IRRIGATION WATER POTENTIAL AND LAND SUITABILITY ASSESSMENT OF MUGER SUB-BASIN, UPPER ABBAY BASIN

Mosisa Yadeta Yadesa

A Thesis Submitted to

The department of Water Resource Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Water Resource Engineering (Specialization in Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

August 2021

Adama, Ethiopia

IRRIGATION WATER POTENTIAL AND LAND SUITABILITY ASSESSMENT OF MUGER SUB-BASIN, UPPER ABBAY BASIN

Mosisa Yadeta Yadesa

Advisor: Mekonen Ayena (PhD)

A Thesis Submitted to

The department of Water Resource Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Water Resource Engineering (Specialization in Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

August 2021

Adama, Ethiopia

APPROVAL SHEET

I, the advisors of the thesis entitled "**Irrigation Water Potential and Land Suitability Assessment of Muger Sub-Basin, Upper Abbay Basin**" and developed by **Mosisa Yadeta Yadesa**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

<u>Mekonen Ayena (PhD)</u>	______________________	________________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Mosisa Yadeta Yadesa have read and evaluated the thesis entitled "**Irrigation Water Potential and Land Suitability Assessment of Muger Sub-Basin, Upper Abbay Basin**" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Water Resource Engineering (Specialization in Irrigation Engineering).

<u>Dereje Birhanu (PhD)</u>	______________________	________________
Chairperson	Signature	Date
<u>Mesfin Benti (PhD)</u>	______________________	________________
Internal Examiner	Signature	Date
<u>Kassa Tadele (PhD)</u>	______________________	________________
External Examiner	Signature	Date

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

______________________	________________	________________
Department Head	Signature	Date
______________________	________________	________________
School Dean	Signature	Date
______________________	________________	________________
Office of Postgraduate Studies, Dean	Signature	Date

DECLARATION OF STUDENT

I hereby declare that this Master Thesis entitled "**Irrigation Water Potential and Land Suitability Assessment of Muger Sub-Basin, Upper Abbay Basin**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Mosisa Yadeta Yadesa	______________________	______________________
Name of the Student	Signature	Date

RECOMMENDATION OF ADVISOR

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Irrigation Water Potential and Land Suitability Assessment of Muger Sub-Basin, Upper Abbay Basin**" prepared under my guidance by Mosisa Yadeta Yadesa submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Water Resource Engineering (Specialization in Irrigation Engineering). Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Mekonen Ayena (PhD)	______________________	__________________
Major Advisor	Signature	Date

ACKNOWLEDGEMENT

Before all, I would like to thank God for helping me in every aspect of my work. Secondly, I would like to forward my innermost gratitude to my advisor Dr. Mekonen Ayena for his critical observations, suggestions, comments, and countless support at various levels of this thesis work. I thank all staff of the Water Resources Engineering program for their encouragement at some point in my thesis work.

Finally, I would like to thank my parents, family, and friends who helped me in every way during my study. I am very grateful to the Adama University of Science and technology for granting me a scholarship to study Master of Science in Water Resource Engineering at Adama Science and Technology University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

BCM	Billion Cubic Meter
CWR	Crop Water Requirement
CROPWAT	Crop Water Assessment Tool
DEM	Digital Elevation Model
ETC	Crop Evapotranspiration
ETO	Reference Crop Evapotranspiration
FAO	Food and Agricultural Organization
GIS	Geographic Information System
GIWR	Gross Irrigation Water Requirement
IWR	Irrigation water requirement
LULC	Land Use Land Cover
MCM	Million cubic meter
MoA	Ministry of Agriculture
MoWIE	Ministry of Water Irrigation and Electricity
NMA	National Meteorological Agency
SRTM	Shuttle Radar Topographic Mission
SWAT	Soil Water Assessment Tool
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WWDSE	Water Works Design and Supervision Enterprise
MCE	multi-criteria evaluation
AHP	analytic hierarchy process
MCDM	multi-criteria decision-making
WGEN	Weather Generator
HRU	hydrologic response unit
CR	consistency ratio
SCS-CN	Soil Conservation System- Curve Number

ABSTRACT

Irrigation is an important factor in improving food security by increasing agricultural production. The development of irrigation and water management for agriculture has a significant role in improving productivity and reducing vulnerability to climate change. This study was concerned with surface irrigation potential assessment in the Muger sub-basin using geo-spatial techniques. The study was identified suitable land, available surface water crop water demand, and supply for dominant crops grown in the sub-basin, and also produced suitability maps for surface irrigation development. To identify suitable land the land suitability parameters were used such as land slope, soil parameters, proximity, and land cover land uses. The suitability of each parameter was analyzed individually and then the weighted overlay analysis was to get the overall suitable land. The result revealed that 0.7% (5652.48 ha) highly suitable, 15.1% (123237.7 ha) moderate suitable, 67.3% (551156 ha) marginally suitable and 16.9% (138753.5 ha) unsuitable. The streamflow was assessed with the ArcSWAT model with an interface ArcGIS. The model calibration and validation using observed streamflow. The result showed that model performance evaluation statistics coefficient of determination, Nash-Sutcliffe model efficiency, and Relative Volume Error for calibration were 0.79, 0.78, and 7% respectively and for validation 0.82, 0.8, and 3% respectively. This shows that a good agreement between the simulated and observed values. The crop water requirement of selected crops was identified by the CROPWAT model using climate data, soil data, and crop data. The comparison of streamflow with the gross irrigation water requirements for selected crops and identified sites for surface irrigation. So, the irrigation potential in the study area was found 136720.12 ha (37.2%) of the total suitable land in the sub-basin. To irrigate the remained suitable land of 543326.4 ha, it requires 1261.1 m^3/s, and to achieve it, a water storage structure is required. The identified surface irrigation potential assists policymakers in the development of irrigation projects. This study considered only slope, land use land cover, and soil physical properties but other suitability factors like, socioeconomic, environmental issues, soil chemical characteristics, and irrigation method should be studied.

Key Words: *Land Suitability, Crop water requirement, ArcGIS, ArcSWAT, Irrigation Potential*

CHAPTER ONE

1. INTRODUCTION

1.1. Background

The population number is growing rapidly. The present estimated world population is 7.9 billion in line with recent united nations estimation and is predicted to reach approximately 10.9 billion by 2100 (https://www.worldometers.info/world-population/). The increase will cause an oversized additional demand for food. FAO analyzed agricultural production in over 90 underdeveloped countries and the results showed that from 1998 to 2030, rain-fed agriculture increased by 49%, and irrigation increased by 81%. Therefore, the irrigation system is predicted to provide more additional food (Bahmani *et al.*, 2013).

The water resources management through the event of irrigated agriculture is a basic factor of economic and social development. Although irrigation in Africa has the potential to increase agricultural productivity by at least 50%, the continent's agricultural system is fed mostly by rain. Irrigation development has been recognized as a key tool for increasing economic growth and rural development and is seen as the foundation for the rationale for food security and poverty reduction in developing countries (Yalew *et al.*, 2011).

The highest portion of the Ethiopian population lives is in mountainous areas, 85% of which are rural populations, who depend upon agriculture for livelihoods and have low levels of productivity. On the other hand, Ethiopia has natural resources like land and water, which can be used sustainably for the country's socio-economic development. The country has abundant water resources, with 12 river basins, an estimated annual runoff of 125 billion cubic meters, and 12 to 30 billion cubic meters of groundwater (Berhanu *et al.*, 2014).

The potential of surface water resources is huge, but the development is less. Ethiopia also has large arable land (30 to 70 million hectares) but only small arable land is used for cultivation due to different reasons. Currently, the total area equipped for irrigation is 3.07million hectares which is the total area, 2.528 million hectares were equipped with small irrigation, and the remaining 539,726 hectares were equipped with medium and large irrigation systems (Awulachew, 2010 and Gebul, 2021).

Irrigation development plays a crucial role in adapting to climate change, ensuring food security, and increasing household income. However, due to technical, financial, and management issues, the country could not fully develop its resources potential. However, there are concerns about the development of irrigation expansion and the management of existing irrigation systems, but the results are not very satisfactory (Perry, 2018).

In recent years, Ethiopia has developed many irrigation schemes in several areas of the country However, because of different environmental and management factors, most of these irrigation systems are not fully utilized, and irrigation as a full does not contribute to the general economic development of the country as needed. Therefore, the irrigation sub-sector should be prioritized in the overall national development plan, the ultimate goal which is to increase agricultural production and maintain crop production and alleviate food insecurity (Ayana, 2011).

The country's irrigation potential is estimated based on master plan studies 1998 for the main basin, which is old and needs to be updated. This means the irrigation potential of the sub-basin in the main basin is also required to be updated.

Muger sub-basin covers a total area of 8188 km^2 area. The farmer cultivates their land only once a year, during the rainy season. In second planting season (end of the wet season), farmer facing shortage of the water supply that only come from rain water. Generally, yield decreased when the rain stops. Generally, the farmers' livelihood fails to famine in case of product reduction. For this matter, irrigation is important to alleviate such problems. Apply irrigation water to the crop as per the crop's need and at the right time during its growth stages.

To properly plan and develop irrigation, it is urgent to know the resources available for irrigation. Therefore, this study will explore the land suitability and the irrigation potential of the Muger sub-basin.

1.2. Problem Statement

Agriculture is an important activity within the world that sustains human life. It is also the leading sector in the Ethiopian economy. However, the country's agricultural sector is highly dependent on the rains. Climate change limits the productivity of the region. This results in food insecurity. To supply food to the growing population, irrigation has been playing a crucial role to ensure food security.

In the Muger sub-basin, most of the population lives in rural areas and depends on traditional rain-fed agriculture. Changes in rainfall greatly affect crop yields and lead to low yields. Also, there are some restrictions; agricultural land cannot be expanded to meet growing needs. Therefore, every effort should be given to manage existing land resources as efficiently as possible.

Master plan study was done for Abbay basin in 1998 in which also Muger sub-basin is located. Since then, the study was not updated. In addition, watershed-based land suitability and irrigation potential assessment are essential for development planning which is not yet done for the Muger sub-basin. Therefore, this study was done to assess and identify land suitability for surface irrigation and irrigation potential of the Muger sub-basin.

1.3. Objective

1.3.1. General objective

The main objective of the study was to assess the suitability of the land and the surface irrigation potential of the Muger River sub-basin.

1.3.2. Specific object

The specific objectives of the study were:

- To identify land that is suitable for surface irrigation in the sub-basin.
- To estimate surface water availability for surface irrigation.
- To estimate the overall surface irrigation potential in the sub-basin.

1.4. Research questions

Based on the above objectives, the following research questions were formulated:

- What is the extent of land that is suitable for surface irrigation in the sub-basin?
- What is the amount of surface water available for surface irrigation?
- What is the extent of surface irrigation potential in the sub-basin?

1.5. Significance of the study

Effective evaluation of the land for its most appropriate use plays a great role in the use of resources in an exceedingly sustainable way, and for its possible use to reinforce the livelihood of the community and economy of the country. It is important to spot the constraints and potentials for sustainable development of irrigation within the area and it helps policy makers as a tool for higher cognitive process on irrigation developmental projects within the sub-basin.

1.6. Scope of the study

The scope of the study mainly focuses on water availability, irrigation demand, and land suitability without considering some chemical properties of the soil type (alkalinity, salinity, and PH) and water quality. Therefore, the study only investigates soil physical properties, land use/cover, land slope, and proximity for determining land suitability for surface irrigation and assess available water for surface irrigation to compare with irrigation water demand for the selected crop.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. An Overview of Irrigation Potential

Irrigation potential is the cumulative suitability of the soil, slope, irrigable land, and suitability or potential of water available for irrigation at the given watershed without affecting the crop growth (FAO, 1997). The location that could probably be irrigated relies upon the bodily resources, soil, and water, combined with the irrigation water necessities as decided with the aid of using the cropping patterns and climate. Hence environmental and social elements considered in the evaluation of irrigation potential to assure a sustainable use of the available resource, land, and water plays a tremendous function for evaluation of making plans of sustainable food production within the country. Surface irrigation is the technique that permits the flowing water on the soil surface with the aid of using gravitational force (Bruinsma, 2003).

Irrigation potential is an important indicator of the extent of land suitable for irrigation development, this implies that its chances for irrigation development. The potential irrigable area depends on the physical soil and water resources in combination with the irrigation water demand, which is determined by cultivation patterns and climate (Valipour, 2015). According to FAO (1998) study, surface irrigation is that the process of diverting water from the river and applying, to irrigable land and properly use it for agricultural production by evaluating land characteristics.

2.2. Irrigation Potential in Ethiopia

Ethiopia covers 112 million hectares (Mha), which makes up 99.3% of the land area, and the remained 0.7% area is also covered by water (MoWE, 2013). Ethiopia also has large cultivable land (30 to 70 Mha), but only little cultivable land developed for cultivation. Currently, the overall area equipped for irrigation has reached some 3.07 million hectares. From this total area equipped for irrigation 2.528 million hectares area is under small irrigation whereas the remains 539,726 hectares equipped for medium and large-scale irrigation. This means that much of the cultivated land in Ethiopia is currently not irrigated. Increasing irrigation is essential to help Ethiopia meet major challenges, including population pressures; Soil and land degradation, high climatic variability, and low agricultural productivity. Additionally, the agricultural water program is crucial for smallholder livelihood and income in Ethiopia, since irrigation can help farmers increase their crop production, increase crop variety, and lengthen their agricultural seasons (Awulachew, 2010 and Gebul, 2021).

The country has a large potential of water and natural resource that might be easily utilized in expanding irrigation agriculture. The country is hydrologically divided into 12 major river basins. 8 are river basins, 1 lakes basin, and also the remaining 3 are dry basins. Among these river basins, Abbay, Baro-akobo, Omo, and Tekeze encompass 80-90% of the country's total surface water resource. Abbay basin is the second largest basin within the country. In general, the 12 river basins of the country generate an annual surface runoff volume of around 125 billion cubic meters and 2.6 to 13.5 billion cubic meters of water (Awulachew, 2010).

Rainfall is available in multiple forms which will be used for agriculture and irrigation. These forms include surface water (perennial and seasonal rivers), renewable groundwater, wetlands, soil moisture, and rainwater (captured or lost through evapotranspiration). However, as shown below, these water sources are severely underdeveloped and under-utilized in Ethiopia, implying that there is significant potential to extend water usage from these and other sources (Awulachew, 2010).

Table 2.1 Irrigation potential of Ethiopia river basins. (Source: Awulachew, 2010)

No.	Name of the Basin	Catchment Area (km^2)	Annual Runoff (BCM)	Irrigable area (ha)	groundwater (BCM)
1	Abbay	199,812	54.8	815,581	1.80
2	Wabi- shebele	202,697	3.4	237,905	0.07
3	Genale-dawa	171,042	5.88	1,074,720	0.14
4	Awash	112,696	4.9	134,121	0.14
5	Tekeze	82,350	8.2	83,368	0.20
6	Baro-Akobo	75,912	23.6	1,019,523	0.28
7	Omo-gibe	79,000	16.6	67,928	0.42
8	Ogaden	52,739	0	-	-
9	Denakil	74,002	0.86	158,776	-
10	Rift Valley	52,739	5.6	139,300	0.10
11	Mereb	5,900	0.72	67,560	0.05
12	Ayisha	2,223	0	-	-
	Total	1,135,494	124.25	3,798,782	2.86

Ethiopia has abundant annual rainfall and other significant water sources that are important with careful planning, infrastructure development, and resources, which can be developed for irrigation and other development needs. Indeed, Ethiopia has significant irrigation potential, which is assessed based on both the potential of water resources and the land available, regardless of accurate estimates of the potentially irrigable land and irrigated built-up area (Awulachew *et al.,* 2010).

2.3. Irrigation Potential in Abbay River Basin

The river basin is that the portion of land drained by a river and its tributaries. It encompasses all areas of the land surface dissected and drained by many streams and creeks that flow downhill into each other, and eventually into one river (Smithson *et al*., 2013).

The Abbay river basin which is of strategic importance to Ethiopia is found within the northwestern part of Ethiopia between 7^0 40’ N and 12^0 51’ N latitude, and 34^0 25’ E and 39^0 49’ E longitude. The river basin is that the second-largest in area coverage (199,812 km^2) and also the largest in annual runoff (54.5 BCM). The basin occupies 20% of the country’s total area and it covers an area of 60% of Amhara, 40% of Oromiya, and 95% of Benishangul-Gumuz regional states. The basin is subdivided into 16 sub-basins based on the major rivers in the basin. The Abbay River is additionally of vital importance to the lower riparian countries, Sudan and Egypt since it contributes about 62% of the total flow within the Nile River. it has a mean annual run-off estimated at 54.8 billion cubic meters (BCM) and accounts for roughly 40% of Ethiopia’s total surface water resources (Awulachew *et al*., 2009).

Its topography is rugged mountainous highlands within the eastern and central portion of the basin, with altitudes ranging from about the lowest 470 amsl to the highest elevation about 4260 amsl. 60% of the topography of the basin which ranges from 1500 to 4000 on average is highland. The remaining 40% is lowland. 64% of the total land of the basin has a slope of 0-15% while the remaining 36% has greater than 15%. About 28% of the whole population of the country dwells within the basin. Since 91% of the population within the basin resides within the countryside, their economy is entirely dependent on agriculture. 60% of the overall land of the basin which is about 119,887 km^2 is suitable for agriculture, and 2.5 million hectares of this arable land can be developed through medium and large-scale irrigation schemes. The feasibility study has been completed for about 526,000 hectares of land out of the aforementioned arable land. According to the plan, only but 2% of the potential of the river has been exploited. It has 16 major sub-basins like Rihad, Dinder Anger, Beles, Dabus, Didessa, Beles, South Gojjam, North Gojjam, Fincha, Guder, Jemma, Lake Tana, Welaka, Wenbera, and Muger. sub-basins (Yilma & Awulachew, 2009).

According to the program, out of the overall arable land of the basin, 2.5 million hectares of land can be developed through medium and large-scale irrigation schemes. Indeed, the Feasibility Study has been completed for about 526,000 ha of land. The study covered 93 irrigation schemes and 10 sub-basins. 28% & 23% of the entire irrigable land within the basin are often developed by Beles sub-basin and Tana sub-basin respectively. Apart from this, 13% & 11% of the irrigable land can be developed by Dedessa sub basin and North Gojam sub-basin respectively. The remaining 25% of the river basin's irrigable land can be developed by the other sub-basins basins (Yilma & Awulachew, 2009).

Table 2.2 Major irrigation potential in the Abbay basin. (*Source: Abbay Basin Authority, 2018)*

No.	Project	Land to be irrigated (ha)	crop to be cultivated
1	Fincha	20,000	Sugar cane
2	Koga	7,004	A variety of crops
3	Beles river	75,000	Sugar cane &
4	Dedesa	80,000	A variety of crops
5	Rib	14,460	Sugar cane
6	Megech/Seraba pump/	5,250	A variety of crops
7	Megech/Robit/	17,000	A variety of crops
8	Jemma	11,615	A variety of crops
9	Gigel Abbay	9,980	A variety of crops
10	Anger	18,000	A variety of crops
11	Dabus	9,661	A variety of crops
12	Gumara	16, 771	A variety of crops
13	Upper Gudar	6,282	A variety of crops

2.4. Land Suitability Classification for Irrigation

According to FAO Guideline: land evaluation for irrigated agriculture, the land is said to be suited, when it is suitable for the growth of selected crops and selected management systems, requires little or no land development and improvement costs, it is not sensitive to land degradation issues and it fits existing socio-economic conditions (FAO, 1985).

Suitability is a measure of how well the qualities of a land unit match the requirements of a selected type of land use. Land suitability is the fitness of a given type of land for an outlined use. The land suitability depends on its present condition or after improvements. The method of land suitability classification is the appraisal and identifying of specific areas of land in terms of their suitability for defined uses (FAO, 1976).

Land evaluation is primarily the analysis of information about the land's soils, climate, vegetation, etc. in terms of realistic alternatives for improving the utilization of that land. For irrigation, land suitability analysis, particular attention is given to the physical properties of the soil, to the distance from available water sources, and the terrain conditions in respect to methods of irrigation considered (Rossiter, 2009).

2.4.1. Structure of the Suitability Classification

According to FAO (1976) Framework for Land Evaluation, the structure of the suitability classification is described by considering different suitability factors and categories into four suitability classifications. Each category retains its basic meaning within the context of the various classifications and as applied to different forms of land use.

There are two Orders: Suitable (S), and Not Suitable (N). Suitable land is land on which sustained use of the kind under consideration is expected to yield benefits which "justify the inputs and development costs, without unacceptable risk of damage to land resources. Not Suitable indicates that the land has qualities that appear to preclude sustained use of the kind under consideration. The land suitability classes reflect the suitability levels. The classes are numbered consecutively according to Arabic numbers in the order of decreasing suitability levels within the order (FAO, 1976).

Table 2.3 Structure of land suitability order and classes. (Source: FAO, 1976)

Order	Class	Description
Suitable (S)	S1 (Highly suitable)	Land having no or insignificant limitations to the given type of use
	S2 (Moderately suitable)	Land with minor limitations to the given type of use
	S3 (Marginally suitable)	having moderate limitations to the given type of use
Unsuitable (N)	N (unsuitable)	Land with severe limitations that preclude the given type of use

2.5. Land Suitability Evaluation for Surface Irrigation

Land assessment is principally the examination of information about the land its soil, environment, vegetation, and so forth as far as reasonable options for improving the utilization of that land. For water system, land reasonableness examination, specific consideration is given to the actual properties of the soil, to the distance from accessible water sources, and the landscape conditions according to techniques for water system considered (FAO, 2007).

To reduce the human influence on natural resources and to identify appropriate land use, it is essential to hold out scientific land evaluations. Such quite analysis allows identifying the main limiting factors for agricultural production and enables decision-makers to develop crop management ready to increase land productivity(Kebede & Ademe, 2016). The basic physical factors in determining the suitability of land for surface irrigation:

2.5.1. Slope

The slope is the inclination of a surface and is often expressed as a percent. The slope is important for soil formation and management due to its influence on drainage, runoff, erosion, and selection of irrigation types. It affects the suitability of an area in terms of land preparation for irrigation and irrigation operation (Hussien *et al*., 2019). According to FAO standard guidelines for the evaluation of the slope gradient, mostly slopes, which are less than 2%, are very suitable for surface irrigation. However, slopes that are greater than 8% are not widely recommended (FAO, 1999).

Table 2.4 Slope classification for rating suitability

Slope	percent	factor of rating
Horizontal	0-2	S_1
very flat	2-5	S_2
flat	5-8	S_3
steep	>8	N

2.5.2. Soils

The assessment of soils for irrigation involves using physical properties that are permanent that cannot be changed or modified. Such physical properties include drainage, texture, and depth (Fasina *et al.,* 2008).

The assessment of soils for irrigation involves using physical properties that are permanent that cannot be changed or modified. Such physical properties include drainage, texture, and depth.

Soil is a major factor for the suitability of irrigation land. Its primary influence is on the productive capacity and influences production and development costs. The foremost desirable soil qualities for diversified crop production under sustained irrigation include; a water-holding capacity, soil aeration root zone, an infiltration rate to replenish soil moisture, an adequate depth to permit optimum root development, and soil chemical properties. Soil texture, soil drainage, soil depth, and soil type are the key physical properties of soil that are important for the evaluation of the irrigation potential of the basin (Tariku Meron, 2007).

2.5.2.1. Soil Texture

Based on their particle size, soils are divided into three major types of soil textures (clay, silt, and sandy soils). The USDA soil taxonomy and WRB soil classification systems use 12 textural classes. The twelve classifications are sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay (Ditzler *et al*., 2017).

Soil textures are classified by the fractions of each soil separate (sand, silt, and clay) present in a soil. Classifications are typically named for the primary constituent particle size or a combination of the most abundant particles sizes. Determining soil texture is often aided with the use of a soil texture triangle plot (NRCS, 1993).

The rate at which water enters the soil is influenced primarily by characteristics of the surface soil texture. When the infiltration capacity greatly exceeds the permeability of the subsoil, the Permeability will greatly influence the essential intake rate of the soil. The infiltration rate may influence the selection of the irrigation method, length of irrigation runs, field size, irrigation development costs, and crop selection. Fine-textured soils will have higher available moisture than coarser-textured soils. However, soils with extremely high clay content may very well have less available water than medium-textured soils. The clay type of the soil under the basin influences permeability, chiefly by its swelling and shrinking qualities with changes in soil moisture (Fischer *et al*., 2014)

2.5.2.2. Soil Depth

Soil depth refers to the thickness of the soil materials. Soil depth provides structural support, nutrients, and water for plants. Soil depth, soil layering, and depth to an estimated water level are also major factors that have to be considered when determining the number of available water soil profiles can hold (Jamshid, 2003).

Soil depth could be a critical attribute of any soil and determines rooting, moisture and nutrient storage, mineral reserve, anchorage, and a variety of conditions that affect plant growth (Yost & Hartemink, 2020). The depth to a contrasting soil layer of sand, clay, and silt affects irrigation management decisions. If the depth to the layer is a smaller amount than 10 centimeters, the rooting depth and available soil water for plants require more frequent irrigations. Plants can extract only the soil water that is to bear with their roots. for many agronomic crops, the basis distribution during a deep uniform soil is concentrated near the soil surface (Scherer *et al*., 2017). The soil depth Rating factor was adopted from FAO (1991) guidelines.

2.5.2.3. Soil Drainage

Evaluation of the soil drainage requirement could be a critical element in selecting land for irrigation, particularly with diversified upland crop production. Adequate soil drainage is essential to make sustained productivity and to permit efficiency in farming operations. In step with FAO evaluation techniques used for evaluation of permeability of soil properties of the land, it classifies soil drainage as well-drained, moderately drained, imperfectly drained, and poorly drained (FAO, 1997).

The soil suitability for surface irrigation according to FAO (1991, 1998 and 1997) is summarized in the following table 2.5.

Table 2.5 Soil suitability parameters for irrigation

Factor	Factor rating			
	S_1	S_2	S_3	N
Texture	C, SiC, SC	Si, SCL	SL, LS, FS	CS
Soil depth (cm)	>100	80-100	50-80	20-50
Drainage	Well drained	Moderately drained	Imperfectly drained	Poorly drained

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, FS = Fine Sandy, CS = Coarse Sandy

2.5.3. Land Cover/Land Use

Land use/ land cover mapping involves identifying surface features at various scales and their hierarchical classification and it plays a serious role within the study of world change. Human activity causes environmental problems resulted in deforestation, biodiversity loss, global warming largely affects land use/land cover. Therefore, a critical input for decision-making of environmental management and planning, in the long run, is often provided by available data toward land use/land cover. Growing population and increasing socio-economic results in unplanned and uncontrolled changes in land use/land cover. The land use/land cover alterations are generally caused by mismanagement of agricultural, and forest lands which result in severe environmental problems like floods and landslides (Reis, 2008).

Defining land cover or use in this way i**s** the basis for determining that land may be suitable for irrigation through accurate and quantitative economic evaluation. Therefore, matching the existing land cover/use with topography and soil characteristics to assess the suitability level of the land suitable for irrigation provides potential land for new agricultural production (Boonyanuphap *et al.*, 2004).

Table 2.6: Land use/land cover suitability criteria. (*Source*: FAO (1996))

Category	Name	Description of land cover types
S_1	Highly suitable	Cultivated dominantly, cultivated moderately, Grassland, bushed, shrub
S_2	Moderately suitable	Open Woodland, riparian, dense Bushland
S_3	Marginal suitable	Open Forest, irrigation cultivated Cultivated- Irrigation, state farm
N	Not suitable	Woodland- dense Bamboo, Urban area, and water bodies

2.6. Water resource potential Assessment

For plans of surface irrigation development priority is given to making sure that the existent enough amount of surface water potential within the geographical region or catchment. If there is a shortage of water systems during some of the irrigation seasons, the suffering of crop production will occur, returns will decline, and also the scheme's investment will lay idle (Brouwer et al., 1988).

Therefore, water supply (water quantity and seasonality**)** is that the important factor to evaluate irrigation potential in keeping with the amount of water during the year which it is available (FAO, 1985). Quantifying the amount of water available for irrigation and determining the precise locations to which water may be economically transported are important within the decision to expand its use. Where possible, the water source preferred to be located above the command area so that the whole field **is** irrigated by gravity. It is also desirable that the water source is near the center of the irrigated area to reduce the dimensions of the delivery channels and pipelines. Therefore, distance from water sources to command area, nearness to rivers, is beneficial to cut back the conveyance system (irrigation canal length) and thereby develop the irrigation system economically (Awulachew et al., 2007).

The water resource importance is not only for irrigation development planning but for a variety of fields, such as for industry, engineering structure design/hydropower/flood control, water resources utilization, and Eco-hydrological services (Gebrekristos, 2015).

Several hydrological models were used for the assessment of surface and ground water potential at a river basin, sub-river basin, watershed, and at a catchment level. The assessment of water availability at a watershed level is realized by quantifying runoff generated in the watershed using hydrological models (Daniel *et al*., 2011).

2.6.1. Hydrological modeling

Hydrological models are simplified, conceptual representations of a part of the hydrologic cycle. They relate something unknown (output) to something known (the input). Hydrological modeling is a process of determining the operation of the hydrological system in the transformation of rainfall into runoff. They are primarily used for hydrological prediction and for understanding hydrological processes. The overall intent of the hydrologic system analysis is to study the system function and predict its output (USDA, 1972).

There are many ways of classifying models generally based on the method of representation of the hydrological cycle or its component. Owing to the complex nature of rainfall-runoff processes, different hydrologists have different modeling approaches even to the same hydrological system (Beven, 2011).

Stochastic models use local hydrometric data to predict flows. These models allow for some randomness that results in different outputs and is based on analysis of past events, commonly rainfall and river discharge (Korolyuk, 2012)

Deterministic models produce a single output of runoff for a given rainfall under identical physical environments. They can be classified as a lumped model, where a variable or parameter is assumed to have an average value for the whole catchment, and distributed models, where all variables and parameters have different values that account for the spatial variation in the catchment. Semi-distributed models use multiple lumped units in a catchment either as sub-basins or HRU. Their hydrological process description is based on the conceptual type (Merritt *et al*., 2003).

2.6.2. Hydrological model selection criteria

Beven (2011) suggested four criteria for selecting model structures. They are,

1. Availability of the model on a minimum investment of time and cost.
2. The ability of the model to produce the intended output to meet the objective of the project.
3. The ability of the model is considered to produce the outputs needed to meet the aims of a particular project.

4. Possibility to prepare a list of assumptions made by the model and the ability to check the assumptions likely to be limiting in terms of the known response of the catchment.
5. Ability to make a list of inputs required by the model and deciding whether all the information required by the model can be provided within time and cost constraints.

Hydrological models require calibration and validation. Model calibration is the process of adjustment of the model parameters and forcing within the margins of the uncertainties (in model parameters) to obtain a model representation of the processes of interest that satisfies pre-agreed criteria. Validation is a comparison of the model outputs with an independent dataset without further adjustments of the values of the parameters. The model's predictive capability is demonstrated as being reasonable in the calibration and validation phase, the model can be used with some confidence for future predictions. The model performance and efficiency evaluated by Nash-Sutcliffe efficiency (NSE), the coefficient of determination (R^2), and the relative volume error (RVE) (Arnold *et al*., 2012)

There are various hydrological models are available for the assessment of a water balance. Some of these models include CREAMS model, SWAT model, GLEAMS, EPIC, AGNPS Model, HEC-HMS, MIKE BASIN, and SWRRB.

2.6.3. SWAT Model and its application

SWAT, a physically-based spatially distributed (semi-distributed) model overcomes these limitations and is being increasingly used to assess the hydrological behavior of large and complex watersheds. The other advantage is that it is a GIS interface model. It is also computationally efficient and a variety of management strategies can be performed without excessive investment of time or money. It enables users to study long term impacts; integration of multiple processes such as climate, hydrology, nutrient and pesticide, erosion,
land cover, management practices, and processes in water bodies (Tyagi *et al*., 2014).

The SWAT model is one of the most widely used and scientifically accepted tools for assessing water quality, sediment transport, and flow in a river basin; this is proven by world conferences and SWAT-related articles and reports. The needs of various environmental agencies have primarily driven the use of this model for direct and exploratory assessments of the impact of human activities, global climate change, and other wide-ranging land management issues on land and water resources (Gassman *et al*., 2007).

The water availability within the is simulated using the SWAT model, which is a semi-distributed, and physically-based model (Fiseha *et al*., 2013). The model has been widely used to evaluate land management practices, sediment transportation**,** and nutrient loading and discharge at the basin scale. SWAT quantifies and describes the impact of land use management practices in different periods on basin water**,** agricultural nutrients, and sediment production (Douglas-Mankin *et al*., 2010).

In SWAT, a basin is sub-divided into sub-basins based on DEM. The sub-basins are then further sub-divided into several hydrologic response units (HRUs) that represent a singular and homogeneous combination of slope, land use, and soil type within a sub-basin. SWAT uses concepts and equations of water balance to calculate hydrological processes, applied at the HRU level of the model (Fiseha *et al*., 2013).

2.7. Estimation of irrigation water requirements

The net irrigation water demand is the water that is required by irrigation to cover the evaporation of the plants and the additional water demand (leaching, temperature change, plant quality) that is not covered by the water stored in the profile, soil, or precipitation. ETc) every crop is essentially required for irrigation planning and water management. The effective use of water in both irrigated and rain-fed areas for crop production is critical. Using the exact or correct amount of water and when to apply it is very important in planning irrigation to meet the plant's water needs and the plant production is optimal (Jensen *et al*., 1990).

To calculate IWR for various crops, the first step is to calculate primary estimates like evapotranspiration (ET_0), crop coefficients throughout the growing interval of crops (Kc), effective rainfall (P_{eff}), and crop water requirement (Allen *et al*., 1998).

2.7.1. CROPWAT model and its application

CROPWAT is software developed by the Land and water program Division of the Food and Agriculture Organization (FAO) for planning and management of irrigation. It is a practical tool to hold out standard calculations for reference evapotranspiration, CWR, IWR, and the planning and management of irrigation schemes. CWR and irrigation timing are important in water resources management (Smith, 1992).

Arku *et al*. (2012) used the CROPWAT model version 8.0 to work out water requirement and irrigation timing for Amaranthus hybridus in Maiduguri Metropolis, North-Eastern Nigeria. Based on the result of the authors the theoretical values of water requirements and irrigation timing were computed using the Penman Montieth equation in CROPWAT 8.0 for dry season drip irrigation system as a water-saving measure and optimum yield.

Dawit *et al.* (2020) used a model from the FAO Crop Irrigation and Water Requirements Program. This model is CROPWAT which is used for estimation irrigation water requirements. To assess the irrigation water requirement, they selected six plants (cabbage, corn, tomato, pepper, peanut, and sugar cane) and estimated their irrigation water needs using the CROPWAT model.

2.8. Overview of GIS Application and remote sensing

A Geographic information system (GIS) is a computer software program used for capturing, querying, storing, analyzing, and displaying geographically referenced data. These data are that describe both the locations and places of spatial features like land parcels, roads, and vegetation stand on the Earth's surface (Goodchild, 2000).

Geographic Information System (GIS) is a conceptual framework that gives the ability to capture and analyze spatial and geographic data. GIS applications are computer tools that allow users to perform interactive queries **(**search created by users), store and edit spatial and non-spatial data, analyze the output of spatial information, and share the results by presenting visualizations as maps (Maliene *et al*., 2011).

It has long been recognized that land suitability is assessed as part of a reasonable agricultural system and that optimizing the use of large parcels of land for specific purposes should be based on its attributes. GIS is used to match the suitability of crops according to the requirements of the crops and the quality and characteristics of the land (Shiferaw, 2007).

The Geographic Information System (GIS) plays an important role in identifying areas where crop**s** and planting patterns change. It is an important tool for crop surveys and mapping (Singh, 2016). The most common geographic analysis to be performed in GIS is found in the following sections.

2.8.1. Mapping

Mapping is the main application of GIS for editing tasks similarly to for a map-based query and analysis (McCleary Jr *et al.,* 1991). This is the most common view for users to use geographic information systems. Represent geographic information as a set of layers and other elements during map view. Common map elements include data frames, scale bars, north arrows, titles, descriptive text, and legends for symbols (Ganole, 2010).

2.8.2. Weighted Overlay Analysis for Land Suitability

It is a method of applying typical measurement scale values to various inputs to form a comprehensive analysis. Geographical issues usually require the use of GIS to analyze various factors. For example, finding the best irrigation site requires weighing factors such as slope, soil, and land use/cover (Jamshid, 2003).

The weighted overlay analysis uses a rating scale of 1 to 5 (from the most inappropriate factor to the most appropriate factor) to prioritize the influence of the values of these factors. The weighted overlay only accepts integer raster as components, such as LULC, soil type, and slope (from the center of the source cell to the straight line from the center of each surrounding cell) the output raster to find the suitable land for the irrigation (Janssen & Rietveld, 1990).

2.8.3. Watershed Delineation

Watershed delineation based on digital elevation models (DEMs) is the prerequisite to set up the SWAT model. Based on ArcGIS and ArcSWAT, improved DEM-based method and pre-defined method were applied in watershed delineation (Luo *et al*., 2011).

The delimitation of a watershed refers to the determination of a specific boundary or area of a watershed. GIS uses DEM data as input and delineates watersheds through Arc SWAT (Winchell *et al*., 2007). DEM of various resolutions provides terrain representation from which watersheds are often derived automatically using GIS with ArcSWAT. The techniques for automated watershed delineation are implemented within the way of GIS systems and applications (Garbrecht & Martz, 1996).

2.9. Multi-criteria Evaluation Techniques

Multi-criteria evaluation (MCE) is an operational tool that uses multiple criteria to solve decision-making problems (Malczewski, 2006a and Grima *et.al*., 2018)). The target of the MCE is to look at selected possibilities based on multiple criteria and objectives.

The MCE technique, along with the geographic system (GIS), can help properly categorize, examine, and organize accessible information regarding spatial planning choices (Pujadas *et al*., 2017).

The Analytical Hierarchy Process (AHP) could be a multi-criteria decision-making method (MCDM) that helps the decision-maker to overcome a complex problem with multiple subjective and conflicting criteria. AHP is designed to optimize decision-making with a combination of qualitative and quantitative factors. It was very effective in making difficult decisions, especially in project management (Mardani *et al*., 2016).

The AHP framework is a popular MCDM decision-making and analysis tool that can be used to rank alternatives and evaluate standard weights through pairwise comparisons (Velasquez & Hester, 2013). The analytic hierarchy process (AHP) method proposed by Saaty (1991) could be a recognized multi-criteria technique that is incorporated into the GIS-based procedures for determining suitability (Marinoni, 2004).

Five steps are identified in the analytic hierarchy process. The first step, the AHP process begins by defining the alternatives that need to be evaluated. These alternatives could be the different criteria that solutions must be evaluated against. At the end of step 1, a comprehensive list of all the available alternatives must be ready. The second step is to model the problem. According to AHP methodology, a problem is a related set of sub-problems. The AHP method, therefore, relies on breaking the problem into a hierarchy of smaller problems. In the process of breaking down the sub-problem, criteria to evaluate the solutions emerge. The third step, use a set of pairwise comparisons based on the AHP preference scale to prepare a comparison matrix (Saaty, 2003; Ramanathan and Ganesh, 1995 and Ramanathan, 2001). The preference scale and reference scale were shown in table 2.7 and table 2.8 respectively according to Saaty (2008))

Table 2.7: Preference Scale

Scale of Importance	Numeric Rating	Reciprocal
Extremely Importance	9	1/9
Very strong to extremely	8	1/8
Very strong importance	7	1/7
Strongly to very strong	6	1/6
Strong Importance	5	1/5
Moderately to strong	4	1/4
Moderate importance	3	1/3
Equally to Moderately	2	1/2
Equal importance	1	1

Table 2.8: Reference scale

Matrix size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

In the fourth step, to maintain the consistency of the judgment matrix, a consistency test is carried out. In AHP, there is a consistency index, called the consistency ratio (CR), which is used to express the probability that the matrix judgment is randomly generated (Saaty, 1980).

$$CR = \frac{CI}{RI} \tag{2.1}$$

Where RI is the average of the resulting consistency index depending on the order of the matrix given by table 2.8 and CI is the consistency index. In the last step, the weights are calculated from the paired comparison matrix by calculating the eigenvalues and eigenvectors. The eigenvector corresponding to the most important eigenvalue of the matrix provides the relative priority of the indicator (Saaty, 2001).

The components of the eigenvector are added to the unit. In this way, a weight vector is obtained, which reflects the relative importance of different indicators in the pairwise comparison matrix.

2.10. GIS role in irrigation potential assessment

GIS is computer software that provides a convenient and powerful platform for suitability assessment. GIS methods and procedures play an excellent role in the analysis of decision-making problems. GIS is often referred to as a decision support mechanism, which involves integrating spatial reference data for problem-solving environments. We can facilitate the spatial analysis of detected changes over time by implementing GIS and overlaying the spatial components of the same feature in two or more periods. Therefore, many spatial decision-making problems have produced multi-standard decision-making analyses based on the GIS technique (Quraishi & Haile, 2014).

There are different studies have been done to assess the irrigation potential and water resources by using the GIS tool (Meron, 2007; Sultan, 2013; Ayalew, 2014; Gebeyehu; 2015; Worqlul *et al.,* 2015; Birhhanu, 2017; Nigussie *et al*., 2019 and Dawit *et al*., 2020)**.**

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

Sultan (2013) conducted a study on the assessment of irrigation land suitability and the development of a map for the Fogera catchment using GIS. A transverse measurement with GPS was carried out to delimit the basin. This data was then downloaded into a GIS environment and used to develop the study area boundaries. The SRTM Digital Elevation Model (DEM) was used for the topographical analysis. Soil and water samples. Locations and heights were recorded as a single point. Soil samples were collected from three profiles and nine auger holes. The soil samples were analyzed for topsoil texture, stoniness, soil salinity, pH, and soil alkalinity. The salinity of the groundwater was measured using an electrical conductivity meter and the pH of the groundwater sample was measured with a pH meter. The slope of the study area is derived from SRTM-DEM. Based on the assigned suitability criteria an overlay analysis was carried out to create a suitability map containing the characteristic of all qualities of the land with its thematic characteristic table.

Ayalew (2014) conducted a study to assess the suitability of the land for surface and sprinkler irrigation using the Geographic Information System (GIS), in the Guang watershed, in Ethiopian Highlands. Geographic Information System (GIS); Techniques were used to develop a land suitability map. The digital elevation model with 30 m spatial resolution was used to generate slopes with the Spatial Analyst Surface Slope Tool " in the ArcGIS environment. Texture, electrical conductivity, pH, drainage, and slope factors. The Irrigation Suitability Map was developed by adapting the reclassified LCs to the Irrigation Land Use Requirements (LUR) using the GIS model builder.

Gebeyehu (2015) conducted a study to assess irrigation potential in the Guder River catchment, a sub-basin of the Abbay river basin. Land evaluation for irrigated agriculture was done by using a geographic information system (GIS). Five crops (Maize, wheat, teff, sorghum, and Barley) and three irrigation methods (surface, center pivot, and portable sprinkler irrigation methods) were selected as land utilization types. Soil properties, land slope, land cover, and water availability were evaluated against the requirements of each land utilization type. Crop water demand was estimated using Penman-Monteith and Hargreaves methods. Surface water potentials of the Guder River catchment were assessed using the SCS-CN method.

Worqlul *et al.* (2015) carried out a study to assess the irrigation potential of surface water in the Tana Lake Basin. The surface water potential was examined by analyzing the long-term daily historical river runoff. The areas suitable for irrigation were determined using a multi-criteria assessment based on GIS, which takes into account the interplay of several factors; such as climate, river proximity, soil type, land cover, topography/gradient, and market outlets.

Birhhanu (2017) studied GIS-based Surface Irrigation Potential Assessment of the Dirma watershed in Dembya Woreda. Suitability of the area concerning slope and soil were evaluated using Arc GIS 10.1 and surface water resources availability obtained from MoWIE was used. Potentially suitable sites for surface irrigation development were evaluated for selected crops. The reference evapotranspiration and net effective rainfall for each of the climatic stations (Gorgora and Gonder) and net and gross irrigation requirement for each of the crops for each of the climatic stations were estimated using CROPWAT software. The water available from the Dirma River during Jan, April and May was more than the gross irrigation water requirement.

Nigussie *et al*. (2019) examined the assessment of areas suitable for surface irrigation in the ungauged catchment in the Blue Nile Basin, a method for quantifying surface water resources and potentially irrigable areas in ungauged catchment areas in the Upper Blue Nile Basin with the Soil and Water Assessment Tool (SWAT) model and Multiple Criteria Decision Evaluation (MCDE). The method was tested on the Lah River basin in the Jabitenan district and then applied to the entire ungauged area. In MCDE, soil type, slope, land use, and proximity to the river were taken into account. Onion, cabbage, and tomato were grown in the identified irrigated areas.

Dawit *et al*. (2020) conducted a study to assess the surface irrigation potential of the Dhidhessa river basin, which mainly focused on estimating the available water resources and their potential for the use of surface irrigation water in the river basin obtained through the use of the Geographic Information System (GIS) based tools, Soil and Water Assessment Tool (SWAT) model and a model of the FAO Crop Water and Irrigation Requirements Program (CROPWAT). Builders were employed to map the irrigation potential of the basin. In the assessment of the irrigation potential, they selected six crops and estimated their irrigation water needs using the CROPWAT model.

CHAPTER THREE

3. MATERIALS AND METHODOLOGY

3.1. Study area description

3.1.1. Location

The study area is located northwest of Oromia State, 120 kilometers away from Addis Ababa, the capital of Ethiopia, and 50 kilometers east of Chancho City. The Muger sub-basin is a component of the Upper Blue Nile Basin. It has an area of 8,188 square kilometers at the confluence of the Abbay River and an area of 468.87 square kilometers at the station near Chancho. The Muger River is a northern tributary of the Abbay Basin in central Ethiopia and is known for its deep gorge. Its confluence with the Abbay River at 9°55'07″N 37°55′50″E. The sub-basin is geographically located between 38°50′10″E and 38°30′20″E longitude and between 9°18'45″N & 9°5′7″N latitude. The tributaries of the river include Labbu, Aleltu, Deneba, Sibilu, and Roba.

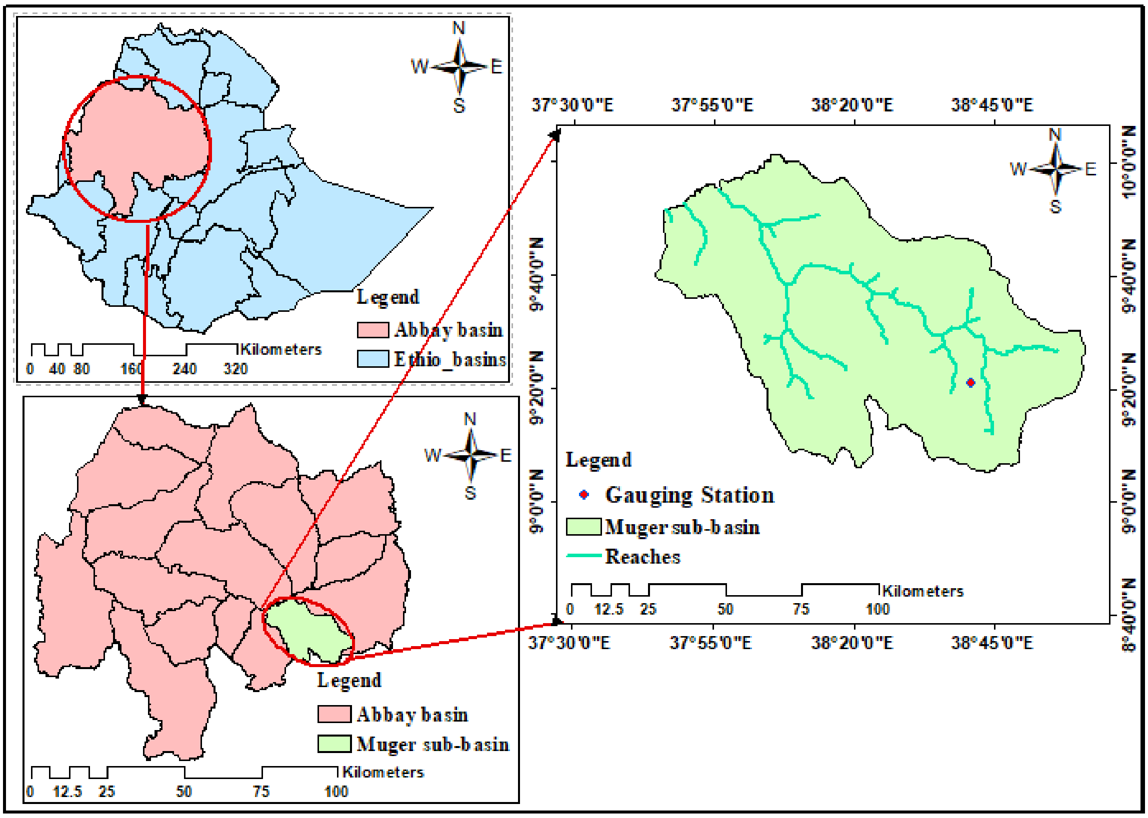

Figure 3.1: Location of Muger sub-basin in Abbay River Basin.

3.1.2. Agro-ecology

The land use in the Muger sub-basin is dominated by pastoral and agriculture. Grazing land has also been observed in some parts of the sub-basin. The agro-ecological zone is characterized by temperate zone to cold and humid highlands. The lowland northwest is warm to humid.

3.1.3. Climate

The sub-basin has annual precipitation that varies between 833 and 1326 mm. Lower annual precipitation ranging from 833 mm up to 1000 mm is observed along the river and lowlands. Relatively high rainfall is recorded in the highlands of the sub-basin. The annual maximum and minimum temperatures in the basin vary between 16-31.5 ℃ and 3-16.5 ℃, respectively. The temperature along the river is relatively high, the highest is 28-31.5 ° C and the lowest is 13-16.5 ° C. The monthly rainfall, maximum temperature and minimum temperature of the various station is given in the following figure 3.2, figure 3.3 and figure 3.4 respectively.

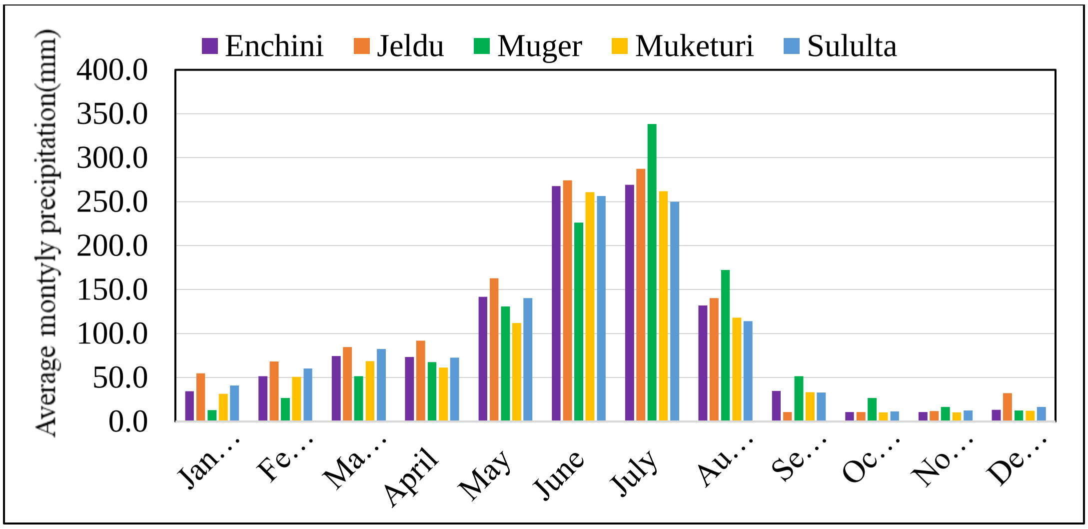

Figure 3.2: Mean monthly precipitation of various stations.

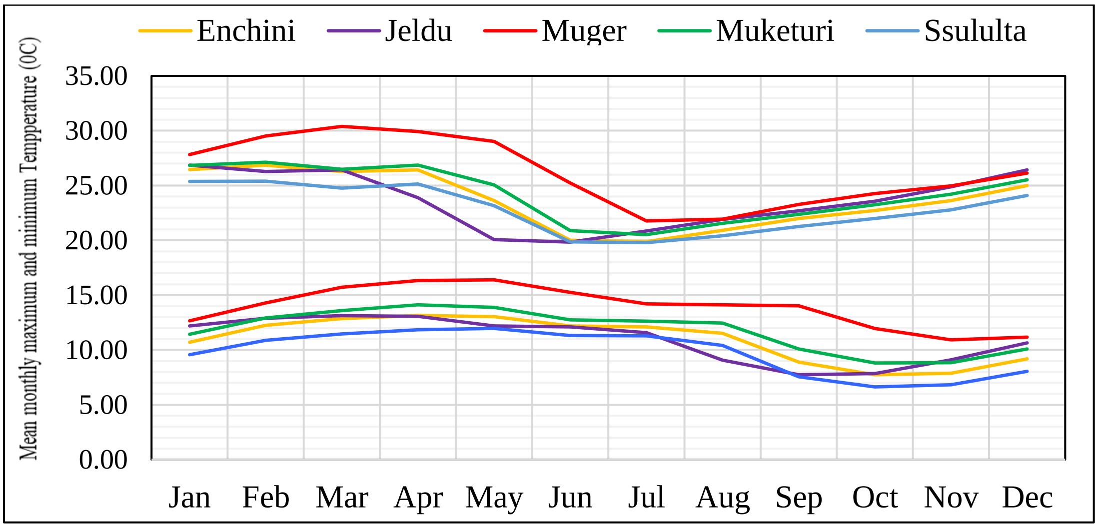

Figure 3.3: Mean monthly maximum and Minimum Temperature of various stations.

3.1.4. Soil

The main soil types of the Muger sub-basin were Leptosole, Luvisole, Vertisole, Fluvisole, and Alisole. Leptosols are the most common soil in the sub-basin. The second dominant soil is Luvisols. In some parts, there are also small spots of cambisols, nitosols, and rigosols (Yilma and Awulachew, 2009).

3.1.5. Topography

The altitude in the Muger sub-basin varies between 953 and 3514 meters above sea level; the highlands in the eastern and southern parts of the sub-basin are higher, greater than 2,600 m to 3,514 m; the lowlands along the Muger River are less than 1,700 meters above sea level (Yilma and Awulachew, 2009).

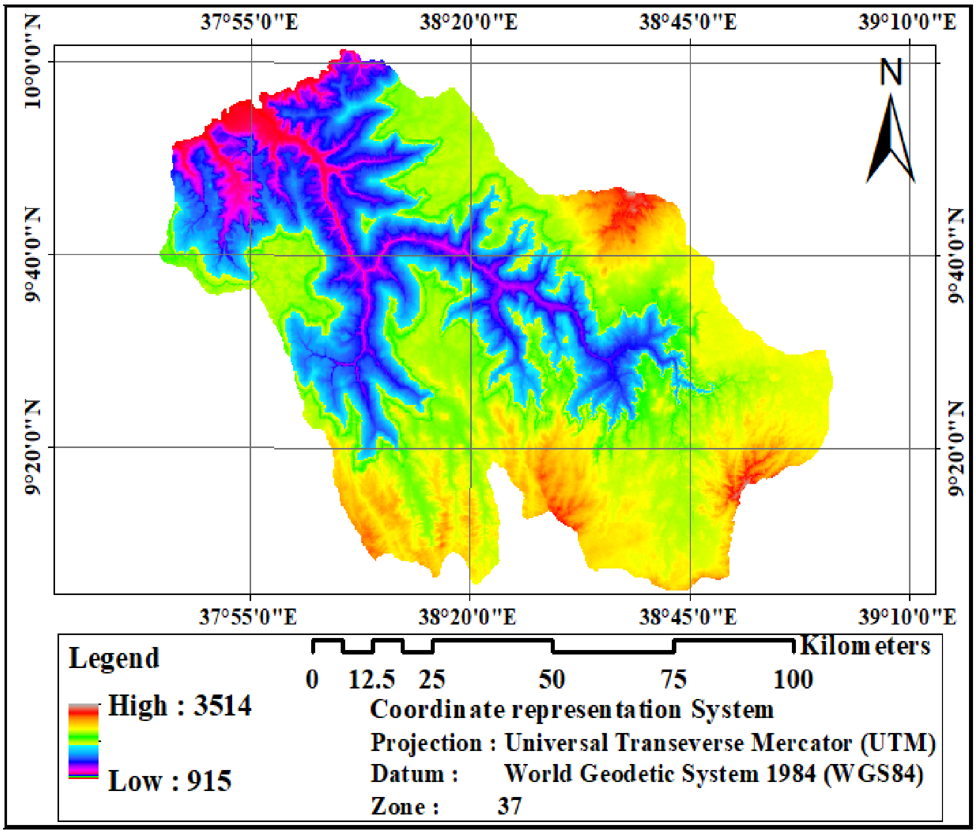

Figure 3.4: Topography of Muger Sub-basin.

3.2. Methods of the Study

Assessment of the land suitability and irrigation potential was don be by collecting available data from different ministers and agencies such as the Ministry of Water, Irrigation and Electricity, Ministry of Agriculture and Natural Resource, and Ethiopian National Meteorological Agencies. After collecting, the necessary data for the research and then filling of missed data and quality checking have been done carefully.

An ArcSWAT model was implemented to estimate the potential of surface water at the outlet of the basin and GIS software to determine the suitability analysis of the land for surface irrigation taking into account the slope/topography, the physical properties of the soil, and the land use land cover. It is used to determine the need for irrigation and plant water for selected crops in the sub-basin area.

The method of the study has been summarized as the following conceptual framework. The general framework of the study is presented in figure 3.5.

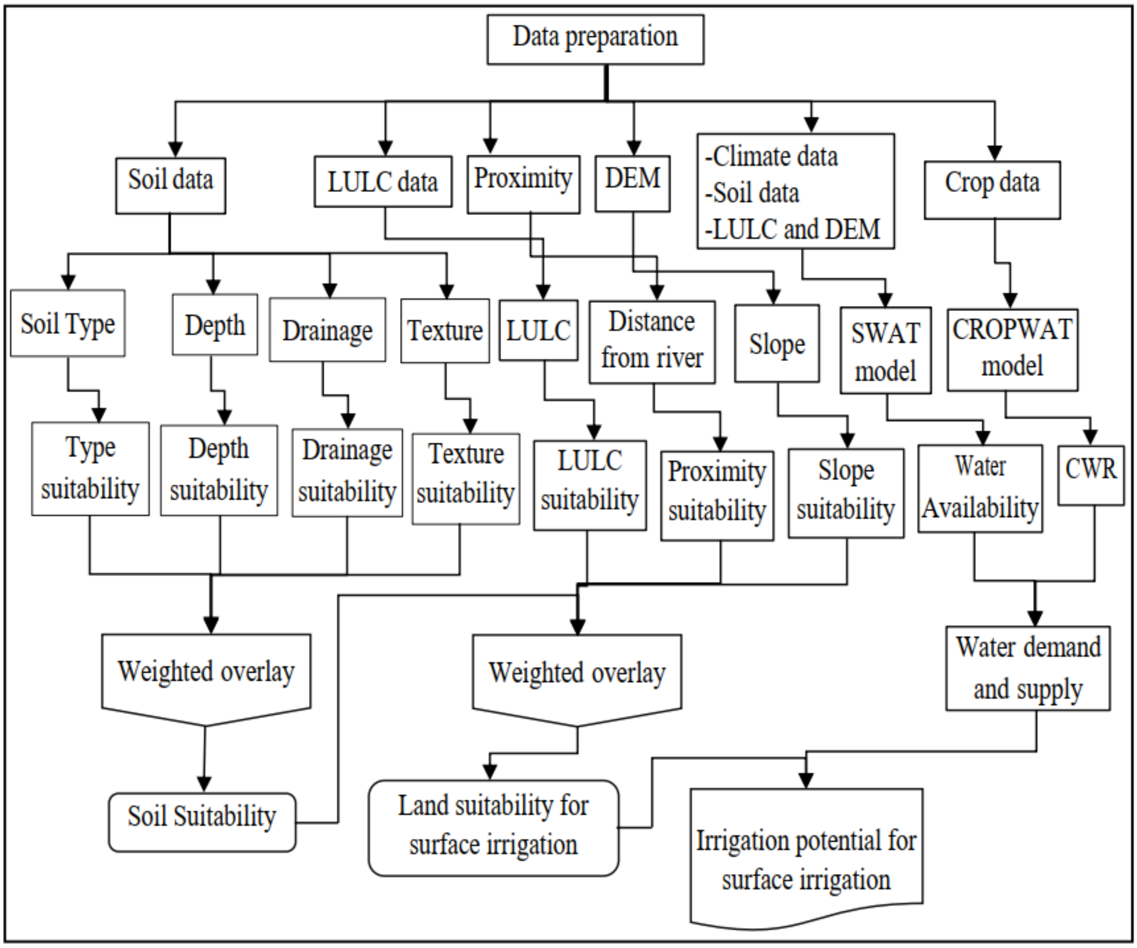

Figure 3.5: Conceptual Frameworks for surface Irrigation Potential assessments.

3.3. Data Sources and quality assessment

For this study, numerous data needed are included digital elevation Model data (DEM), land use and land cowl data, soil data, climatic data (daily precipitation, most and minimum temperature, relative humidity, wind speed, and solar radiation), and agronomic data. The land uses land cover obtained from the Ethio-GIS map server organization. Soil, DEM, and hydrological data were collected from the MOWIE. The climatic data were obtained from the national meteorological agency of Ethiopia (NMAE) and agronomic data from the ministry of agriculture (MoA). The data used and the sources also software used were mentioned in table 3.1.

Table 3.1: Data and software used in the study.

Data and Software	Purposes	Source
ArcSWAT 2012	For Watershed Delineation by integrating with ArcGIS and for streamflow simulation	https://swat.tamu.edu/software/
Arc GIS 10.5	To Evaluating Suitable land for surface irrigation	Environmental System Research Institute (ESRI)
Swat Cup	For Calibration, Validation, and sensitivity analysis	https://swat.tamu.edu/software/
CROPWAT 8.0	For crop water requirement estimation	Food and Agricultural Organization (FAO)
IDRISI SELVA-17	To evaluate of parameters weight and consistency ratio	https://getin-topc.com/idrisi-selva-17/
DEM	To generate the slope with ArcGIS and for delineation with ArcSWAT	Ministry of Water, Irrigation, and Electricity of Ethiopia from the hydrology department.
Soil	The input of ArcGIS and ArcSWAT	Ministry of Water, Irrigation, and Electricity and Harmonized World Soil Database
LULC	The input of ArcGIS and ArcSWAT	Ehio-map server organization
Weather data	The input of ArcSWAT and CROPWAT 8.0	National Meteorology Agency
Hydrological data	For Calibration and Validation	Ministry of Water, Irrigation, and Electricity

3.3.1. Estimation of the missed data

In the climate data preparation process, gaps in precipitation and temperature statistics are usually checked before filling in missing data. According to the principles indicated in (Subramanya, 2013), using meteorological and climatic data from nearby or neighboring stations, the missing climatic data for each station can be calculated. In this study, when the monthly average precipitation of all index stations is within 10% of the station, a simple arithmetic averaging technique is used to consider the station (x) in equation 3.1. However, the traditional ratio method is used when the average monthly precipitation of one or more adjacent stations differs from the average monthly precipitation of the station (x) by more than 10%.

The normal ratio method was used for this study and calculated by Equation 3.2.

a. The arithmetic mean method

According to the arithmetic mean method the missing precipitation P_X is given as

$$P_X = \frac{1}{n}\sum_{i=1}^{i=n} P_i = \frac{1}{n}(P_1 + P_2 + P_3 + \cdots + P_n) \qquad 3.1$$

Where n is the number of nearby stations

P_i is precipitation at the i^{th} station and

P_X is missing precipitation

b. Normal Ratio Method

According to the Normal Ratio Method, the missing precipitation P_X is given as

$$P_X = \frac{1}{n}\sum_{i=1}^{i=n} \frac{N_X}{N_i} P_X = \frac{1}{n}\left(\frac{N_X}{N_1}P_1 + \frac{N_X}{N_2}P_2 + \frac{N_X}{N_3}P_3 + \cdots + \frac{N_X}{N_n}P_n\right) \qquad 3.2$$

Where: N_x = annual normal rainfall at the station under consideration Where, P_X is the precipitation for the station with the missed record, N is the number of stations used in the computation, P_1, P_2, P_3…. P_n are the corresponding precipitation at the index stations and N_1, N_2, N_3…. N_n and N_x are the long-term mean precipitation at the index stations and the station (x) under consideration respectively.

3.3.2. Homogeneity test of rainfall and streamflow records

The quality testing of streamflow and rainfall data is essential to visualize unrealistic records, such as negative flow and constant observation in the days following a rainfall event. The Rainbow software package is designed to verify the homogeneity of the streamflow record and provide a homogeneity test, which is compatible with cumulative deviations from their average value (Raes *et al.*, 2006).

$$S_k = \sum_{i=1}^{k}(X_i - \bar{X}) \qquad 3.3$$

Where S_k is residual mass, X_i is the records from the series X_1, X_2…X_k and $\bar{X}$ is the mean. For a homogenous record, one may expect that the S_k fluctuates around zero since there is no systematic pattern in the deviations of the X_i from their average value X. To test the homogeneity of the data set, the cumulative deviations are rescaled. It is obtained by dividing the S_k by the sample standard deviation value (S). By evaluating the maximum (Q) or the range (R) of the rescaled cumulative deviations from the mean, the homogeneity of the data of a time series can be tested:

$$Q = Max\left[\frac{S_K}{S}\right] \tag{3.4}$$

$$R = Max\left(\frac{S_K}{S}\right) - Min\left(\frac{S_K}{S}\right) \tag{3.5}$$

When the deviation crosses one of the horizontal lines the homogeneity of the data set is rejected on 90%, 95%, and 99% probability. Therefore, the homogeneity Muger station was rejected on both 95% and 99%. Whereas Enchini, Jeldu, Muketuri, and Sululta were rejected only on 99%. The streamflow homogeneity shows rejection on 99%. This also suggests that the Stream and rainfall data recorded at these five stations can be used directly for further analysis.

3.3.3. Consistency of rainfall data

To prepare the rainfall data for later application, a double mass curve analysis was used to verify its consistency. Use the cumulative rainfall data for the location of interest to plot the cumulative average of the surrounding stations to verify the consistency of the rainfall data. To check the degree of consistency, (Nemec, 1972) provides the following values of correlation coefficients:

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

The double mass curve to check the consistency of rainfall data is described below.

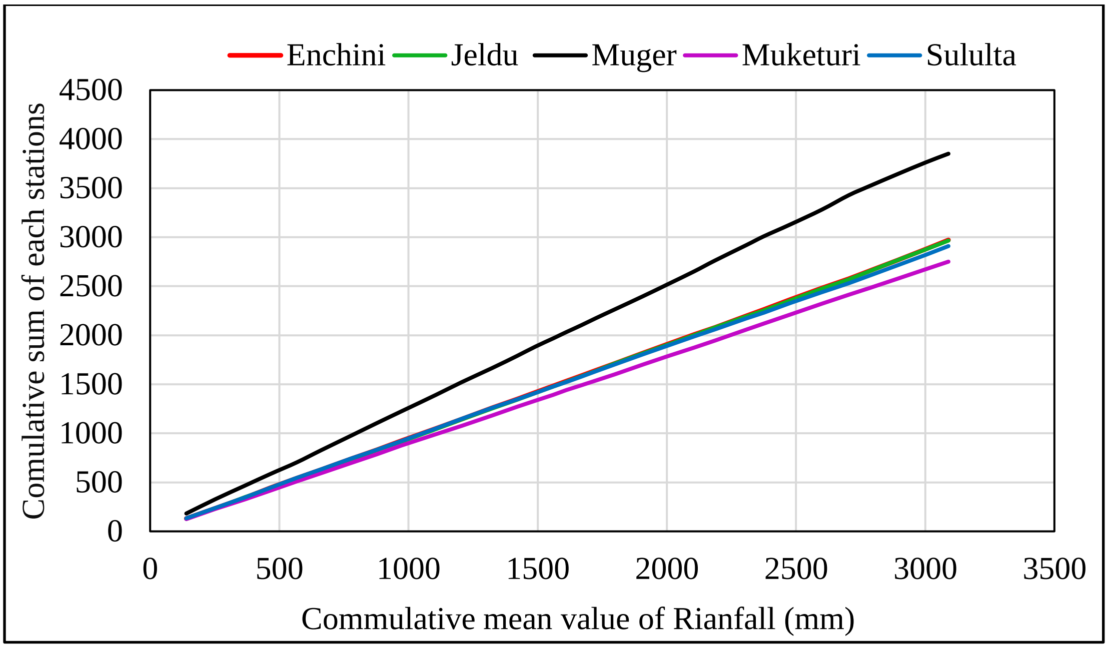

Figure 3.6: Double Mass Curve of Used Rainfall Stations.

The coefficient of correlation for each station Enchini, Jeldu, Muger, Muketuri, and Sululta were 0.9999, 0.9999, 0.9999, 1.0000, and 0.9999 respectively. The results of the double-mass curve analysis of the rainfall stations revealed that the rainfall recorded at the five gauging stations (Enchini, Jeldu, Muger, Muketuri, and Sululta) are consistent with no significant change of slope on their respective plots as presented in figure 3.6. This also suggests that the rainfall data recorded at these five stations can be used directly for further analysis.

3.4. Identification of suitable land for surface irrigation

The assessment of suitable areas for surface irrigation was carried out taking into account the slope, the soil, the land cover/use, and the proximity. The individual suitability of each factor was first analyzed and finally weighted to get potential irrigable sites.

3.4.1. Slope Suitability

To obtain the slope suitability map of the study area, the digital elevation model of the SRTM study area was clipped with a resolution of 30 meters from the mask layer of the study area. Then use the "spatial analysis tool" in ArcGIS to export the slope map of the study area. According to the FAO (1996) classification system, the slopes obtained by DEM are classified using the "reclassification" tool, an attribute generalization technique in ArcGIS. The four suitable ranges (S_1, S_2, S_3, and N) were classified as shown in table 3.2.

Table 3.2: Slope Suitability Classification for Surface Irrigation.

No.	Slope (%)	Factor Rating
1	0-2	S_1
2	2-5	S_2
3	5-8	S_3
4	>8	N

3.4.2. Soil Suitability

The basic physical parameters of the soils in the sub-basin are texture, depth, and drainage classes were used in the suitability analysis. The following soil suitability ratings were used based on FAO guidelines for land evaluation (FAO, 1991 and FAO, 1997).

Table 3.3: Soil Suitability Factor Rating.

Factors	Factor rating			
	S_1	S_2	S_3	N
depth	>120	100-120	50-100	<50
texture	C	SiCL, CL	SL	Coarse sand
drainage class	W	M	I	P

C = Clay, SiCL = Silty Clay Loam, CL = Clay Loam, SL = Sandy Loam, W=Well drained, M=Moderately drained, I=Imperfectly drained, P=Poorly drained

Using the conversion tool in the ArcGIS Arc toolbox to convert the soil vector layer to a raster layer. Then, the rasterized soil map of the study area was reclassified according to texture, depth, and drainage level. Perform these factors in the form of the weighted overlay addition tool in the spatial analysis tool (Arc GIS Spatial Analysis> Overlay> Weighted Overlay Analysis) to determine soil suitability. Analytical Hierarchy Process (AHP) technique in integration with Geographical Information System (GIS) and Weighted Overlay Analysis (WOA) had been incorporated to classify the land for agriculture production. In AHP, weights were determined with the use of a pairwise comparison matrix based on expert opinions. The steps of AHP: Step (1) Define Alternatives, Step (2) Define the Problem and Criteria, Step (3) Establish Priority amongst Criteria Using Pairwise Comparison, Step (4) Check Consistency, and Step (5) Get the Relative Weights. The new values were given based on a common evaluation scale from 1 to 4. A value of 1 represents highly suitable, 2 for moderately suitable, 3 for marginally suitable, and 4 for not suitable classes. Once the pairwise comparison matrix is entered in the IDRISI SELVA weight derivation module. The pairwise comparison and weights of soil factors were shown in table 3.4.

Table 3.4: Pairwise comparisons of soil factor layers.

	Pairwise Comparison				Principal Eigenvector	
Parameters	Soil Drainage	Soil Depth	Soil Texture	Soil Type	Weight	Percent of Influence
Soil Depth	1				0.3774	38
Soil Texture	1	1			0.2972	30
Soil Type	1/2	1/2	1		0.1842	18
Soil Drainage	1/3	1/2	1/2	1	0.1412	14
Consistency ratio (CR) is 0.02						

3.4.3. Land Use Land Cover Suitability

The land cover/use in the study area is also a factor in assessing whether the land is suitable for irrigation. The sub-basin land use/land cover (LULC) includes grasslands, forests, barren land, agriculture, urban, and shrubs. Based on these suitability levels, the LULC map of the sub-basin is rasterized and used in the evaluation process to determine locations that may be suitable for surface irrigation systems.

3.4.4. Proximity

An important parameter considered to determine the potential land suitable for surface irrigation is to analyze the proximity of the study area to the water source. To identify irrigated lands, close to the water supply (river), a DEM with a pixel size of 30 by 30 m was used to calculate the straight-line distance (Euclidean) and reclassified. The reclassification distance is then used with other factors for the weighted overlay analysis.

3.4.5. Determining factor weights

Pairwise comparison has been done for factors used in land suitability analysis for surface irrigation of the area for selected crop cultivation. The standardization also made for layers that are constraints only have (true or false) possibilities. The difference in rating of factors is mostly solved by making scales to the same range and the derivation of the relative criterion importance using the pairwise comparison method. The criterion weights are automatically calculated; once the pairwise comparison matrix is entered in the IDRISI

SELVA weight derivation module. Table 3.5 illustrates the way of calculating Eigenvalues to know the relative importance of the factors/evaluation criteria.

Table 3.5: Pairwise comparisons of all factors.

	Pairwise Comparison				Principal Eigenvector	
Parameters	Slope	Soil	Proximity	LULC	Weight	Influence (%)
Slope	1				0.4076	41
Soil	1/2	1			0.2772	28
Proximity	1/3	1/2	1		0.1836	18
LULC	1/3	1/3	1/2	1	0.1316	13
Consistency ratio (CR) is 0.03						

To compare their relative influence on the objective of the study all factors are reclassified according to the requirement of land utilization type of the study. After reclassifying the factors to the requirements of weight, the rank have been given to each class of the criteria based on FAO (1976) framework. The reclassified thematic maps of layers used in the evaluation and their relative rank of classes according to importance to wheat suitability are also shown in table 3.5.

3.4.6. Weighted Overlay Analysis

The determined relative importance values were used in the linear weighted overlay analysis, it has been done for the criteria by using ArcGIS 10.5 spatial analysis tool. Factors derived have different degrees of influence on suitability evaluation. Hence, from the principal eigenvector calculation, the relative importance of each parameter has been determined. The decreasing of influences was slope 41 %, soil 28%, proximity 18%, and Land use/land cover 13%. Therefore, the higher the weight, the more influence a particular factor will have in land suitability evaluation.

The suitability map is developed by using the following equation.

$$S = \sum_{i=1}^{n} W_i * F_i \qquad 3.6$$

Where; S = Suitability index (score)

W_i = weight of i_{th} factor

F_i = rank /rating of i_{th} factor

$$S = 0.41*A + 0.28*B + 0.18*C + 0.13*D$$

Where; A= Slope, B = Soil, C= LULC and D = Proximity to water resource

The factors involved were examined according to their relative importance in solving the stated problem and weights are assigned and used as indicated in equation 3.6. Accordingly, all the reclassified factor layers are used in weighted overlay analysis done as shown in ModelBuilder. Then the land suitability map was prepared.

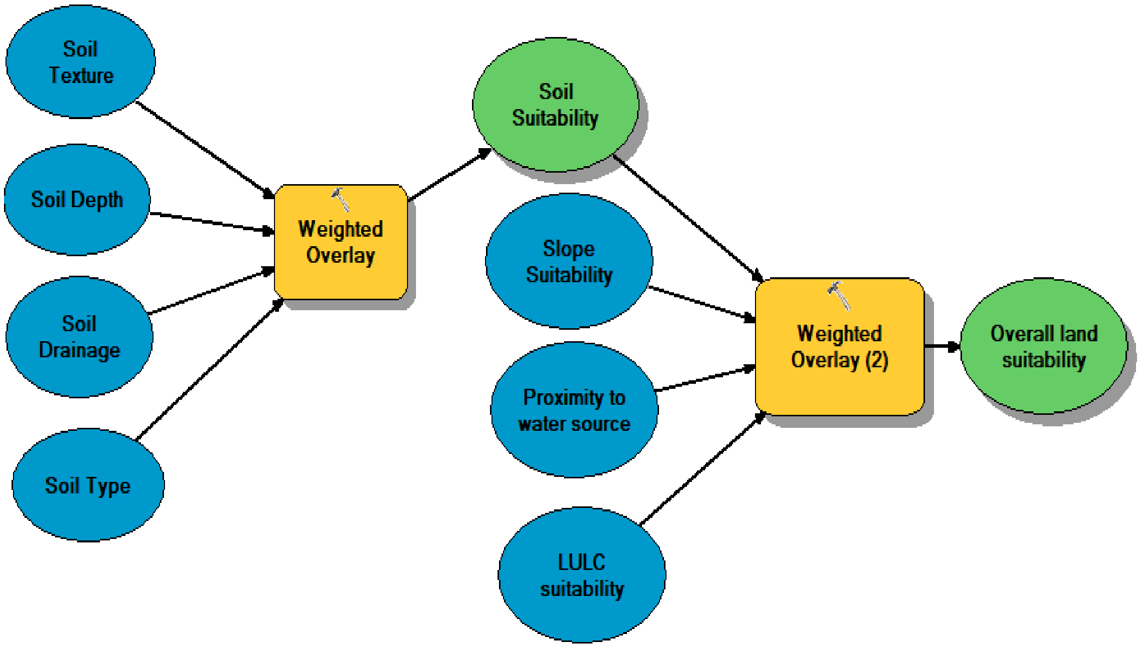

Figure 3.7: ModelBuilder used for Weighted Overlay Analysis.

3.5. Surface Water Availability Assessment

The simulated value of the streamflow from the output of the ArcSWAT model is used to assess the available surface water in the sub-basin. The flow obtained from the Ministry of Water, Irrigation and Energy; the Department of Hydrology is used by SWAT-CUP for flow calibration and verification after sensitivity analysis.

3.5.1. ArcSWAT Model Approach

The Arc-SWAT is a semi-distributed hydrological model incorporated into an ArcGIS interface. The SWAT model consists of hydrological, sedimentation/erosion, weather, plant growth, nutrients, land management, channel routing, and pond/reservoir routing components. Sub-basin can be subdivided into sub-watershed and then subdivided into hydrological response units (HRUs) to account for differences in soil, land use, crops, topography, and climate. The model has a weather generator that can generate daily precipitation, temperature, solar radiation, wind speed, and relative humidity from statistical parameters derived from the monthly average value.

3.5.2. Model set-up

The configuration of the model includes five steps: (1) data preparation, (2) discretization of sub-watersheds, (3) HRU definition, (4) parameter sensitivity analysis, (5) calibration, and uncertainty analysis. A pre-defined digital stream network layer is imported and overlaid on the DEM to accurately describe the location of the stream.

The sub-basin delineation process includes five main steps: DEM establishment, stream definition, outlet and inlet definition, outlet selection, and definition and calculation of sub-watershed parameters. For stream definition, the threshold-based stream definition option is used to define the minimum size of the sub-watershed. Land use, soil, and slopes datasets are imported, overlaid, and linked to the SWAT database. The sub-watershed is subdivided into Hydrological Response Units (HRUs). These areas have unique combinations of land use, soil, and slope, and can study differences in evapotranspiration and other hydrological conditions of different land covers. The model was run using daily precipitation and maximum and minimum temperature data from five spatially interpolated stations over the basin. Most of the sites are recently established or have a lot of missing data. So, use a weather generator based on monthly statistics to fill in the gaps. Relative humidity, solar radiation, and wind speed are generated by meteorological generators. The model ran every day for 32 years; the period from 1990 to 2008 was used for calibration and the period from 2009 to 2018 was used for validation. The monthly flow was used to calibrate and validate the model at the measurement station in the upper Muger river basin near Chancho.

3.5.3. SWAT Model Input

a. Digital elevation model

The 30 by 30 m resolution digital elevation model (DEM) was obtained from the Ministry of Water, Irrigation, and Energy. The DEM is used to delineate watersheds and analyze drainage patterns of the topography of the surface.

b. Weather data definition

All-weather stations have temperature and precipitation data, but only Enchini and Sululta stations are weather used to generate the remaining weather data for other stations. After loading the WXGEN parameters and location table, the daily meteorological data (daily precipitation, daily minimum, and maximum temperature) will be filled with missing data.

c. Soil Data

The SWAT model requires different soil physical and chemical properties of the soils, such as soil texture, effective water content, hydraulic conductivity, bulk density, and organic carbon content of different layers of each soil type.

d. Land Use

Land use is one of the most important factors influencing runoff, evapotranspiration, and surface erosion in the study area. The reclassification of land use maps is intended to represent the land use according to certain land cover types.

e. River Discharge

The value of the daily river output in the upper reaches of the Muger sub-basin was obtained from the Hydrology Department of the Ministry of Water, Irrigation, and Energy of Ethiopia. These monthly river flow data are used for model calibration (1990-2008) and validation (2009-2018).

3.5.4. Watershed delineation

Masking of the digital elevation model (DEM) with the boundary of the Muger watershed. The delineation process requires a digital elevation model (DEM) in the ESRI grid format. The following steps were followed to delineate the watershed using ArcSWAT.

a. Importing DEM data

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

b. Computing flow direction

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

c. Creating watershed outlets

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

d. Delineation of main and sub-watersheds

The main watershed was delineated by using the watershed delineator tool in Arc SWAT based on an automatic procedure using the watershed outlets created in step 3 above. To create sub-watersheds, additional drainage outlets need to be defined. After defining multiple nodes or vertices in drainage outlets along with stream links, the same method as used for defining watershed outlets in step 3 was used again to delineation the sub-basin. So, the delineated watershed of Muger with a threshold area of 30,000 ha was delineated into seventeen sub-watershed and shown in figure 3.8.

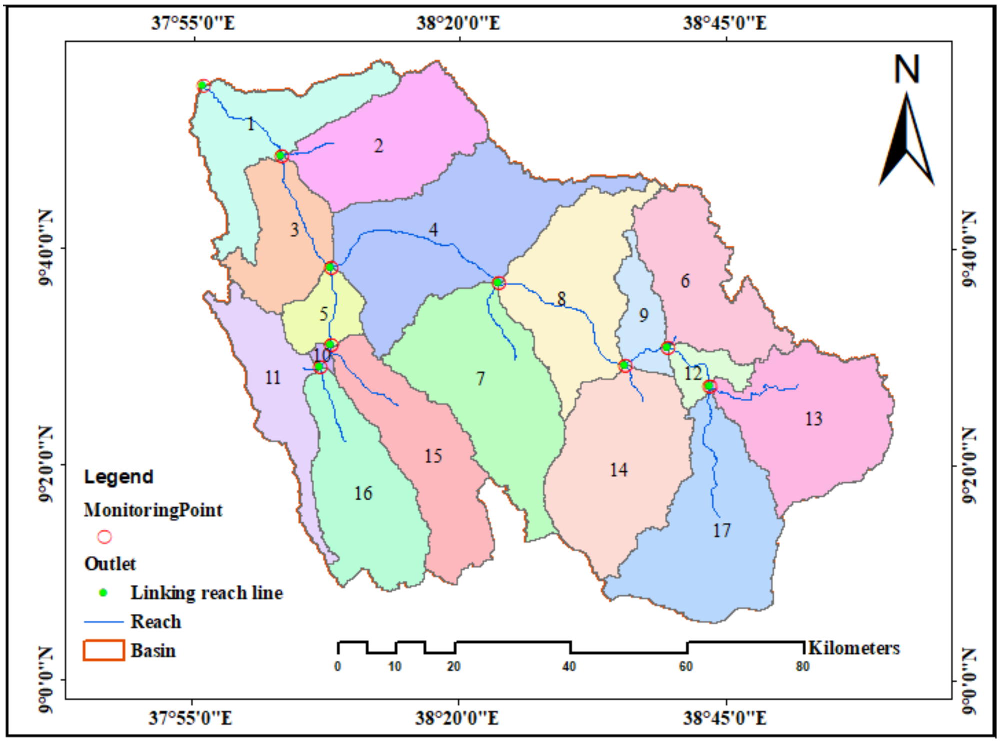

Figure 3.8: Delineated Main Watershed into sub-watershed.

3.5.5. SWAT Model Simulation, Sensitivity Analysis, Calibration and Validation

After loading all the data required for the SWAT model, run the model and read the simulation output. This model is adjusted for running simulations for a length of data's duration. The simulation results cannot be used directly for further analysis. Instead, the ability of the model to fully predict the current flow should be evaluated through sensitivity analysis, model calibration, and model validation (White and Chaubey, 2006).

a. Sensitivity analysis

It is the process of identifying the model parameters that have the greatest impact on model calibration or model prediction. Describe how the output of the model changes within the range of a given input variable. It is necessary to determine the key parameters and the accuracy of the parameters required for calibration. Generally speaking, an important goal of parameter sensitivity analysis is to allow the possible reduction of the number of parameters, thereby reducing the calculation time required for model calibration. The model parameters with higher sensitivity should be selected carefully because small changes in their values will lead to larger changes in the model output. Therefore, it is important to ensure that the parameter values are the best estimates. Model parameters with low sensitivity do not need to be selected, because small changes in their values will not cause large changes in model output.

b. Calibration

Calibration is to better parameterize the model to a set of given local conditions, thus reducing the uncertainty of the prediction. Model calibration is performed by comparing a set of predictions (outputs) of the model from a given set of assumptions with observations of the same conditions, carefully selecting the values of the model's input parameters (within their respective uncertainty ranges). Calibration is performed using predefined parameters that have been determined to be the most sensitive. Then adjust the parameter values to more closely match the behavior of the model with the behavior of the watershed. The adjustment process can be done "manually" or using computer-based "automatic" methods. After the calibration, verify the R^2, NSE, and RVE values and calibrate at least until the model contains the recommended minimum values of $R^2 > 0.6$, NSE> 0.5, and RVE < ± 15 (Arnold *et al*., 2012).

c. Validation

Model validation is the process of demonstrating that a specific model at a given location can perform sufficiently accurate simulations depending on the project objectives. The validation procedure involves running the model with the parameters determined during the calibration process and comparing the predictions with the observational data not used in the calibration (Refsgaard, 1997).

3.5.6. The measure of Model performance efficiency

During calibration and validation, two goodness-of-fit measures of model prediction will be used. These numerical measures of model performance are the regression coefficient (R^2), the Nash-Sutcliffe simulation efficiency (NSE), and the relative volume error (RVE) (Nash and Sutcliffe, 1970). The value of R^2 ranges from 1.0 (best) to 0.0 (bad). The coefficient R^2 measures the variation ratio of the measured data replicated in the results of the simulation model. The R^2 value of 0.0 means that the model prediction does not replicate any variation in the measured data. On the other hand, a value of 1.0 means that all variations in the measured data are replicated by the model's predictions. To evaluate the performance of the model, an efficiency criterion is used which is the Nash-Sutcliffe efficiency (NSE), the coefficient of determination (R^2), and the relative volume error (RVE).

a. Nash-Sutcliffe efficiency

According to Moriasi *et al.*(2007), it is recommended that the NSE value between 0.75 and 1 be very good and the NSE value between 0.65 and 0.75 good squared difference between the predicted value, normalized by the variance of the observed value during the Investigation period.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_o - Q_s)^2}{\sum_{i=1}^{n}(Q_o - \bar{Q}_o)^2} \qquad 3.7$$

Where Q_o is observed flow at i^{th} period, Q_s is simulated flow at the i^{th} period and $\bar{Q}$ is mean of the observed flow.

b. Coefficient of determination

The coefficient of determination R^2 is expressed as the square relationship between the covariance and the standard deviation of the product of the observed value and the predicted value and is defined as the square value of the correlation coefficient.

$$R^2 = \left[\frac{[\sum_{i=1}^{n}(Q_S - \bar{Q}_S)\,(Q_O - \bar{Q}_O)]^2}{[\sum_{i=1}^{n}[(Q_O - \bar{Q}_O)^2] * \sum_{i=1}^{n}[(Q_S - \bar{Q}_S)^2]]}\right] \qquad 3.8$$

Where Q_O = observed discharge (m3/s)

Q_S = simulated discharge (m3/s)

Q_O = mean of observed discharge (m3/s)

Q_S = mean of simulated discharge (m3/s) and n is the number of observations.

R^2 is indicated how the simulated data correlates to the observed values of data.

The coefficient of determination (R^2) ranges from zero (unacceptable) to one. If the simulation is accurate, R^2 is equal to one. Moriasi *et al.* (2007) recommend that the value of R^2 between 0.75 and 1 is very good and the value of R^2 between 0.65 and 0.75 good for the monthly time steps.

c. Relative Volume Error (RVE)

Measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of RVE is zero, with values of small magnitude indicating an accurate simulation of the model. Positive values indicate underestimation bias of the model and negative values indicate overestimation bias of the model (Gupta *et al*., 1999) and calculated by equation next.

$$RVE = \frac{\sum_{i=0}^{n}(Q_{ob} - Q_{sim})}{\sum_{i=0}^{n}(Q_{ob})} \times 100 \qquad 3.9$$

Where RVE = Relative Volume Error (percentage)

Q_{ob} = observed flow (m3/s)

Q_{sim} = simulated flow (m3/s) and n is the number of observations.

3.5.7. Mean Areal Rainfall of Sub-basin

Mean areal rainfall of sub-watersheds, which were used as input data to estimate stream flows in un-gauged sites, were calculated by the Theissen polygon method using geo-spatial techniques. Figures 3.9 shows the Theisen polygon of the study area. This depends on rainfall stations' influence and stations' mean monthly rainfall contribution (calculated by multiplying stations area fraction by long-term mean monthly rainfall data). This is used in the estimation of ungauged streamflow in the sub-basin.

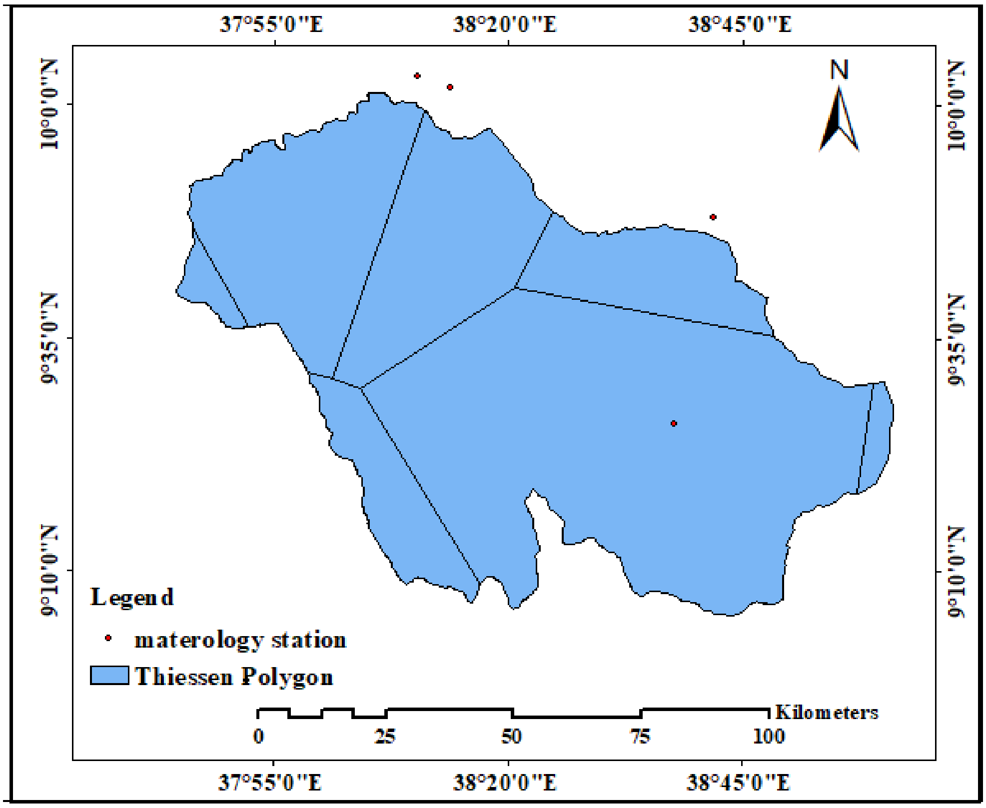

Figure 3.9: Thiessen polygons depend on climatic stations in the study area

3.5.8. Estimating Discharges at Ungauged Sites

The analysis of the rainfall data, together with the discharges from gauged sites, is used to estimate the streamflow at the ungauged sites in the sub-basin. The long-term average flow at the streamflow at gauged sites and mean monthly areal rainfall of the sites are used to estimate the discharges at the ungauged site (Goldsmith, 2000 and Lawrence, 2004). According to the study by Goldsmith (2000) and Lawrence (2004), to estimate the average monthly runoff volume of ungauged sites from gauged sites, the characteristics of the watershed must be similar, and the distance between the watershed areas of the gauged and ungauged river less than 50 kilometers and at least the monthly average flow of 10 years of the gauged site must be provided. This is done by applying the runoff coefficient from the gauged station to the ungauged station. Then runoff volume per month at the ungauged site is estimated. For ungauged rivers, the discharges from gauged sites are transferred to the site of interest using the following formula:

$$Q_{site} = \left(\frac{DA_{site}}{DA_{guaged}}\right)^{n} \times Q_{guaged} \qquad 3.10$$

Where: Q_{site}= Discharge at the site of interest (m^3/s)

DA_{site}= Drainage area at the site of interest (m^2)

DA $_{gauged}$ = Drainage area at the gauged site (m^2)

Q $_{gauged}$ = discharge at gauged site (m^3/s) and n = exponent between 0.6 and 1

If the DA $_{ungauged}$ should be 20% of the DA$_{gauged}$ $\left(0.6 \leq \frac{DA_{unguaged}}{DA_{guaged}} \leq 1.2\right)$,n value equal to 1, unless n equal to 0.6.

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

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

$$MAR_g = K * MAP_g \qquad 3.11$$

Where: MARg = Mean annual runoff at the gauged site (mm)

MAP = Mean annual precipitation at the gauged site (mm)

$$K = \frac{MAR_g}{MAP_g} \qquad 3.12$$

K = Runoff coefficient at gauged site

b. Determine the MAR at the ungauged site as

$$MAR_u = K * MAP_u \quad 3.13$$

MAR_u= Mean annual runoff at the un-gauged site (mm)

The mean annual or monthly runoff depth obtained from equitation (3.13) at an un-gauged site can be converted to mean monthly runoff considering, average areal monthly rainfall and watershed area of both gauged and ungauged sites (Jamshid, 2003). Therefore, estimating the precipitation area of a given watershed area is useful for estimating the total runoff produced by the entire watershed area. There are several methods for determining the spatial distribution of rainfall, all of which result in slightly different changes in rainfall patterns in the area.

The Thiessen method is widely accepted, which has proven to be quite accurate for estimating areal precipitation distribution. The main assumption of the Thiessen method is that the area closest to the rainfall station is more likely to experience rainfall conditions similar to those measured at the station location (Chow *et al*., 1998).

Almost all sub-watersheds in the Muger sub-basin have almost similar properties in both gauged and ungauged watersheds with similar slope range, soil type, and land cover are identified and the results are presented in appendix 7.8. The sub-watersheds 17 have both gauged watersheds and the ungauged sub-watersheds were estimated from gauged sub-watershed depending on watershed characteristics.

3.6. Computing irrigation water requirement of crops

3.6.1. CROPWAT Model

CROPWAT 8.0 for Windows is a computer program for calculating the water requirements of plant-based on existing plant and climate data. In addition, the program enables the development of an irrigation plan for different management conditions and the calculation of the planned water supply for different crops. CROPWAT has been used extensively to assess plant water needs, watering schedules, and planting patterns. A comparison of CROPWAT with other similar models shows that CROPWAT is a better tool for estimating the water needs of plants (Kang *et al.*, 2009).

All calculation procedures used in CROPWAT 8.0 are based on the FAO guidelines specified in FAO Irrigation and Drainage Publication No. 56 "Crop Evapotranspiration Guidelines for Estimating Crop Water Requirements (FAO, 1998).

Inputs to CROPWAT are:

a. Climate/ETo:

The software uses the FAO Penman-Monteith model to estimate reference evapotranspiration (FAO, 1998).

$$ET_O = \frac{\left(0.408\Delta(R_n - G)\right) + \left(\gamma \frac{900}{T + 273} u_2(e_s - e_a)\right)}{\Delta + (\gamma(1 + 0.34u_2)} \qquad 3.14$$

Where ET_o = reference evapotranspiration [mm day^{-1}],

R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}],

G = soil heat flux density [MJ m^{-2} day^{-1}],

T = mean daily air temperature at 2 m height [°C],

u_2 = wind speed at 2 m height [m s^{-1}],

e_s = saturation vapor pressure [kPa],

e_a = actual vapor pressure [kPa],

[e_s – e_a] = saturation vapor pressure deficit [kPa],

Δ = slope vapor pressure curve [kPa °C^{-1}],

γ = psychrometric constant [kPa °C^{-1}].

The equation uses standard climatological records of solar radiation (sun), air temperature, humidity, and wind speed. To ensure the integrity of the calculations, meteorological measurements should be taken at a height of 2 m (or converted to this height) over a large surface of green grass, the shade of the ground, and no shortage of water. The climate data used for the calculations were obtained from a meteorological station.

b. Effective rainfall

The CROPWAT 8.0 model uses the Effective Rainfall method to calculate effective rain from monthly mean rainfall. Effective rainfall methods to calculate the four methods specified in CROPWAT 8.0 (Fixed Percentage, dependable Rain, Empirical Formula, and USDA Soil Conservation Service) can be selected to take into account losses through runoff or infiltration. The efficiency of rainfall decreases with increasing rainfall. With most rain values below 100 mm/month, the efficiency is around 80% (FAO, 1998).

Effective rainfall is defined as the portion of rainfall that is effectively used by the crop after losses from surface runoff and deep seepage have been taken into account. Effective rainfall is the rainfall that is ultimately used to determine the crop's irrigation needs.

Monthly rainfall data are required to calculate the effective rainfall (on monthly basis) P_{ef}, which can be calculated depending on the USDA Soil Conservation Service method provided in the CROPWAT model (FAO, 1998).

When total rainfall is < 250 mm, effective rainfall (P_{ef}) is given by the following equation;

$$P_{ef} = \frac{TR \times (125 - 0.2 \times TR)}{125} \quad 3.15$$

When total rainfall is > 250 mm, effective rainfall is given by the following equation;

$$P_{ef} = 125 + 0.1 \times TR \quad 3.16$$

Where TR is Total rainfall

c. Crop

Crop input data are crop name, planting date, crop coefficient (K_C), stages length, rooting depth, critical depletion fraction (p), yield response factor (K_Y), and maximum crop height.

d. Soil

For different types of soils input data such as total available soil moisture (Field Capacity-Wilting Point) in mm/meter, Maximum rain infiltration rate in mm/day, Maximum rooting depth in centimeters, and initial soil moisture depletion (as % TAM) in percentage are collected and inserted in the soil module of the model to calculate the initially available soil moisture in mm/meter.

Outputs to CROPWAT are:

a. Crop water requirement:

After entering all the required CROPWAT 8.0 input data (weather / ETO, precipitation, crop, and soil) and successively calling up the corresponding weather and precipitation data sets with the corresponding harvest files and planting dates, the CWR module calculates the water requirements of the crop such as (FAO, 1998):

The values of ETC and CWR (Crop Water Requirements) are identical, whereby ETC refers to the quantity of water lost through Evapotranspiration and CWR refers to the amount of water that's required to compensate for the loss. ETC is calculated directly from ET_O and K_C.

$$NIR = ET_C - P_{ef} \quad 3.17$$

Where, NIR = the net irrigation requirement of crops,

ET_C = crop Evapotranspiration

P_{ef} = effective rainfall.

Where IWR is irrigation water requirement in mm/day and P_{ef} is effective rainfall in mm/day.

b. Gross irrigation water requirements

Gross irrigation water requirements of the crops at the identified potential irrigable sites are estimated based on efficiency from the source to the identified command area. Then, the gross irrigation water requirement will be computed using the following formula.

$$\text{GIWR} = \left(\frac{NIWR}{E * T}\right) \qquad 3.18$$

Where, GIWR = the gross irrigation requirement of crops (m^3/s) and

E = overall Efficiency of irrigation in percentage.

T= time of irrigation

Based on the available water, the effective irrigable area can be estimated in the following equation.

$$A(ha) = \frac{A_{crop} * E * Low\ flow}{GIWR} \qquad 3.19$$

Where: A_{crop} = Area covered by crop (ha), A (ha) = irrigated Area, E = irrigation efficiency and GIWR = Grosse irrigation water requirement (m^3/s).

Irrigation efficiencies: Efficiency is the ratio of the water output to the water input, and is usually expressed as a percentage. Input minus output is nothing but losses, and hence, if losses are more, the output is less, and therefore, efficiency is less. To calculate the gross irrigation requirement of crops at specified potential irrigable sites, irrigation efficiencies of 54% are used for surface irrigation (FAO, 1989,).

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1. Irrigation Land Suitability analysis

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

4.1.1. Slope suitability

The slope is one of the evaluation parameters in the suitability analysis of the irrigation system. Based on FAO land suitability classification, the major slope of the basin is divided into four classes (S1, S2, S3, and N). The slope map of the study area was derived from the digital elevation model (DEM) in ArcGIS and divided into four classes for suitability for surface irrigation, such as 0-2% as highly suitable (S_1), 2-5% as moderately suitable (S_2), 5-8% as marginally suitable (S_3) and >8% as not suitable (N). The suitability of the slope for irrigation is shown in Figure 4.1.

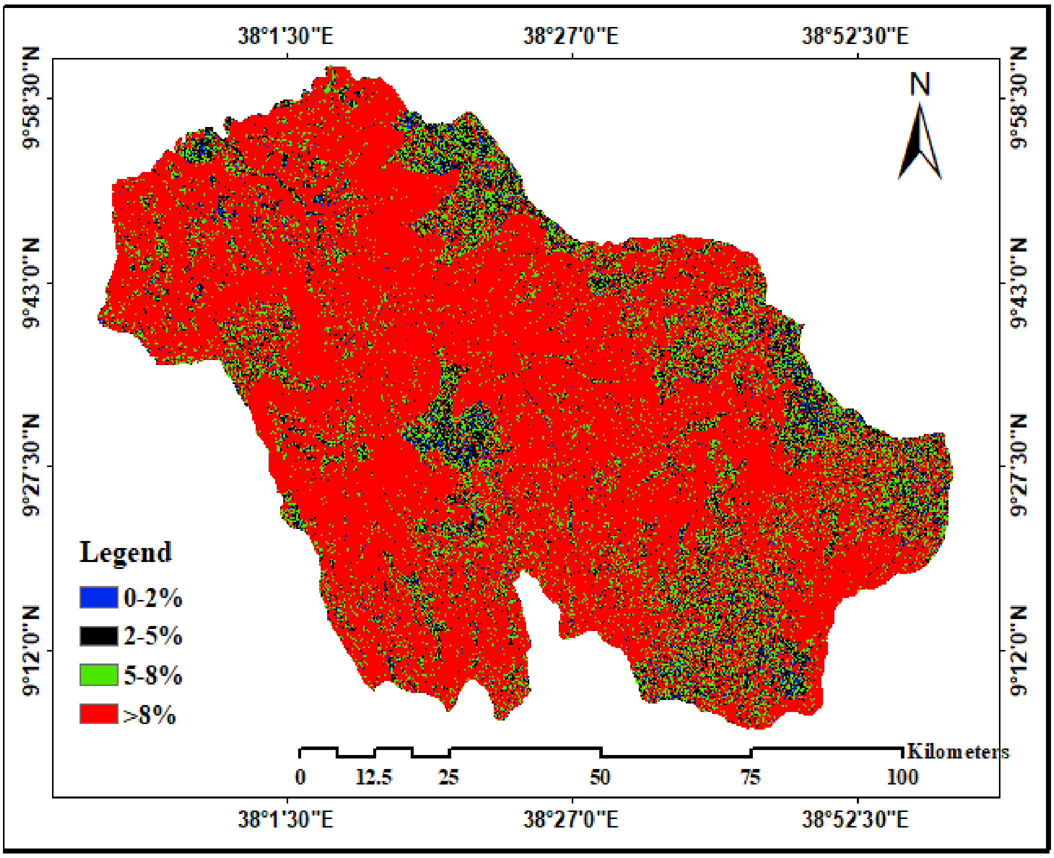

Figure 4.1: Slope suitability map of the study area for surface irrigation.

According to the slope classification result, the land that has a slope range below 2 % was classified as highly suitable while the slope range > 8% was categorized as an unsuitable class for surface irrigation. The suitability result indicates that 2.46% of the land was highly suitable, 9.75% moderately suitable, 12.77% marginally suitable and only 75.02% was not a suitable class for surface irrigation development. The slope suitability map of the sub-basin and area coverage of each suitability class was described in Table 4.1 below.

Table 4.1: Suitability Classes of each Slope Category.

Slope category (%)	Area coverage (ha)	Area coverage (%)	Suitability
0-2	20133.46	2.46	S1
2-5	79858.76	9.75	S2
5-8	104555.10	12.77	S3
>8	614194.49	75.02	N

Thus, 24.98% (204,547.32 ha) area range was from highly to marginally suitable for surface irrigation development in the study area. The left 75.02% (614,194.49 ha) is unsuitable for surface irrigation. This shows that most parts of the study area were unsuitable.

4.1.2. Suitability of Soil

The land suitability of the sub-basin concerning soil has been established by evaluating the soil suitability parameters; soil texture, soil depth, soil type, and soil drainage suitability through overlay analysis.

4.1.2.1. Soil type suitability

Soil type was taken as one input to develop an irrigation suitability map for the study area. It was found that the major soil groups identified in the study area were Rendzic Leptosols, Eutric Leptosols, Calcic Vertisols, Eutric Vertisols, Eutric Regosols, Rhodic Nitisols, Eutric Cambisols, Haplic Nitisols, Eutric Fluvisols, Haplic Alisols, Chromic Luvisols, Urban, Water, and Haplic Luvisols. The summary of soil suitability classification results was shown in figure 4.2 and table 4.2 respectively.

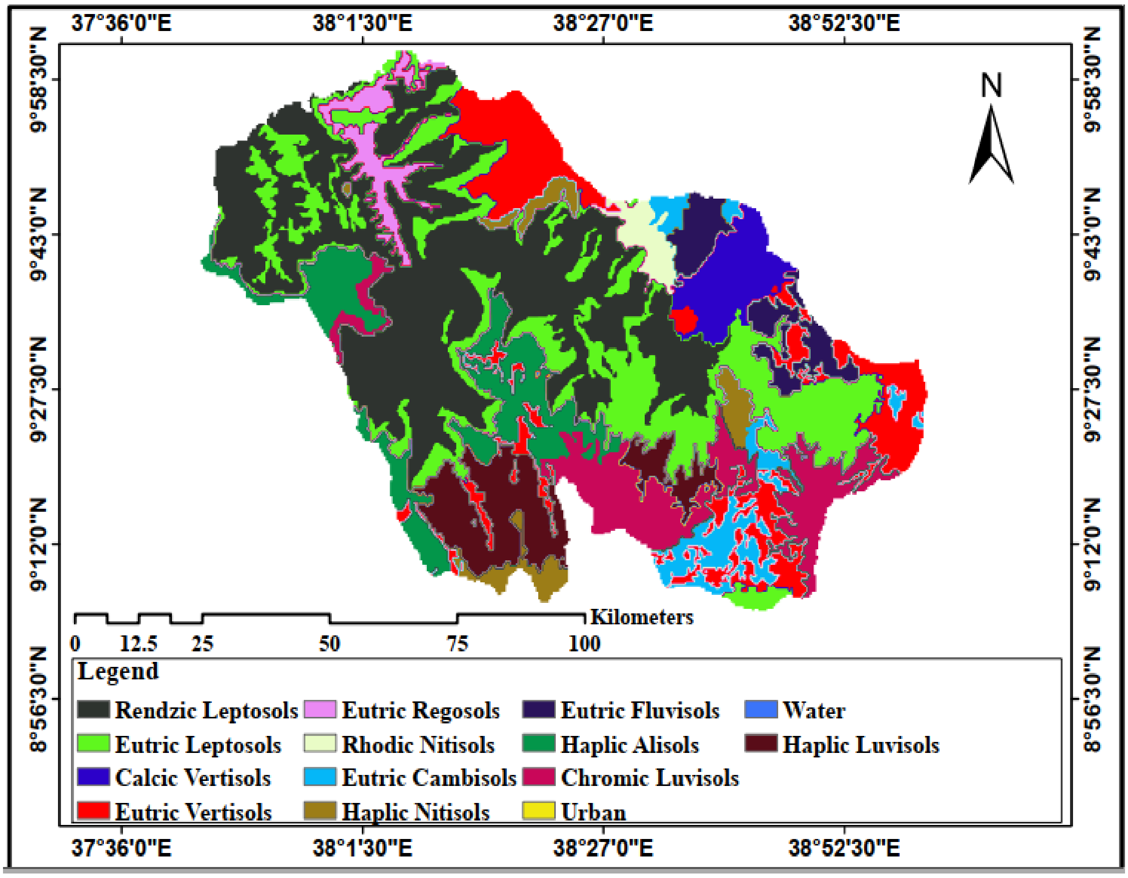

Figure 4.2: Suitability of soil type with their area coverage.

Table 4.2: Soil type Suitability with their area coverage.

Soil type category	Area(ha)	Area (%)	Suitability
Calcic Vertisols, Rhodic Nitisols, Haplic Nitisols, and Chromic Luvisols	130,596.77	15.95	S_1
Eutric Cambisols, Haplic Luvisols and Eutric Fluvisols	109,723.19	13.41	S_2
Eutric Leptosols and Eutric Regosols	171,010.23	20.89	S_3
Rendzic Leptosols, Eutric Vertisols, Haplic Alisols, Urban and Water	407,445.51	49.76	N

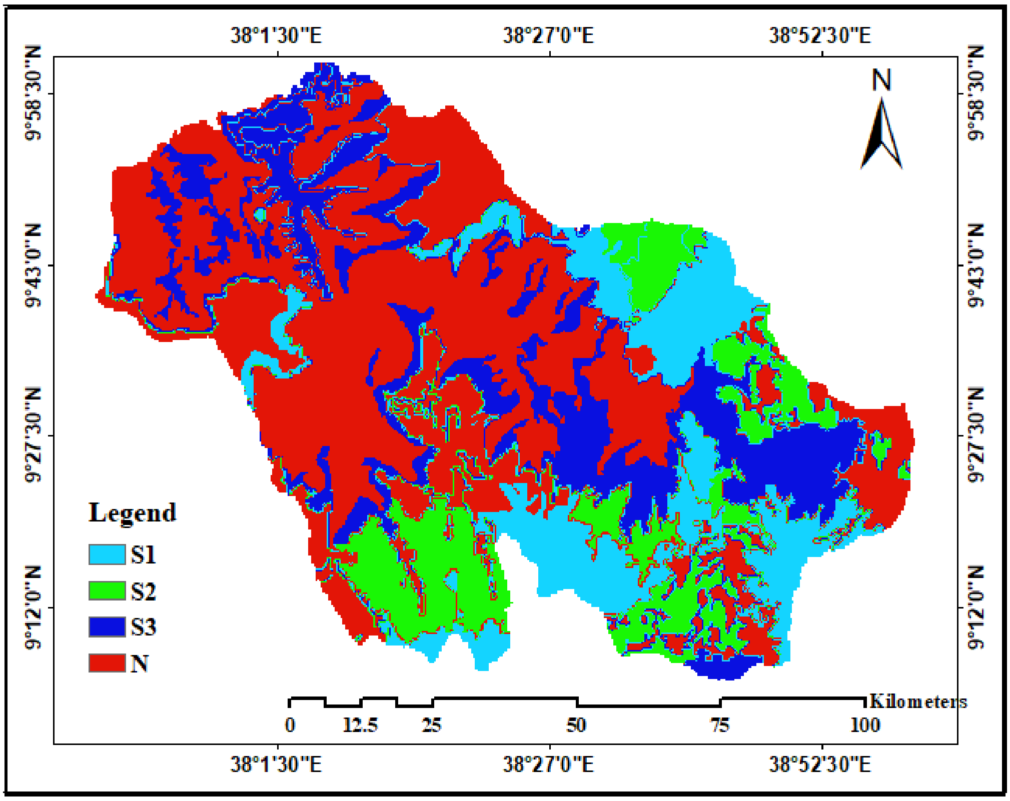

Figure 4.3: Suitability Map of Soil type.

Soil types of the study area were generally classified into four irrigation suitability classes based on soil suitability, such as S_1 (highly suitable), S_2 (moderately suitable), S_3 (marginal suitability), and N (not suitable). Calcic Vertosols, Rhodic Nitisols, Haplic Nitisols, and Chromic Luvisols covering an area of 15.95% of the study area, which is 130596.77 ha, was classified as highly suitable (S_1) for surface irrigation. The second soil type is Eutric Cambisols, Eutric Fluvisols, and Haplic Luvisols covering an area of 13.41% of the study area, which is 109723.19 ha, was classified as moderately suitable (S_2) for surface irrigation. Eutric Leptosols and Eutric Regosols were another soil type that covers 171009.4 ha, equivalent to 20.89% of the land in the study area were marginally suitable. According to FAO (2006), these soils are classified as marginal suitable for surface irrigation. The remaining soil types like Rendzic Leptosols, Eutric Vertisols, Haplic Alisols, Urban and Water classified which covering 49.76% with area coverage of 407445.51 ha were grouped as not suitable in terms of soil type suitability analysis.

4.1.2.2. Soil texture suitability

According to FAO guidelines for soil evaluation, the soil texture of the study area was evaluated and classified into clay (C), clay loam (CL), Loam (L), and sandy loam (SL).

The soil textural classes of investigated soils in the current study area vary from clay to sandy clay loam. The results of texture class analysis reveal that the area was dominated by Clay Loam and Sandy Loam soil. Figure 4.4 elaborates the geographic distribution of the identified soil textural classes in the study area.

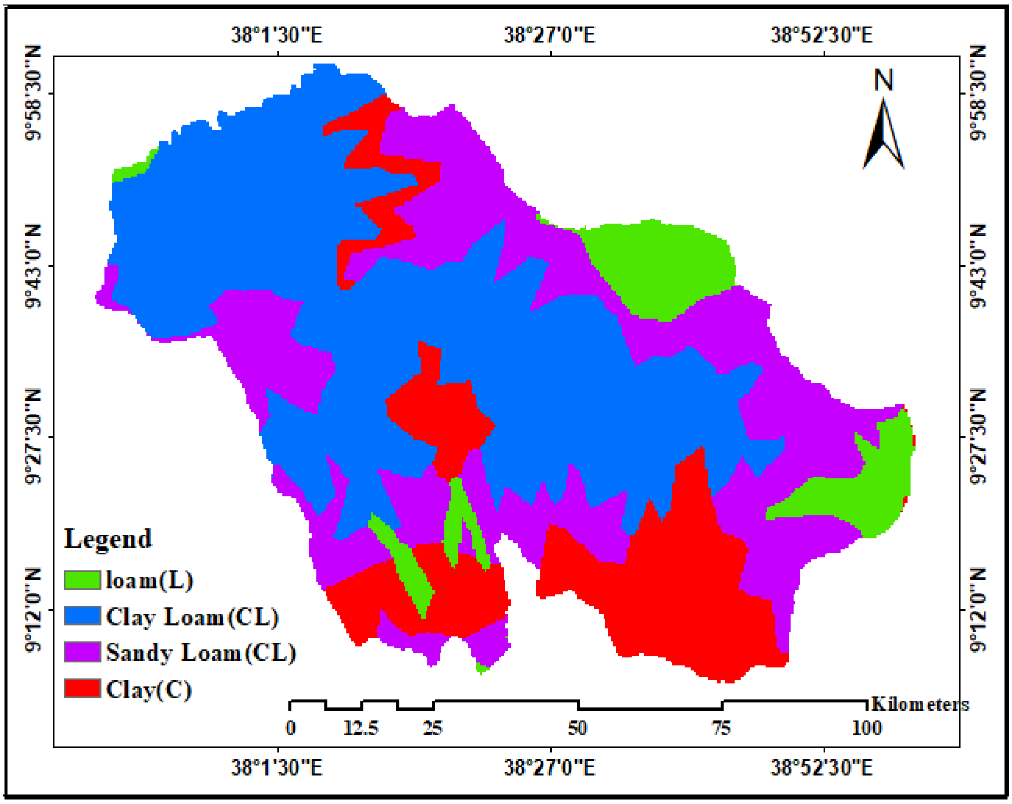

Figure 4.4: Soil Texture Classes of the Study Area.

Table 4.3: Soil Texture Classes of the Study Area.

Texture Class	Area(ha)	Area (%)	Suitability Class
Clay(C)/Loam(L)	211340.205	25.81	S_1
Clay Loam (CL)	380782.281	46.50	S_2
Sandy Loam (SL)	226692.614	27.69	S_3

The soil textural classes and their area coverages were shown in table 4.3 above. As described in table 4.3: 25.81% of the total areas covered by the Clay and Loam soil texture, about 46.50% area of the watershed were covered by Clay Loam and the left 27.69% covered by Sandy Loam. The result of soil textural suitability analysis of the area showed that 25.81% of soils in the area was under highly suitable for surface irrigation, around 46.50% of the total area's soil was categorized under moderately suitable class for surface irrigation, and the left 27.69% of study area classified as marginally suitable for surface irrigation.

4.1.2.3. Soil depth suitability

Soil depth was considered as one of the major factors that determine the selection of land for surface irrigation potential in the study area. Soil depth determines the roots' growth as well as the presence of a volume of water and air in the soil. The depth of the soil layer in the study area was divided into four: >150, 100-150, 50-100, and < 50 cm with a suitability class S_1, S_2, S_3, N respectively according to FAO (1991). The suitability result of soil depth and their area in the study area is shown in figure 4.5.

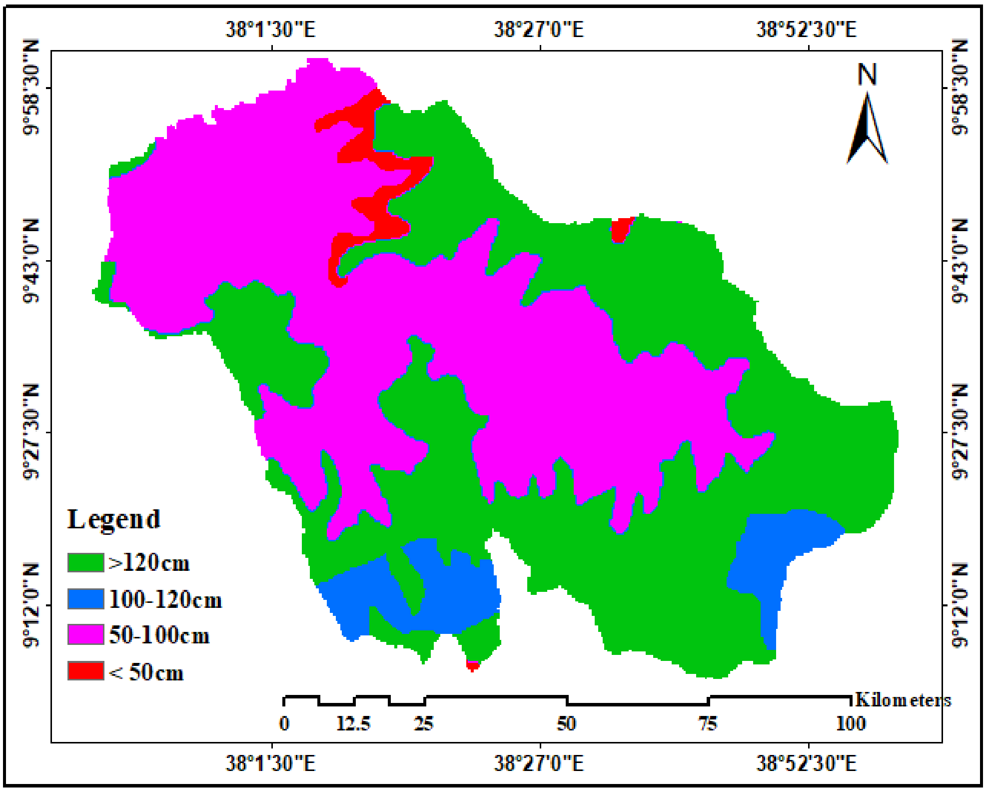

Figure 4.5: Soil Depth Suitability for Surface Irrigation.

The soil depth suitability of the area was summarized with its suitability classification and area of overage as revealed in the following table 4.4.

Table 4.4: Soil Depth Suitability for Surface Irrigation.

Soil depth class (cm)	Coverage Area (ha)	Coverage Area (%)	Suitability
>150	382379.41	46.70	S_1
100 – 150	51093.59	6.24	S_2
50 - 100	365780.22	44.67	S_3
<50	19556.80	2.39	N

The soil depth suitability analysis result indicates that about 46.7% of the total area of the watershed was categorized under highly suitable, the area which is about 6.24% of the watershed was moderately suitable, 44.67% of the total study area was marginally suitable and 2.39% of the total study area is not suitable for surface irrigation development. Generally, 97.61% of the soil in the study area is in the range of high to marginally suitable and the remaining 2.39% of the area is grouped as not suitable in terms of soil depth suitability analysis.

4.1.2.4. Soil drainage suitability

FAO (1997) suggested that the soil drainage condition of a specific area be classified into; well-drained, moderately well-drained, imperfectly drained, poorly drained, and very poorly drained. The well-drained soils are classified as a highly suitable class, moderately well-drained soils are classified as a moderately suitable class, and the imperfectly drained soils are categorized under marginal suitable and not drained soil class are not suitable for surface irrigation according to FAO guidelines. Consequently, a suitability map of soil drainage within the study area was developed as can be seen in figure 4.6.

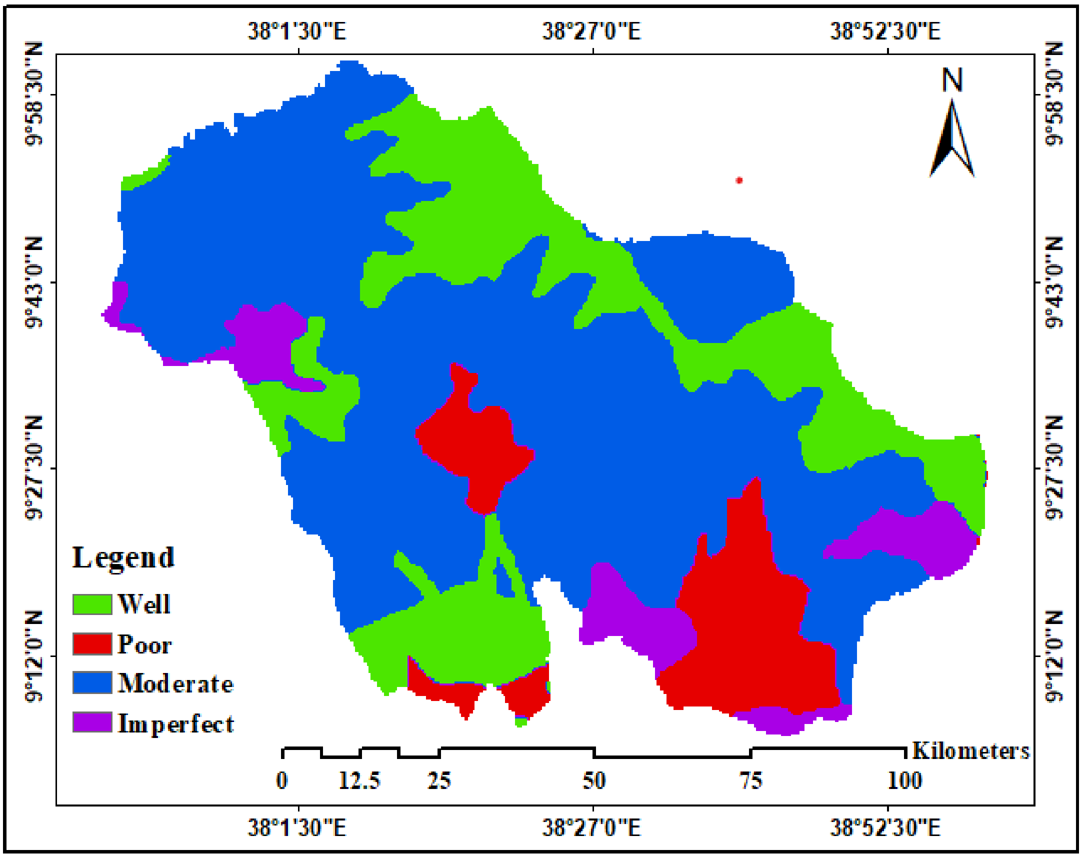

Figure 4.6: Soil Drainage Suitability of the watershed for surface irrigation.

Table 4.5: Soil Drainage Suitability of the study area.

Soil drainage class	Area(ha)	Area (%)	Suitability
Well	186369.96	22.76	S_1
Moderate	494286.28	60.37	S_2
Imperfect	52045.30	6.36	S_3
Poor	86109.46	10.52	N

About 22.76% (186369.96 ha) of the area have well-drained soil, 60.37% (494286.28 ha) of the area have moderately well-drained soil, 6.36% (52045.30 ha) of the area have imperfectly drained soil and 10.52% (86109.46 ha) of the soils were categorized as poorly drained. The weighted overlay analysis of all soil parameters was shown as in map 4.7.

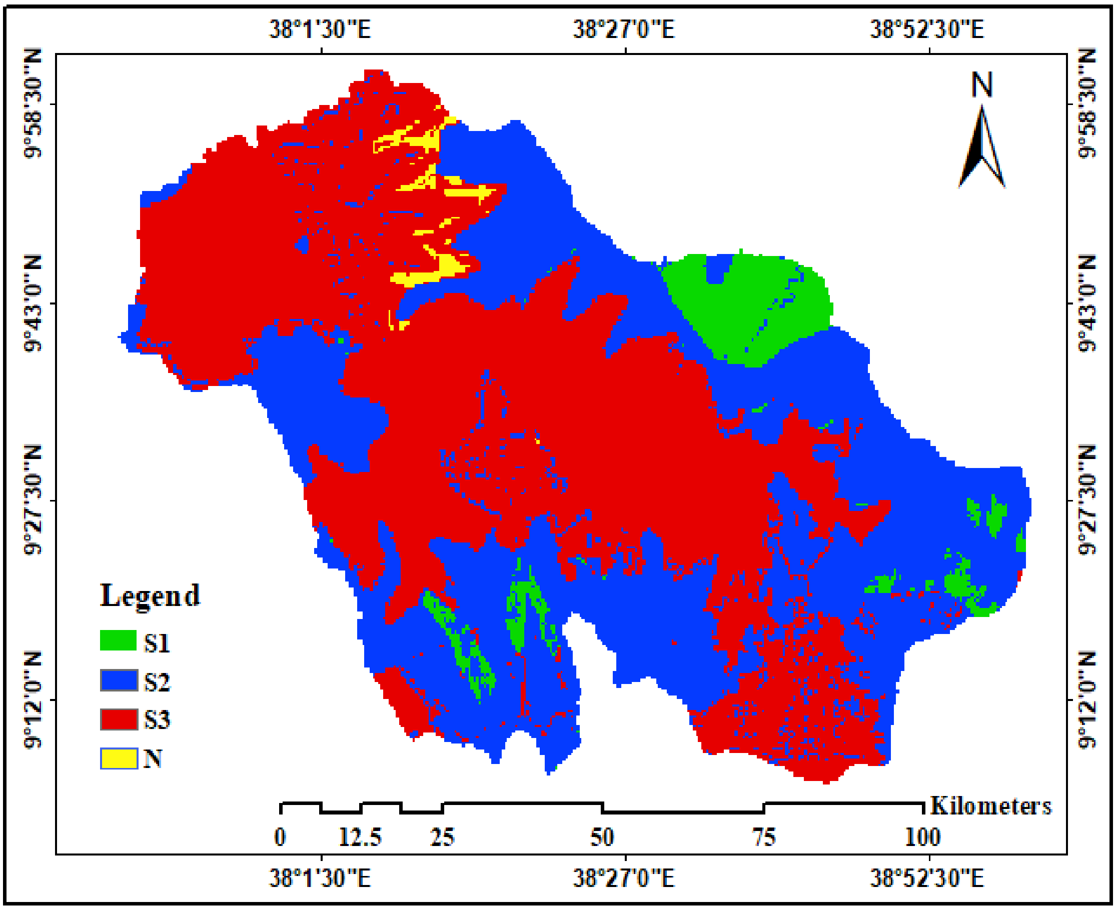

Figure 4.7: Overall Soil Suitability.

Table 4.6: Overall Soil Suitability.

No	Potentially suitable class	Area coverage (ha)	Area coverage (%)
1	Highly suitable (S_1)	42489.6	5.2
2	Moderately suitable (S_2)	341573.9	41.7
3	Marginally suitable (S_3)	427138.9	52.2
4	Not suitable (N)	7597.6	0.9

4.1.3. Land use/land cover suitability

The eight land use/land cover types in the study area included dominantly Forest, Woodland, Shrub/bush, Cropland, Grassland, Barren land, Waterbody, and Settlement. As shown in Figure 4.8, Cropland is the greatest share of land use land cover from all the land classes, which covers an area of 93.5 % of the total area. The land use land cover was shown in the following figure 4.8.

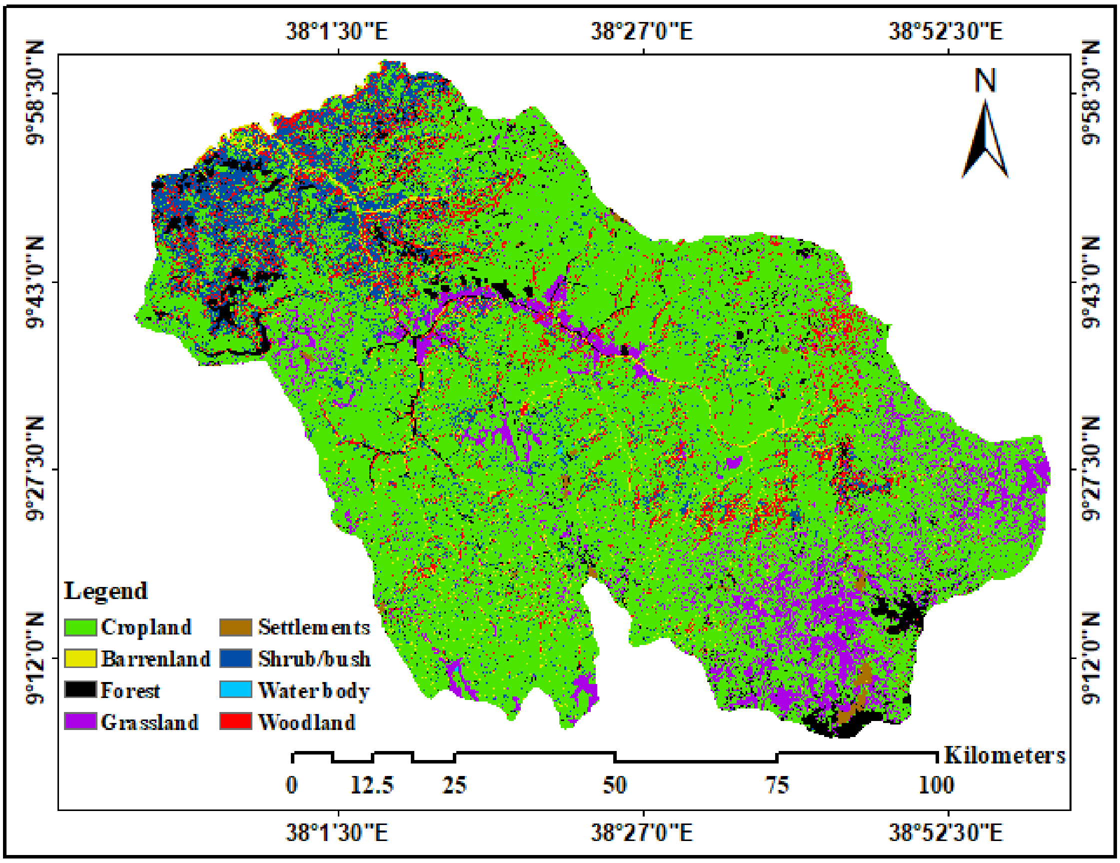

Figure 4.8: land use land cover suitability map of Muger sub-basin.

Table 4.7: Land use land cover suitability Classification.

Land use land cover class	Area(ha)	Area (%)	Suitability
Cropland and Grassland	633,089.03	77.31	S_1
Woodland and Shrub/bush	130,338.72	15.92	S_2
Forest and Barren-land	51,949.44	6.34	S_3
Waterbody and Settlements	3432.51	0.42	N

As shown in Figure 4.7 the land use land cover suitability classification 77.31% (633,089.03 ha), 15.92% (130,338.72 ha), 6.34% (51,949.44 ha) and 0.42% (3432.51 ha) were highly, moderately, marginally and not suitable respectively. Generally, in the land use land cover suitability investigation, 99.58% (815,377.19 ha) of the watershed is high to moderately suitable and the remaining 0.42% of the total watershed is not suitable for surface irrigation development.

4.1.4. Proximity to water

To identify irrigable areas near the water supply (rivers), the horizontal distance in a straight line (Euclidean) from the river was calculated; the spatial proximity to water sources was calculated with GIS spatial layers; The influences of the distance parameters on the suitability of the surface irrigation land were estimated with the clipping feature class. Then converted to raster with the conversion tool and reclassified into the suitability class. Based on the distance from the water source, was shown in Figure 4.9 and Table 4.8.

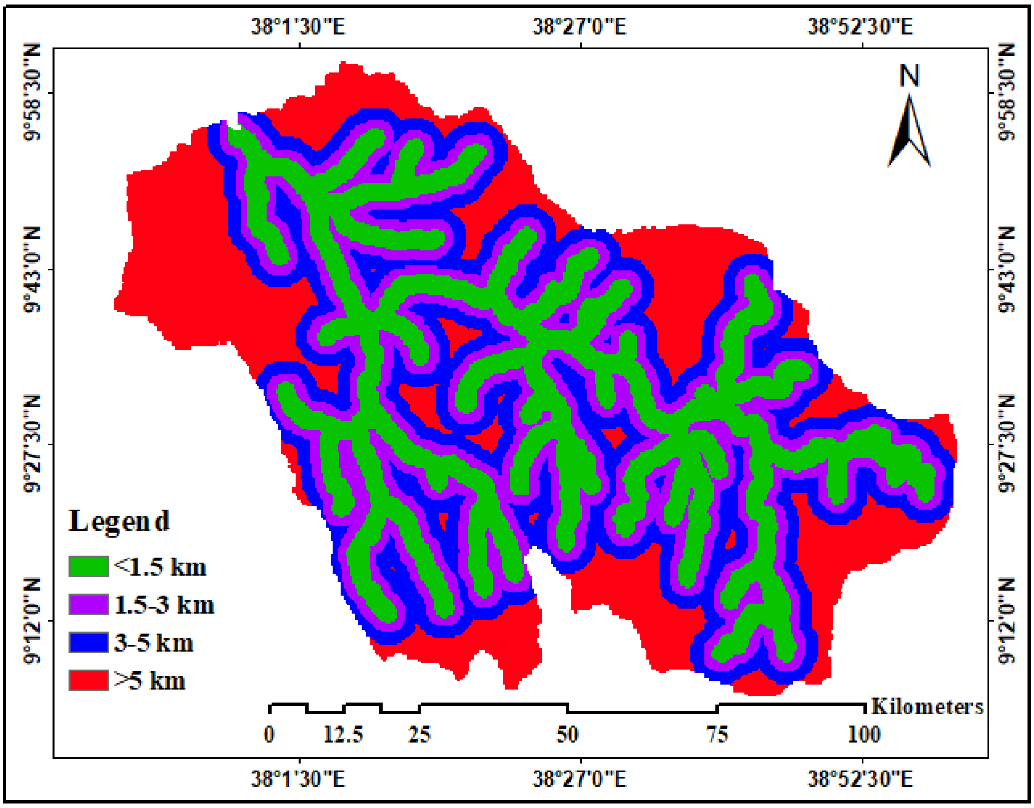

Figure 4.9: Proximity to water suitable for surface irrigation.

Table 4.8: Proximity to water suitable for surface irrigation.

Proximity to water	Area coverage (ha)	Area coverage (%)	Suitability class
<1.5	268597.13	32.80	S_1
1.5 - 3	219176.86	26.768	S_2
3 - 5	200040.00	24.43	S_3
>5	131001.11	16.00	N

The result of Proximity to water suitable indicates that about 32.80%, 26.768%, 24.43%, and 16.00 % area of the study was covered by highly suitable, moderately, marginally suitable, and not suitable respectively.

4.2. An overall suitable site for surface irrigation

Potential irrigable sites via the intended irrigation method were obtained using an irrigation suitability analysis model developed on ArcGIS. The suitability model involved the weighting of values of data sets such as soil, slope, land use/land cover, and proximity suitability. Rasterized and reclassified suitability maps of each parameter were used as input for the model. The four suitability parameters used (Slope suitability, soil suitability, land use/land cover suitability, and proximity suitability) were used to identify potentially irrigable sites in the Muger sub-basin.

In the irrigation suitability assessment, suitability classes of 1 to 4 were used, whereby by 1 was used. 1 represents a highly suitable class, 2 moderately suitable class, 3 marginally suitable class and 4 represents not suitable classes. In the weighted overlay analysis, the highest weight (% of influence) was given for slope to lowest weight proximity, since it is the determinant factor in the evaluation of the given area for surface irrigation development. The Result of the weighted overlay analysis of the irrigation suitability model was presented in figure 4.10 and table 4.9 as shown in the following.

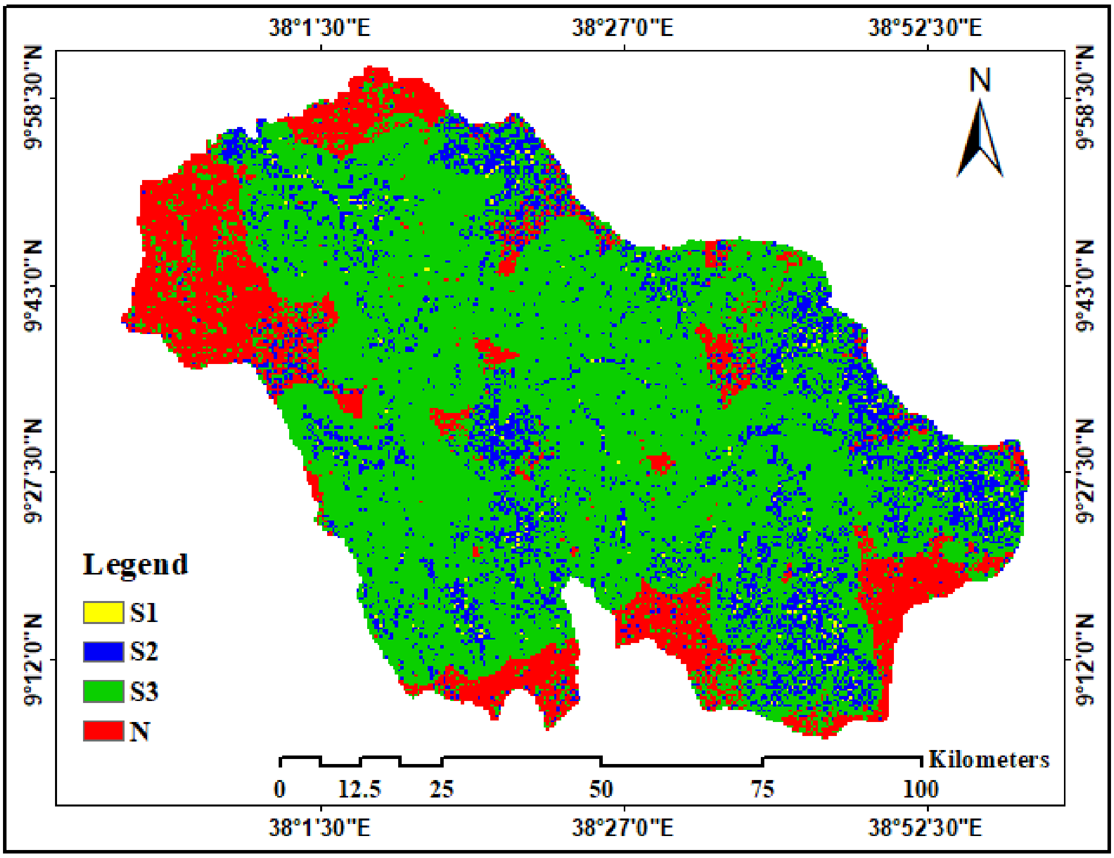

Figure 4.10: Map of suitable sites for surface irrigation.

The overall surface irrigation of suitability classification of the Muger sub-basin has been summarized as shown in the following table 4.9.

Table 4.9: Overall land suitable area for surface irrigation

No	Potentially suitable class	Area coverage (ha)	Area coverage (%)
1	Highly suitable (S_1)	5652.8	0.7
2	Moderately suitable (S_2)	123237.7	15.1
3	Marginally suitable (S_3)	551156.0	67.3
4	Not suitable (N)	138753.5	16.9

The weighted overlay analysis of surface irrigation suitability revealed that 0.7% of the total area covers a highly suitable class, 15.1 % covers a moderately suitable class, about 67.3 % of the watershed was covered in marginally suitable class and the rest 16.9% is the unsuitable class. As the result indicated suitable sites for surface irrigation have a higher coverage due to the combined effect of slope, soil, land use/cover, and distance to water resources (proximity). Generally, the result of suitability analysis indicated that 83.1% of the sub-basin is found in the range of high suitable to marginal suitable. The most area was marginally suitable. The remaining 16.9% of the area was unsuitable.

4.3. Water Availability Assessment

Water availability assessments have been analyzed from the simulated value of streamflow, implementing through the ArcSWAT model in the gauged watershed of a sub-basin. The model was running successfully first and the observed flow data were used for model calibration and validation by considering sensitive parameters using SWAT-CUP software. The water availability assessment is understanding the potential of irrigation water supply in each sub-watershed obtained from the ArcSWAT simulated outputs and comparing with the irrigation water demand for dominant crops of the watershed. The mean monthly simulated streamflow result of gauged sub-watersheds is given in Table 4.10 below.

Table 4.10: Mean monthly simulated flow.

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
W-17	1.8	1.7	2.2	2.3	3.2	9.3	27.4	38.1	18.8	4.7	3.2	2.3

4.3.1. Streamflow sensitivity analysis

A sensitivity analysis was carried out to identify which parameter of the model is more important or more sensitive. The flow sensitivity analysis was carried out for 22 years including a three-year warm-up period (from January 1, 1987, to December 31, 1989). About 450, iteration has been done by SWAT-CUP sensitivity analysis at the watershed of sub-watershed 17. Where the outlet of the watershed found in flow calibration with the output of 11 parameters was reported as sensitive in different degrees of sensitivity for flow. The reported parameters, most of the parameters were grouped under a high sensitivity range.

T-stat provides a measure of sensitivity (large in absolute values are more sensitive) to the model whereas the P-values determined the significance of sensitivity. When the value of P is close to zero indicates a higher significance. According to Shiferaw E. (2014) the degrees of sensitivity were ranged from: 0 < mean relative sensitivity < 0.05 means small; 0.05< mean < 0.6 means medium; 0.6 < mean < 1 means High and mean > =1 means very high. The most sensitive parameters have an effect when changed ranging from high to small and will be used for flow calibration. The result of SWAT sensitivity analysis revealed that 11.

Table 4.11: Result of sensitive analysis of model parameters in gauged sub-watershed.

No	Parameter Name	Description	T_stat value	P_value	Sensitivity
1	GW_DELAY	Ground Water Delay (Days)	-4.1	0.00004	1
2	GWQMN	Threshold Depth of Water In The Shallow Aquifer Required For Return Flow to Occur (Mm)	-2.8	0.004	2
3	GW_REVAP	Ground Water Evaporation Coefficient (Unit Less)	2.7	0.006	3
4	CN2	SCS_CN for Moisture Condition II	-1.6	0.09	4
5	EPCO	Plant Evaporation Compensation Factor (Unit Less)	-1.4	0.15	5
6	SOL_AWC	Available Water Capacity of the Soil Layer (mm/mm)	1.12	0.26	6
7	CH_K2	Effective Channel Hydraulic Conductivity (mm/H)	0.97	0.33	7
8	CANMX	Maximum Canopy Storage (mm)	0.95	0.33	8
9	SOL_Z	Soil Depth (Mm)	0.61	0.54	9
10	ALPHA_BF	Base Flow Alpha Factor (Days)	0.52	0.59	10
11	ESCO	Soil Evaporation Compensation Factor (Unit Less)	0.27	0.78	11

Among 27 hydrological parameters, the most sensitive parameters were identified and ranked (Table 4.11). The next table indicates the best-fitted values of the model parameters that occurred from the swat cup sensitivity analysis of the output.

Table 4.12: lists of best-fitted parameters for mean monthly streamflow

No	Parameter Name	Description	Lower and Upper bound	Fitted value
1	CN2	SCS_CN for Moisture Condition II	±25%	-5%
2	ALPHA_BF	Base Flow Alpha Factor (Days)	0 - 1	0.69
3	GW_DELAY	Ground Water Delay (Days)	30 - 450	279.5
4	GWQMN	Threshold depth of water in the Shallow aquifer required for return flow to occur (mm)	0 to 5000	1903.8
5	GW_REVAP	Ground water evaporation coefficient (Unit Less)	0.02 to 0.2	0.15
6	REVAPMN	Threshold Depth of Water in the Shallow Aquifer Required for Evaporation to Occur (mm)	0 to 500	476.4
7	CANMX	Maximum Canopy Storage (mm)	0 to 10	7.7
8	ESCO	Soil Evaporation Compensation Factor (Unit Less)	0 to 1	0.86
9	EPCO	Plant Evaporation Compensation Factor (Unit Less)	0 to 1	0.16
10	SOL_Z	Soil Depth (mm)	±25%	-15.70%
11	SOL_AWC	Available Water Capacity of the Soil Layer (mm/mm)	±25%	16%

4.3.2. Model calibration and validation

Flow calibration was done using 22 years of data (from January 1, 1990, to December 31, 2008) which includes three years for model initialization (warm-up). Therefore, data considered for calibration was from 1990 to 2008. While conducting calibration auto-calibration was used. Auto-calibration allows the model to change the parameters until both observed and simulated flow data will be in the acceptable range automatically. After each simulation, the model goodness-of-fit was evaluated and the model performance after adjusting all the parameters. The objective functions that were used for evaluation like the coefficient of determination, Nash Sutcliff efficiency, and percent of baize were in the acceptable range for the calibration time of the model in the monthly time step and the R^2, NSE, and RVE indicates 0.79, 0.78 and 7% respectively. Since the acceptable ranges of parameters R^2, NSE and RVE are $R^2 > 0.6$, NSE > 0.5 and RVE < ±15% respectively as Moriasi *et al*. (2007). Therefore, it is confirmed that all the values obtained are in the acceptable range and the legend in the graph represents the observed and best estimations or simulated values as the next Figure 4.11.

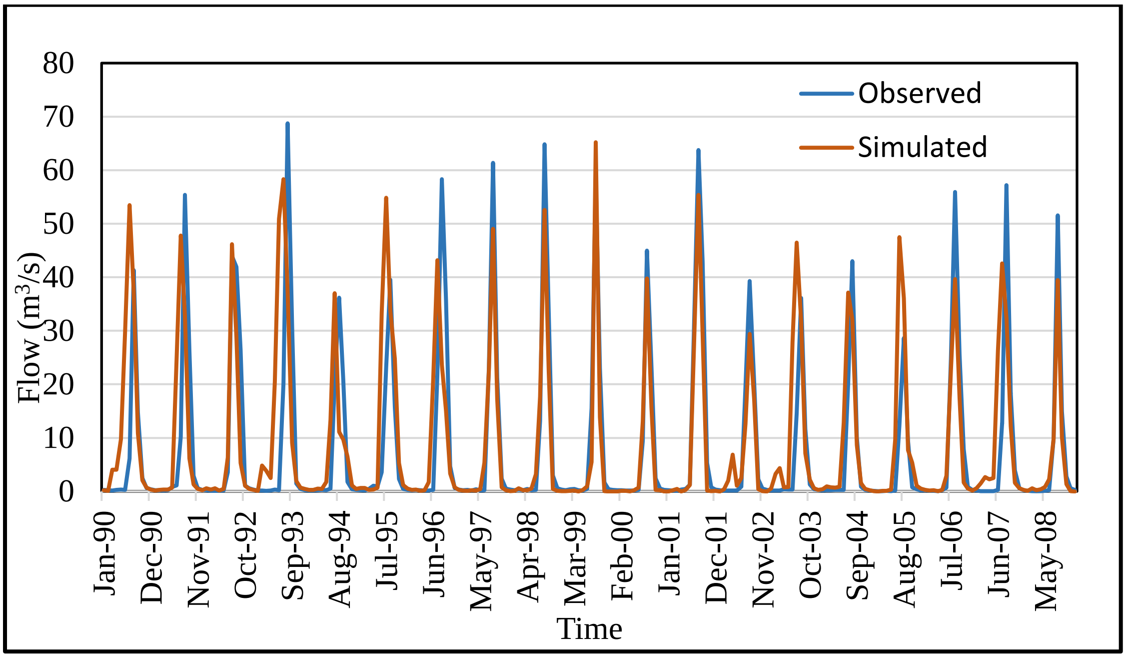

Figure 4.11: Observed and simulated flow for calibration period.

The calibration period of the observed and simulated flows is shown in Figure 4.11. As can be seen from the result, the model mostly overestimated and underestimated for some part of the year in a calibration period. Flow validation for the watershed was carried out using the data from January 1, 2009, to December 31, 2018, without further adjustment of the parameters. The objective functions that were used for evaluation like the coefficient of determination, Nash Sutcliff efficiency, and percent of baize were in the acceptable range for the validation time of the model in the monthly time step and the R^2, NSE, and RVE indicates 0.82, 0.8 and 3% respectively. The validation period of the observed and simulated flow in monthly estimation was underestimated and overestimate in some of the years.

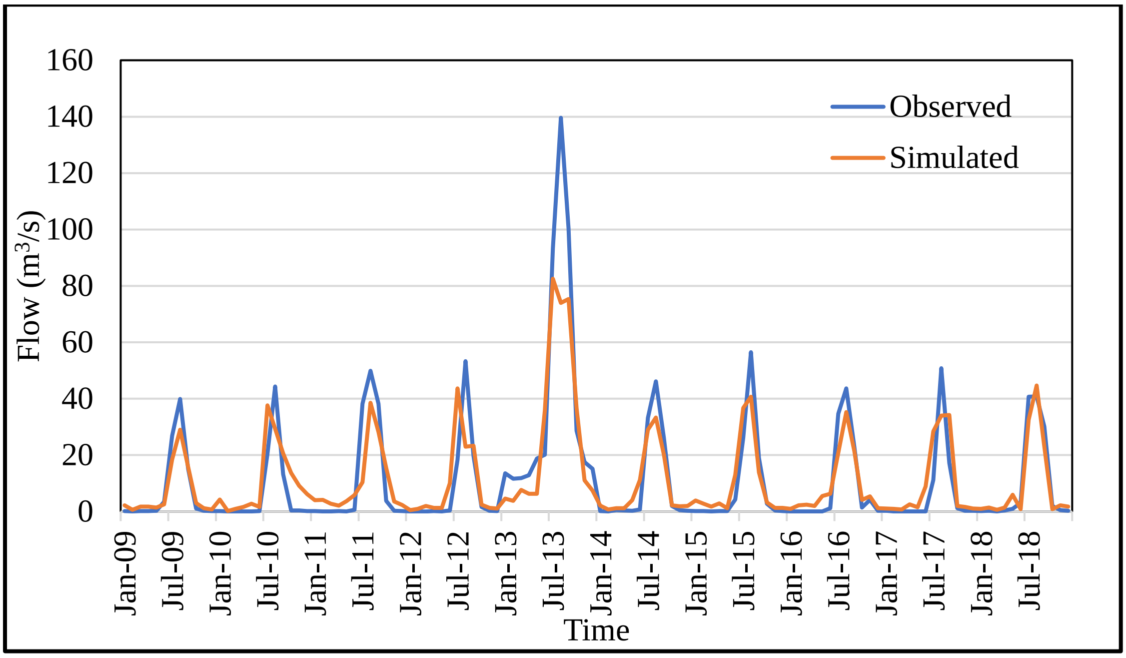

Figure 4.12: Observed and simulated monthly flow for the validation period.

By considering the watershed similarities, stream flows at un-gauged sites were estimated from the gauged sites by applying the runoff coefficient method. In the case of gauged sites, discharges from the gauged site are transferred to the site of interest. These results are discussed under the following subsections:

4.3.3. Gauged and un-gauged watersheds similarities

The Muger sub-basin was delineated into seventeen sub-watersheds. Among these sixteen sub-watersheds were ungauged and one gauged sub-watershed. The similarity between gauged and ungauged sub-watersheds depend on land cover, soil type, and slope range are identified and the results are presented in appendix 7.8.

4.3.4. Stream flows at un-gauged sites

The streamflow in the ungauged watershed was estimated using the runoff coefficient method and ratio method. The gauged and ungauged watersheds in the sub-basin were shown in figure 4.13. The sub-watershed labeled as number seventeen was the gauged and the remained all sub-watersheds were ungauged. Thus, estimated mean monthly discharges at the un-gauged sites from the gauged site were presented in Table 4.13.

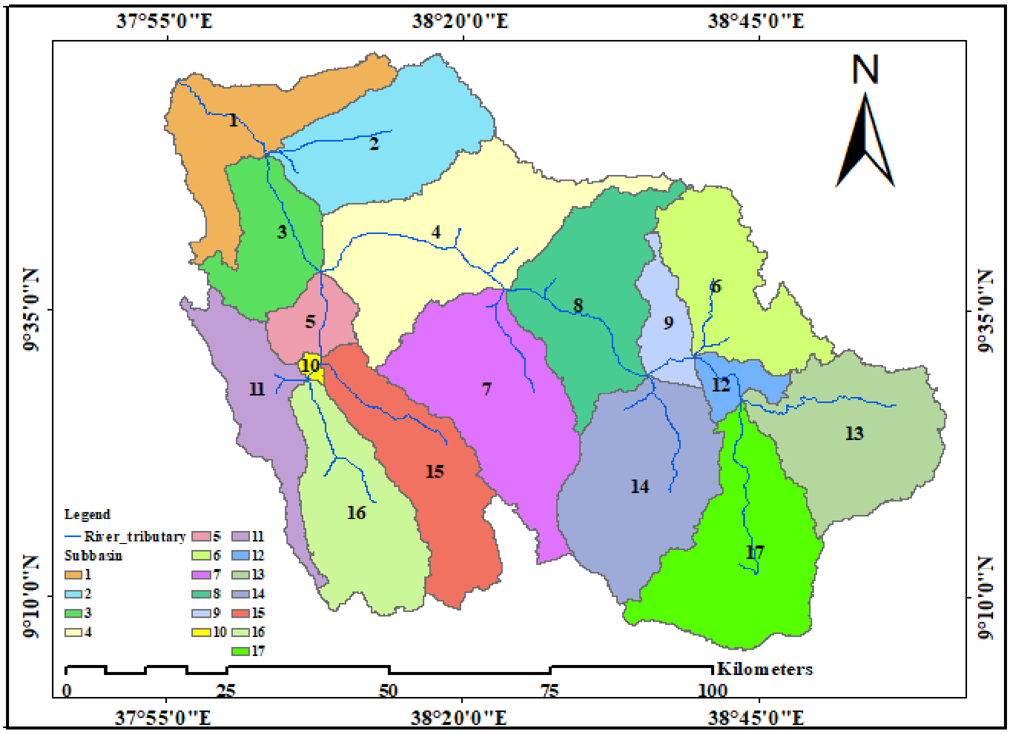

Figure 4.13: gauged and ungauged sub-watershed.

Table 4.13: Mean monthly streamflow in gauged and ungauged sub-watershed.

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
W-1	1.2	1.1	1.4	1.5	2.1	6.2	18.2	25.3	12.5	3.1	2.1	1.5
W-2	1.4	1.3	1.7	1.8	2.5	7.3	21.3	29.6	14.6	3.6	2.5	1.8
W-3	0.9	0.9	1.0	1.1	1.3	2.5	4.7	5.8	3.8	1.6	1.3	1.1
W-4	1.6	1.5	1.8	1.8	2.3	4.3	8.2	10.0	6.6	2.8	2.3	1.9
W-5	0.6	0.5	0.6	0.6	0.8	1.5	2.9	3.5	2.3	1.0	0.8	0.7
W-6	1.3	1.2	1.5	1.5	2.2	6.4	18.7	26.1	12.9	3.2	2.2	1.6
W-7	2.0	1.8	2.3	2.4	3.4	9.9	28.9	40.3	19.9	4.9	3.4	2.5
W-8	1.6	1.5	1.9	2.0	2.8	8.2	23.9	33.3	16.4	4.1	2.8	2.0
W-9	0.6	0.6	0.6	0.7	0.8	1.5	2.9	3.6	2.3	1.0	0.8	0.7
W-10	0.1	0.1	0.2	0.2	0.2	0.4	0.7	0.9	0.6	0.3	0.2	0.2
W-11	0.9	0.9	1.0	1.1	1.3	2.5	4.8	5.8	3.8	1.6	1.3	1.1
W-12	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
W-13	1.7	1.5	1.9	2.0	2.9	8.4	24.7	34.3	16.9	4.2	2.9	2.1
W-14	1.8	1.7	2.1	2.2	3.2	9.2	27.1	37.7	18.6	4.6	3.2	2.3
W-15	1.4	1.3	1.6	1.7	2.4	7.1	20.8	29.0	14.3	3.5	2.5	1.8
W-16	1.4	1.3	1.7	1.7	2.5	7.2	21.0	29.2	14.4	3.6	2.5	1.8
W-17	1.8	1.7	2.2	2.3	3.2	9.3	27.4	38.1	18.8	4.7	3.2	2.3
Q_{outlet}	19	17	22	23	31	83	229	315	160	44	31	23

4.4. Calculation of Crop water requirement

The selection of Crops was made based on local cropping patterns, farmer's practice, preference, the value of crops to sustain the area with food security, and their economic value to improve livelihood. The six crops were selected to be evaluated for irrigated agriculture development in the study area Potato, Tomato, barley cabbage, wheat, and other small garden vegetables.

Selected crops to be grown in the area were calculated assuming double-cropping practice in the area. After crops of the first phase, cultivation was harvested; land preparation was overtaken and the second phase cultivation was preceded using the intended irrigation method. According to the crop calendar of the area, the first phase of land preparation and second land preparation finished the planting of crops were followed. The planting and harvesting phase for double cultivation has shown in table 4.14.

Table 4.14: Crops cultivation calendar.

Crops type	planting date	harvesting date	planting date	harvesting date
Potato	1-Jan	10-Apr	1-Aug	8-Dec
Tomato	1-Jan	25-May	1-Aug	23-Dec
Barley	1-Jan	30-Apr	1-Jul	28-Oct
Cabbage	1-Jan	14-Jun	1-Sept	12-Feb
Wheat	1-Jan	10-May	1-Aug	8-Dec
other vegetables	1-Jan	5-Apr	1-Jul	3-Oct

ET_C or CWR was estimated using climate data for the CROPWAT 8.0 model. The average of all climate stations was used. The CROPWAT results are shown in Appendix 7.11 and Appendix 7.12.

Table 4.15: Monthly crop water requirement of selected crops.

Crops	Jan	Feb	Mar	Apr	Ma	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Potato	45.3	72.5	80.3	77	21.3	0	0	0	24.7	97.1	92.3	18.2
Tomato	54	61	77.9	87.2	68.3	0	0	0	14.4	95.6	102.6	63.6
Barley	38.7	87.7	79.7	35.7	0	0	0	0	32.2	36.4	0	0
Cabbage	63.8	54.3	53.4	76.1	99.1	32.1	0	0	3.9	55.4	81.5	98.6
vegetables	66.2	76.4	67.9	10.5	0	0	0	0	22.1	3	0	0
Wheat	24	53.5	80	65.2	6.6	0	0	0	15.2	96.7	79.7	8.4
Total	292	405.4	439.2	351.7	195.3	32.1	0	0	112.5	384.2	356.1	188.8

Different crops have different crop water requirements within the study area. Crop water requirement of all crops such as Potato, Tomato, cabbage, Barley, wheat, and other vegetables, was presented for each month in table 4.15. The commanded area for selected crops was assumed as stated in table 4.16.

Table 4.16: Command area for selected crops.

Crops	Area (ha)	Area (%)
Potato	122175	15
Tomato	81449.98	10
Barley	244349.9	35
Cabbage	81449.98	5
Wheat	162900	25
Other vegetables	122175	10

4.5. Gross Irrigation Water Requirements

The gross irrigation water requirement for selected crops at the identified irrigable land was estimated using climate output data from the CROPWAT 8.0. The overall irrigation efficiency was calculated using the according to FAO it was reduced from 100 % to 54 %. The gross irrigation water requirement of selected crops in m^3/s was given in table 4.17.

Table 4.17: Gross irrigation water demand for each crop.

Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	oct	Nov	Dec
Potato	31.9	56.6	56.6	56.1	15.0	0.0	0.0	0.0	18.0	68.5	67.3	12.8
Tomato	25.4	31.8	36.6	42.4	32.1	0.0	0.0	0.0	7.0	44.9	49.8	29.9
Barley	63.7	159.8	131.2	60.7	0.0	0.0	0.0	0.0	54.8	59.9	0.0	0.0
Cabbage	15.0	14.1	12.6	18.5	23.3	18.1	0.0	0.0	0.9	13.0	19.8	23.2
Vegetables	31.1	39.8	31.9	5.1	0.0	0.0	0.0	0.0	10.7	1.4	0.0	0.0
Wheat	28.2	69.6	94.0	79.2	7.8	0.0	0.0	0.0	18.5	113.7	96.8	9.9
Total	195	372	363	262	78	18	0	0	110	301	234	76

4.6. Irrigation Potential of the sub-basin

The irrigation potential of the study area was obtained by comparing irrigation requirements of the identified land suitable for surface irrigation and the available mean monthly flows in the Muger River basin according to area division for each crop based on the method suggested by (FAO, 1997). The streamflow of 25% of the available in the streamflow in the sub-basin was released for downstream ecological balance. Monthly streamflow and grosses irrigation water requirement of selected crops such as Potato, Tomato, Cabbage, Wheat, Barley, and other vegetables were presented in table 4.18.

Table 4.18: Comparison of gross irrigation water demand with available streamflow.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow	2.7	2.4	3.2	3.3	4.4	11.9	32.8	45.1	22.9	6.3	4.4	3.3
Potato	38.3	67.8	67.8	67.2	18.0	0.0	0.0	0.0	21.6	82.0	80.6	15.4
Flow	2.1	1.9	2.5	2.6	3.5	9.3	25.6	35.2	17.9	4.9	3.5	2.6
Tomato	30.4	38.0	43.9	50.7	38.5	0.0	0.0	0.0	8.4	53.8	59.7	35.8
Flow	3.8	3.4	4.4	4.6	6.1	16.4	45.3	62.4	31.7	8.7	6.1	4.6
Barley	65.4	148.2	149.1	60.3	0.0	0.0	0.0	0.0	56.2	61.5	0.0	0.0
Flow	1.1	1.0	1.3	1.4	1.8	4.9	13.6	18.7	9.5	2.6	1.8	1.4
Cabbage	35.9	33.9	30.1	44.3	55.8	18.1	0.0	0.0	2.3	31.2	47.4	55.5
Flow	0.9	0.8	1.0	1.0	1.4	3.7	10.3	14.2	7.2	2.0	1.4	1.0
Vegetables	74.6	95.3	76.5	11.8	0.0	0.0	0.0	0.0	25.7	3.4	0.0	0.0
Flow	3.7	3.3	4.3	4.5	6.0	16.1	44.3	61.0	31.0	8.5	6.0	4.5
Wheat	20.3	50.0	67.6	56.9	5.6	0.0	0.0	0.0	13.3	81.7	69.6	7.1

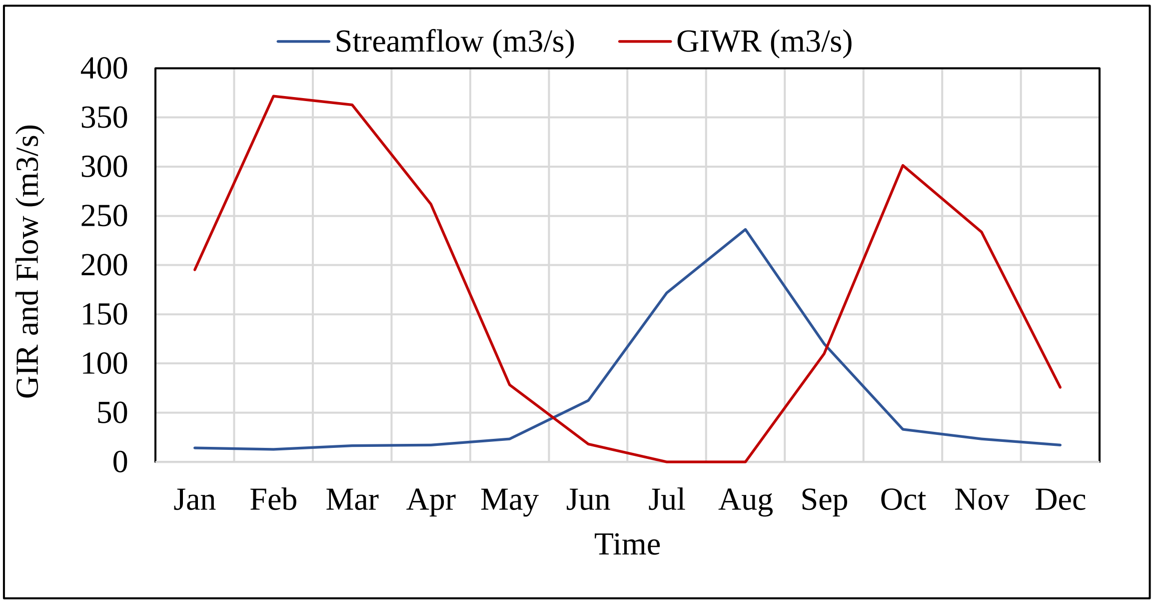

Figure 4.14: Comparison of gross irrigation water demand with available streamflow.

Based on the available water, the effective irrigable area (ha) can be estimated in each month depending on the command crop area for each crop were shown in table 4.19 as the following.

Table 4.19: Effective irrigable area at each month for each crop.

Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
potato	4693	2370	3065	3234	16283	0	0	0	70136	5070	3636	14139
tomato	3071	2197	2465	2228	3961	0	0	0	93849	4017	2552	3156
barley	7592	2708	4269	9642	0	0	0	0	74362	18693	0	0
cabbage	1378	1309	1906	1353	1448	4995	0	0	183724	3675	1703	1079
vegetables	1009	706	1139	7450	0	0	0	0	24624	51547	0	0
wheat	11964	4337	4156	5159	70984	0	0	0	153950	6877	5689	41380
Total	29707	13626	17000	29066	92676	4995	0	0	600645	89879	13580	59755

As shown in Table 4.19, the effective irrigable area varies throughout the months but the real effective irrigable area was the least area of the month. The total gross irrigation water demand for all selected crops and irrigable land was 2009.1 m^3/sec, but the total available streamflow was 748 m^3/sec which can irrigate 136720.11 ha of irrigable land. Accordingly, to irrigate the remained whole irrigable area 543326.4 ha of land requires 1261.1 m^3/s of irrigation water throughout the growing period. Due to this reason storage structure is required within the study area. So, the irrigation potential of the Muger sub-basin was found to be 136720.11 ha which accounts for 37.2 % of the total suitable land area of the sub-basin.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The assessment of surface irrigation potential was carried out through the combined use of geospatial techniques, ArcSWAT, and CROPWAT8.0. Land suitability was assessed using parameters; land slope, soil type, land use land cover, and proximity to water resource were identified in the sub-basin. Lands with slope of < 8 % were categorized under highly suitable to marginally suitable class which covers 24.98 % (204,547.32 ha) and > 8% were categorized in unsuitable class covers 75.02% (614,194.49 ha) of the total area.

The soil types were found to be Calcic Vertisols, Rhodic Nitisols, Haplic Nitisols and Chromic Luvisols, Eutric Cambisols, Eutric Fluvisols, Haplic Luvisols, Eutric Leptosols, and Eutric Regosols which are covering an area of 51.24% (411330.19 ha) were classified as highly suitable to marginally suitable. The remained soil types Rendzic Leptosols, Eutric Vertisols, Haplic Alisols, Urban and Water bodies are covering 49.76% (407445.51) ha and grouped as not suitable. The soil texture was dominated by Clay Loam and Sandy Clay Loam soil. The soil texture was classified as highly suitable to marginally suitable. The land suitable in terms of soil depth was about 97.61% (799,253.22 ha) which covers from the range of high to marginally suitable. The remained 2.39% (19,556.80 ha) of the area is considered unsuitable. In terms of soil drainage, about 89.48% (732,701.54) and 10.52% (86,109.46 ha) of the soils were categorized as unsuitable. The soil drainage of the study area is classified as highly to marginally suitable 89.48% (732701.54 ha) and the remained 10.52% (86,109.46). The soil depth suitable was classified as 97.02% (799253.2 ha) highly to marginally suitable and 2.98% (19556.80 ha) was classified as unsuitable.

The eight land use/land cover types in the sub-basin. Cropland is the greatest share of land use land cover from all the land classes, which covers an area of 93.5 % of the total area. Generally, in the land use land cover suitability assessment, 99.58% (815,377.19 ha) of the watershed was high to moderately suitable and the remained 0.42% (3432.51 ha) of the total watershed is not suitable for surface irrigation development.

To identify the closeness to the water supply (rivers), straight-line (Euclidean) distance from river points was calculated. The result of Proximity to water suitable for surface irrigation indicates that 84% (687,813.99 ha) were classified as highly suitable to marginally suitable. The remaining 14% (131001.11 ha) is classified as not suitable for surface irrigation.

The overall suitability of the land for surface irrigation was evaluated using the weighted overlay analysis. About 83.1% (680,046 ha) of the total land were found in the range of highly suitable to marginally suitable for surface irrigation development, whereas 16.9% (138753.5 ha) were unsuitable class due to the combined effect of slope, soil, land use land cover and distance to water resources suitability of Muger sub-basin.

The Water availability assessments have been done using ArcSWAT as interface ArcGIS for simulation of streamflow. The ArcSWAT model was calibrated using SWAT-CUP using data from 1990 to 2008 and validated from 2009 to 2018 monthly data. The model performance was evaluated using the coefficient of determination (R^2), Nash-Sutcliffe model efficiencies (NSE), and Relative Volume Error (RVE) during both the calibration and validation periods. The model performance efficiency indicators; coefficient of determination (R^2), the Nash-Sutcliffe (NSE), and Relative Volume Error (RVE) are found to be 0.79, 0.78, and 7% respectively in calibration and 0.82, 0.80, and 3% respectively in the validation of streamflow analysis.

The crop water requirement of the selected crops was made using climatic data through CROPWAT 8.0 model. Available stream flow obtained from ArcSWAT simulated outputs used to estimate other streamflow in the study area and the streamflow obtain at Muger river outlet were compared with the gross irrigation water requirements of the crops and potentially irrigable sites were identified in the sub-basin. So, the irrigation potential in the sub-basin was found to be 136720.11 ha (37.2 %) of the total suitable land area in the sub-basin.

5.2. Recommendations

Irrigation is considered is an important investment for improving rural income through increased agricultural production. However, this can be achieved, by assessing available land and water resources for irrigation. Therefore, the identified surface irrigation potential of the Muger sub-basin assists policymakers in the development of irrigation projects. The data generated in the present study such as estimated discharges at ungauged sites, evapotranspiration, and identified potential irrigable sites in the sub-basin assist local or regional planners to facilitate preliminary surveys and prepare irrigation projects in the study area. This study needs to be continued to include the following points for the future:

- The surface irrigation potential was carried out in this research by considering water sources availability, irrigation requirement, and physical land suitability for surface irrigation. Yet the effects of other factors such as chemical suitability factors, water quality, and environmental, economic, and social terms may also be assessed to get sound and reliable results.
- The estimation of irrigation water requirement of identified command areas was carried out by selecting some crops types only. But the future research should select several crops to calculate irrigation requirements of identified potential irrigable land in the sub-basin.
- Stream flows at un-gauged sites were estimated using the area ratio method. However, future research may test other methods such as regional regression analysis, base flow correlation, and development of unit hydrograph to estimate discharges at ungauged sites from gauged sites.
- The reliability of the analysis results depends on the existing GIS data set used for the overlaying process. The results can be improved by updating the GIS database using new technologies like remotely sensed images interpretation when it is available.
- SWAT model calibrated using observed flow data at the gauging station. To improve the model performance, the weather stations should be improved both in quality and quantity.
- Storage structures must be constructed to irrigate the whole irrigable area of land in the study area.

This research was funded by Adama Science and Technology University (ASTU) under the grant number of **ASTU/SM-R/296/21**

6. REFERENCE

Adisu, G. (2018). Water Resources Management in Abbay River Basin. *Abay Basin Authority*.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Arku, A. Y., Musa, S. M., & Mofoke, A. L. E. (2012). Determination of water requirement and irrigation timing for Amaranthus hybridus in Maiduguri metropolis, north-eastern Nigeria. *Fourth International Conference on Sustainable Irrigation*, 279–289.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., Van Griensven, A., & Van Liew, M. W. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491–1508.

Awulachew, S. B. (2010). Irrigation potential in Ethiopia. *Constraints and Opportunities for Enhancing the System; International Water Management Institute: Addis Ababa, Ethiopia*.

Awulachew, S. B., McCartney, M., Steenhuis, T. S., & Ahmed, A. A. (2009). *A review of hydrology, sediment and water resource use in the Blue Nile Basin* (Vol. 131). IWMI.

Awulachew, S. B., Merrey, D., Van Koopen, B., & Kamara, A. (2010). Roles, constraints and opportunities of small-scale irrigation and water harvesting in Ethiopian agricultural development: Assessment of existing situation. *ILRI Workshop*, 14–16.

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M., & Alamirew, T. (2007). *Water resources and irrigation development in Ethiopia* (Vol. 123). Iwmi.

Ayalew, G. (2014). Land Suitability Evaluation for surface and sprinkler irrigation Using Geographical Information System (GIS) in Guang Watershed , Highlands of Ethiopia. *Journal of Environment and Earth Science*, *4*(22), 140–150.

Ayana, M. (2011). Deficit irrigation practices as alternative means of improving water use efficiencies in irrigated agriculture: Case study of maize crop at Arba Minch, Ethiopia. *African Journal of Agricultural Research*, *6*(2), 226–235.

Bahmani, O., Nasab, S. B., & Behzad, M. (2013). Opinions of the Management to Realize and Improve Water Productivity in Agriculture. *University of Ahwaz, Iran*.

Berhanu, B., Seleshi, Y., & Melesse, A. M. (2014). Surface water and groundwater resources of Ethiopia: potentials and challenges of water resources development. In *Nile River Basin* (pp. 97–117). Springer.

Beven, K. J. (2011). *Rainfall-runoff modelling: the primer*. John Wiley & Sons.

Birhhanu, A. (2017). *Gis-Based Surface Irrigation Potential Asssessment of Dirma Watershed, Dembia Wereda, North Gonder Zone, Ethiopia*.

Boonyanuphap, J., Wattanachaiyingcharoen, D., & Sakurai, K. (2004). GIS-based land suitability assessment for Musa (ABB group) plantation. *J. Appl. Hort*, *6*(1), 3–10.

Brouwer, C., Prins, K., Kay, M., & Heibloem, M. (1988). Irrigation water management: irrigation methods. *Training Manual*, *9*.

Bruinsma, J. (2003). *World agriculture: towards 2015/2030: an FAO perspective*. Earthscan.

Chow, V. Te, Maidment, D. R., Mays, L. W., & Ven Te Chow, David R. Maidment, L. W. M. (1998). *Applied Hydrology Chow 1988.pdf* (pp. 1–294). http://ponce.sdsu.edu/Applied_Hydrology_Chow_1988.pdf

Daniel, E. B., Camp, J. V, LeBoeuf, E. J., Penrod, J. R., Dobbins, J. P., & Abkowitz, M. D. (2011). Watershed modeling and its applications: A state-of-the-art review. *The Open Hydrology Journal*, *5*(1).

Dawit, M., Olika, B. D., Muluneh, F. B., Leta, O. T., & Dinka, M. O. (2020). Assessment of Surface Irrigation Potential of the Dhidhessa River Basin, Ethiopia. *Hydrology*, *7*(3), 68.

Ditzler, C., Scheffe, K., & Monger, H. C. (2017). Soil science division staff. *Soil Survey Manual. USDA Handbook*, *18*, 603.

Douglas-Mankin, K. R., Srinivasan, R., & Arnold, J. G. (2010). Soil and Water Assessment Tool (SWAT) model: Current developments and applications. *Transactions of the ASABE*, *53*(5), 1423–1431.

FAO. (1976). *A Framework for Land Evaluation.* Soil Resources Management and Conservation Service Land and Water Development Division. *FAO Soil Bulletin No. 32*. FAO-UNO, *Rome*.

FAO. (1985). Soil Resources, Management, & Conservation Service. Guidelines: land evaluation for irrigated agriculture (No. 55).

FAO. (1991). *Land Use Planning Applications: Proceedings of the FAO Expert Consultation, Rome 10-14 December 1990* (Vol. 68). Food & Agriculture Org.

FAO. (1997). Irrigation potential in Africa; A basin approach. *FAO Land and Water Development Division. FAO Land and Water Bulletin 4. Rome, Italy.*

FAO. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome*, *300*(9), D05109.

FAO. (2007). *Land Evaluation: Towards a Revised Framework. Fao Land and Water Discussion Paper 6. FAO, Rome,Italy.*

FAO, U. (1999). *The future of our Land–Facing the Challenge, Guidelines for Integrated Planning for Sustainable Management of Land Resources*.

Fasina, A. S., Awe, G. O., & Aruleba, J. O. (2008). Irrigation suitability evaluation and crop yield an example with Amaranthus cruentus in Southwestern Nigeria. *African Journal of Plant Science*, *2*(7), 61–66.

Fischer, C., Roscher, C., Jensen, B., Eisenhauer, N., Baade, J., Attinger, S., Scheu, S., Weisser, W. W., Schumacher, J., & Hildebrandt, A. (2014). How do earthworms, soil texture and plant composition affect infiltration along an experimental plant diversity gradient in grassland? *PloS One*, *9*(6), e98987.

Fiseha, B. M., Setegn, S. G., Melesse, A. M., Volpi, E., & Fiori, A. (2013). Hydrological analysis of the Upper Tiber River Basin, Central Italy: a watershed modelling approach. *Hydrological Processes*, *27*(16), 2339–2351.

Ganole, K. (2010). *GIS-based surface irrigation potential: Assessment of river catchments for irrigation development in Dale Woreda, Sidama Zone, SNNP*. Haramaya University.

Garbrecht, J., & Martz, L. W. (1996). Comment on "Digital Elevation Model Grid Size, Landscape Representation, and Hydrologic Simulations' by Weihua Zhang and David R. Montgomery. *Water Resources Research*, *32*(5), 1461–1462.

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, *50*(4), 1211–1250.

Gebeyehu, A. (2015). *Irrigation Potential Assessment*: A Case Study of Guder River Watershed.

Gebrekristos, S. T. (2015). *Understanding Catchment Processes and Hydrological Modelling in the Abay/Upper Blue Nile Basin, Ethiopia*.

Gebul, M. A. (2021). Trend, status, and challenges of irrigation development in Ethiopia—A review. *Sustainability (Switzerland)*, *13*(10). https://doi.org/10.3390/su13105646

Goldsmith, P. (2000). Review note on soil erosion assessment. *Unpublished Project Working*.

Goodchild, M. (2000). The current status of GIS and spatial analysis. *Journal of Geographical Systems*, *2*(1), 5–10.

Grima, N., Singh, S. J., & Smetschka, B. (2018). Improving payments for ecosystem services (PES) outcomes through the use of Multi-Criteria Evaluation (MCE) and the software OPTamos. *Ecosystem Services*, *29*, 47–55.

Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering*, *4*(2), 135–143.

Hussien, K., Woldu, G., & Birhanu, S. (2019). A GIS-Based Multi-Criteria Land Suitability Analysis for Surface Irrigation along the Erer Watershed, Eastern Hararghe Zone, Ethiopia. *East African Journal of Sciences*, *13*(2), 169–184.

Jamshid, Y. (2003). The integration of satellite images, GIS and CROPWAT model to investigation of water balance in irrigated area. A case study of Salmas and Tassoj plain, Iran. *International Institute for GEO-Information Science and Earth Observation. Enschede, The Netherlands*.

Janssen, R., & Rietveld, P. (1990). Multicriteria analysis and geographical information systems: an application to agricultural land use in the Netherlands. In *Geographical information systems for urban and regional planning* (pp. 129–139). Springer.

Jensen, M. E., Burman, R. D., & Allen, R. G. (1990). *Evapotranspiration and irrigation water requirements*.

Kang, Y., Khan, S., & Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security–A review. *Progress in Natural Science*, *19*(12), 1665–1674.

Kebede, T., & Ademe, Y. (2016). Evaluating land suitability for irrigation purpose in Abaya district, Borena zone, Ethiopia. *African Journal of Agricultural Research*, *11*(46), 4754–4761.

Korolyuk, V. S., & Korolyuk, V. V. (2012). *Stochastic models of systems* (Vol. 469). Springer Science & Business Media.

Lawrence, P. (2004). *Sedimentation in small dams. Development of a catchment characterisation and sediment yield prediction procedure*.

Luo, Y., Su, B., Yuan, J., Li, H., & Zhang, Q. (2011). GIS techniques for watershed delineation of SWAT model in plain polders. *Procedia Environmental Sciences*, *10*, 2050–2057.

Malczewski, J. (2006). Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. *International Journal of Applied Earth Observation and Geoinformation*, *8*(4), 270–277.

Maliene, V., Grigonis, V., Palevičius, V., & Griffiths, S. (2011). Geographic information system: Old principles with new capabilities. *Urban Design International*, *16*(1), 1–6.

Mardani, A., Zavadskas, E. K., Khalifah, Z., Jusoh, A., & Nor, K. M. D. (2016). Multiple criteria decision-making techniques in transportation systems: A systematic review of the state of the art literature. *Transport*, *31*(3), 359–385.

Marinoni, O. (2004). Implementation of the analytical hierarchy process with VBA in ArcGIS. *Computers & Geosciences*, *30*(6), 637–646.

McCleary Jr, G. F., Jenks, G. F., & Ellis, S. R. (1991). Cartography and map displays. In *Pictorial Communication In Real And Virtual Environments* (pp. 91–114). CRC Press.

Meron, T. (2007). *Surface irrigation suitability analysis of Southern Abbay Basin by implementing GIS techniques*. MSc thesis, Addis Ababa University.

Merritt, W. S., Letcher, R. A., & Jakeman, A. J. (2003). A review of erosion and sediment transport models. *Environmental Modelling & Software*, *18*(8–9), 761–799.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885–900.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology*, *10*(3), 282–290.

Nemec, J. (1972). Hydrological analysis and Design. *Engineering Hydrology, Mc-Graw Hill London*, 162–166.

Nigussie, G., Moges, M. A., Moges, M. M., & Steenhuis, T. S. (2019). Assessment of Suitable Land for Surface Irrigation in Ungauged Catchments: Blue Nile Basin, Ethiopia. *Water*, *11*(7), 1465.

NRCS, U. (1993). Soil survey division staff (1993) soil survey manual. Soil conservation service. *US Department of Agriculture Handbook*, *18*, 315.

Perry, C. (2018). Improving Irrigation Management in Conditions of Scarcity: Myth vs Truth. *Global Water Forum*.

Pujadas, P., Pardo-Bosch, F., Aguado-Renter, A., & Aguado, A. (2017). MIVES multi-criteria approach for the evaluation, prioritization, and selection of public investment projects. A case study in the city of Barcelona. *Land Use Policy*, *64*, 29–37.

Quraishi, S., & Haile, Y. T. (2014). *GIS-Based Land Suitability Assessment for Surface Irrigation and Mapping: The Case of Azule Catchment, Arsi Zone, Oromia Region, Ethiopia*. Haramaya University.

Raes, D., Willems, P., & Gbaguidi, F. (2006). RAINBOW–A software package for hydrometeorological frequency analysis and testing the homogeneity of historical data sets. *Proceedings of the 4th International Workshop on 'Sustainable Management of Marginal Drylands (SUMAMAD), February*, 27–31.

Ramanathan, R. (2001). A note on the use of the analytic hierarchy process for environmental impact assessment. *Journal of Environmental Management*, *63*(1), 27–35.

Ramanathan, R., & Ganesh, L. S. (1995). Energy resource allocation incorporating qualitative and quantitative criteria: An integrated model using goal programming and AHP. *Socio-Economic Planning Sciences*, *29*(3), 197–218.

Refsgaard, J. C. (1997). Parameterisation, calibration and validation of distributed hydrological models. *Journal of Hydrology*, *198*(1–4), 69–97.

Reis, S. (2008). Analyzing land use/land cover changes using remote sensing and GIS in Rize, North-East Turkey. *Sensors*, *8*(10), 6188–6202.

Rossiter, D. G. (2009). *Land evaluation: towards a revised framework; Land and Water Discussion Paper 6, FAO. FAO, Rome (2007), 107 pp., ISSN: 1729-0554.*

Saaty, T. L. (1980). The analytic hierarchy process (AHP). *The Journal of the Operational Research Society*, *41*(11), 1073–1076.

Saaty, T. L. (2001). Fundamentals of the analytic hierarchy process. In *The analytic hierarchy process in natural resource and environmental decision making* (pp. 15–35). Springer.

Saaty, T. L. (2003). Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research*, *145*(1), 85–91.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *1*(1), 83–98.

Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Srinivasan, R., & Hauck, L. M. (2001). Validation of the swat model on a large rwer basin with point and nonpoint sources 1. *JAWRA Journal of the American Water Resources Association*, *37*(5), 1169–1188.

Scherer, T. F., Franzen, D., & Cihacek, L. (2017). Soil, Water and Plant Characteristics Important to Irrigation. *K-State Research and Extension*, *1675*(December), 1–8. www.ksre.ksu.edu/irrigate

Shiferaw, H. (2007). Irrigation potential evaluation and crop suitability analysis using GIS and remote sensing technique in Beles subbasin, Beneshangul Gumez Region. *Addis Ababa University School of Graduate Studies Department of Earth Sciences. Addis Ababa: Addis Ababa University*.

Singh, A. (2016). Managing the water resources problems of irrigated agriculture through geospatial techniques: An overview. *Agricultural Water Management*, *174*, 2–10.

Smith, M. (1992). *CROPWAT: A computer program for irrigation planning and management* (Issue 46). Food & Agriculture Org.

Smithson, P., Addison, K., & Atkinson, K. (2013). *Fundamentals of the physical environment*. Routledge.

Subramanya, K. (2013). *Engineering hydrology, 4e*. Tata McGraw-Hill Education.

Sultan, D. (2013). Assessment of irrigation land suitability and development of map for the fogera catchment using GIS, South Gondar. *Asian Journal of Agriculture and Rural Development*, *3*(393-2016–23817), 7–17.

Tariku Meron. (2007). *Surface irrigation suitability analysis of southern Abbay basin by implementing GIS techniques (a case study in Dedessa sub-basin)*. *February*, 1–73.

Tyagi, J. V, Rai, S. P., Qazi, N., & Singh, M. P. (2014). Assessment of discharge and sediment transport from different forest cover types in lower Himalaya using Soil and Water Assessment Tool (SWAT). *International Journal of Water Resources and Environmental Engineering*, *6*(1), 49–66.

USDA, S. C. S. (1972). National engineering handbook, section 4: Hydrology. *Washington, DC*.

Valipour, M. (2015). Future of agricultural water management in Africa. *Archives of Agronomy and Soil Science*, *61*(7), 907–927.

Velasquez, M., & Hester, P. T. (2013). An analysis of multi-criteria decision making methods. *International Journal of Operations Research*, *10*(2), 56–66.

White, K. L., & Chaubey, I. (2005). Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model 1. *JAWRA Journal of the American Water Resources Association*, *41*(5), 1077–1089.

Winchell, M., Srinivasan, R., Di Luzio, M., & Arnold, J. (2007). ArcSWAT interface for SWAT 2005. *User'sGuide, Blackland Research Center, Texas Agricultural Experiment Station, Temple*.

Worqlul, A. W., Collick, A. S., Rossiter, D. G., Langan, S., & Steenhuis, T. S. (2015). Assessment of surface water irrigation potential in the Ethiopian highlands: The Lake Tana Basin. *Catena*, *129*, 76–85.

Yalew, B., Hussein, K., Ermias, B., & Sorssa, N. (2011). Small-scale irrigation situation analysis and capacity needs assessment, a tripartite cooperation between Germany, Israel and Ethiopia. *Natural Resources Management Directorate through the Support of GIZ. Sustainable Land Management Program, Ministry of Agriculture, Ethiopia*.

Yilma, A. D., & Awulachew, S. B. (2009). *Characterization and Atlas of the Blue Nile Basin and its Sub basins*.

Yost, J. L., & Hartemink, A. E. (2020). How deep is the soil studied–an analysis of four soil science journals. *Plant and Soil*, *452*, 5–18.

7. APPENDIX

Appendix 7-1: Meteorological stations and their location.

ID	Name	Latitude	Longitude	Elevation
SHENCH14	Enchini	9.316667	38.366667	2687
SHJELD13	Jeldu	9.25	38.08333	2952
SHMUGE23	Muger	9.4585	38.34317	2553
SHMUKE14	Muketuri	9.542	38.87083	2649
SHSULU31	Sululta	9.18	38.73	2610

Appendix 7-2: Mean Monthly Rainfall Data at Enchini (mm).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	3.2	7.9	4.6	8.8	7.0	8.3	7.4	3.6	1.0	0.1	0.1	0.3
1988	1.5	0.3	1.9	0.5	4.6	10.1	10.5	8.5	2.0	0.0	0.2	0.5
1989	1.3	3.5	4.1	0.3	4.2	12.5	10.0	3.8	1.0	0.3	1.2	0.3
1990	4.8	1.7	3.0	0.9	3.5	8.7	10.7	5.1	0.9	0.1	0.2	0.1
1991	1.0	2.7	1.5	1.2	4.1	10.1	10.7	4.4	0.2	0.1	0.4	1.5
1992	1.8	0.7	2.9	0.8	5.0	8.4	9.8	2.9	1.3	0.4	0.3	0.8
1993	1.0	0.8	5.1	2.3	7.5	9.3	10.3	5.4	1.5	0.1	0.3	0.0
1994	0.1	1.5	2.1	1.7	5.2	10.7	9.5	4.7	0.1	0.3	0.0	0.0
1995	2.1	1.2	2.6	1.2	3.4	8.6	10.5	4.2	0.2	0.1	0.7	1.0
1996	0.5	4.5	2.3	3.1	9.6	12.7	10.0	5.5	0.5	0.5	0.2	0.8
1997	0.0	1.3	2.9	2.8	5.8	6.9	8.1	2.5	3.9	0.8	0.1	1.1
1998	2.1	1.1	1.6	2.3	4.5	13.8	9.7	4.9	4.7	0.2	0.0	0.7
1999	0.3	1.1	0.6	2.2	7.5	8.4	8.9	3.6	3.6	0.0	0.1	0.1
2000	0.0	0.3	1.7	1.4	3.5	8.2	6.7	2.6	0.9	0.2	0.4	0.2
2001	0.6	2.8	0.8	2.3	3.7	6.3	6.1	2.2	0.5	0.2	0.1	0.6
2002	0.3	1.5	1.5	0.9	3.0	4.5	5.0	1.5	0.1	0.0	0.5	0.3
2003	0.3	1.7	1.4	0.3	2.7	4.7	7.2	2.5	0.0	0.2	1.1	0.1
2004	0.3	1.6	1.9	0.3	2.7	5.5	4.7	2.4	0.7	0.2	0.9	0.7
2005	0.2	2.3	3.7	3.6	2.0	6.6	5.0	2.7	0.8	0.2	0.0	0.2
2006	1.9	3.8	2.3	1.7	5.1	11.5	8.1	4.9	1.6	0.3	0.3	0.4
2007	1.5	2.3	1.8	4.5	4.2	8.7	8.0	6.1	0.4	0.2	0.0	0.2

2008	0.1	0.1	1.4	1.7	3.1	10.8	10.6	5.0	0.8	2.0	0.1	1.5
2009	0.4	0.6	1.4	1.2	2.7	7.8	7.3	3.2	2.3	0.1	1.4	0.1
2010	2.7	2.0	3.5	3.9	6.6	9.6	8.9	6.2	0.4	0.7	0.4	0.2
2011	0.3	2.2	1.6	3.2	4.6	5.3	4.9	2.8	0.1	0.8	0.0	0.0
2012	0.0	0.5	3.2	0.9	3.4	12.1	12.5	5.5	0.1	0.0	0.3	0.9
2013	0.1	2.3	4.8	3.4	6.0	12.6	8.5	5.3	2.6	0.8	0.0	0.1
2014	1.0	1.8	2.4	3.8	3.6	8.1	7.3	5.6	2.1	0.6	1.0	0.1
2015	0.5	0.8	0.2	4.4	5.4	7.4	9.6	2.4	0.3	0.6	1.2	0.9
2016	1.0	1.3	3.7	5.2	3.5	8.6	10.2	6.5	0.7	0.2	0.1	0.0
2017	3.2	2.2	1.0	5.3	2.7	11.3	10.1	7.8	1.1	0.2	0.0	0.0
2018	1.4	0.4	3.7	2.1	6.1	7.8	10.9	2.0	0.8	0.9	0.0	0.0
Mean	1.1	1.8	2.5	2.4	4.6	8.9	8.7	4.5	1.1	0.4	0.4	0.4

Appendix 7-3: Mean Monthly Rainfall Data at Jeldu (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	7.4	5.1	8.4	6.9	8.2	7.8	3.7	1.0	0.1	0.1	0.3	1.4
1988	0.4	1.9	0.4	4.5	9.7	11.0	8.7	2.1	0.0	0.2	0.5	1.3
1989	3.4	4.3	0.3	3.8	12.1	10.4	3.8	1.4	0.3	1.2	0.3	4.7
1990	1.8	3.0	0.9	3.2	8.4	11.2	5.4	1.0	0.1	0.2	0.1	1.1
1991	2.6	1.5	1.1	3.6	10.0	10.8	4.9	0.2	0.1	0.4	0.8	2.4
1992	0.6	2.9	0.9	4.9	8.2	10.0	3.2	1.3	0.4	0.3	0.7	1.2
1993	0.7	4.8	2.8	7.1	9.5	10.1	5.9	1.6	0.1	0.3	0.0	0.1
1994	1.4	2.1	1.7	4.8	10.5	9.6	5.4	0.1	0.3	0.0	0.0	2.1
1995	1.1	2.8	1.1	3.3	8.2	11.0	4.5	0.2	0.1	0.7	1.1	0.3
1996	4.4	2.4	3.0	9.7	12.2	10.0	5.8	0.8	0.5	0.2	0.8	0.1
1997	1.4	2.9	2.2	5.7	7.4	8.4	2.5	3.8	0.9	0.1	1.1	2.1
1998	1.0	1.5	2.3	4.5	13.1	10.2	4.9	4.8	0.2	0.0	0.7	0.2
1999	1.1	0.5	2.2	6.5	9.4	8.7	3.9	3.7	0.0	0.1	0.1	0.0
2000	0.3	1.6	1.5	3.4	8.2	6.6	2.8	1.0	0.2	0.3	0.3	0.6
2001	2.6	0.8	2.3	3.0	6.7	5.6	3.1	0.6	0.2	0.0	0.7	0.1
2002	1.6	1.5	0.9	3.0	4.3	5.2	1.8	0.1	0.0	0.4	0.4	0.3
2003	1.5	1.6	0.3	2.7	4.4	7.7	2.4	0.1	0.2	1.0	0.1	0.4
2004	1.5	1.8	0.4	2.7	5.3	5.0	2.3	0.8	0.2	0.9	0.6	0.3

2005	2.1	3.2	4.3	1.8	6.4	5.2	2.8	0.8	0.2	0.0	0.0	2.0
2006	3.7	2.3	1.6	4.9	11.1	8.2	5.3	1.6	0.4	0.4	0.3	1.6
2007	2.1	1.9	4.0	4.4	8.4	8.1	5.9	1.0	0.2	0.0	0.2	0.1
2008	0.1	1.4	1.6	3.2	10.2	10.5	5.8	0.7	2.1	0.1	1.1	0.8
2009	0.7	1.4	1.2	2.6	7.5	7.6	3.3	2.3	0.1	1.4	0.1	2.5
2010	2.1	3.8	3.7	6.3	9.7	8.9	6.5	0.6	0.8	0.4	0.2	0.3
2011	2.0	1.7	2.9	4.8	5.4	4.7	3.2	0.1	0.7	0.1	0.0	0.0
2012	0.5	3.4	0.9	3.1	11.7	12.8	5.8	0.2	0.1	0.3	0.9	0.1
2013	2.1	4.9	3.4	5.5	13.0	8.6	5.2	3.0	0.8	0.0	0.1	1.0
2014	1.8	2.4	3.7	3.5	7.8	7.2	6.0	2.3	0.5	1.0	0.1	0.5
2015	0.7	0.2	4.2	5.5	7.0	10.0	2.6	0.3	0.6	1.1	0.9	1.0
2016	1.2	3.1	5.7	3.4	8.6	9.8	6.4	1.7	0.2	0.1	0.0	2.9
2017	2.2	0.9	5.0	2.8	11.0	10.0	7.7	1.8	0.2	0.0	0.0	1.4
2018	0.5	3.6	2.3	5.7	8.1	11.0	2.4	0.8	0.9	0.0	0.0	0.4
Mean	1.8	2.5	2.4	4.4	8.8	8.8	4.7	1.3	0.4	0.3	0.4	1.0

Appendix 7-4: Mean Monthly Rainfall Data at Muger (mm).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	0.1	3.4	6.8	3.7	11.6	13.5	12.4	10.5	7.0	2.1	0.1	0.3
1988	0.4	1.9	0.3	1.7	2.2	9.1	12.9	12.5	12.3	3.4	0.3	0.1
1989	0.7	1.3	4.4	2.8	0.9	6.9	16.4	11.6	6.3	0.9	0.3	1.6
1990	0.6	3.2	1.7	2.1	1.8	6.2	11.4	13.5	6.7	0.4	0.2	0.1
1991	0.2	0.9	2.5	1.1	2.2	6.8	12.8	11.8	5.4	0.7	0.2	0.5
1992	1.0	1.6	0.9	3.3	2.7	9.1	9.6	12.7	4.4	2.7	0.7	0.3
1993	0.9	0.8	1.0	4.3	4.3	12.5	11.7	13.3	7.8	2.0	0.1	0.1
1994	0.0	0.3	1.4	2.3	4.1	8.7	13.2	12.6	6.6	0.3	0.3	0.1
1995	0.0	1.7	1.1	2.7	3.3	8.8	11.2	12.6	4.7	0.4	0.1	1.3
1996	1.0	0.4	3.7	3.1	6.0	13.0	15.9	12.8	7.9	0.6	0.7	0.3
1997	0.8	0.0	1.6	2.8	5.2	10.7	8.8	9.1	4.4	5.5	1.3	0.3
1998	0.8	1.1	0.9	1.6	4.5	5.3	16.2	11.4	8.3	5.6	0.4	0.0
1999	0.9	0.2	0.5	1.5	5.4	7.8	9.7	11.6	5.8	5.7	0.0	0.2
2000	0.1	0.0	0.5	2.3	3.1	5.1	9.5	8.7	4.8	2.0	0.6	0.2
2001	0.2	0.6	1.8	1.1	2.5	7.4	7.6	6.9	2.9	1.3	0.3	0.1

2002	0.6	0.3	1.6	1.5	1.3	6.2	4.7	5.6	2.8	0.3	0.1	0.3
2003	0.2	0.4	1.5	0.8	0.9	3.8	5.3	8.4	4.7	0.1	0.3	0.9
2004	0.1	0.2	0.8	2.3	1.5	4.3	6.2	6.0	4.6	1.0	0.5	0.9
2005	0.5	0.2	1.9	3.2	3.7	4.5	8.3	6.6	4.4	1.1	0.2	0.0
2006	0.3	1.2	2.7	1.8	3.9	8.8	13.5	10.1	7.4	2.6	0.6	0.5
2007	0.4	1.2	1.4	2.0	6.2	6.6	12.1	11.4	7.5	0.5	0.1	0.0
2008	0.3	0.1	0.3	2.0	4.8	5.9	13.9	12.5	5.5	2.4	1.7	0.2
2009	1.0	0.8	1.0	2.4	2.4	5.6	10.1	10.1	5.7	3.3	0.2	0.9
2010	0.2	1.5	1.4	2.8	7.3	11.9	12.5	12.5	8.9	0.8	1.1	0.5
2011	0.5	0.1	1.6	1.5	5.5	8.0	6.4	6.7	3.9	0.5	1.1	0.0
2012	0.0	0.0	0.8	2.2	2.6	5.6	13.8	12.7	8.0	0.5	0.5	0.4
2013	0.8	0.3	1.3	2.6	7.9	9.2	15.5	10.5	6.5	3.6	1.3	0.0
2014	0.2	0.6	2.3	3.6	6.4	7.5	10.6	10.4	10.0	3.8	0.7	1.3
2015	0.1	0.5	1.2	0.4	5.4	6.4	7.5	8.8	3.5	1.2	1.7	1.4
2016	0.3	1.2	1.6	2.3	6.9	5.9	10.2	11.1	6.0	0.7	0.2	0.0
2017	0.0	2.7	2.3	2.2	5.6	4.7	11.9	9.4	6.4	1.3	0.5	0.0
2018	0.1	1.6	0.5	1.9	3.3	5.6	7.4	8.8	2.7	1.2	1.5	0.1
Mean	0.4	0.9	1.7	2.3	4.1	7.5	10.8	10.4	6.3	1.8	0.6	0.4

Appendix 7-5: Mean Monthly Rainfall Data at Muketuri (mm).

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	2.2	8.2	5.1	8.7	5.5	7.5	7.9	3.0	1.1	0.1	0.1	0.4
1988	1.8	0.4	1.6	0.3	3.9	10.4	11.0	7.2	2.3	0.1	0.3	0.5
1989	1.5	3.2	4.0	0.4	2.7	11.6	9.7	3.9	0.8	0.3	1.3	0.3
1990	4.2	1.9	2.6	0.5	2.2	8.3	9.1	5.3	0.6	0.1	0.2	0.1
1991	1.1	3.0	1.5	1.5	3.3	9.6	9.9	3.9	0.6	0.1	0.4	1.3
1992	1.7	0.9	2.6	0.8	4.0	7.7	9.7	2.7	1.2	0.4	0.3	0.7
1993	1.0	0.8	5.1	2.4	5.7	8.8	9.5	5.8	1.4	0.1	0.3	0.0
1994	0.1	1.3	1.6	2.3	3.9	10.3	10.2	4.7	0.2	0.4	0.0	0.0
1995	1.9	1.4	2.7	1.2	2.4	9.3	10.9	3.5	0.2	0.1	0.9	0.9
1996	0.5	4.4	3.0	3.0	7.8	11.5	9.1	4.6	0.5	0.6	0.2	0.8
1997	0.0	1.5	2.1	2.1	5.3	6.9	6.8	2.0	3.7	0.9	0.1	1.1

1998	1.9	1.3	1.3	2.2	3.6	12.5	9.2	4.9	3.9	0.1	0.0	0.8
1999	0.3	1.4	0.6	1.4	6.1	8.8	9.7	3.9	3.7	0.0	0.2	0.1
2000	0.0	0.2	1.7	0.9	2.3	8.1	6.7	2.3	0.8	0.2	0.4	0.2
2001	0.5	2.7	0.9	1.7	3.6	6.1	5.6	2.0	0.5	0.1	0.1	0.5
2002	0.3	1.4	1.4	0.7	3.1	5.3	4.4	1.5	0.1	0.0	0.4	0.3
2003	0.2	1.4	1.0	0.2	2.2	4.1	7.1	2.1	0.0	0.1	1.1	0.1
2004	0.3	1.2	1.9	0.1	1.9	5.0	4.2	2.2	0.5	0.1	0.9	0.6
2005	0.2	2.1	3.6	2.8	1.4	6.2	4.5	2.2	0.6	0.2	0.0	0.2
2006	1.7	3.6	2.0	1.3	4.2	11.5	8.4	4.8	1.5	0.2	0.3	0.4
2007	1.4	2.0	1.9	3.3	3.3	9.0	7.9	5.3	0.6	0.1	0.0	0.2
2008	0.1	0.0	1.4	1.3	2.3	10.6	10.4	4.4	0.5	1.7	0.1	1.1
2009	0.4	0.6	1.0	0.6	2.2	8.5	8.2	3.1	2.3	0.1	1.2	0.1
2010	2.3	1.9	3.0	3.1	5.1	10.8	10.9	5.3	0.3	0.7	0.3	0.2
2011	0.2	2.0	1.4	2.7	3.7	5.4	5.4	2.0	0.1	0.6	0.0	0.0
2012	0.0	0.5	2.4	0.6	2.8	12.2	12.3	4.5	0.1	0.1	0.3	0.9
2013	0.1	1.8	3.2	2.2	4.6	14.2	9.1	4.5	2.9	0.6	0.0	0.1
2014	0.8	1.7	2.6	3.0	3.1	8.4	7.9	5.3	1.6	0.5	0.8	0.2
2015	0.7	0.9	0.1	3.3	4.2	4.8	8.3	2.1	0.4	0.8	1.0	0.7
2016	1.3	1.2	3.4	4.6	2.8	8.6	8.8	5.0	0.7	0.2	0.0	0.0
2017	2.4	2.3	0.9	4.9	1.8	9.7	8.7	5.7	1.3	0.2	0.0	0.1
2018	1.4	0.3	3.3	1.4	4.4	6.7	9.0	2.1	0.9	1.0	0.0	0.0
Mean	1.0	1.8	2.3	2.0	3.6	8.6	8.4	4.0	1.1	0.4	0.4	0.4

Appendix 7-6: Mean Monthly Rainfall Data Sululta (mm).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	4.6	7.2	5.3	10.0	6.5	7.7	6.9	3.5	0.7	0.1	0.3	0.2
1988	2.3	0.1	2.3	0.7	5.0	9.6	10.1	7.4	2.0	0.0	0.4	0.7
1989	1.5	4.4	3.8	0.4	4.6	11.6	9.4	3.6	0.7	0.4	1.4	0.6
1990	5.8	2.2	2.5	1.1	3.3	8.9	9.5	4.8	0.7	0.1	0.3	0.2
1991	1.3	3.8	1.3	1.5	4.5	9.6	9.7	4.1	0.1	0.3	0.4	1.9
1992	2.0	1.1	3.0	0.9	4.7	8.5	8.6	2.8	1.1	0.5	0.4	1.2
1993	1.0	1.1	6.0	2.8	6.9	9.0	10.3	4.3	1.3	0.1	0.5	0.0
1994	0.1	1.6	2.3	2.4	4.5	11.3	8.8	3.6	0.2	0.4	0.0	0.0

1995	2.5	1.5	3.2	1.1	4.0	8.1	10.0	3.5	0.3	0.0	1.0	1.0
1996	0.7	5.5	2.9	3.4	9.6	12.0	8.9	4.9	0.4	0.6	0.2	1.0
1997	0.0	2.1	2.6	3.3	6.2	6.9	6.9	2.0	5.0	0.9	0.4	1.3
1998	2.7	0.9	2.3	2.1	4.5	13.4	8.2	5.1	4.1	0.2	0.0	0.7
1999	0.5	1.3	0.7	2.5	7.5	7.0	8.8	3.2	3.3	0.0	0.1	0.1
2000	0.0	0.6	2.0	0.9	3.4	7.5	6.3	2.4	0.7	0.2	0.5	0.2
2001	0.7	3.2	1.1	2.3	4.0	5.7	5.8	1.7	0.5	0.2	0.2	0.5
2002	0.7	1.6	1.4	0.9	3.0	4.5	4.4	1.3	0.1	0.0	0.6	0.4
2003	0.4	1.8	1.5	0.3	2.5	5.1	6.2	2.1	0.0	0.4	0.9	0.3
2004	0.2	2.0	1.8	0.2	2.7	5.1	4.3	2.3	0.7	0.1	1.0	0.8
2005	0.3	2.4	5.0	2.9	2.1	6.1	4.4	2.5	0.8	0.2	0.0	0.3
2006	2.2	4.6	2.6	1.6	4.8	10.7	7.8	4.0	1.9	0.4	0.3	1.2
2007	0.9	2.7	2.1	4.5	4.1	8.0	7.7	5.4	0.3	0.2	0.0	0.2
2008	0.1	0.3	1.8	1.7	2.7	10.8	10.0	4.0	1.5	1.3	0.1	1.5
2009	0.4	1.1	1.1	1.3	2.4	8.2	6.8	2.2	2.3	0.2	1.5	0.1
2010	3.5	2.0	3.8	3.6	6.6	9.1	8.1	5.2	0.3	0.7	0.4	0.3
2011	0.2	2.2	2.2	3.0	4.0	4.6	5.1	2.1	0.3	0.6	0.0	0.0
2012	0.1	0.8	2.9	0.8	3.5	12.2	11.4	4.6	0.1	0.2	0.2	0.9
2013	0.1	2.6	5.4	2.9	5.8	11.1	8.8	4.7	2.0	0.8	0.0	0.1
2014	1.2	2.0	2.6	3.7	3.6	7.8	6.9	5.5	1.4	0.6	0.9	0.2
2015	0.5	0.8	0.5	4.0	4.9	8.0	7.8	2.3	0.4	0.6	1.1	1.0
2016	1.1	1.9	4.2	4.1	4.0	8.2	10.0	5.1	0.4	0.2	0.0	0.0
2017	3.4	2.3	1.3	4.7	3.4	9.8	10.3	6.0	1.2	0.2	0.0	0.1
2018	1.5	0.8	3.8	2.4	5.4	7.4	10.1	1.4	0.8	0.9	0.1	0.0
Mean	1.3	2.1	2.7	2.4	4.6	8.5	8.1	3.9	1.1	0.4	0.4	0.5

Appendix 7-7: Mean monthly streamflow of upper Muger near Chancho.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	0.36	0.32	0.17	0.21	0.33	0.44	31.85	45.81	23.28	2.35	0.44	0.26
1988	0.18	0.13	0.15	0.14	0.12	0.33	23.10	51.26	19.39	1.44	0.33	0.20
1989	0.13	0.12	0.26	0.39	0.23	0.14	25.55	52.46	32.83	3.57	0.48	0.28
1990	0.30	0.21	0.16	0.31	0.33	0.30	7.42	40.59	14.26	2.38	0.63	0.37
1991	0.22	0.23	0.19	0.23	0.92	1.10	11.60	55.47	25.01	2.68	0.59	0.29

1992	0.21	0.13	0.13	0.11	0.21	4.30	47.10	42.25	22.26	0.93	0.58	0.30
1993	0.17	0.13	0.08	0.15	0.32	0.26	24.18	68.89	26.83	1.33	0.42	0.23
1994	0.17	0.19	0.21	0.28	0.21	0.64	22.04	36.62	18.62	1.57	0.41	0.26
1995	0.20	0.16	0.46	1.01	1.25	3.51	25.52	38.37	14.64	2.04	0.47	0.29
1996	0.21	0.26	0.18	0.20	0.14	0.31	25.52	56.91	34.62	3.44	0.58	0.31
1997	0.25	0.27	0.22	0.36	0.17	0.27	27.51	62.39	16.18	1.92	0.47	0.34
1998	0.23	0.33	0.23	0.48	0.21	0.33	17.35	70.24	24.20	2.36	0.55	0.34
1999	0.21	0.43	0.48	0.18	0.14	0.77	20.01	57.77	19.50	1.37	0.41	0.30
2000	0.25	0.22	0.14	0.16	0.19	0.65	12.23	46.19	19.43	2.05	0.47	0.26
2001	0.19	0.17	0.11	0.46	0.45	1.70	43.20	64.34	30.58	3.56	0.65	0.33
2002	0.21	0.11	0.14	0.19	0.20	1.22	24.41	38.47	16.80	1.63	0.50	0.28
2003	0.15	0.21	0.14	0.41	0.35	0.57	19.22	34.75	8.31	1.01	0.35	0.26
2004	0.15	0.23	0.21	0.33	0.21	0.69	30.05	34.75	8.50	0.64	0.24	0.16
2005	0.10	0.06	0.07	0.11	0.07	0.32	15.46	30.05	4.72	0.66	0.36	0.17
2006	0.20	0.10	0.07	0.11	0.20	0.94	34.76	52.33	20.61	6.38	0.63	0.26
2007	0.17	0.05	0.08	0.05	0.07	0.43	21.80	52.16	15.04	3.02	0.45	0.21
2008	0.11	0.04	0.04	0.10	0.11	0.37	14.29	52.02	10.92	1.65	0.49	0.24
2009	0.14	0.06	0.22	0.13	0.33	5.08	36.79	34.33	9.28	0.79	0.28	0.18
2010	0.15	0.08	0.10	0.10	0.07	0.40	26.13	42.32	9.41	0.29	0.35	0.20
2011	0.11	0.06	0.08	0.15	0.06	1.44	52.81	45.11	29.01	2.19	0.25	0.15
2012	0.10	0.05	0.04	0.24	0.07	1.75	27.19	50.33	13.04	1.10	0.27	3.28
2013	13.26	11.49	11.79	14.52	17.77	31.69	123.51	150.91	82.15	24.68	16.89	11.65
2014	0.11	0.10	0.56	0.39	0.24	1.88	42.02	45.16	17.80	1.27	0.42	0.22
2015	0.17	0.10	0.09	0.12	0.25	7.05	40.22	45.61	14.36	1.46	0.36	0.20
2016	0.08	0.05	0.04	0.05	0.37	2.91	49.26	49.60	10.80	2.41	2.59	0.27
2017	0.24	0.06	0.05	0.04	0.07	0.47	23.90	47.89	7.00	0.97	0.27	0.33
2018	0.17	0.26	0.11	0.57	0.85	6.65	50.44	37.55	20.70	1.34	0.39	0.23
Mean	0.59	0.51	0.53	0.70	0.83	2.47	31.14	51.03	20.00	2.64	1.02	0.71

Appendix 7-8: Watershed similarity between gauged and ungauged.

Watershed	Soil type	LULC	Slope class
W_1	Rendzic Leptosols, Eutric Leptosols, Eutric Vertisols, Eutric Regosols and Haplic Nitisols	Forest, Woodland, Shrubland, Cropland, Grassland, Barren, Settlement	0-10, 10-20, 20-30, 30-50 and >50
W_2	Rendzic Leptosols, Eutric Leptosols, Eutric Vertisols, Eutric Vertisols, Eutric Regosols and Haplic Nitisol	Forest, Shrubland, Cropland, Grassland, Barren, Settlement	0-10, 10-20, 20-30, 30-50 and >50
W_3	Rendzic Leptosols, Eutric Leptosols, Eutric Vertisols, Chromic Luvisols and Haplic Alisols	Woodland, Shrubland, Cropland, Grassland, Barren and Settlement	0-10, 10-20, 20-30, 30-50 and >50
W_4	Rendzic Leptosols, Eutric Leptosol, Haplic Alisols, Haplic Nitisols, Rhodic Nitisols and Eutric Cambisols	Woodland, Shrubland, Cropland, Grassland, Barren, Settlement and Forest	0-10, 10-20, 20-30, 30-50 and >50
W_5	Rendzic Leptosols, Eutric Leptosol, Chromic Luvisols and Haplic Alisols	Woodland, Shrubland, Cropland, Grassland, Barren and Forest	0-10, 10-20, 20-30, 30-50 and >50
W_6	Calcic Vertisols, Eutric Fluvisols, Eutric Vertisols, Eutric Leptosols and Rendzic Leptosols	Forest, Woodland, Shrubland, Cropland, Grassland and Barren	0-10, 10-20, 20-30, 30-50 and >50
W_7	Rendzic Leptosols, Haplic Alisols, Chromic Luvisols, Eutric Vertisols and Haplic Luvisols	Forest, Woodland, Shrubland, Cropland, Grassland, Barren, Water bodies and Settlement	0-10, 10-20, 20-30, 30-50 and >50
W_8	Rendzic Leptosols, Rhodic Nitisols, Eutric Leptosols, Eutric Fluvisols,	Forest, Woodland, Shrubland, Cropland, Grassland, Barren	0-10, 10-20, 20-30, 30-50 and >50

	Eutric Vertisols and Calcic Vertisols	and Settlement	
W_9	Rendzic Leptosols, Eutric Leptosols, Eutric Vertisols, Calcic Vertisols, Haplic Nitisols and Eutric Fluvisols	Forest, Woodland, Shrubland, Cropland, Grassland and Barren	0-10, 10-20, 20-30, 30-50 and >50
W_{10}	Rendzic Leptosols	Settlement, Forest, Woodland, Shrubland, Cropland and Grassland	0-10, 10-20, 20-30, 30-50 and >50
W_{11}	Chromic Luvisols, Rendzic Leptosols, Eutric Leptosols, Haplic Alisols, Eutric Vertisols	Barren, Forest, Woodland, Shrubland, Cropland and Grassland	0-10, 10-20, 20-30, 30-50 and >50
W_{12}	Haplic Nitisols, Eutric Leptosols, Eutric Fluvisols and Eutric Vertisols	Settlement, Forest, Woodland, Shrubland, Cropland and Grassland	0-10, 10-20, 20-30, 30-50 and >50
W_{13}	Eutric Leptosols, Eutric Vertisols, Eutric Cambisols, Eutric Fluvisols and Chromic Luvisols	Barren, Forest, Woodland, Shrubland, Cropland and Grassland	0-10, 10-20, 20-30, 30-50 and >50
W_{14}	Rendzic Leptosols, Eutric Leptosols, Haplic Luvisols, Haplic Nitisols and Eutric Vertisols	Settlement, Forest, Woodland, Shrubland, Cropland, Grassland and Barren	0-10, 10-20, 20-30, 30-50 and >50
W_{15}	Rendzic Leptosols , Eutric Leptosols, Haplic Alisols, Haplic Luvisols, Eutric Vertisols and Haplic Nitisols	Settlement, Forest, Woodland, Shrubland, Cropland, Grassland and Barren	0-10, 10-20, 20-30, 30-50 and >50
W_{16}	Rendzic Leptosols, Eutric Leptosols, Haplic Alisols, Eutric Vertisols,	Settlement, Forest, Woodland,	0-10, 10-20, 20-30, 30-

	Haplic Nitisols and Haplic Luvisols	Shrubland, Cropland, Grassland and Barren	50 and >50
W_{17}	Eutric Leptosols, Eutric Vertisols, Eutric Cambisols, Chromic Luvisols and Haplic Nitisols	Water bodies, Forest, Woodland, Shrubland, Cropland, Grassland, Barren and Settlement	0-10, 10-20, 20-30, 30-50 and >50

Appendix 7-9: Average climate and reference evapotranspiration.

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun hours	Rad MJ/m²/day	ETo mm/day
January	9.6	23.1	50	147	7.5	18.6	3.84
February	10.5	24.3	49	156	7.5	19.8	4.28
March	11.5	24.8	49	156	6.5	19.3	4.4
April	12	25.2	56	156	6.8	19.9	4.44
May	11.9	23.9	52	147	6.8	19.5	4.33
June	10.8	22.7	65	121	5.5	17.3	3.63
July	10.1	18.8	77	104	3.6	14.6	2.82
August	10	18.4	79	112	3.6	14.8	2.75
September	10.1	20	72	138	5	17	3.25
October	10.1	21.5	54	190	7.3	19.7	4.15
November	8.7	21.2	51	190	9	20.8	4.16
December	7.8	21.8	49	156	8.5	19.4	3.82
Average	10.3	22.1	58	148	6.5	18.4	3.82

Appendix 7-10: Rainfall and effective rain fall.

Month	Rain (mm)	Eff rain (mm)
January	2	2
February	11	10.8
March	26	24.9
April	40	37.4
May	131	103.5
June	146	111.9
July	291	154.1
August	245	149
September	144	110.8

October	33	31.3
November	20	19.4
December	6	5.9
Total	1095	761

1. Irrigation Water requirement for Potato for first growing period

Appendix 7-11: Irrigation Water requirement for Potato for first growing period

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.5	1.59	15.9	1.5	14.4
Jan	2	Init	0.5	1.59	15.9	1.6	14.4
Jan	3	Deve	0.54	1.78	19.5	3	16.5
Feb	1	Deve	0.74	2.51	25.1	3.9	21.2
Feb	2	Deve	0.95	3.31	33.1	4.9	28.3
Feb	3	Mid	1.11	3.98	31.9	8.8	23
Mar	1	Mid	1.13	4.14	41.4	14.4	27
Mar	2	Mid	1.13	4.25	42.5	18.7	23.7
Mar	3	Mid	1.13	4.23	46.6	16.9	29.6
Apr	1	Mid	1.13	4.22	42.2	14.4	27.7
Apr	2	Late	1.06	3.93	39.3	13.3	26
Apr	3	Late	0.92	3.57	35.7	12.4	23.3
May	1	Late	0.79	3.18	31.8	10.5	21.3
					421	124.4	296.6

Appendix 7-12: Irrigation requirement for Potato for second growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	1	Init	0.5	1.63	16.3	53.9	0
Aug	2	Init	0.5	1.66	16.6	54.7	0
Aug	3	Deve	0.54	1.82	20.1	45.6	0
Sep	1	Deve	0.74	2.54	25.4	35	0
Sep	2	Deve	0.94	3.32	33.2	26.8	6.4
Sep	3	Mid	1.11	3.92	39.2	20.9	18.3
Oct	1	Mid	1.12	3.99	39.9	13.8	26.1
Oct	2	Mid	1.12	4.02	40.2	7	33.2

Oct	3	Mid	1.12	3.98	43.8	6.1	37.8
Nov	1	Late	1.11	3.94	39.4	5.7	33.7
Nov	2	Late	1.02	3.57	35.7	4	31.6
Nov	3	Late	0.89	3.01	30.1	3.1	27
Dec	1	Late	0.77	2.52	20.2	1.6	18.2
					400	278.3	232.3

Appendix 7-13: Irrigation water requirement for Tomato for first growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.6	1.91	19.1	1.5	17.6
Jan	2	Init	0.6	1.91	19.1	1.6	17.6
Jan	3	Deve	0.6	1.98	21.8	3	18.8
Feb	1	Deve	0.69	2.32	23.2	3.9	19.3
Feb	2	Deve	0.82	2.85	28.5	4.9	23.7
Feb	3	Deve	0.94	3.36	26.8	8.8	18
Mar	1	Deve	1.06	3.88	38.8	14.4	24.4
Mar	2	Mid	1.13	4.25	42.5	18.7	23.8
Mar	3	Mid	1.13	4.23	46.6	16.9	29.7
Apr	1	Mid	1.13	4.22	42.2	14.4	27.8
Apr	2	Mid	1.13	4.21	42.1	13.3	28.8
Apr	3	Late	1.11	4.31	43.1	12.4	30.6
May	1	Late	1.01	4.05	40.5	10.5	30
May	2	Late	0.89	3.71	37.1	9	28.1
May	3	Late	0.8	3.31	16.6	5.8	10.2
					488	139.2	348.2

Appendix 7-14: Irrigation water requirement for Tomato for second growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	1	Init	0.6	1.96	19.6	53.9	0
Aug	2	Init	0.6	1.99	19.9	54.7	0
Aug	3	Deve	0.6	2.03	22.4	45.6	0
Sep	1	Deve	0.68	2.36	23.6	35	0

Sep	2	Deve	0.81	2.87	28.7	26.8	1.8
Sep	3	Deve	0.94	3.35	33.5	20.9	12.6
Oct	1	Mid	1.07	3.83	38.3	13.8	24.5
Oct	2	Mid	1.12	4.02	40.2	7	33.3
Oct	3	Mid	1.12	3.99	43.9	6.1	37.8
Nov	1	Mid	1.12	3.95	39.5	5.7	33.8
Nov	2	Mid	1.12	3.92	39.2	4	35.1
Nov	3	Late	1.09	3.69	36.9	3.1	33.7
Dec	1	Late	0.98	3.21	32.1	2	30.1
Dec	2	Late	0.87	2.75	27.5	0.9	26.6
Dec	3	Late	0.79	2.52	7.6	0.3	6.9
					452.6	279.9	276.3

Appendix 7-15: Irrigation water requirement for Cabbage for first growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.7	2.23	22.3	1.5	20.8
Jan	2	Init	0.7	2.23	22.3	1.6	20.7
Jan	3	Init	0.7	2.3	25.3	3	22.3
Feb	1	Deve	0.7	2.37	23.7	3.9	19.8
Feb	2	Deve	0.74	2.57	25.7	4.9	20.8
Feb	3	Deve	0.79	2.81	22.5	8.8	13.7
Mar	1	Deve	0.84	3.07	30.7	14.4	16.3
Mar	2	Deve	0.89	3.36	33.6	18.7	14.8
Mar	3	Deve	0.95	3.56	39.2	16.9	22.3
Apr	1	Deve	1.01	3.77	37.7	14.4	23.3
Apr	2	Mid	1.03	3.85	38.5	13.3	25.2
Apr	3	Mid	1.03	4	40	12.4	27.6
May	1	Mid	1.03	4.15	41.5	10.5	31.1
May	2	Mid	1.03	4.3	43	9	34
May	3	Late	1.03	4.25	46.7	12.7	34
Jun	1	Late	0.99	4.03	40.3	14.9	25.4
Jun	2	Late	0.95	3.8	15.2	6.8	6.7

					548.4	167.9	378.9

Appendix 7-16: Irrigation water requirement for Cabbage for second growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Sep	1	Init	0.7	2.42	24.2	35	0
Sep	2	Init	0.7	2.46	24.6	26.8	0
Sep	3	Init	0.7	2.48	24.8	20.9	3.9
Oct	1	Init	0.7	2.5	25	13.8	11.2
Oct	2	Deve	0.73	2.63	26.3	7	19.3
Oct	3	Deve	0.79	2.82	31	6.1	24.9
Nov	1	Deve	0.85	3	30	5.7	24.3
Nov	2	Deve	0.91	3.17	31.7	4	27.7
Nov	3	Deve	0.96	3.26	32.6	3.1	29.5
Dec	1	Mid	1.02	3.34	33.4	2	31.4
Dec	2	Mid	1.04	3.3	33	0.9	32.1
Dec	3	Mid	1.04	3.3	36.3	1.2	35.1
Jan	1	Mid	1.04	3.31	33.1	1.5	31.6
Jan	2	Mid	1.04	3.31	33.1	1.6	31.6
Jan	3	Late	1.03	3.4	37.4	3	34.4
Feb	1	Late	0.98	3.31	33.1	3.9	29.2
Feb	2	Late	0.93	3.26	6.5	1	6.5
					496.2	137.5	372.8

Appendix 7-17: Irrigation water requirement for Barley for first growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.3	0.96	9.6	1.5	8.1
Jan	2	Deve	0.35	1.11	11.1	1.6	9.6
Jan	3	Deve	0.66	2.18	24	3	21
Feb	1	Mid	1	3.4	34	3.9	30.1
Feb	2	Mid	1.12	3.92	39.2	4.9	34.3
Feb	3	Mid	1.12		32.2	8.8	23.3
Mar	1	Mid	1.12	4.12	41.2	14.4	26.8
Mar	2	Mid	1.12	4.23	42.3	18.7	23.5
Mar	3	Mid	1.12	4.21	46.3	16.9	29.4

Apr	1	Late	0.96	3.6	36	14.4	21.6
Apr	2	Late	0.67	2.51	25.1	13.3	11.8
Apr	3	Late	0.38	1.48	14.8	12.4	2.3
					355.7	113.9	241.8

Appendix 7-18: Irrigation requirement for Barley for second growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.3	1.02	10.2	44.8	0
Jul	2	Deve	0.35	1.07	10.7	57	0
Jul	3	Deve	0.65	2.05	22.5	55.2	0
Aug	1	Mid	0.98	3.2	32	53.9	0
Aug	2	Mid	1.1	3.63	36.3	54.7	0
Aug	3	Mid	1.1	3.71	40.8	45.6	0
Sep	1	Mid	1.1	3.78	37.8	35	2.8
Sep	2	Mid	1.1	3.86	38.6	26.8	11.7
Sep	3	Late	1.09	3.86	38.6	20.9	17.7
Oct	1	Late	0.88	3.16	31.6	13.8	17.8
Oct	2	Late	0.6	2.17	21.7	7	14.7
Oct	3	Late	0.35	1.24	9.9	4.4	3.9
					330.7	419.1	68.6

Appendix 7-19: Irrigation requirement for Wheat for first growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.3	0.96	9.6	1.5	8.1
Jan	2	Init	0.3	0.96	9.6	1.6	8
Jan	3	Deve	0.3	1	10.9	3	7.9
Feb	1	Deve	0.48	1.62	16.2	3.9	12.3
Feb	2	Deve	0.75	2.63	26.3	4.9	21.4
Feb	3	Deve	1	3.58	28.7	8.8	19.8
Mar	1	Mid	1.12	4.13	41.3	14.4	26.9

Mar	2	Mid	1.12	4.23	42.3	18.7	23.6
Mar	3	Mid	1.12	4.22	46.4	16.9	29.5
Apr	1	Mid	1.12	4.21	42.1	14.4	27.6
Apr	2	Late	0.97	3.63	36.3	13.3	23
Apr	3	Late	0.7	2.71	27.1	12.4	14.6
May	1	Late	0.42	1.7	17	10.5	6.6
					353.8	124.4	229.4

Appendix 7-20: Irrigation water requirement for Wheat for second growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	1	Init	0.3	0.98	9.8	53.9	0
Aug	2	Init	0.3	0.99	9.9	54.7	0
Aug	3	Deve	0.3	1.02	11.2	45.6	0
Sep	1	Deve	0.48	1.64	16.4	35	0
Sep	2	Deve	0.75	2.63	26.3	26.8	0
Sep	3	Mid	1.02	3.6	36	20.9	15.2
Oct	1	Mid	1.11	3.98	39.8	13.8	26
Oct	2	Mid	1.11	4.01	40.1	7	33.1
Oct	3	Mid	1.11	3.97	43.7	6.1	37.6
Nov	1	Late	1.11	3.91	39.1	5.7	33.4
Nov	2	Late	0.91	3.19	31.9	4	27.8
Nov	3	Late	0.64	2.17	21.7	3.1	18.5
Dec	1	Late	0.4	1.3	10.4	1.6	8.4
					336.3	278.3	200

Appendix 7-21: Irrigation water requirement for other vegetables for first growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.7	2.23	22.3	1.5	20.8
Jan	2	Init	0.7	2.23	22.3	1.6	20.7
Jan	3	Deve	0.77	2.52	27.7	3	24.7
Feb	1	Deve	0.88	2.99	29.9	3.9	26
Feb	2	Mid	0.99	3.46	34.6	4.9	29.7

Feb	3	Mid	1.03	3.69	29.5	8.8	20.7
Mar	1	Mid	1.03	3.79	37.9	14.4	23.5
Mar	2	Mid	1.03	3.88	38.8	18.7	20.1
Mar	3	Late	1	3.75	41.2	16.9	24.3
Apr	1	Late	0.95	3.54	17.7	7.2	10.5
					302	81	221

Appendix 7-22: Irrigation requirement for other vegetables for second growing period.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	1	Init	0.7	2.37	23.7	44.8	0
Jul	2	Init	0.7	2.15	21.5	57	0
Jul	3	Deve	0.76	2.4	26.4	55.2	0
Aug	1	Deve	0.87	2.85	28.5	53.9	0
Aug	2	Mid	0.98	3.23	32.3	54.7	0
Aug	3	Mid	1.01	3.42	37.7	45.6	0
Sep	1	Mid	1.01	3.49	34.9	35	0
Sep	2	Late	1.01	3.56	35.6	26.8	8.7
Sep	3	Late	0.97	3.42	34.2	20.9	13.4
Oct	1	Late	0.92	3.3	9.9	4.1	3
					284.8	398.1	25.1