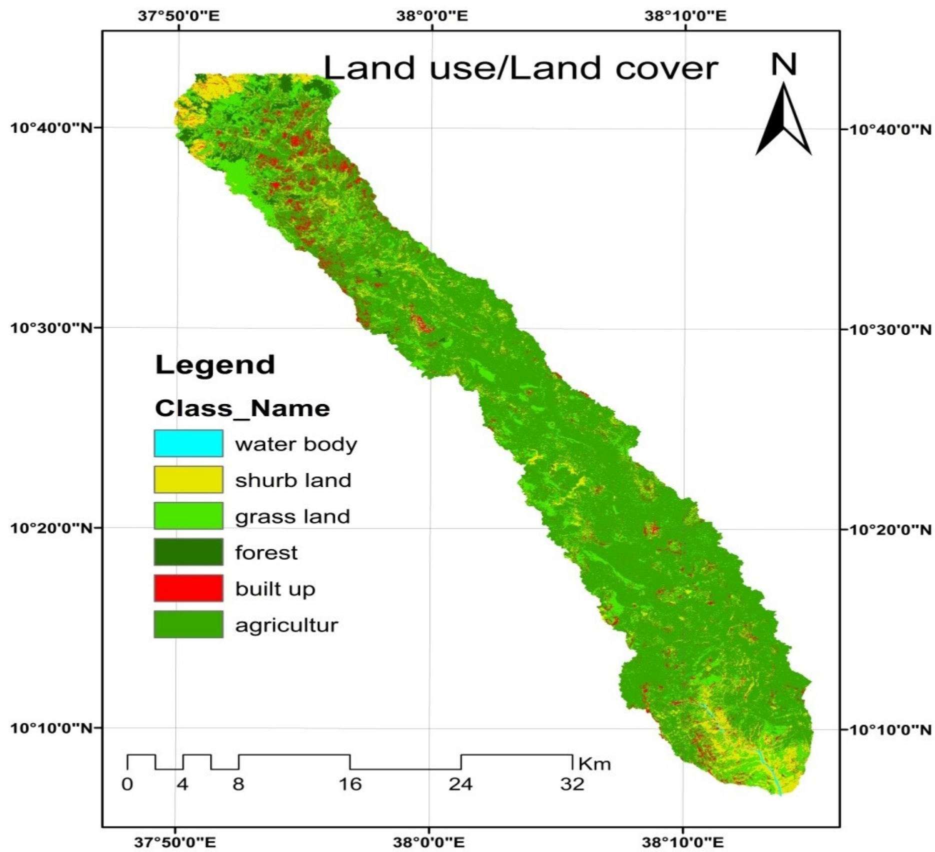

Figure 4.7: LULC map of study area by supervised classification

Table 4.4: LULC class of the study area

LULC class	Area (ha)	Percentage	Suitability
Agricultural land	444793	66.36	S1
Grass land	10618	15.73	S2
Shrub land	6475	9.59	S3
Forest area	2072	3.07	N
Built up area	3409	5.05	N
Water body	135	0.20	N

The result in table 4.4 revealed that agricultural land was the dominating land cover when compared to other land cover types in the study area (66.36%) of the total study area. This land cover type was categorized as highly suitable for surface irrigation. Grass land cover type was mostly characterized as an area which is covered by open grass. It is mostly used for grazing purpose in the area. The grass land covers an area of 15.7% and categorized as moderately suitable for surface irrigation.

Shrub land type of land cover is characterized by degraded and with small trees. Shrub land was classified as marginally suitable for surface irrigation with a cover of 9.59% from the total study area. Forest area land cover is found in the top side of the study area with a cover of 3.07% from the total area. It is not suitable for an irrigation purpose. There were some areas which are small towns in the study area. The built up area or settlements area not suitable for irrigation purpose. It covers 5.05% from the total area.

There was no any water body in the study area except the Muga streams with small attributers. It covers an area of around 0.2%. It is not suitable for surface irrigation.

The suitability of land for surface irrigation development was categorized in to four classes according to FAO 1996 framework, ranging from highly suitable to non-suitable were shown in the figure 4.8 below and the percentage of suitability for surface irrigation development was described in table 4.5 below.

Table 4.5: LULC suitability for surface irrigation development

LULC	Area (ha)	Percentage (%)	Suitability class
Cultivated land	44793	66.36	Highly suitable
Grass land	10618	15.73	Moderately suitable
Shrub land	6475	9.59	Marginally suitable
Forest /water/built up areas	5616	8.32	Non-suitable
Total	67531	100	

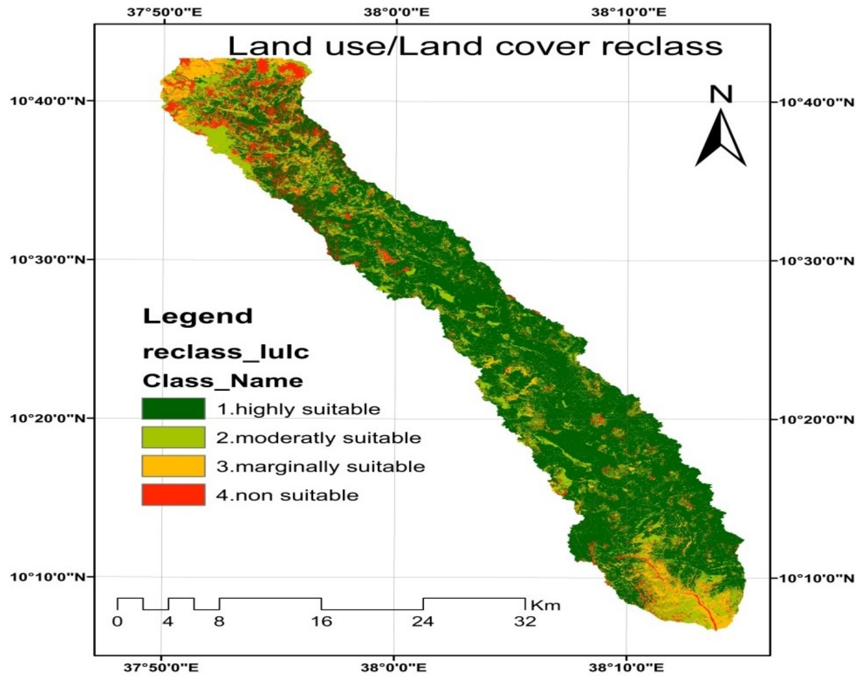

Figure 4.8: LULC suitability classifications for irrigation development

4.1.8 Distance from the water supply (sources)

This parameter analysis was important to evaluate the cost which is necessary to build an irrigation infrastructure. If the location of the command area is near to the river it is classified as suitable for surface irrigation.

Table 4.6: River proximity suitability for surface irrigation development

River proximity (km)	Area (ha)	Percentage (%)	Suitability class
0-1.5	37901.2	56.15	Highly suitable
1.5-3	21573	31.96	Moderately suitable
3-5	7519.5	11.14	Marginally suitable
>5	506.25	0.75	Non suitable
Total	67531	100	

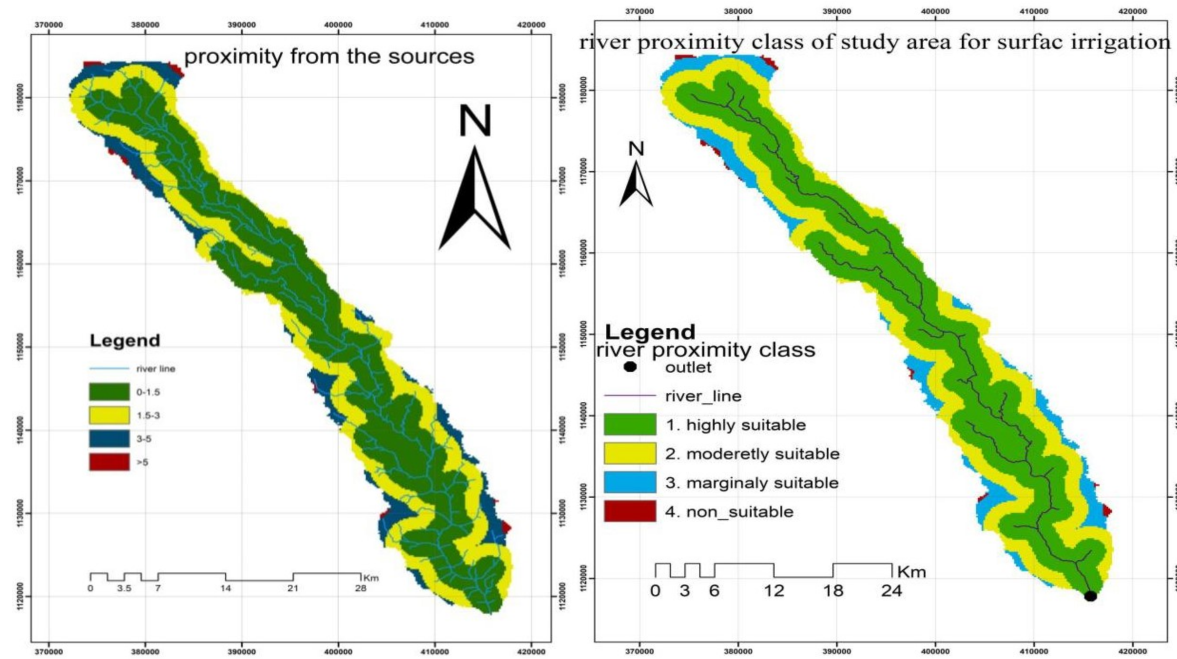

Figure 4.9: River proximity class and suitability for surface irrigation

As we have seen from the map majority of the land in the study area was highly suitable for surface irrigation. From table 4.6 it was revealed that 37901.2ha (56.15%) were highly suitable; 21573ha (31.96%) moderately suitable and also there were some area of land in the watershed with a class of marginally suitable and non-suitable for surface irrigation with an area of 7519.5ha (11.14%) and 506.25ha (0.75%) respectively for surface irrigation development.

4.1.9 Weighted overlay

The weighting of decision factors was determined based on the importance of each factor for surface irrigation project development, knowledge of those experts on the irrigation area and some other study on surface irrigation suitability. Based on this slope was judged as very important for surface irrigation because any surface irrigation is functional for flat land slope. Also if the river is far away the command area highly investment is needed for construction of conveyance structures. Soil was considered as important parameter, and LULC is less important for surface irrigation project development. Based on this judgment the AHP table was described below.

Table 4.7: Pairwise comparison matrix

parameters	Soil	Slope	River	LULC
Soil	1	0.333	0.5	3
Slope	3	1	2	5
River	2	0.5	1	4
LULC	0.333	0.2	0.25	1
Sum	6.333	2.033	3.75	13

To calculate the normalized pair wise matrix all the elements of the column were divided by the sum of the column. The criteria weight was calculated by averaging the entire row, which means the normalized values in each row, was added and divided by the number of the suitability parameters.

4.8: Normalized pairwise matrix

Parameters	Soil	Slope	River	LULC	Criteria weight
Soil	0.1579	0.1638	0.1333	0.2307	0.1714
Slope	0.4737	0.4919	0.5333	0.3846	0.4709
River	0.3158	0.2459	0.2666	0.3077	0.2840
LULC	0.0526	0.0984	0.0666	0.0769	0.0736

After normalizing the matrix it was necessary to calculate consistency for checking whether the calculated value was correct or not. From this matrix the weighted sum value was determined by summing each in the row.

Table 4.9: Matrix consistency

parameters	soil	Slope	River	LULC	Weighted Sum value	Criteria weight	W.S/C.W
Soil	0.1714	0.1568	0.1420	0.2209	0.6912	0.1714	4.03
Slope	0.5143	0.4709	0.5681	0.3682	1.9215	0.4709	4.08
River	0.3429	0.2354	0.2840	0.2945	1.1569	0.2840	4.07
LULC	0.0571	0.0942	0.0710	0.0736	0.2959	0.0736	4.02

λ_{max} was calculated by summing all the ratio value and divided by the number of suitability parameters.

$$\lambda_{max}=\frac{4.03136+4.08056+4.07328+4.01855}{4}=4.0527575$$

Consistency index (C.I) $=\frac{\lambda \max - n}{n-1}$ where n is the number of suitability parameters.

$$=\frac{4.0527575-4}{4-1}=0.017586$$

R= $\frac{C.I}{R.I}$ which is $\frac{0.017586}{0.9}$=0.0195 this was less than the maximum allowable 0.1

Table 4.10: Percentage of influence for each parameter

Parameters	% influence
Slope	47.1
River	28.4
Soil	17.1
LULC	7.4

Potential irrigable land was obtained by creating irrigation suitability model analysis which involved weighting of suitability parameters which are soil, slope, and LULC and river proximity. The model for this analysis was described below in the chart.

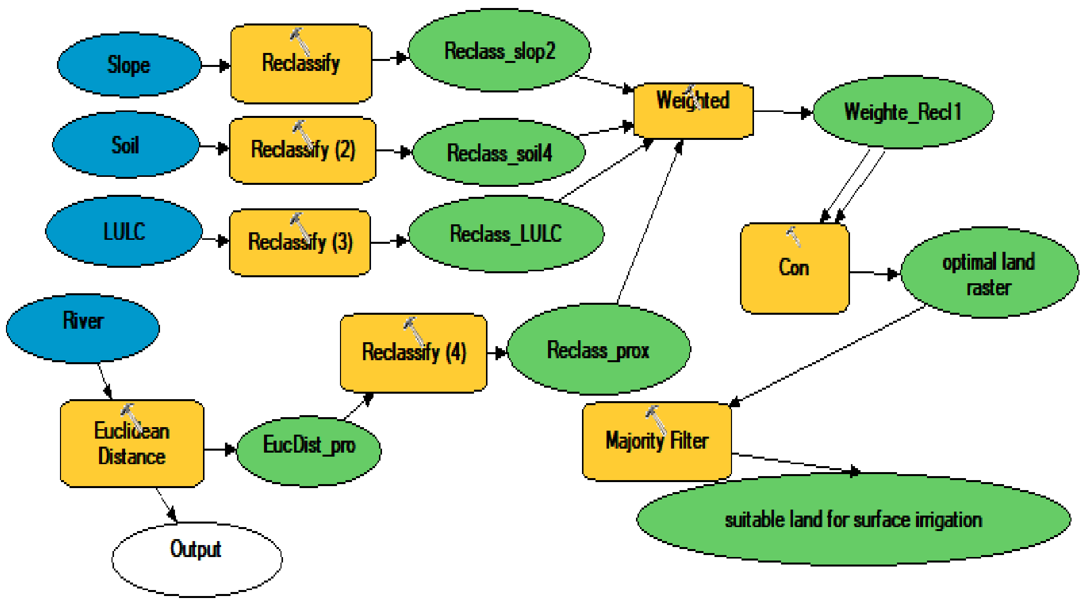

Figure 4.10: Models for weighted overly analysis

4.2 Suitable Land for Surface Irrigation

Potential irrigable land was obtained by creating irrigation suitability model with weighting values of all data sets which are soil, slope, LULC, and proximity of water to the command. The figure10.14 below shows identified potential irrigable lands below the diversion structure site among the tributary rivers. The tributary rivers are referring for the sub watersheds obtained by watershed delineation. Attempts were made to identify potential diversion site above the irrigable command area. The manually added outlet on the map indicates the location of the diversion site, which is added during the watershed delineation based on the location of the site of interest. This diversion site was selected to calculate the available flow from the Arc SWAT simulation directly. Also the identified irrigable areas with the location of the diversion site were described in the table 4.11 below.

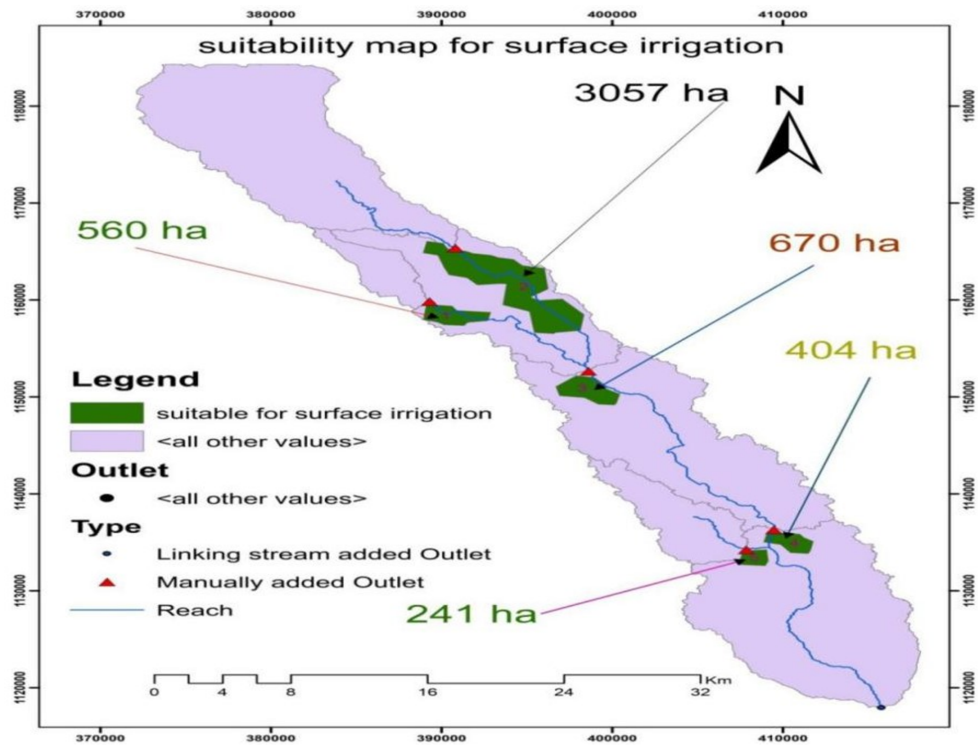

Figure 10.11: Suitable sites for surface irrigation development with diversion site

Table 4.11: Suitable command areas for development of surface irrigation

No.	River (water sources)	Diversion site location		Command area (ha)
		Longitude	Latitude	
1	Sub_basin1	389623	1166473	3057
2	Sub_basin2	389118	1159904	560
3	Sub_basin3	396319	1151439	670
4	Sub_basin4	409331	1136659	404
5	Sub_basin5	408952	1134385	241

4.3 Estimation of Available Flow

During watershed delineation six manually added outlets with six sub basins were found. The area of the sub basin were 173km2, 20.63km2, 109km2, 152km2, 43km2 and 179km2 respectively. The available flow of this sub basins were simulated with Arc SWAT model. The added outlet and sub basin were shown in the figure 4.12 below.

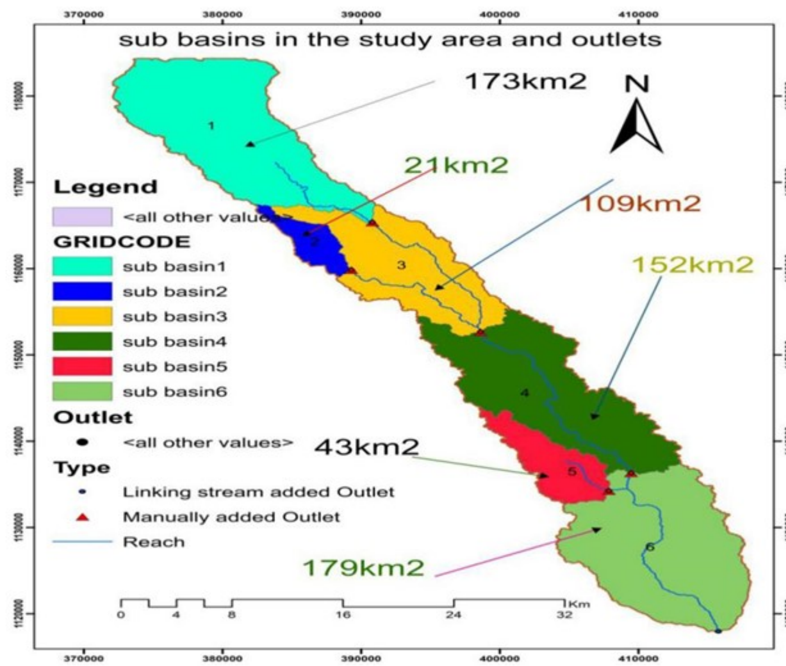

Figure 4.12: Sub basins and outlets of the study area for simulation

The water available for the six sub basin was simulated with Arc SWAT2012 model on the monthly time step for the year 1994-2018. Water availability evaluation was analyzed through the implementation of Arc SWAT model in each sub basin. The SWAT model was run successfully and observed flow data from 1994-2008 was used for model calibration and validation with the consideration of sensitive parameters using SWAT CUF Sufi 5.1.2.6 software. The water availability evaluation understands the potential of irrigation water supply in each sub basins obtained from the SWAT simulated output and comparing with the irrigation water requirement for dominating crops in the study area.

Table 4.12: Mean monthly simulated flow of sub basins (m3/s)

Month	sub_basin1	sub_basin2	sub_basin3	sub_basin4	sub_basin5	Sub_basin6
Jan	1.85	0.24	3.31	5.04	0.48	7.83
Feb	1.95	0.25	3.51	5.34	0.52	8.20
Mar	1.66	0.21	2.98	4.55	0.44	7.01
Apr	1.38	0.18	2.48	3.79	0.37	5.86
May	2.28	0.27	3.98	5.98	0.57	9.08
Jun	2.99	0.34	5.15	7.71	0.72	11.63
July	4.17	0.48	7.17	10.70	1.00	16.05
Aug	4.40	0.52	7.64	11.48	1.08	17.18
Sep	4.40	0.54	7.77	11.75	1.13	17.67
Oct	2.80	0.35	4.97	7.56	0.73	11.61
Nov	3.41	0.41	5.93	8.87	0.84	13.67
Dec	2.69	0.34	4.73	7.14	0.68	11.04
Average	2.83	0.34	4.97	7.49	0.71	11.40

4.3.1 Sensitivity analysis

In the sensitivity analysis 12 parameters were identified as the most sensitive which are considered in the calibration. The parameters were listed in the table below with their level of sensitivity.

Table 4.13: Sensitivity analysis of model parameters in Muga watershed

Parameters	Parameter Code	T-stat	P-value	Sensitivity
Initial SCS CN II value	CN2	-6.0	0.0	2
Threshold water depth in shallow aquifer	GWQMN	0.5	0.63	11
Base flow Alpha Factor	ALPHA_BF	10.4	0.0	1
Ground water delay	GW_DEY	-1.7	0.12	5
Soil evaporation compensation factor	ESCO	-0.9	0.4	9
Soil depth	SOL_Z	1.0	0.32	7
Threshold depth of water in the shallow aquifer required for evaporation to occur	REVAPMN	-3.1	0.01	3
Maximum canopy storage	CANMX	1.02	0.33	8
Ground water evaporation coefficient	GW_REVAP	-1.2	0.23	6
Effective hydraulic conductivity in the main channel	CH_K2	0.5	0.61	10
Available water capacity of the soil layer	SOL_AWC	-2.4	0.04	4

4.3.2 Model calibration

The ENS of 0.55, R^2 of 0.61 and mean deviation values of 26.1% was obtained from the initial model run. Since some adjustment was required for the sensitive parameters calibration need to be performed. The calibration was done for 10 years including warm up period (1994-2003) for gauged stream flow. Model parameters were calibrated manually followed to auto-calibration. In the calibration process 12 parameters were considered and their values were varied iteratively with in the allowable range until the measured and simulated flow agreed. The fit between monthly observed and simulated flow were checked by plotting a time series bar chart.

Table 4.14: List of best fitted parameters with calibrated values for mean monthly flow

Parameters	Parameter code	Range	Adjusted parameter
Initial SCS CN II value	CN2	±0.20	-0.034
Threshold water depth in shallow aquifer	GWQMN	0-5000	219
Base flow Alpha Factor	ALPHA_BF	0-1	0.975
Ground water delay	GW_DELAY	30-450	250.5
Soil evaporation compensation factor	ESCO	0-1	0.835
Soil depth	SOL_Z	0-3500	2887
Threshold depth of water in the shallow aquifer required for evaporation to occur	REVAPMN	0-500	327.5
Maximum canopy storage	CANMX	0-10	2.6
Ground water evaporation coefficient	GW_REVAP	0.02-0.2	0.095
Effective hydraulic conductivity in the main channel	CH_K2	0.01-150	76.2
Available water capacity of the soil layer	SOL_AWC	0-1	0.085

Calibration resulted in Nash–Sutcliffe simulation efficiency (ENS) of 0.83, correlation coefficient (R^2) of 0.88, and mean deviation of -12 % showing a good agreement between measured and simulated monthly flows. The result also indicated that model was calibrated satisfactorily to simulate monthly stream flows adequately. The calibration result demonstrates the SWAT's ability to predict realistic flow.

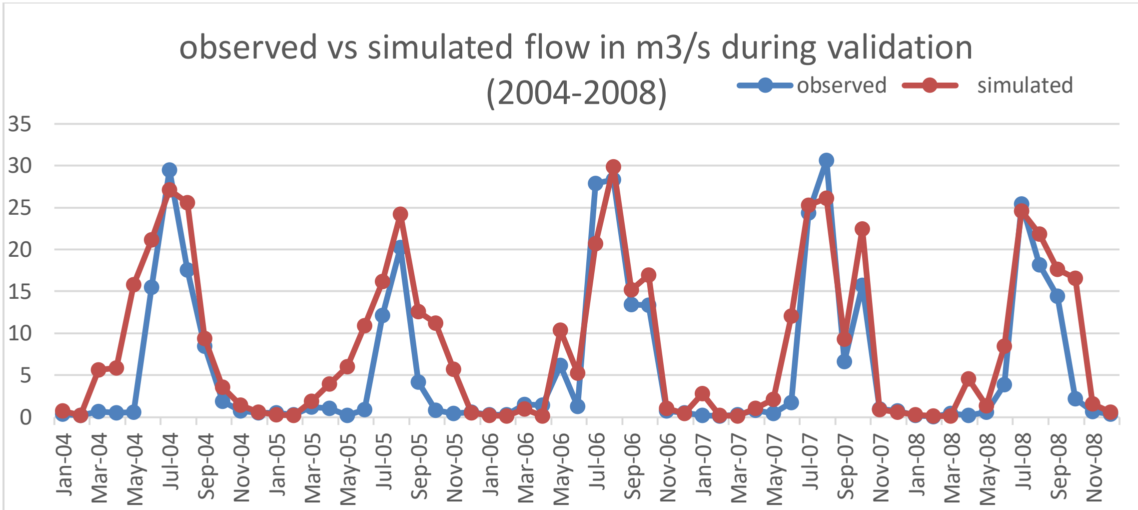

Figure 4.13: Calibration result of average monthly observed and simulated flow (1997-2003)

4.3.3 Model validation

With the calibrated parameters the SWAT need to be validated using an independent steam flow data that was not used for model calibration. In this study stream flow data of Muga river watershed of 5 years period were used during validation (2004-2008).The three statistical goodness of fit were used for model validation. Therefore ENS is 0.81, R^2 of 0.86 and deviation of discharge -14.

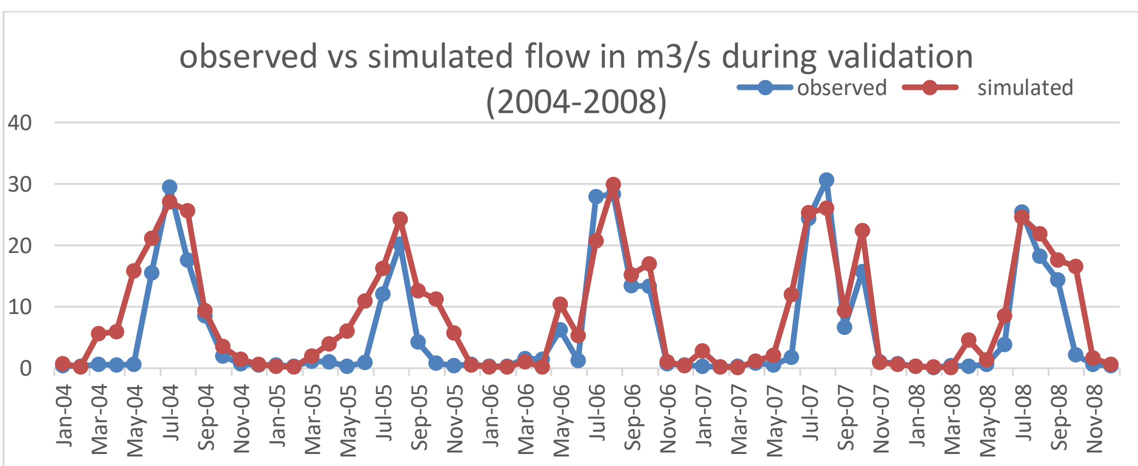

Figure 4.14: Observed and simulated flow for the validation period (2004-2008)

4.4 Irrigation Water Requirement for the Command Areas

Irrigation water requirement of maize, onion and potato for the identified potentially suitable land were calculated using ETO and other climatic dates by CROPWAT8.0 which was derived from the computation in the appendix table 15 to 19 present monthly gross irrigation water requirements that must met from the river. The result gives 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) by irrigation method.

Table 4.15: Gross monthly irrigation water requirement for growing maize (Mm^3)

No	Command area (ha)	Months						
		Jan	Feb	Mar	Apr	May	June	Total
1	560	0.44	0.47	0.61	0.63	0.45	0.04	2.65
2	3057	2.41	2.55	3.34	3.44	2.48	0.21	14.4
3	670	0.53	0.56	0.73	0.76	0.54	0.05	3.16
4	404	0.32	0.34	0.44	0.46	0.33	0.03	1.91
5	241	0.19	0.20	0.26	0.27	0.20	0.02	1.14
Total	4932							23.29

Table 4.16: Gross monthly irrigation water requirement for growing onion (Mm^3)

No	Command area (ha)	Months					
		Jan	Feb	Mar	Apr	May	Total
1	560	0.46	0.59	0.57	0.47	0.28	2.37
2	3057	2.49	3.21	3.13	2.57	1.55	12.96
3	670	0.55	0.7	0.69	0.56	0.34	2.84
4	404	0.33	0.43	0.41	0.34	0.21	1.71
5	241	0.20	0.25	0.25	0.20	0.12	1.02
Total	4934						20.91

Table 4.17: Gross monthly irrigation water requirement for Growing potato (Mm^3)

No	Command area (ha)	Months					
		Jan	Feb	Mar	Apr	May	Total
1	560	0.30	0.52	0.69	0.55	0.11	2.17
2	3057	1.65	2.82	3.79	2.99	0.58	11.83
3	670	0.36	0.62	0.83	0.66	0.13	2.59
4	404	0.22	0.37	0.50	0.40	0.08	1.56
5	241	0.13	0.22	0.30	0.24	0.05	0.93
Total	4932						19.1

4.5 Transferring Discharge to Site of Interest

The discharges at the site of interest were obtained by transferring the river discharge at the gauged site or from the simulated discharge to the site of interest in the same river. The site of interest in the case of this study was the point where it is closer to and above the command area. All the drainage areas of the site of interest were found within 20% of the drainage area of the gauged site. Hence the area ratio method suggested by (Awulachew *et al*., 2010) was adopted and the calculated result presented in the table 4.18 below.

Table 4.18: Mean monthly discharge (m^3/s) at site of interest

	Mean monthly discharge at site of interest in m^3/s											
Site of interest	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bora	1.22	1.31	1.11	0.93	1.43	1.82	2.52	2.72	2.83	1.82	2.11	1.2
G/wit	1.73	1.83	1.57	1.31	2.0	2.56	3.53	3.84	3.98	2.59	2.94	2.41

4.6 Irrigation Potential of River Sub-Basin

Irrigation potential of the river sub-basin in the study area was obtained by comparing the irrigation water requirements of the identified suitable land of the selected crop for surface irrigation with the available mean monthly flow in the river sub basins obtained from simulation based on the suggested method by FAO, 1997. The table, 4.19, 4.20 and 4.21 below shows the comparison of gross irrigation requirement of the selected crops and the available mean monthly flow of the corresponding sub basin. Result of this analysis concluded that the monthly irrigation requirement of the selected crops (maize, onion and potato) is less than the mean available flow of Bora, Gibstawit and Genet River, while the irrigation water requirement of G/muga and E/muga were calculated as greater than available flow for the month January, February, March and April.

Hence the critical command areas were calculated for growing these crops with the available flow (Micheal, 2008). The available flow simulated for January, February, March and April was (0.24, 0.25, 0.21 and 0.18) m3/s for G/muga and (1.85, 1.95, 1.66 and 1.38) m3/s for E/muga respectively. But the gross irrigation requirement of maize from CROPWAT8.0 was calculated as 0.48l/s/ha, 0.68l/s/ha, 0.80l/s/ha and 0.73l/s/ha for the month January, February, March and April respectively. On the other hand the gross irrigation requirement of potato on January, February, March and April was 0.35l/s/ha, 0.72l/s/ha, 0.77l/s/ha and 0.60l/s/ha respectively. For onion it was calculated as 0.50l/s/ha, 0.72l/s/ha, 0.63l/s/ha and 0.55l/s/ha for the same month with irrigation efficiency of 60% in all cases. Based on this the critical irrigable land was calculated as 246ha for G/muga and 1882ha for E/muga river which was in the month April for growing maize. For the other identified sites the monthly flows were greater than the irrigation water requirement of the selected crops.

Table 4.19: Comparing irrigation requirement and available flow of the sub basin for maize

River name	Command area (ha)		Mean monthly flow available in each sub basin and GIR (m^3/s)					
			Jan	Feb	Mar	Apr	May	June
G/muga		Available flow(m^3/s)	0.24	0.25	0.21	0.18	0.27	0.34
	560	GIR(m^3/s)	0.27	0.38	0.45	0.42	0.13	0.0
E/muga		Available flow(m^3/s)	1.85	1.95	1.66	1.38	2.28	2.99
	3057	GIR(m^3/s)	1.48	2.08	2.45	2.25	0.72	0.0
Bora		Available flow(m^3/s)	1.22	1.31	1.11	0.93	1.43	1.82
	670	GIR(m^3/s)	0.32	0.45	0.53	0.48	0.15	0.0
Gibstawit		Available flow(m^3/s)	1.73	1.83	1.57	1.31	2.0	2.56
	404	GIR(m^3/s)	0.20	0.28	0.32	0.30	0.10	0.0
Genet		Available flow(m^3/s)	0.48	0.52	0.44	0.37	0.57	0.72
	241	GIR(m^3/s)	0.12	0.17	0.20	0.18	0.05	0.0

Table 4.20: Comparing irrigation requirement and available flow of the sub basin for potato

River name	Command area (ha)		Mean monthly flow available in each sub basin and GIR (m^3/s)				
			Jan	Feb	Mar	Apr	May
G/muga		Available flow(m^3/s)	0.24	0.25	0.21	0.18	0.27
	560	GIR(m^3/s)	0.20	0.40	0.43	0.33	0.05
E/muga		Available flow(m^3/s)	1.85	1.95	1.66	1.38	2.28
	3057	GIR(m^3/s)	1.07	2.18	2.35	1.83	0.25
Bora		Available flow(m^3/s)	1.22	1.31	1.11	0.93	1.43
	670	GIR(m^3/s)	0.23	0.48	0.52	0.40	0.05
Gibstawit		Available flow(m^3/s)	1.73	1.83	1.57	1.31	2.0
	404	GIR(m^3/s)	0.13	0.28	0.32	0.25	0.03
Genet		Available flow(m^3/s)	0.48	0.52	0.44	0.37	0.57
	241	GIR(m^3/s)	0.08	0.17	0.18	0.15	0.02

Table 4.21: Comparing irrigation requirement and available flow of the sub basin for onion

River name	Command area (ha)		Mean monthly flow available in each sub basin and GIR (m^3/s)				
			Jan	Feb	Mar	Apr	May
G/muga		Available flow(m^3/s)	0.24	0.25	0.21	0.18	0.27
	560	GIR(m^3/s)	0.28	0.40	0.35	0.30	0.18
E/muga		Available flow(m^3/s)	1.85	1.95	1.66	1.38	2.28
	3057	GIR(m^3/s)	1.53	2.18	1.93	1.68	0.97
Bora		Available flow(m^3/s)	1.22	1.31	1.11	0.93	1.43
	670	GIR(m^3/s)	0.33	0.48	0.42	0.37	0.22
Gibstawit		Available flow(m^3/s)	1.73	1.83	1.57	1.31	2.0
	404	GIR(m^3/s)	0.20	0.28	0.25	0.25	0.13
Genet		Available flow(m^3/s)	0.48	0.52	0.44	0.37	0.57
	241	GIR(m^3/s)	0.12	0.17	0.15	0.13	0.08

The identified potential irrigable site was taken as their irrigation potential (IFAD, 1987 and MoWR, 2002). Therefore the total irrigation potential of Muga watershed was found to be 3443ha for growing maize which account for 5.1% of the study area.

N.B. all the river names in the sub basin were local name of the community.

Table 4.22: Summery of irrigation potential and their rank for irrigation development

River name	Irrigation potential (ha)			Rank
	Maize	Potato	Onion	
Enat muga	1882	2165	2509	1
Gilgel muga	246	274	327	4
Bora	670	670	670	2
Gibstawit	404	404	404	3
Genet	241	241	241	5

5. SUMMARY AND CONCLUSION

5.1 Summary and Conclusion

Land suitability evaluation is concerned with the assessment of land performance when used for specified purpose. It involves the execution and interpretation of basic data of climate, soil, vegetation and other aspects of land in terms of the requirements of alternative form of land use.

This study was initiated with the assessment of surface irrigation potential of Muga watershed with six sub-basins during delineation. The total watershed area was obtained as 67535ha with six outlets added manually for further flow determination using Arc SWAT. Identification of suitable land, estimation of surface water resources of the watershed and estimation of irrigation water requirement were the main tasks of the study.

Different types of data were utilized to attain the objectives. This includes satellite image, soil data, stream flow data, meteorological data, and other information about crop and cropping pattern were collected from different sources.

The result of simulation was presented in monthly base. The performance and applicability of SWAT model was evaluated through sensitivity analysis, calibration and validation. Calibration and validation were performed for the period of 1994-2003 and 2004-2008 respectively on monthly base for evaluation of its applicability to simulate flow of un-gauged sub basins. The result of performance and applicability were satisfactory for gauging station with R^2=0.88 and ENS= 0.83 for calibration and R^2=0.86 and ENS=0.81 for validation.

The surface irrigation land suitability analysis was done for the physical parameters of land (slope, soil drainage, soil depth, soil texture, LULC and river proximity). The suitability for surface irrigation in the study area was done using GIS and ERDAS IMAGINE.

Gross irrigation water requirement was carried out for three crops in Crop WAT software. From this calculation it was concluded that different crops has different IWR for different months. Also the cropping period, kc, yield response and critical depletion values of the crops were different. After calculating the irrigation water requirement and simulate the river flow, it was done comparison to determine the potential suitable area for surface irrigation development.

From the study it was concluded that: - The surface irrigation land suitability analysis indicates that 53.4% of slope and 83.2% of soil in the study area ranges from highly suitable to moderately suitable. But 46.6% for slope and 16.8% for soil was not suitable for surface irrigation. For the other parameters LULC and river proximity it was concluded that 82.1% and 88.11% ranges from highly suitable to moderately suitable respectively. When these physical parameters were weighted using Arc GIS the suitable irrigable site were 7.3% of the total area. This indicates that as more suitability factors were considered in the assessment the irrigable land is expected to reduced and more accurate estimation was done.

The mean monthly flow of the sub-basins from the model simulation were determined as (2.83, 0.34, 4.97, 7.49, 0.71 and 11.4) m3/s respectively from sub-basin one to sub-basin six. The mean monthly flow of the main river at the outlet was simulated and determined as the average, maximum and minimum 11.4 m3/s 17.67m^3/s in September and 5.86m^3/s in April respectively. From the simulation it was concluded that amount of river flow for different months and drainage area was changed.

The mean monthly gross irrigation requirement from January to April were (0.48, 0.68, 0.80 and 0.73)l/s/ha for maize; (0.35, 0.72, 0.77, 0.60)l/s/ha for potato and 0.5, 0.72, 0.63, 0.55)l/s/ha for onion. The maximum and minimum monthly gross irrigation requirements were 0.8l/s/ha to grow maize in March and 0.35l/s/ha to grow potato in January respectively. From this estimation it was concluded that different crops in different stage of development need different amount of water in different months.

In the comparison of IWR and available simulated flow with the identified command area and selected crops the potential surface irrigable commands were determined as 3443ha (5.1%). This implies that surface irrigation potential of the river was limited by the total land to be irrigated, season of cultivation and the crop which is grown in the area.

Generally from the study it was concluded that integrated approach of GIS and SWAT model can produce reliable estimation of irrigation potential in the study area.

5.2 Recommendations

About half of the land was not suitable for surface irrigation development in the study area on the basis of slope. This shows that an appropriate drainage provision and cost wise land leveling should be taken into consideration.

The suitability for surface irrigation in this study was carried out by considering only some physical parameters of land, but there are other suitability factors that need to be checked like other water sources, water quality, chemical properties of soil, climatic condition, environment which are difficult get data easily to get reliable result.

Irrigation is the main for improving the income of the rural population through increasing agricultural production. But in the study area only 5.1% of the total area was potentially suitable for surface irrigation, therefore further potential assessment analysis for other irrigation types and water sources should be carried out.

The estimation of the irrigation water requirement was carried out by selecting three major crops (onion, maize and potato) only. But for further analysis other researcher need to be select other several crops to calculate irrigation water requirement.

The study result could assist policy makers for better decision during the development of irrigation project in the Muga watershed. Hence Suitability of the land for surface irrigation was examined on the current development need only, but further investigation should be include future scenarios.

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APPENDIXES

Appendix1: Cumulative mean annual precipitation of each metrological station (mm)

Year	Debre Markos	dejen	motta	Yetnora	cumulative mean
1989	1444.4	1438.5	1108.2	1498.1	1372.3
1990	2757.9	2666.3	2186.0	3424.8	2758.7
1991	4070.8	3767.7	3744.8	4460.1	4010.9
1992	5328.2	4902.4	4762.1	5423.8	5104.1
1993	7091.5	6324.4	5995.7	6847.2	6564.7
1994	8292.6	7640.1	7099.7	8103.8	7784.0
1995	9541.5	8880.2	8070.0	8948.8	8860.1
1996	11131.9	10456.3	9493.2	10262.7	10336.0
1997	12649.6	12365.5	10777.7	11262.2	11763.7
1998	13867.5	14103.9	12201.6	12631.7	13201.2
1999	15211.6	16107.7	13469.7	13958.9	14686.9
2000	16608.5	18092.8	14598.6	15060.4	16090.0
2001	17982.7	19942.4	16018.8	16187.0	17532.7
2002	19288.2	21451.3	17165.9	17330.8	18809.0
2003	20499.0	22593.5	18331.7	18203.9	19907.0
2004	21817.3	23602.4	19331.1	19236.0	20996.7
2005	23069.3	24684.6	20525.8	20277.2	22139.2
2006	24590.9	26172.5	21927.0	21803.0	23623.3
2007	25991.4	27530.2	23007.2	22973.3	24875.5
2008	27306.6	29211.7	24331.6	24041.5	26222.8
2009	28566.1	30393.1	25427.2	25064.9	27362.8
2010	29934.4	31501.6	26719.0	26277.2	28608.0
2011	31418.2	32701.7	28029.5	27459.5	29902.2
2012	32690.7	33863.6	29166.0	28587.8	31077.0

2013	33920.1	35087.7	30640.6	29749.6	32349.5
2014	35257.2	36358.4	32097.1	30683.7	33599.1
2015	36316.6	37427.0	33448.7	31579.4	34692.9
2016	37504.0	38637.0	34656.8	32803.0	35900.2
2017	38941.1	39802.6	36198.8	33868.7	37202.8
2018	40271.5	40929.6	37532.9	34985.4	38429.9

Appendix 2: Mean monthly rain fall, max and min temperature, humidity, wind and radiation

Month	PPC(mm)	Tmax(^{O}C)	Tmin(^{O}C)	SLR(hr)	WND(m/sec)	HMD (%)
Jan	6.9	24.7	8.6	9.4	1.2	50.7
Feb	11.7	25.8	9.8	9.2	1.4	46.5
Mar	48.1	26.5	10.9	8.3	1.6	47.9
Apr	64.8	26.2	11.4	8.0	1.6	51.0
May	98.9	25.8	11.5	7.9	1.5	58.0
Jun	145.7	23.6	10.9	6.5	1.4	68.8
Jul	305.5	20.6	10.9	4.8	1.3	79.7
Aug	301.9	20.4	10.8	5.1	1.3	82.3
Sep	177.7	21.9	10.3	7.2	1.2	76.5
Oct	79.7	23.2	9.9	8.9	1.3	67.2
Nov	28.5	23.8	9.0	9.1	1.2	58.8
Dec	12.3	24.1	8.5	9.6	1.2	53.8
Mean	106.8	23.9	10.2	7.8	1.4	61.9

Appendix 3: Mean monthly rainfall data at Debre Markos (mm)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	6.5	22.8	142.5	91.0	25.0	163.1	355.4	330.7	204.4	9.4	7.7	85.9
1990	4.8	18.9	52.1	70.2	32.9	148.5	325.1	353.3	275.8	11.2	20.7	0.0
1991	8.8	3.9	68.7	116.8	149.3	215.2	221.3	311.8	168.0	50.8	32.5	51.0

1992	28.6	31.6	31.0	123.9	83.1	144.9	164.9	307.9	168.7	94.6	72.7	5.5
1993	8.0	27.4	37.8	177.8	197.6	209.6	305.8	314.7	322.1	159.4	5.5	0.0
1994	9.3	5.0	35.5	42.7	139.6	147.6	281.2	301.0	218.1	7.4	13.2	0.5
1995	0.0	1.0	20.3	90.4	146.6	126.4	246.1	344.6	151.2	14.4	12.4	95.5
1996	27.6	4.6	74.1	108.0	228.0	291.7	252.3	360.5	152.1	33.1	35.2	23.2
1997	14.3	0.0	29.6	97.5	118.7	151.0	286.8	338.8	205.8	183.5	85.0	6.7
1998	2.9	2.2	21.0	4.4	152.4	100.8	203.2	252.6	270.7	200.8	6.9	0.0
1999	72.6	0.0	2.8	43.2	46.8	180.7	252.1	340.3	164.3	210.5	2.5	28.3
2000	0.0	0.0	2.9	110.5	29.5	174.9	281.7	211.1	271.0	265.9	32.7	12.3
2001	0.0	3.7	58.1	101.2	129.6	154.7	365.2	322.3	170.3	66.9	0.0	2.2
2002	57.0	0.0	92.2	75.2	11.2	155.9	276.3	335.5	234.6	3.9	2.2	61.5
2003	3.6	57.4	69.6	19.2	5.3	212.0	205.5	351.6	256.8	10.7	0.3	18.8
2004	4.1	7.6	13.8	120.1	19.8	195.0	286.6	317.7	205.2	87.5	37.7	23.2
2005	2.3	0.6	110.6	42.9	43.7	150.4	314.0	220.5	235.3	90.2	41.5	0.0
2006	3.5	20.7	87.8	67.4	104.5	190.9	364.1	281.1	301.5	37.1	30.7	32.3
2007	1.7	15.6	77.5	71.0	162.9	188.0	250.6	325.9	269.0	37.9	0.4	0.0
2008	0.0	0.0	0.0	15.7	169.9	290.3	250.5	273.9	195.1	71.2	39.1	9.5
2009	11.7	21.1	50.8	22.7	16.8	159.3	276.7	452.3	98.5	116.9	10.9	21.8
2010	18.7	22.8	35.4	84.7	153.4	151.0	216.5	339.6	307.0	17.5	16.7	5.0
2011	2.0	3.1	110.4	68.9	237.8	143.0	231.1	288.3	282.9	7.5	97.3	11.5
2012	13.9	0.0	33.1	33.1	23.4	124.2	372.2	250.9	362.4	21.3	30.9	7.1
2013	3.6	4.7	16.4	11.8	125.0	161.3	282.8	245.4	194.8	147.3	34.2	0.0
2014	9.1	8.6	42.9	138.4	130.1	101.9	274.6	257.1	255.5	100.5	9.2	9.2
2015	6.0	14.6	45.5	20.1	244.1	119.1	149.7	237.2	129.4	12.7	65.0	16.0
2016	0.0	18.1	53.8	25.5	168.4	117.1	236.1	243.6	270.1	54.8	0.0	0.0
2017	0.0	34.1	65.4	77.5	344.9	107.9	285.6	246.6	193.2	60.5	21.4	0.0
2018	0.0	91.8	17.0	66.8	54.1	290.6	307.3	222.7	123.4	73.7	83.0	0.0
mean	10.7	14.7	50.0	71.3	116.5	168.9	270.7	299.3	221.9	75.3	28.3	17.6

Appendix 4: Mean monthly rainfall data at Dejen (mm)

year	Jan.	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep	Oct.	Nov.	Dec.
1989	0.0	18.7	159.9	117.9	43.1	103.2	216.2	429.7	215.2	69.5	0.0	65.1
1990	0.8	19.6	109.3	57.9	27.3	124.3	348.0	304.9	214.9	20.8	0.0	0.0
1991	2.7	3.4	8.8	11.6	37.1	199.0	276.8	343.6	189.0	18.5	0.0	10.9
1992	40.4	32.9	32.8	77.5	69.5	154.3	185.1	230.2	186.2	98.6	27.2	0.0
1993	8.8	11.7	35.7	171.9	164.4	171.3	283.7	239.7	212.0	122.8	0.0	0.0
1994	0.0	0.0	60.6	14.2	116.8	97.8	401.9	364.0	259.0	0.0	1.4	0.0
1995	0.0	0.0	15.2	56.3	87.4	120.8	329.5	388.0	193.1	6.0	4.7	39.1
1996	5.2	2.3	86.5	129.5	195.8	152.7	491.7	356.8	98.3	18.3	31.8	7.2
1997	54.8	0.0	95.9	173.3	96.1	310.9	376.3	335.0	53.6	200.7	198.7	13.9
1998	0.4	13.0	62.1	3.6	188.1	166.7	384.6	472.1	193.3	254.5	0.0	0.0
1999	4.9	0.0	0.0	28.8	117.5	161.0	637.4	595.4	128.7	322.5	2.1	5.5
2000	0.0	0.0	0.0	187.0	101.9	136.9	484.7	558.8	288.0	158.8	65.8	3.2
2001	0.0	9.0	120.8	87.5	83.7	298.0	645.4	361.5	134.3	100.9	2.4	6.1
2002	60.9	12.3	77.2	55.1	20.2	168.0	483.4	422.7	200.5	0.0	0.0	8.6
2003	0.8	36.0	139.3	64.1	3.3	123.9	273.0	283.3	192.5	0.0	16.1	9.9
2004	6.5	19.0	46.0	56.4	12.5	125.2	266.0	249.6	92.3	115.8	19.6	0.0
2005	6.0	0.0	69.3	49.4	90.0	151.2	260.8	222.7	139.0	80.5	13.3	0.0
2006	7.1	9.2	108.0	124.4	72.3	140.5	336.6	308.2	297.4	46.1	4.4	33.7
2007	17.6	68.2	42.8	83.4	177.7	180.7	335.2	261.4	175.5	15.2	0.0	0.0
2008	0.0	0.0	0.0	42.6	78.1	307.4	420.9	316.3	278.4	133.3	104.5	0.0
2009	0.0	3.0	52.2	66.2	19.8	101.1	331.8	339.5	132.4	113.5	9.9	12.0
2010	0.0	4.7	93.3	95.8	174.7	77.6	244.6	296.7	79.2	13.7	28.2	0.0
2011	0.0	0.0	100.3	44.8	86.3	151.2	195.2	360.6	148.6	0.0	113.1	0.0
2012	0.0	0.0	100.3	44.8	28.7	137.9	322.8	294.1	220.1	1.4	11.8	0.0
2013	0.0	0.0	15.4	14.1	122.0	172.4	351.4	310.7	118.1	110.1	9.9	0.0

2014	0.0	38.8	19.6	95.6	147.6	52.0	279.3	227.4	286.0	86.0	38.4	0.0
2015	0.0	4.1	10.4	0.0	185.2	89.9	129.6	319.4	166.7	29.9	110.4	23.0
2016	0.0	6.2	55.6	52.7	120.9	113.1	270.8	287.9	197.7	56.9	42.6	5.8
2017	0.0	12.3	25.3	37.8	143.9	102.9	257.8	286.4	171.2	70.7	50.3	7.2
2018	0.0	7.5	30.4	28.0	150.0	96.6	219.4	297.9	165.0	52.5	67.8	12.0
mean	7.2	11.1	59.1	69.1	98.7	149.6	334.7	335.5	180.9	77.2	32.5	8.8

Appendix 5: Mean monthly rainfall data at Motta (mm)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	1.5	16.0	18.7	67.5	82.4	95.8	301.3	239.5	172.0	78.7	24.9	10.1
1990	1.3	32.2	14.4	45.1	20.7	112.6	375.2	178.1	258.8	38.1	1.3	0.0
1991	0.9	5.1	150.4	127.0	170.5	207.7	318.7	276.7	236.3	44.8	1.2	19.6
1992	0.0	2.3	13.6	67.7	62.3	73.3	184.1	324.4	78.2	122.5	56.4	32.5
1993	3.0	13.1	36.7	124.7	143.4	94.3	333.4	154.4	200.5	118.0	12.0	0.0
1994	1.7	16.3	10.0	32.3	103.3	102.9	312.3	301.1	150.3	36.2	29.7	7.9
1995	0.0	7.0	9.0	22.0	77.8	60.2	355.2	238.0	104.5	70.3	4.1	22.2
1996	0.3	2.1	66.4	61.4	110.6	203.7	310.9	365.7	164.0	58.4	70.5	9.2
1997	0.4	0.0	54.4	58.7	139.9	176.5	272.0	184.4	163.7	188.2	43.0	3.3
1998	5.7	1.0	18.2	34.4	119.6	93.4	363.4	368.6	170.7	198.8	49.2	0.9
1999	18.8	0.0	0.0	22.6	52.9	109.9	300.4	371.6	157.2	202.7	5.5	26.5
2000	0.0	0.0	7.6	111.5	8.0	38.4	243.1	267.8	148.2	209.8	63.0	31.5
2001	0.0	15.3	53.2	28.5	83.3	137.5	443.6	327.1	144.3	146.7	37.2	3.6
2002	10.8	0.0	30.8	93.0	26.8	127.9	296.7	288.6	186.1	60.9	7.0	18.5
2003	0.0	11.4	33.6	8.5	8.8	76.5	339.8	354.1	265.3	52.8	14.7	0.3
2004	0.0	7.4	7.0	59.0	14.2	142.0	203.0	269.2	181.3	92.4	23.9	0.0
2005	3.8	4.5	50.7	27.9	20.3	138.5	261.3	226.2	204.5	195.6	61.4	0.0
2006	0.0	2.2	27.9	76.9	106.3	164.1	366.2	339.0	158.0	80.3	52.7	27.6

2007	26.2	12.4	32.4	16.5	116.6	175.5	225.8	295.7	136.4	42.5	0.2	0.0
2008	41.7	0.7	0.0	78.9	145.1	94.2	362.4	279.8	209.7	96.5	15.4	0.0
2009	0.0	13.3	28.1	30.7	9.0	61.8	317.3	338.6	109.4	158.9	28.4	0.2
2010	7.2	0.7	23.3	37.5	64.0	34.1	364.4	450.4	203.4	84.2	22.4	0.2
2011	21.8	0.0	48.0	52.4	93.9	69.4	260.9	408.9	197.0	32.1	126.1	0.0
2012	2.7	0.0	16.3	3.5	37.2	157.7	355.3	322.5	147.9	50.0	23.6	19.8
2013	3.1	0.0	14.5	50.3	77.4	193.0	370.1	381.6	135.6	195.0	54.0	0.0
2014	0.2	4.0	86.5	127.1	239.5	93.9	283.7	292.1	176.8	118.3	26.9	7.5
2015	0.0	0.0	55.7	3.0	165.9	144.4	194.5	341.1	230.5	60.4	61.5	94.6
2016	0.0	0.0	7.0	11.2	88.4	175.4	380.1	273.5	138.3	134.2	0.0	0.0
2017	0.0	47.8	23.8	93.1	152.9	35.4	425.9	380.4	235.9	127.8	19.0	0.0
2018	0.0	18.2	34.3	13.0	38.7	238.1	362.6	367.6	106.0	88.2	67.4	0.0
Mean	5.0	7.8	32.4	52.9	86.0	120.9	316.1	306.9	172.4	106.1	33.4	11.2

Appendix 6: Mean monthly rainfall data at Yetnora (mm)

year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	0.0	23.6	155.1	117.6	20.1	100.5	321.5	431.1	148.1	46.9	0.6	133.0
1990	1.4	74.3	174.1	119.5	35.3	185.7	505.0	480.1	326.7	17.0	7.6	0.0
1991	2.0	10.2	94.0	116.3	56.7	143.1	206.0	242.5	121.2	35.9	0.0	7.4
1992	3.3	30.9	22.3	66.3	44.4	115.3	187.0	220.9	111.4	137.1	23.9	0.9
1993	1.0	16.7	24.3	161.9	127.0	171.0	371.2	280.6	148.5	121.2	0.0	0.0
1994	0.0	6.3	37.7	35.4	126.4	149.2	418.6	338.0	143.7	0.0	1.3	0.0
1995	0.0	3.8	19.7	45.3	91.5	99.2	225.2	242.1	65.2	2.3	6.5	44.2
1996	5.1	0.0	132.6	91.5	135.8	155.9	289.0	231.1	146.7	97.1	15.2	13.9
1997	2.5	0.0	63.6	80.3	92.1	203.0	177.8	184.0	72.7	59.2	54.1	10.2
1998	0.0	0.0	75.1	7.9	185.1	95.5	334.4	368.3	120.2	183.0	0.0	0.0
1999	4.8	0.0	0.0	33.7	96.0	179.5	390.2	259.9	75.6	277.5	2.2	7.8

2000	0.0	0.0	0.0	133.9	32.1	132.4	316.1	324.4	128.1	27.3	1.4	5.8
2001	10.5	9.1	23.4	52.6	35.4	198.8	377.2	225.6	132.5	53.3	3.5	4.9
2002	36.6	6.4	33.3	43.9	13.3	201.7	403.2	314.2	80.5	0.2	0.0	10.5
2003	0.4	30.0	60.1	30.9	0.0	145.2	261.5	222.1	108.9	2.7	9.0	2.3
2004	14.0	9.7	23.7	66.8	8.2	211.0	230.5	223.3	151.3	74.5	7.1	12.0
2005	17.3	0.0	53.6	84.0	58.9	125.1	232.7	243.6	154.2	39.3	32.5	0.0
2006	3.1	13.0	114.3	69.1	92.2	112.5	481.4	300.9	267.4	28.8	7.8	35.3
2007	10.3	22.5	40.2	72.1	129.8	152.1	287.9	227.9	198.9	16.6	0.0	12.0
2008	0.0	0.0	0.0	21.3	101.2	167.7	323.6	180.3	122.9	81.8	69.4	0.0
2009	8.7	11.2	37.8	42.5	18.2	46.4	292.5	321.4	99.3	113.9	5.2	26.3
2010	3.5	23.3	38.8	81.4	190.1	72.1	258.8	281.3	222.1	19.1	20.5	1.3
2011	0.7	0.0	96.8	53.6	178.7	116.2	254.6	262.8	106.6	20.0	92.3	0.0
2012	0.0	0.0	79.0	53.0	38.3	153.3	357.5	233.1	176.4	34.9	2.8	0.0
2013	3.7	0.6	12.6	31.0	143.8	244.4	317.0	288.7	65.6	42.4	12.0	0.0
2014	0.0	45.2	22.4	93.3	112.2	52.8	157.3	180.3	180.4	65.4	24.8	0.0
2015	0.0	6.6	0.0	21.2	124.7	182.7	107.9	212.2	94.2	14.8	108.7	22.7
2016	17.8	15.1	47.5	74.9	278.4	111.1	333.3	209.7	99.6	36.2	0.0	0.0
2017	0.0	9.6	32.4	16.7	227.4	52.3	284.3	230.7	128.0	71.4	12.9	0.0
2018	0.0	24.2	18.1	55.4	41.2	232.2	306.7	212.2	68.6	91.2	66.9	0.0
mean	4.9	13.1	51.1	65.8	94.5	143.6	300.3	265.8	135.5	60.4	19.6	11.7

Appendix 7: Mean monthly max-temperature at Debre Markos station (^{0}C)

year	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	23.3	23.7	23.6	22.6	23.3	20.5	18.5	19.1	20.2	21.5	23.3	22.0
1990	23.7	24.4	25.1	25.0	24.9	21.3	18.7	18.8	19.9	21.8	23.3	24.0
1991	24.7	25.2	23.1	23.3	22.5	21.6	18.0	18.6	20.4	22.0	22.9	22.6
1992	22.7	22.8	25.6	24.8	23.5	20.3	18.2	17.7	19.2	20.6	21.2	23.3

1993	23.7	23.8	25.8	23.0	22.7	20.5	19.5	19.7	20.1	22.1	23.5	24.3
1994	25.3	26.3	25.7	26.0	24.0	20.3	18.9	18.7	20.8	23.1	24.1	24.9
1995	25.5	26.4	26.7	25.4	23.6	22.3	18.4	19.2	21.0	23.0	24.5	24.1
1996	23.5	24.7	25.1	24.3	22.7	19.5	19.1	19.0	20.6	22.2	22.7	22.4
1997	23.4	25.3	25.9	24.2	23.8	21.2	18.9	19.7	21.6	22.0	22.0	23.2
1998	24.2	25.4	26.1	27.8	24.5	21.6	18.9	18.6	20.2	20.5	21.9	22.8
1999	22.8	25.5	25.8	26.0	24.4	21.2	18.1	18.4	20.4	20.2	22.1	22.8
2000	24.3	24.8	27.3	23.8	24.6	21.3	19.0	18.8	20.5	21.0	21.8	23.2
2001	23.7	25.6	23.9	25.3	23.6	20.0	19.3	18.9	21.5	21.8	22.6	23.7
2002	23.5	25.6	25.4	25.8	26.6	21.4	20.1	19.2	20.8	23.0	24.0	23.5
2003	24.2	25.5	25.3	26.3	27.9	21.4	18.2	18.9	20.2	22.2	23.4	23.8
2004	24.7	24.7	26.0	24.7	25.6	21.1	19.0	19.4	20.2	21.4	23.1	23.7
2005	24.0	27.4	26.0	25.6	25.4	21.8	19.0	19.7	20.6	21.3	22.4	23.6
2006	23.7	26.0	25.5	25.1	24.0	21.1	19.4	19.0	20.1	22.7	23.2	23.6
2007	24.2	25.1	26.6	25.2	24.1	20.4	19.1	19.4	20.0	22.1	23.9	24.0
2008	24.8	24.6	26.9	26.1	23.1	20.7	19.7	19.2	21.2	21.9	22.1	23.3
2009	24.3	25.8	26.8	26.4	26.6	23.9	19.2	19.9	21.4	22.0	23.6	23.4
2010	24.3	25.4	25.9	25.7	23.3	21.6	19.2	19.4	20.8	23.5	24.0	23.6
2011	24.1	26.5	24.3	26.4	24.3	21.2	20.5	19.6	20.8	23.4	23.0	23.5
2012	24.6	25.4	26.4	26.5	26.6	22.1	18.9	19.5	20.0	22.7	23.9	23.8
2013	25.2	26.9	26.6	27.8	24.1	21.1	18.7	18.6	20.6	21.4	22.9	23.2
2014	24.3	25.2	25.8	25.0	22.8	22.0	19.6	19.3	20.3	21.9	22.8	22.8
2015	24.1	25.9	26.2	26.8	24.3	21.6	20.8	20.4	21.7	23.9	23.6	23.5
2016	24.6	25.5	27.5	26.6	22.4	22.1	19.5	19.8	20.8	21.2	23.3	23.6
2017	24.4	25.1	26.5	25.9	22.7	22.0	19.6	19.7	21.0	22.2	22.6	23.4
2018	23.9	24.9	25.4	25.3	24.8	20.3	19.6	19.8	21.7	22.7	22.1	23.8
mean	24.1	25.3	25.8	25.4	24.2	21.2	19.1	19.2	20.6	22.1	23.0	23.4

Appendix 8: Mean monthly min-temperature at Debre Markos station (^{0}C)

year	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	5.9	8.0	8.9	9.0	9.4	8.6	9.0	8.8	8.7	7.8	7.1	8.8
1990	7.9	9.0	9.7	10.3	11.2	9.8	10.3	10.1	9.7	8.8	9.1	8.3
1991	9.9	9.8	10.5	10.7	10.8	11.1	11.3	10.9	10.4	9.4	8.5	8.6
1992	8.8	9.4	12.0	12.0	12.5	10.9	10.7	11.0	10.0	10.1	8.8	8.9
1993	8.5	9.5	10.8	11.0	11.3	10.7	10.7	11.0	9.9	9.8	8.8	8.6
1994	9.1	10.0	10.8	12.3	11.5	11.1	11.0	10.9	10.1	9.6	9.4	8.3
1995	9.1	10.8	10.8	12.6	12.3	10.6	11.4	10.9	9.8	9.7	9.2	9.6
1996	9.9	9.9	11.5	11.9	11.1	11.2	10.9	11.0	10.4	8.9	9.0	9.0
1997	9.2	9.9	11.7	11.7	11.5	11.2	11.1	10.9	10.5	10.9	10.7	9.3
1998	9.7	10.7	12.6	13.6	12.8	10.8	11.4	11.7	10.7	10.8	8.1	7.5
1999	8.9	10.5	10.2	12.5	11.3	10.2	10.7	10.5	9.8	10.0	7.6	8.0
2000	8.7	9.7	11.6	11.4	10.9	10.5	10.5	10.6	10.3	10.2	8.7	7.6
2001	7.8	10.1	11.0	12.0	11.5	10.7	10.8	11.3	10.1	10.4	8.4	9.0
2002	9.4	10.7	11.3	12.0	12.4	11.1	11.0	10.6	10.1	9.9	10.0	9.5
2003	9.4	10.4	11.4	12.3	14.0	10.8	11.5	11.2	10.5	9.6	9.5	8.7
2004	9.5	9.8	11.8	12.4	11.8	11.3	10.7	10.7	10.0	8.9	8.9	8.8
2005	8.6	11.3	11.5	13.5	12.0	11.2	11.1	11.2	11.0	9.7	8.8	7.4
2006	8.9	10.6	11.5	12.0	11.6	10.9	11.5	11.3	10.5	10.5	9.4	9.4
2007	9.7	10.6	11.7	12.5	12.2	11.1	11.2	11.1	11.0	9.5	9.1	7.6
2008	10.0	10.4	12.0	12.8	11.8	10.8	11.0	10.3	10.3	10.3	8.7	8.6
2009	9.2	11.5	11.8	12.5	12.5	11.3	11.6	11.3	10.5	10.2	8.3	9.7
2010	9.4	11.4	12.5	13.2	12.8	11.8	11.0	11.6	10.7	10.4	9.2	9.2
2011	9.5	10.0	11.7	12.4	12.2	11.3	10.9	11.3	10.7	9.9	9.5	8.5
2012	9.2	10.4	11.7	11.8	12.8	11.2	11.3	11.2	10.5	9.6	9.4	9.3
2013	9.4	10.9	12.4	12.5	12.6	11.7	11.3	10.9	10.7	10.8	9.4	6.9

2014	9.8	10.1	11.8	11.8	12.1	11.5	11.8	10.8	10.7	10.8	8.9	8.8
2015	8.9	10.9	12.8	12.8	12.3	11.9	11.2	11.3	10.9	10.9	10.3	10.0
2016	9.5	11.0	13.2	13.3	12.4	11.8	11.5	11.2	10.3	10.2	8.7	9.2
2017	8.0	11.6	12.8	13.4	12.2	11.7	11.9	12.0	10.9	11.1	9.2	8.1
2018	9.1	11.6	11.3	12.1	12.6	11.5	11.4	11.3	10.4	10.8	9.8	9.6
mean	9.0	10.3	11.5	12.1	12.0	11.0	11.1	11.0	10.3	10.0	9.0	8.7

Appendix 9: Mean monthly max-temperature at Motta station (^{0}C)

year	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	23.6	24.4	24.5	24.8	25.4	24.3	20.7	20.0	21.2	21.7	22.8	22.1
1990	23.7	24.1	25.6	26.1	26.4	25.2	20.2	20.7	21.0	22.4	23.6	23.5
1991	24.6	25.8	27.9	28.4	27.8	23.2	19.8	19.8	21.4	22.2	23.4	22.5
1992	23.2	24.0	26.6	25.9	26.1	25.5	20.8	18.6	20.8	20.4	20.4	22.2
1993	22.7	23.4	25.5	23.6	24.0	22.8	20.6	21.5	21.4	22.1	23.1	23.7
1994	24.5	27.8	28.4	24.1	23.5	22.4	19.6	19.5	21.1	22.9	23.3	23.7
1995	24.7	25.9	26.6	26.6	25.9	26.4	20.8	20.5	22.1	22.9	23.5	24.2
1996	24.9	25.5	25.6	25.4	23.6	22.1	20.5	20.4	21.8	22.8	22.1	22.9
1997	24.2	25.6	26.0	25.3	25.0	23.4	21.1	21.1	23.0	22.1	22.6	24.2
1998	25.1	26.1	27.3	27.2	26.1	24.8	19.7	20.0	21.6	21.8	22.0	22.6
1999	23.1	26.1	26.4	26.8	26.7	25.2	19.9	20.0	21.4	21.1	22.0	22.5
2000	23.7	24.3	26.8	23.9	26.9	25.2	20.9	20.0	21.2	21.4	22.2	23.1
2001	23.5	25.4	24.7	26.5	25.7	23.4	20.7	20.2	21.7	23.0	23.0	23.6
2002	23.7	25.8	26.2	27.0	27.6	24.7	22.3	20.6	21.4	23.1	23.5	24.0
2003	24.8	26.0	26.1	27.3	28.3	25.3	20.6	20.5	21.2	22.1	23.3	23.3
2004	24.8	24.2	26.6	26.0	27.2	23.5	21.7	20.9	21.6	21.9	23.1	23.6
2005	24.1	27.0	26.4	26.9	26.4	25.7	20.6	21.0	21.5	21.9	22.2	23.0
2006	24.5	25.6	25.3	25.2	25.2	24.3	21.3	20.7	21.6	23.1	23.0	23.4

2007	24.2	25.5	27.3	26.6	26.7	23.1	20.6	21.2	22.0	22.6	23.7	23.8
2008	24.6	24.7	27.8	26.0	24.9	23.7	21.4	21.2	22.1	22.5	22.7	23.5
2009	24.5	25.8	26.8	27.3	27.6	27.2	21.3	21.4	22.8	22.3	23.5	23.7
2010	24.5	26.1	26.5	26.7	25.9	25.8	21.1	20.4	21.8	22.8	23.3	23.0
2011	23.8	26.0	25.0	26.7	25.6	24.4	21.6	20.9	22.0	23.7	23.7	23.7
2012	24.7	25.0	26.6	26.8	27.1	24.8	20.9	20.7	22.0	23.4	23.4	23.7
2013	24.6	26.8	27.3	28.0	26.1	23.8	20.8	20.1	22.2	22.4	23.1	23.4
2014	24.4	25.4	25.9	25.9	24.0	24.4	22.1	20.6	22.0	22.8	23.5	27.1
2015	24.4	26.7	27.1	27.8	26.1	24.7	23.8	22.4	22.8	24.7	24.1	24.3
2016	25.2	25.9	29.0	28.1	25.5	25.3	21.7	21.5	22.7	23.1	23.2	24.1
2017	24.9	25.9	28.1	27.5	25.2	26.8	22.9	21.7	23.3	23.9	24.4	24.7
2018	24.9	25.8	26.7	26.3	26.8	23.0	21.1	20.9	22.7	22.7	21.9	23.7
mean	24.3	25.6	26.5	26.3	26.0	24.5	21.0	20.6	21.8	22.5	23.0	23.6

Appendix 10: Mean monthly min-temperature at Motta station (^{0}C)

year	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	6.5	8.3	9.9	10.5	11.3	10.4	11.0	11.0	10.3	9.3	7.1	7.9
1990	7.0	8.3	9.6	10.9	11.5	10.6	10.9	11.2	10.8	8.9	8.5	7.1
1991	9.1	9.3	10.3	10.6	10.9	11.5	11.4	11.3	10.1	8.4	8.0	7.3
1992	7.7	8.2	11.5	11.8	12.4	11.2	11.4	11.6	9.8	10.2	8.3	7.8
1993	6.6	7.6	10.2	11.6	11.6	11.7	11.4	11.0	9.9	9.3	8.4	7.0
1994	7.5	9.3	9.5	9.8	9.3	11.0	11.3	10.8	10.0	8.5	8.7	7.1
1995	6.7	8.6	9.3	12.3	12.1	10.9	11.7	11.3	10.8	10.5	9.5	9.6
1996	10.3	9.1	10.9	12.1	11.2	11.1	10.2	9.8	8.7	7.3	7.3	5.6
1997	5.4	8.4	10.0	10.5	11.1	10.7	10.8	10.5	9.1	9.7	9.7	7.3
1998	7.0	7.5	11.2	12.8	12.6	11.2	11.6	11.8	11.2	11.1	7.9	6.2
1999	7.2	9.4	7.8	11.7	10.1	8.8	9.5	9.5	8.5	8.7	5.3	5.9

2000	5.5	6.6	8.7	9.6	10.0	9.2	10.0	9.7	8.9	8.8	7.5	6.7
2001	4.2	6.6	8.5	10.6	10.8	10.3	10.5	11.0	9.5	9.3	6.9	7.1
2002	7.0	8.5	10.0	11.8	11.9	10.3	10.7	10.9	10.0	8.5	7.8	6.5
2003	6.7	10.5	12.1	12.6	13.4	12.2	11.6	11.6	11.1	8.8	8.2	7.5
2004	8.6	9.5	12.5	12.8	11.8	11.0	11.2	11.3	10.2	8.9	9.5	7.7
2005	7.2	10.4	11.6	13.0	8.9	9.6	11.8	11.8	11.2	10.5	8.6	6.7
2006	8.6	10.6	11.3	11.7	11.8	11.3	12.0	11.7	10.7	10.5	9.1	8.0
2007	7.5	8.6	10.8	11.7	12.6	11.1	11.5	11.3	10.5	7.7	7.0	5.8
2008	7.5	7.6	10.4	11.9	10.7	13.0	13.9	14.1	14.1	14.6	14.3	12.8
2009	6.9	11.0	11.0	12.2	10.9	10.4	10.8	10.4	8.5	8.0	6.1	6.4
2010	6.2	9.8	11.0	13.3	12.9	12.2	11.8	11.9	11.3	9.7	9.0	8.0
2011	7.7	8.7	10.1	12.3	11.5	11.4	11.5	11.7	10.9	9.2	9.3	7.4
2012	7.1	8.9	10.9	11.0	12.1	11.6	11.4	10.8	10.3	9.1	8.5	7.5
2013	7.5	9.6	11.8	11.6	12.0	11.8	11.6	12.1	11.8	10.4	10.7	10.2
2014	8.6	11.4	10.6	11.9	11.8	11.1	11.4	10.6	11.1	10.5	8.5	12.3
2015	7.7	10.2	12.3	13.1	11.9	11.6	10.8	11.2	10.2	9.6	9.2	9.1
2016	6.6	8.4	12.1	12.1	11.4	11.0	11.3	11.2	10.2	9.3	6.5	7.1
2017	6.8	10.7	10.9	12.8	12.6	11.6	11.6	11.9	11.2	10.9	8.8	7.1
2018	7.6	11.0	10.3	11.3	12.6	11.7	11.7	11.7	10.2	10.0	9.5	8.3
mean	7.2	9.1	10.6	11.7	11.5	11.0	11.3	11.2	10.4	9.5	8.5	7.7

Appendix 11: Mean monthly max-temperature at Dejen station (^{0}C)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	25.8	25.9	27.8	24.6	26.0	25.1	24.2	21.9	21.8	22.9	25.6	24.1
1990	24.9	26.3	26.2	28.2	27.8	28.0	25.0	28.2	24.6	24.9	25.6	25.4
1991	27.0	26.2	27.5	26.7	27.5	27.4	25.0	25.6	24.5	24.6	25.5	25.2
1992	25.4	25.6	28.5	27.3	28.8	29.1	25.7	26.8	27.1	26.0	25.2	26.0

1993	25.7	26.5	28.6	26.8	27.5	26.0	22.9	24.3	24.8	25.7	26.1	26.3
1994	27.3	28.5	28.4	28.1	29.1	25.3	22.0	21.4	22.8	24.5	25.6	26.5
1995	27.2	27.9	28.0	28.6	28.2	27.7	23.1	23.2	24.3	26.5	26.9	26.0
1996	26.9	28.5	29.0	28.2	26.7	25.4	23.5	24.0	25.2	25.9	26.5	27.3
1997	27.3	28.2	29.2	28.5	30.1	27.8	24.9	25.3	27.2	27.7	28.5	28.7
1998	30.0	30.8	28.8	30.3	28.9	27.6	21.8	22.5	25.7	26.9	28.6	28.3
1999	28.4	29.9	28.4	28.6	28.5	26.8	22.9	21.9	23.3	23.9	25.6	26.1
2000	26.9	26.7	28.9	26.7	28.0	26.7	22.6	22.4	22.5	24.7	24.6	26.8
2001	28.6	29.6	27.2	27.1	26.7	24.7	22.7	22.4	23.7	26.4	26.9	26.8
2002	26.0	29.8	29.7	30.0	32.4	28.8	27.1	24.4	25.9	28.1	27.1	25.2
2003	25.8	28.7	27.5	28.9	29.1	25.3	20.6	20.8	21.8	24.1	24.5	24.5
2004	25.4	25.4	26.2	25.0	27.6	24.5	21.5	21.4	22.8	24.2	24.1	25.0
2005	25.1	27.3	27.5	28.0	26.0	25.7	21.3	22.0	22.6	24.2	22.5	24.8
2006	25.2	26.2	26.2	25.8	26.2	25.3	22.1	20.5	22.3	24.6	25.0	25.2
2007	25.6	25.7	27.1	26.4	26.4	23.7	20.9	20.9	23.0	25.2	25.9	24.9
2008	25.3	24.9	27.2	27.1	26.3	24.5	22.1	21.0	23.0	24.9	24.8	24.9
2009	25.6	26.0	28.3	27.5	27.4	27.4	21.4	21.5	23.3	24.9	26.0	24.0
2010	25.3	25.5	26.4	26.3	25.8	25.6	23.4	20.6	24.9	26.1	26.0	25.2
2011	25.3	27.0	25.2	26.8	25.8	25.0	23.3	21.0	23.3	24.8	24.2	24.4
2012	25.6	26.2	27.4	27.3	27.4	25.6	21.4	21.8	23.4	24.9	25.5	25.7
2013	26.7	27.9	28.3	28.8	27.8	25.7	20.9	20.7	23.4	24.2	25.5	25.5
2014	25.9	26.5	26.9	27.2	27.6	26.1	23.4	23.0	24.1	24.9	25.9	26.7
2015	27.5	27.2	27.2	27.5	27.6	26.0	23.1	23.5	24.3	26.0	26.2	26.4
2016	26.4	25.7	26.7	26.5	26.4	26.4	25.4	26.0	26.2	25.8	25.9	26.4
2017	26.4	26.4	26.6	26.7	26.4	26.0	26.2	26.0	26.5	26.6	26.8	26.9
2018	26.9	26.8	26.8	26.8	26.5	26.0	25.4	25.9	26.7	26.0	26.2	26.6
Mean	26.4	27.1	27.6	27.4	27.6	26.2	23.2	23.0	24.2	25.3	25.8	25.9

Appendix 12: Mean monthly min-temperature at Dejen station (^{0}C)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	4.0	4.7	9.2	8.0	7.0	7.2	8.7	7.6	8.0	8.1	8.5	4.6
1990	6.4	8.4	7.5	8.6	10.2	9.1	9.3	7.9	9.4	9.1	8.2	8.7
1991	10.2	7.8	8.8	9.3	9.5	8.8	8.6	8.0	9.0	8.6	8.2	8.1
1992	8.8	10.0	9.5	11.2	11.4	10.0	7.8	8.3	9.5	8.7	7.9	10.9
1993	7.9	10.2	10.6	11.1	11.5	10.7	10.0	10.9	10.6	10.6	8.3	7.5
1994	8.5	10.6	10.6	11.0	12.0	10.2	10.3	10.6	9.9	9.4	9.2	7.2
1995	8.9	12.3	10.5	11.8	11.5	11.4	11.2	11.2	10.8	10.5	9.5	9.6
1996	9.7	10.0	11.4	11.7	11.2	10.5	10.6	11.1	9.8	8.6	7.9	8.0
1997	9.2	9.0	11.3	11.6	11.9	11.4	11.4	11.3	10.2	10.5	10.2	8.1
1998	9.4	11.0	10.6	13.6	13.3	11.7	11.6	11.8	11.1	10.8	7.7	4.7
1999	8.0	9.4	11.0	11.3	12.3	10.8	10.8	10.9	9.7	9.7	6.5	7.8
2000	8.7	9.8	11.8	11.2	12.5	10.1	11.0	10.2	10.4	9.8	8.0	6.6
2001	6.4	9.9	10.3	11.4	11.8	10.8	10.7	10.9	10.6	10.6	9.0	9.4
2002	10.1	9.7	10.1	10.0	10.5	11.2	11.7	10.4	10.9	11.3	9.4	8.3
2003	6.7	8.5	7.1	7.7	8.1	9.4	11.3	11.0	10.9	10.6	9.5	9.2
2004	9.2	9.6	3.7	5.4	5.1	12.4	11.7	11.7	11.3	9.9	10.1	9.8
2005	10.7	11.7	11.9	13.2	12.5	12.0	11.8	12.0	12.0	13.2	10.3	8.0
2006	8.8	10.0	11.0	11.5	12.5	11.7	12.1	12.0	11.2	12.7	12.1	12.1
2007	12.6	12.1	12.4	12.8	13.1	11.9	12.3	12.1	12.2	12.9	12.6	11.0
2008	10.9	11.6	13.0	12.9	12.9	12.1	11.2	11.7	11.2	11.5	11.2	11.1
2009	10.8	12.3	12.3	13.0	13.0	13.0	11.8	11.9	12.8	12.1	12.2	11.3
2010	11.4	11.5	12.2	12.2	12.5	12.4	11.8	12.0	11.7	12.1	12.2	11.8
2011	11.2	11.5	11.0	12.2	12.2	11.6	11.4	11.9	11.2	11.2	10.9	9.3
2012	9.6	10.1	11.4	12.0	12.5	12.2	11.8	11.8	11.3	10.3	10.3	10.4
2013	11.2	11.7	13.3	12.9	12.9	12.4	12.1	11.9	11.6	11.6	11.7	11.1

2014	12.1	12.1	11.7	12.2	12.5	11.1	11.4	11.3	11.5	11.1	11.9	11.8
2015	12.3	11.8	12.1	12.1	12.1	11.6	11.1	11.2	11.2	11.7	11.5	11.6
2016	11.4	11.1	11.7	11.5	11.4	11.4	10.8	11.0	11.4	11.2	10.9	11.4
2017	11.4	11.4	11.6	11.6	11.4	11.0	11.1	11.0	11.5	11.6	11.4	11.9
2018	11.9	11.6	11.8	11.8	11.5	11.0	10.5	10.8	11.7	11.0	11.2	11.6
Mean	9.6	10.4	10.7	11.2	11.4	11.0	10.9	10.9	10.8	10.7	9.9	9.4

Appendix 13: Mean monthly max-temperature at Yetnora station (^{0}C)

year	Jan.	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	22.7	23.6	23.7	22.3	24.4	22.6	18.9	19.1	20.6	21.6	23.1	22.0
1990	23.4	23.3	24.3	24.7	25.3	23.2	19.8	19.8	20.9	22.6	23.7	24.0
1991	24.8	25.1	24.7	24.4	25.1	23.1	18.3	18.6	20.9	22.1	23.7	22.8
1992	23.2	23.8	26.1	26.3	25.6	23.4	19.6	18.1	20.4	21.2	21.9	23.0
1993	24.1	24.7	25.2	25.6	25.5	23.7	19.4	18.3	20.4	22.1	23.3	23.4
1994	23.9	24.6	25.4	26.0	25.6	24.0	19.7	18.2	20.2	22.1	23.2	23.7
1995	24.5	24.9	26.1	25.4	26.1	23.0	19.1	17.9	21.0	23.3	23.5	23.6
1996	24.2	25.4	25.5	25.2	24.5	20.4	19.4	19.2	21.8	23.3	23.5	24.0
1997	23.8	25.3	24.9	24.4	24.7	21.5	18.5	19.9	22.3	23.1	22.8	24.7
1998	24.3	24.4	24.9	26.1	25.7	24.8	20.2	18.3	19.9	23.0	24.4	24.5
1999	25.5	26.3	27.5	25.8	27.6	24.2	19.6	19.0	22.0	24.0	24.2	23.7
2000	24.4	23.0	26.2	24.2	25.7	20.2	17.7	16.2	21.4	24.9	23.3	23.6
2001	24.5	25.2	26.7	25.4	26.4	22.9	18.5	18.2	21.2	23.3	23.6	23.4
2002	24.2	25.2	26.8	25.1	25.3	21.3	18.3	17.9	20.9	23.1	23.0	23.2
2003	24.2	25.5	26.9	25.3	25.2	21.6	18.5	18.3	20.8	22.6	22.9	23.2
2004	24.1	24.7	27.0	25.3	25.0	21.3	18.5	18.3	20.7	22.4	22.7	23.1
2005	24.0	25.8	27.0	25.7	25.4	22.5	18.3	18.5	20.9	22.4	22.6	23.1
2006	24.0	25.3	26.5	25.6	25.3	21.6	19.4	18.4	20.1	23.0	23.1	23.2

2007	24.1	25.2	26.6	24.9	25.1	21.2	18.6	18.7	20.2	22.1	23.5	23.1
2008	24.0	25.6	27.6	25.8	24.2	21.1	18.5	18.4	21.0	22.0	21.6	22.9
2009	23.9	25.5	26.5	26.7	27.1	26.2	18.0	18.9	21.2	22.3	23.4	23.4
2010	23.8	24.2	25.5	24.7	23.7	23.5	19.0	18.9	21.0	23.1	23.1	23.0
2011	22.9	25.9	25.1	26.2	25.4	22.4	19.8	19.2	21.0	23.3	22.8	23.3
2012	24.7	25.2	26.8	25.8	26.4	24.1	18.7	18.7	20.4	22.7	23.8	24.1
2013	24.9	26.6	27.2	27.3	25.0	21.2	18.3	18.5	21.2	22.0	23.8	23.3
2014	24.8	24.9	26.7	26.1	24.2	23.9	20.3	19.5	20.5	22.3	23.7	23.3
2015	24.6	26.4	26.6	27.3	25.1	22.6	20.8	20.2	22.1	24.2	24.0	23.6
2016	24.7	25.4	28.1	26.2	22.6	22.1	19.4	19.5	21.8	23.3	23.8	23.6
2017	24.5	25.4	27.0	26.9	24.5	24.0	18.6	18.7	20.9	22.8	23.1	23.5
2018	23.8	25.7	26.3	25.6	26.1	21.0	19.4	19.4	22.0	22.7	22.2	24.2
mean	24.1	25.1	26.2	25.5	25.3	22.6	19.0	18.7	21.0	22.8	23.2	23.4

Appendix 14: Mean monthly min-temperature at Yetnora station (^{0}C)

year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1989	6.5	8.7	9.8	10.3	10.0	9.4	10.7	10.5	9.7	7.5	6.4	9.6
1990	7.5	9.6	9.7	10.3	10.0	9.7	10.9	10.9	10.4	7.3	7.6	6.7
1991	8.7	8.4	10.2	10.7	10.6	9.9	9.9	12.4	9.3	8.5	6.8	7.0
1992	8.6	9.2	10.7	11.3	11.7	10.2	10.3	10.7	9.5	9.0	7.3	6.6
1993	7.4	9.1	10.4	10.9	10.5	10.1	10.1	10.2	9.9	8.6	7.4	8.3
1994	8.0	9.4	10.4	10.8	10.5	10.1	10.0	10.0	9.8	8.7	7.6	8.2
1995	8.0	9.4	10.4	10.8	10.5	10.1	10.0	10.0	9.8	8.7	7.6	8.2
1996	9.3	8.7	10.9	11.5	11.0	10.9	9.7	10.1	10.2	9.2	8.1	7.2
1997	8.3	10.3	10.6	10.8	10.5	10.0	9.6	9.5	9.6	9.4	8.5	7.9
1998	9.5	9.4	9.3	10.6	10.2	10.1	8.8	8.3	9.1	9.6	8.1	7.6
1999	9.2	8.9	10.9	10.2	10.4	9.0	7.8	8.4	9.1	9.8	10.1	9.4

2000	9.4	8.6	10.4	8.5	10.0	8.5	9.7	8.8	9.9	9.7	9.6	9.3
2001	9.2	9.1	10.8	9.4	10.5	9.4	9.3	8.9	9.4	9.8	10.1	9.8
2002	9.1	9.2	10.7	9.1	10.6	9.7	10.1	9.2	9.5	9.8	10.0	10.0
2003	9.1	9.3	10.8	9.2	10.7	10.0	10.3	9.4	9.4	9.8	10.1	10.2
2004	9.1	9.0	10.8	9.0	10.8	10.4	11.1	9.6	9.5	9.8	9.8	10.0
2005	8.9	9.6	11.0	9.5	11.1	10.6	10.5	9.7	9.1	9.9	10.6	10.8
2006	8.9	9.6	10.9	9.0	11.2	12.1	13.0	10.4	9.6	9.9	9.3	10.0
2007	8.6	10.2	11.3	9.1	11.6	10.8	10.8	10.2	8.6	10.0	12.3	13.2
2008	8.5	9.3	11.1	9.5	12.1	11.6	11.4	11.4	9.9	10.2	8.3	7.4
2009	8.4	11.5	11.8	11.8	11.9	11.7	11.6	11.6	10.9	9.6	6.7	9.9
2010	8.3	10.8	12.0	6.6	12.3	11.3	10.5	10.7	10.7	8.7	7.6	7.6
2011	8.1	7.2	10.1	11.1	10.9	9.5	8.0	9.5	9.7	7.1	7.2	4.6
2012	6.6	7.2	8.5	10.4	9.6	10.5	10.2	10.8	10.1	7.7	7.4	7.5
2013	7.9	10.3	12.0	11.7	11.7	11.4	11.3	11.4	10.7	9.7	8.5	6.2
2014	9.7	10.7	11.9	12.4	11.9	11.4	10.9	10.7	11.0	10.1	8.9	7.5
2015	8.1	10.6	11.6	12.6	12.4	12.3	11.7	11.9	11.1	10.4	9.9	9.7
2016	9.2	10.7	13.0	12.0	12.5	11.4	11.8	11.4	10.3	8.6	6.8	6.2
2017	6.0	11.1	12.2	13.0	12.0	11.2	11.1	11.5	10.7	9.8	6.3	5.0
2018	8.2	10.1	10.3	11.4	11.7	11.0	10.8	10.8	9.7	9.0	8.1	7.1
mean	8.4	9.5	10.8	10.5	11.1	10.5	10.4	10.3	9.9	9.2	8.4	8.3

Appendix 15: ET_o and other climatic data for Debre Markos metrological station

Monthly ETo Penman-Monteith - C:\ProgramData\CROPWAT\data\climate\ETO.PEM

Country: Ethiopia   Station:

Altitude: 2446 m.   Latitude: 10.33 °N   Longitude: 37.74 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	8.6	24.7	51	102	9.4	21.0	3.89
February	9.8	25.8	47	125	9.2	22.1	4.45
March	10.9	26.5	48	137	8.3	22.0	4.74
April	11.4	26.2	51	142	8.0	21.9	4.76
May	11.5	25.8	58	132	7.9	21.3	4.51
June	10.9	23.6	69	120	6.5	18.8	3.81
July	10.9	20.6	80	113	4.8	16.4	3.10
August	10.8	20.4	82	110	5.1	17.1	3.12
September	10.3	21.9	77	106	7.2	20.3	3.64
October	9.9	23.2	67	111	8.9	21.9	3.98
November	9.0	23.8	59	102	9.1	20.8	3.80
December	8.5	24.1	54	104	9.6	20.7	3.76
Average	**10.2**	**23.9**	**62**	**117**	**7.8**	**20.4**	**3.96**

Appendix 16: Irrigation water requirement of maize (mm/dec)

Crop Water Requirements

ETo station: Crop: maize

Rain station: debre markos   Planting date: 01/01

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.70	2.69	26.9	2.6	24.4
Jan	2	Init	0.70	2.72	27.2	1.8	25.4
Jan	3	Init	0.70	2.85	31.4	2.5	28.9
Feb	1	Deve	0.70	2.99	29.9	2.4	27.4
Feb	2	Deve	0.77	3.41	34.1	2.5	31.5
Feb	3	Deve	0.86	3.89	31.1	6.6	24.5
Mar	1	Deve	0.95	4.39	43.9	11.7	32.2
Mar	2	Deve	1.05	4.96	49.6	15.7	33.9
Mar	3	Deve	1.15	5.47	60.1	16.9	43.2
Apr	1	Mid	1.20	5.72	57.2	17.5	39.7
Apr	2	Mid	1.20	5.73	57.3	18.9	38.4
Apr	3	Mid	1.20	5.63	56.3	21.8	34.5
May	1	Mid	1.20	5.53	55.3	24.9	30.4
May	2	Mid	1.20	5.43	54.3	27.7	26.6
May	3	Late	1.17	5.00	55.0	30.8	24.1
Jun	1	Late	1.00	4.04	40.4	33.6	6.8
Jun	2	Late	0.82	3.13	31.3	36.5	0.0
Jun	3	Late	0.65	2.33	21.0	37.5	0.0
					762.1	**312.0**	**471.8**

Appendix 17: Irrigation water requirement of onion (mm/dec)

Crop Water Requirements

ETo station | Crop: onion

Rain station: debre markos | Planting date: 01/01

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.70	2.69	26.9	2.6	24.4
Jan	2	Init	0.70	2.72	27.2	1.8	25.4
Jan	3	Deve	0.76	3.10	34.1	2.5	31.6
Feb	1	Deve	0.87	3.70	37.0	2.4	34.6
Feb	2	Mid	0.97	4.31	43.1	2.5	40.6
Feb	3	Mid	1.01	4.57	36.6	6.6	29.9
Mar	1	Mid	1.01	4.67	46.7	11.7	34.9
Mar	2	Mid	1.01	4.76	47.6	15.7	31.9
Mar	3	Mid	1.01	4.77	52.5	16.9	35.6
Apr	1	Mid	1.01	4.78	47.8	17.5	30.3
Apr	2	Mid	1.01	4.79	47.9	18.9	29.0
Apr	3	Late	1.00	4.70	47.0	21.8	25.2
May	1	Late	1.00	4.61	46.1	24.9	21.2
May	2	Late	1.00	4.52	45.2	27.7	17.6
May	3	Late	1.00	4.28	42.8	28.0	11.9
					628.5	**201.6**	**424.1**

Appendix 18: irrigation water requirement of potato (mm/dec)

Crop Water Requirements

ETo station | Crop: potato

Rain station: debre markos | Planting date: 01/01

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.50	1.91	19.1	2.6	16.6
Jan	2	Init	0.50	1.93	19.3	1.8	17.5
Jan	3	Deve	0.50	2.04	22.4	2.5	19.9
Feb	1	Deve	0.64	2.73	27.3	2.4	24.8
Feb	2	Deve	0.86	3.82	38.2	2.5	35.6
Feb	3	Deve	1.06	4.79	38.3	6.6	31.7
Mar	1	Mid	1.16	5.35	53.5	11.7	41.7
Mar	2	Mid	1.16	5.46	54.6	15.7	38.9
Mar	3	Mid	1.16	5.47	60.2	16.9	43.2
Apr	1	Mid	1.16	5.48	54.8	17.5	37.3
Apr	2	Late	1.14	5.39	53.9	18.9	35.1
Apr	3	Late	1.01	4.73	47.3	21.8	25.5
May	1	Late	0.88	4.03	40.3	24.9	15.4
May	2	Late	0.78	3.50	17.5	13.8	3.7
					546.7	**159.7**	**387.0**

Appendix 19: Net Irrigation Requirement of the selected crops from CROPWAT

	Jan	Feb	Mar	Apr	May	Jun
Precipitation deficit						
1. maize	78.7	99.5	128.8	113.4	38.2	0.0
Net scheme irr.req.						
in mm/day	2.5	3.6	4.2	3.8	1.2	0.0
in mm/month	78.7	99.5	128.8	113.4	38.2	0.0
in l/s/h	0.29	0.41	0.48	0.44	0.14	0.00
Irrigated area	100.0	100.0	100.0	100.0	100.0	0.0
(% of total area)						
Irr.req. for actual area	0.29	0.41	0.48	0.44	0.14	0.00
(l/s/h)						

	Jan	Feb	Mar	Apr	May
Precipitation deficit					
1. Potato	55.8	104.7	124.0	92.3	12.4
Net scheme irr.req.					
in mm/day	1.8	3.7	4.0	3.1	0.4
in mm/month	55.8	104.7	124.0	92.3	12.4
in l/s/h	0.21	0.43	0.46	0.36	0.05
Irrigated area	100.0	100.0	100.0	100.0	100.0
(% of total area)					
Irr.req. for actual area	0.21	0.43	0.46	0.36	0.05
(l/s/h)					

	Jan	Feb	Mar	Apr	May
Precipitation deficit					
1. onion	81.4	105.1	102.4	84.5	50.7
Net scheme irr.req.					
in mm/day	2.6	3.8	3.3	2.8	1.6
in mm/month	81.4	105.1	102.4	84.5	50.7
in l/s/h	0.30	0.43	0.38	0.33	0.19
Irrigated area	100.0	100.0	100.0	100.0	100.0
(% of total area)					
Irr.req. for actual area	0.30	0.43	0.38	0.33	0.19
(l/s/h)					

Appendix 20: Observed Monthly flow of Muga River at gauging station (m^3/s) (1989-2008)

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Grand Total
1989	0.21	0.15	0.24	0.31	0.17	5.51	14.60	22.15	13.34	2.21	0.35	0.24	5.00
1990	0.14	0.11	0.92	0.69	3.82	4.89	5.83	19.56	2.27	0.84	0.32	0.48	3.36
1991	0.23	0.33	0.08	0.11	0.40	0.39	22.37	45.07	14.79	9.26	0.90	0.17	7.94
1992	0.19	0.31	1.64	1.60	0.61	1.69	16.75	21.33	8.68	1.10	0.17	3.74	4.87
1993	0.51	0.91	0.61	0.48	0.54	0.21	7.53	16.42	9.20	1.49	0.25	0.18	3.22
1994	0.13	0.08	0.17	0.07	0.12	0.40	23.21	30.28	9.26	0.96	0.50	0.31	5.53
1995	0.25	0.28	0.18	0.72	0.96	0.42	5.87	21.51	11.09	4.68	0.71	0.44	3.96
1996	0.59	0.16	0.09	2.24	3.14	2.89	23.69	15.40	13.35	5.56	0.73	0.20	5.71
1997	0.59	0.16	0.19	0.14	0.52	1.48	34.56	47.52	15.36	1.49	0.71	0.45	8.71
1998	0.71	0.18	0.19	0.67	0.81	0.65	11.52	22.18	8.14	7.03	0.30	0.28	4.44
1999	1.40	0.49	0.60	0.31	5.97	1.96	21.55	33.23	7.47	1.33	1.52	0.53	6.45
2000	0.36	0.21	0.44	0.84	0.83	3.65	17.88	21.55	2.62	8.03	3.07	1.03	5.10
2001	0.86	0.31	0.56	0.39	1.94	2.36	22.64	41.67	12.19	14.43	1.75	0.68	8.42
2002	0.48	0.25	0.54	0.32	0.26	0.71	18.20	31.78	5.74	15.72	0.92	0.43	6.38
2003	0.30	0.27	0.73	0.56	0.77	1.34	18.95	28.95	7.56	6.43	4.97	0.64	6.03
2004	0.36	0.24	0.63	0.48	0.61	5.48	43.51	37.55	8.48	1.91	0.73	0.51	8.47
2005	0.52	0.26	1.17	1.06	0.24	0.88	12.10	20.24	4.21	0.80	0.40	0.62	3.59
2006	0.26	0.30	1.54	1.46	0.19	1.27	27.92	28.32	13.40	3.32	0.75	0.54	6.68
2007	0.24	0.14	0.29	0.79	0.46	1.70	24.40	30.66	6.61	5.70	0.97	0.73	6.15
2008	0.24	0.05	0.41	0.24	0.59	0.84	25.42	18.21	14.42	2.17	0.65	0.35	5.34
Grand Total	0.43	0.26	0.56	0.67	1.15	1.94	19.93	27.68	9.41	4.72	1.03	0.63	5.77