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FACULTY OF CIVIL AND ENVIRNMENTAL ENGINEERING

CHAIR OF HYDROLOGY AND HYDRAULIC ENGINEERING

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GIS BASED PHYSICAL IRRIGATION POTENTIAL ASSESSMENT: THE CASE OF SIBILU RIVER CATCHMENT, ETHIOPIA

BY: SIFAN BEKELE

A Thesis Submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Hydraulic Engineering.

January, 2020

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Main Advisor: Dr-Ing. Fekadu Fufa (PhD)

Co-Advisor: Mr.Deme Betele (MSc.)

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Jimma, Ethiopia

DECLARATION

I hereby declare that the Thesis entitled **“GIS BASED PHYSICAL IRRIGATION POTENTIAL ASSESSMENT:THE CASE OF SIBILU RIVER CATCHMENT ,ETHIOPIA**” is my original work which I submit for partial fulfillment of the degree of Masters of Science in Hydraulic Engineering to school of graduate studies; Jimma Institute of Technology, Jimma University; Hydrology and Hydraulic Engineering Chair. The Thesis was conducted under the guidance of main Advisor, Dr-Ing. Fekadu Fufa (PhD) and Co-Advisor Mr.Deme Betele (MSc.)

(MSc.) Candidate	Signature	Date
Sifan Bekele Binagdie	---------------------	-------------------

This thesis has been submitted for examination with my approval as University supervision.

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Dr-Ing. Fekadu Fufa (PhD)	------------------------	-----------------------
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Mr.Deme Betele (MSc.)	--------------------------	------------------------

APPROVAL

The thesis entitled **"GIS BASED PHYSICAL IRRIGATION POTENTIAL ASSESSMENT: THE CASE OF SIBILU RIVER CATCHMENT,"** submitted by Sifan Bekele Binagdie is approved and accepted as a partial fulfillment of the Requirement for the Degree of Masters of Science in Hydraulic Engineering at Jimma Institute of Technology.

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Main Advisor:	Dr-Ing. Fekadu Fufa (PhD)	--------------------------	-----------------------
Co-Advisor:	Mr.Deme Betele (MSc.)	---------------------------	-----------------------

As members of the examing board of MSc-thesis, we certify that we have read and evaluated the thesis prepared by Sifan Bekele Binagdie.We recommend that the thesis could be accepted as a Partial Fulfillment of the Requirements for the Degree of Masters of Science in Hydraulic Engineering.

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ACKNOWLEDGEMENT

First and foremost, I would like to thank the Almighty of God for the tremendous strength and courage throughout my life. Next to this; I would like to express my deepest gratitude to my main advisor Dr-Ing. Fekadu Fufa (PhD) and co- advisor Mr.Deme Betele (MSc.) for their professional guidance and constructive comments during the research period.

My acknowledgements are also extended to Ministry of Water Irrigation and Electricity, Ethiopian Mapping Agency and National Metrological Agency for their cooperation in providing relevant data.

Lastly, my deep sense of gratitude to my father Ato Bekele Binagdie, my mother W/ro Shashitu Nagawo, my brothers, sisters and my husband Dr Gutu Ijigu for their love, encouragement and affection. I express my gratitude to all my friends whose names have not been mentioned individually but have helped me directly or indirectly in this work.

ABSTRACT

Evaluating the suitability of a landscape for irrigation in advance is critical for the sustainability of an irrigation system. It needs supplementation from irrigated agriculture during dry season. Assessment of land suitability for irrigation purpose is important to utilize scarce resources efficiently and effectively for sustainable production of crops. There were only few studies on assessment of irrigation potential in Ethiopia and none has been done in the study area. Therefore, the aim of study was to assess the physical irrigation potential of Sibilu River catchment, using Geographic Information System. The irrigation suitability factors such as slope soil and land use land cover were weighted overlay in order to determine the most suitable land by using pairwise analysis in order to determine the weight of each parameter. The collected data were checked for inconsistency using double mass curve and the missing metrological data were filled by normal ratio method. Irrigation suitability factors were classified based on the Food and Agricultural Organization guideline for land evaluation in to highly suitable, moderately suitable, marginally suitable and not suitable classes, where the final irrigable land was identified by weighting the factors of suitability. The study used slope, soil and land use/ cover for irrigation suitability analysis with Geographic Information System based. The irrigation suitability analysis of these factors indicated that 56.5% of slope,19.3% of soil and 89.82% of land use/cover area were in the range of highly suitable for surface irrigation system. Over all the weighted overlay analysis of these factors gave potential irrigable land 57.53% of the study area were found to be highly suitable whereas 0.42% not suitable for irrigation developments. To grow on these identified irrigable areas, three crops such as cabbage, potato and pepper were computed from climate input data using Food and Agricultural Organization penman-monteith in CROPWAT 8.0 software and the command area was identified by comparing the irrigation water demand and water potential of the water source in the study area. In Conclusion, Sibilu River is highly suitable for surface irrigation in terms of suitability factors. However, only 133 ha were irrigable and therefore the dry flows should be increased or ground water should be constructed and water should be stored to meet irrigation potential.

Key Words*: CROPWAT, GIS, Irrigation Potential, Land Suitability, Sibilu Catchment*

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ACRONYMS

CROPWAT	Crop Water Requirement
DEM	Digital Elevation Model
EMA	Ethiopian Mapping Agency
FAO	Food and Agricultural Organization of United Nations
GIS	Geographic Information System
GLCN	Global Land Cover Network
IWIM	International Water Institute Management
MCE	Multi-Criteria Evaluation
MOA	Ministry of Agriculture
MOARD	Ministry of Agriculture and Rural Development
MOWIE	Ministry of Water Resources, Irrigation and Electricity
MOWR	Ministry of Water Resources
NASA	National Aerostatic and Survey Agency
NGA	National Geospatial Intelligence Agency
NMSA	National Metrological Service Agency
RS	Remote Sensing
UTM	Universal Trans-Mercator

1. INTRODUCTION

1.1. Background

Studies indicate that compared to 2009, by 2050, 70% more food production is required to meet the global food demand and 100% for developing countries (Dubois, 2011). This indicates that the increase in food demand for developing countries is very high as compared to developed countries, and it is true for Ethiopia. The population of Ethiopia has been increasing and it is around one hundred million currently (Hirko et al., 2017). To feed this highly increasing population, extensive system of increasing the agricultural product may not satisfactorily work since the supply of land is constant. Irrigation plays a fundamental role for food provision but, until recent years, it has performed below expectations in Sub-Saharan Africa (Garcia et al., 2011). In Oromia region, many areas are susceptible to problems arising from shortage of rainfall. It is also true for Sululta District which has been affected by onset delay in rain and its early cessation in different years (Hirko et al., 2017).

Ethiopia has a large potential of water and land resources that could be developed for irrigation, which can contribute to sustain food security and has 12 major river basins ,of which nine are wet and three are dry with annual runoff volume of 122 billion $m^3$of surface water and 2.6–6.5 billion m^3 of groundwater potential (Awulachew et al.,2010). Despite this abundance of water, Ethiopia receives food aid for about 10% of population (Worqlul et al.,2015). Ethiopia is estimated to have 3.7 M ha of potentially irrigable area with the available surface water resources and the land irrigated through the development of traditional and modern irrigation schemes are estimated to be about 386,603 hectares, which is about 10 percent of potentially irrigable land (Awulachew and Ayana, 2011).

Ethiopia depends on the rain-fed agriculture with limited use of irrigation for agricultural production. While the country has high potential to irrigate its agriculture, about 97 percent of Ethiopia's food crops are produced by rain-fed agriculture, whereas only three percent is from irrigated agriculture (FAO, 2015).

The major problem related with the rainfall-dependent agriculture in the country is the high degree of rainfall variability and unreliability. Due to this variability, crop failures due to dry spells and droughts are frequent.

As a result, food insecurity often turns into famine with the slightest adverse climatic incident, particularly, affecting the livelihoods of the rural poor. Hence, the solution for food insecurity could be provided by irrigation development that can lead to security by reducing variation in harvest, as well as intensification of cropping by producing more than one crop per year (FAO, 1994).

It is obvious that the utilization of water resources in irrigated agriculture provide supplementary and full season irrigation to overcome the effects of rainfall variability and unreliability. Therefore, irrigation agriculture has the potential to reduce spatial and temporal yield variability rather than only depending on rain-fed crop cultivation (Berti, 2003).

GIS is a computer based system that offers a convenient and powerful platform for performing suitablity evaluation and also it facilitates data entry, analysis and presentation as well as integration of different layers of data (Paul and Chosen, 2001).GIS has contributed to the identification and evaluation of potential solutions to water resource problems during the past decade (Pyradharshini and Canessane, 2015). The ability of GIS to manipulate various types of data helps to perform complex analysis extracting information about spatially distributed phenomena in greater efficiency (Nandi et al., 2016) makes GIS a preferable technology to study irrigation potential of a basin with evaluation of water resources and currently irrigated area.

Land suitability for potential surface irrigation was done following the standard FAO guidelines (FAO, 1976). Identification of suitable sites for irrigation were carried out by considering the soil, slope and land cover/use (FAO, 1976) could be weighted and evaluated using ArcGIS according to their suitability for irrigation. Since there was no study conducted in the study area based on weighting the land resources for irrigation potential, this study was added some asset to explore the irrigation resource (potential) in the study area. And also potential irrigable areas in the study area have not been identified and matched with the water requirements of some crops grown in the study area. Therefore; the aim of this study was to assess the irrigation potential of the Sibilu river catchment for irrigation using Geographic Information System technique.

1.2. Statement of the Problem

It is estimated that the eight major river basins of Ethiopia can irrigate about 5.3 M hectares of land (Awulachew et al.,2010).However; combination of population growth, land degradation and more frequent droughts resulted in frequent food-related crises. Irrigation development is therefore, perceived as one of the strategies with the potential for solving the paradox (Makombe et al., 2011). However, there is no consistent and reliable inventory and well-studied document in water and irrigation related potentials in the Ethiopian context (Haile and Kasa, 2015).

The agricultural practice in the country in general and in the study area in particular is rain-fed agriculture and seasonal. The rainfall agriculture is at high degree of rainfall variability and unreliability. Irrigation is necessary to minimize the impact of rainfall variability and to increase a number of annual crops, perennial and commercial crops with control regulated water supply throughout the year (Abraham et al., 2015).

While the country has high potential to irrigate its agriculture, about 97 percent of Ethiopia's food crops are produced by rain-fed agriculture, whereas only three percent is from irrigated agriculture (FAO, 2015).

There is a huge gap between the potential and the level of irrigation applied in the country due to technical, physical and economic challenges (Gebregziabher et al.,2016), but the determinants of participation in irrigation are not fully identified in specific areas of the country.

Due to the recurrent food insecurity and increased magnitude and complexity of the poverty, there is a need of creating irrigation potential assessment. Proper evaluation and assessment of the potential and suitability of the land area is important for better utilization of land resources for irrigation (Abraham et al., 2015). In study area, there is high water resource potential and limited irrigation, with no previous resource potential assessment and evaluation and where the water resource potential assessment has not been evaluated. Therefore, this study was intended to assess potential suitability of Sibilu river catchment for irrigation using GIS technique.

1.3. Objective of the Study

1.3.1. General Objective

The general objective of this study was to assess the irrigation potential of Sibilu river catchment for surface irrigation using GIS technique.

1.3.2. Specific Objectives

1. To assess suitable area of Sibilu river catchment for surface irrigation.

2. To estimate irrigation water requirement for surface irrigation for the catchment area.

3. To develop land suitability map for surface irrigation in the study area.

1.4. Research Questions

1. How much area of Sibilu river catchment is potentially suitable for surface irrigation?

2. What is the estimated irrigation water requirement for surface irrigation for the catchment area?

3. How was the distribution of the lands suitable for surface irrigation in the area?

1.5. Scope of the Study

This study is limited to Sibilu River Catchment, the tributary of Muger River basin. Geographic Information System based irrigation potential assessment that was assumed to take place in the Sibilu River Catchment was discussed. Suitability factors considered in this study include slope, soil and land use land cover.

1.6. Significance of the study

Irrigation is the most common method of ensuring sustainable agriculture. However about 85% of the people of the Ethiopian country is based in agriculture; the activity still depends on rain-fed. Rainfall distribution in Ethiopia is seasonal and variable and suffers from the most unstable rainfall régime. Irrigation will contribute significantly to poverty alleviation, food security and improving the quality of life for the country's population in general and rural population in particular if the irrigation potential is known. Hence, the land and water resources of the basin could be used for future irrigation project expansion/development. The results of the study will provide awareness for local community and stakeholders on the suitability of the land for irrigation and availability of resources so that they utilize the opportunity to improve agricultural products.

1.7. Limitations of the Study

Shortage of data in the study area was the main problem faced. The recorded data by different organization were not recorded correctly. Some of metrological data for the study area in the station were missing.

1.8. Organization of the Thesis

The whole thesis is divided into five chapters. The first chapter provides general introduction about the research work including introduction of the research, research statement, research objectives and significance of the research. The second chapter deals with literature review in which the related works with respect to the research work are presented. In the third chapter information about the chosen study area is given, and description about the methodology and the materials/data used. Fourth chapter presents the findings of this research work and discussion on the results obtained. And also, the 5th chapter were including the conclusion were drawn based on the results obtained along with some recommendations.

2. LITERATURE REVIEW

2.1. Irrigation Potential

Irrigation is a continuous and reliable water supply to the different crops in accordance with their different needs (Garg, 2005).When sufficient and timely water does not become available to the crops, the crop fade way, ensuring in lesser crop yield, consequently creating famines and disasters, irrigation can prevent such catastrophic consequences (FAO, 1987).

Irrigation is the provision of water to agricultural crops by artificial means, intended to permit farming in arid regions and to overcome the effect of drought in semi-arid regions. Even in areas where total seasonal rainfall is adequate on average, it may be unevenly distributed during the year and varies from year to year. Where traditional rain-fed farming is a high-risk enterprise, irrigation can help to safeguard stable agricultural production (FAO, 1997).

2.2. Irrigation Potential in Ethiopia

In Ethiopia the prevalent rain-fed agricultural production system the progressive degradation of the natural resource base, climate variability has intensified the incidence of poverty and food insecurity (Awulachew et al., 2010).Water resources management for agriculture includes both supports for sustainable production in rain-fed agriculture and irrigation.

Irrigation will play a significant role in the substantial increase in food production for food security enhancement and economic development of Ethiopia with the efficient use of land and water resources (Haile and Kasa, 2015; Sultan, 2013). The production function analysis done by (Makombe et *al*.,2011) shows that irrigation could shift the agricultural production frontier to a higher level. However, its contribution to the national economy is not significant when compared to rainfed agriculture.

2.3. Water Resources

2.3.1. Surface Water Resources

The geographical location of Ethiopia and its endowment with favorable climate provides relatively higher amount of rainfall in the region (Awulachew et al., 2010). Ethiopia has 12 river basins with total mean annual flow from all the 12 river basins is estimated to be 124.25 billion cubic meters (Awulachew et al., 2007).

Table 2. 1: Surface water potential and coverage area of Ethiopian river basins (Awulachew, 2010).

River Basins	Catchment area (Km^2)	Irrigation potentials (ha)
Abbay	199,812	815,581
Tekeze	82,350	83,368
Baro-Akob	75,912	1,019,523
Omo-Gibe	79,000	67,928
Rift valley	52,739	139,300
Awash	112,696	134,121
Genale-Dawa	171,042	1,074,720
Wabi-Shebele	202,697	237,905
Denakil	74,002	158,776
Ogaden	77,121	-
Aysha	2,223	-
Total	11,180,745.53	3,731,222

2.3.2. Lakes and Reservoirs

Ethiopia has 11 fresh and 9 saline lakes, 4 crater lakes and over 12 major swamps or wetlands (Awulachew et al., 2007).Majority of the lakes are found in the Rift Valley Basin (Tafesse, 2003).The total surface area of these natural and artificial lakes in Ethiopia is about 7,500 km^2.

2.3.3. Ground Water Resources

As compared to surface water resources, Ethiopia has lower ground water potential (Awulachew et al., 2007). Based on the limited data available on groundwater resources, the potential is estimated to be about 40 billion m^3 annually rechargeable resources; which provide a little higher value (Berhanu et al., 2014).

2.4. Land Suitablity Classification

Land suitability is the fitness of a given type of land for a defined use (Huajun et al., 1991). The land may be considered in its present condition or after improvements. Land evaluation is primarily the analysis of data about the land its soils, climate and vegetation in terms of realistic alternatives for improving the use of that land (Rossiter, 2009).

2.4.1. Structure of the Suitability Classification

In FAO's Framework for Land Evaluation, the structure of the suitability classification is described recognizing qualitative, quantitative and current or potential suitability in four categories of decreasing generalization. Each category retains its basic meaning within the context of the different classifications and as applied it different kinds of land use (Meron, 2007).

Table 2.2: Structure of land suitability classification FAO (1976).

Land Suitability Orders:	Reflecting kinds of Suitability.
Land Suitability Classes:	Reflecting degrees of suitability within Orders.
Land Suitability Subclasses:	Reflecting kinds of limitation or main kinds of improvement measures required, within Classes.
Land Suitability Units:	Reflecting minor differences in required management within Subclasses.

2.4.1.1. Land Suitability Orders

Land Suitability orders indicate whether land is assessed as suitable or not suitable for the use under consideration. There are two orders Suitable and Not suitable represented in maps, tables. by the symbols S and N respectively.

Order S (Suitable): Land on which sustained use of the kind under consideration is expected to yield benefits which justify the inputs, without unacceptable risk of damage to land resources. **Order N (Not Suitable)**: Land, which has qualities that appear to preclude sustained use of the kind under consideration (FAO, 1976).

2.4.1.2. Land Suitability Classes

According to (FAO, 1976), land suitability Classes reflect degrees of suitability. The classes are numbered consecutively, by Arabic numbers, in sequence of decreasing degrees of suitability within the Order.

Class S1 Highly Suitable: Land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level.

Class S2 Moderately suitable: Land having limitations which in aggregate are moderately Severe for sustained application of a given use; the limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained.

Class S3 Marginally Suitable: Land having limitations which in aggregate are severe for sustained application of a given use and will so reduce productivity or benefits, or increases required inputs, that this expenditure was only marginally justified. With the order not suitable, there are normally two classes:

Class N1 Currently Not suitable: Land having limitations which may be Surmountable in time but which cannot be corrected with existing knowledge at currently acceptable cost.

Class N2 Permanently Not suitable: Land having a limitation which appears as severe as to preclude any possibilities of successful sustained use of the land in the given manner.

2.4.1.3. Land Suitability Subclasses

Land suitability subclasses reflect kinds of limitations, e.g. moisture deficiency, erosion hazard. Subclasses are indicated by lower-case letters. The number of subclasses recognized and the limitations chosen to distinguish them will differ in classifications for different purposes.

2.4.1.4. Land Suitability Units

Land suitability units are subdivisions of a subclass. All the units within a subclass have the same degree of suitability at the class level and similar kinds of limitations at the subclass level.

Suitability units are distinguished by Arabic numbers following a hyphen, e.g. S2e-1, S2e-2.

2.5. Irrigation Land Suitability Factors

The fundamental physical factors in determining the suitability of land for irrigation are soil, topography, drainage, water quality and quantity, and climate. Water and climate differ from the others in that they are usually uniform throughout the specific area to be investigated (Stanhill, 2002).

2.5.1. Slope

Slope is the incline or gradient of a surface and is commonly expressed as a percent. According to FAO standard guidelines for the evaluation of slope gradient, slopes which are less than 2%, are very suitable for surface irrigation. But slopes, which are greater than 8%, are not generally recommended for surface irrigation (FAO, 1990).

2.5.2. Soils

Assessment of land resource, with particular regard to soil survey is necessary prerequisite for all agricultural developments, particularly where irrigation is concerned. Soil act, as a storehouse of water, supplying plant needs during dry periods when rain is inadequate (Meron, 2007).The assessment of soils for irrigation involves using properties that are permanent in nature that cannot be changed. Such properties include drainage, texture, depth, salinity, and alkalinity (Fasina et al., 2008). Even though salinity and alkalinity hazards possibly improved by soil amendments or management practices, they could be considered as limiting factors in evaluating the soils for irrigation (FAO, 1997).

2.5.3. Land Use Land Cover

They are often used interchangeably; land use refers to the actual economic activity for which the land is used for food production, commercial forestry. Land cover refers to the cover of the earth's surface i.e. Vegetation, bare soil, urban development (Ganole, 2010).

2.6. Assessment of Water Resource

Investigations of water resources should be considered an integral part of the land resources evaluation process (FAO, 1985). The quality and quantity of the water supply are equally as important as land and other factors to the success of an irrigation project (Meron, 2007).Irrigation water requirement of the potentially irrigable command area was computed using the CROPWAT 8.0 software.

2.6.1. Precipitation Data Analysis

Precipitation is one of the most important components of the water source. Rainfall and other forms of precipitation are measured in terms of depth, the values being expressed in millimeters (WMO, 2008). About 95 percent of all agricultural land and 83 percent of cropland in the world depends on precipitation as the sole source of water for agricultural production (Wood et *al*., 2000).

1. Missing data analysis

Both consistency and continuity may be disturbed due to change in observational procedure and incomplete records (missing observations) which may vary in length from one or two days to decades of years. Some of the techniques which are used to estimate missing rainfall data are the normal ratio method, arithmetic mean, inverse distance method, areal precipitation ration method and multiple regression analysis methods (De Silva et *al*., 2007). The most common method used to estimate missing rainfall data is Normal Ratio method (Chow et al., 1988). Here are the formulae for some of the different missing data estimation methods (De Silva et al., 2007).

A.Normal ratio method: This approach enables an estimation of missing rainfall data by weighting the observation at N gauges by their respective annual average rainfall values as expressed as below (Yemane, 2004).

$$PX=\frac{1}{N}\left(\sum \frac{\mathrm{px}}{\mathrm{pi}} . \mathrm{p}g\right) \quad (2.1).$$

Where:

PX = missing data

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

Pi = annual average values of neighboring stations

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

N = the total number of gages under consideration

B.Inverse distance method: The rainfall at a station is estimated as a weighted average of the observed rainfall at the neighboring stations (Simanton and Osborn, 1980).

$$Px=\sum_{i=1}^{N} \frac{1}{d^2} pi \qquad (2.2).$$

Where, Px = estimate of rainfall for the un-gauged station

Pi= rainfall values of rain gauges used for estimation

d = distance from each location the point being estimated

N = No. of surrounding stations

The limitation of Inverse distance method is strongly influenced by the minimum distances between the target station and neighboring stations as well as weighting is strictly based on distance, hence this method is not satisfactory for hilly regions (Abraham, 2015).

C.Arithmetic mean method: If the normal annual precipitations at surrounding gauges are within the range of 10% of the normal annual precipitation at missed data station, then the arithmetic procedure could be adopted to estimate the missing observation of missed data station (Chow et al, 1988).

$$Pavg=\frac{1}{n}\sum_{i=1}^{n} Pi \qquad (2.3).$$

Where: Pavg= Average precipitation, n= total number of stations and Pi=precipitation depth at gauge i.Its limitations are assigns the same weight to each station regardless to location and other conditions as well as it uses the arithmetic mean of precipitation records of them as estimate.

2. Consistency analysis

Rainfall series from a given station is checked for consistency by the well-known double-mass curve method**.** When using the double mass curve it is apparent that the more homogeneous the base station records are, the more accurate will be the corrected values at the station under consideration. (Garg, 2005).

$$P=Px.\frac{M\prime}{M} \qquad (2.4).$$

Where, P= corrected precipitation at station X (mm)

Px = original recorded precipitation at station X (mm)

M' = corrected slope of the double mass curve (%)

M = original slope of the double mass curve (%)

2.6.2. Irrigation Water Requirement

Irrigation water should perform the necessary function without any adverse effects on the fertility of the soil or on the proper growth of plants. Suitability of water for irrigation are described in which relate to the general irrigation problems of salinity, sodicity, acidity and specific ion toxicity of other elements (FAO, 1985, Meron, 2007). In quantifying how much water is required for irrigation, it is necessary to distinguish between crop water requirement, net irrigation water requirement, gross irrigation water requirement, and their components as listed below with respect to the irrigable command area (FAO, 1985).

1. Effective rainfall

It is part of the rainfall that can be effectively used by the crop, depending on its root zone depth and the soil storage capacity. It contributes to crop water requirement, net irrigation water requirement or both (FAO, 2002).

2. Reference crop Evapo-transpiration (ETO)

The evapo-transpiration rate from a reference surface, not short of water, is called the Reference crop evapo-transpiration or reference evapo-transpiration and is denoted as ETO. The reference surface is a hypothetical grass reference crop with specific characteristics. The only factors affecting ETO are climatic parameters (Ganole, 2010). Consequently, ETO is a climatic parameter and can be computed from weather data. ETO expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The FAO Penman-Monteith method is recommended as the sole method for determining ETO. Moreover, procedures have been developed for estimating missing climatic parameters.

$$ETO==\frac{0.408\,\Delta(Rn-G)+\gamma\frac{900}{T+273}U2(es-ea)}{\Delta+\gamma\,(1+0.34\,U2)} \qquad (2.5).$$

Where: ETo = Reference evapotranspiration (mm/day), Rn = Net radiation at the crop surface (MJ/m^2 per day), G = Soil heat flux density (MJ/m^2 per day), T = Mean daily air temperature at 2 m height (°C), u2 = Wind speed at 2 m height (m/sec),es = Saturation vapour pressure (kPa)

ea = Actual vapour pressure (kPa), es - ea = Saturation vapour pressure deficit (kPa)

Δ = Slope of saturation vapour pressure curve at temperature T (kPa/°C) and γ = Psychrometric constant (kPa/°C).

Crop water requirement (CWR) and crop evapotranspiration (ETc)

FAO (1984) defined crop water requirements as the depth of water needed to meet the water loss through evapotranspiration of a crop, being disease-free, growing in large fields under non restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment.

The values of ETc and CWR (Crop Water Requirements) are identical, whereby ETc refers to the amount of water lost through evapotranspiration and CWR refers to the amount of water that is needed to compensate for the loss (FAO, 2002).According to FAO, (2002), ETc can be calculated from climatic data by directly integrating the effect of crop characteristics into ETo. Using recognized methods, an estimation of ETO is done. Experimentally determined ratios of ETc/ ETO, called crop coefficients (Kc), are used to relate ETc to ETO.

$$ETc = ETO \times KC \quad (2.6).$$

Where: ETc = Crop evapotranspiration (mm/day), ETO = Reference crop evapotranspiration (mm/day) and Kc = Crop coefficient (fraction).

Net irrigation water requirement (NIWR)

Irrigation water requirements (IWR) refer to the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirements. If irrigation is the sole source of water supply for the plant, the irrigation requirement will always be greater than the crop water requirement to allow for inefficiencies in the irrigation system (FAO, 2002).

Gross irrigation water requirement (GIWR) GIWR is defined as the net irrigation water requirement, plus conveyance losses between the source of the water and the field, plus any additional water for leaching over and above percolation (FAO, 2002).

2.7. Overview of CROPWAT Model

CROPWAT is a decision support system developed by the Land and Water Development Division of FAO for planning and management of irrigation practice in water resource development (FAO, 1985). CROPWAT is meant as a practical tool to carry out standard calculations for reference evapo-transpiration, crop water requirements and crop irrigation requirements, and more specifically the design and management of irrigation schemes (Meron, 2007). According to FAO (1985) calculations of the crop water requirements and irrigation requirements are carried out with inputs of climatic, crop and soil data. For the estimation crop water requirements (CWR) the model requires:

Reference Crop Evapo-transpiration (ETO) values calculated using the FAO Penman-Montieth equation based on decade/monthly climatic data: minimum and maximum air temperature, relative humidity, sunshine duration and wind speed (Meron,2007).

Rainfall data (daily/decade/monthly data); monthly rainfall is divided into a number of rain storm each month.

Effective Rain Fall: In order to account for the losses due to runoff or percolation, effective rain fall is calculated by empirical method. Dependable rain empirical formula according to Food and Agriculture Organization of United Nations/Water Resources Development Management Service (FAO/AGLW) is:

$$\text{Effective rain fall, } Pe = 0.6 * P - 10 \text{ for rain fall} <= 70 \text{ mm.} \quad (2.7).$$

$$\text{Effective rain fall, } Pe = 0.8 * P - 24 \text{ for rain fall} >= 70 \text{ mm.} \quad (2.8).$$

Cropping Pattern consisting of the planting date, crop coefficient data files (including K c values, stage days, root depth, depletion fraction) and the area planted.

Once all the data is entered, CROPWAT8.0 windows automatically calculates the results as tables or plotted in graphs. The time step of the results can be any convenient time step: daily, weekly, decade or monthly.

2.8. Overview of GIS Technology

A Geographic Information System (GIS) is computer software used for capturing, storing, querying, analyzing, and displaying geographically referenced data (FAO,2015). Geographically referenced data are data that describe both the locations and characteristics of spatial features such as roads, land parcels, and vegetation stands on the Earth's surface.

GIS is a computer based system that offers a convenient and powerful platform for performing suitablity evaluation (Meron, 2007). GIS technique and procedures have an important role in analyzing decision problem (Malczewski, 2005). Geographically referenced data are data that describe both the locations and characteristics of spatial features such as roads, land parcels, and vegetation stands on the Earth's surface (FAO,2015.Therefore, important advantage of using GIS technology is to perform a spatial multi-criteria decision study. Through this application of GIS, various criteria can be developed based on neighborhood analysis operations (Pereira, 1993). A GIS also provides a means for visualizing resource characteristics, thereby enhancing understanding in support of decision making.

2.8.1. Application of GIS

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

2. Watershed Delineation: Watershed is the catchment area that drains into a common outlet. Simply, watershed of a particular outlet is defined as an area, which collects the rainwater and drains through gullies, to a single outlet (Winchell et al., 2008).Delineation of a watershed means determining the boundary of the watershed. GIS uses DEM data as input to delineate watersheds with integration of Arc GIS spatial analysis (Winchell et al., 2008).

As ESRI (2011) reported Arc Hydro tools are used to derive several data sets that collectively describe the drainage patterns of a catchment. Raster analysis is performed to generate data on flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation. These data are then used to develop a vector representation of catchments and drainage lines. Using this information, a geometric network is constructed. Utility of Arc Hydro tools is demonstrated by applying them to develop attributes that can be useful in hydrologic modeling. To accomplish these objectives, the user is exposed to important features and functionality of Arc Hydro tools, both in raster and vector environment.

3. Weighted Overlay Analysis: Weighted overlay is a method for applying a regular measurement scale of principles to diverse and dissimilar inputs to produce an integrated analysis. Geographic problems often require the analysis of many different factors using GIS. For instance, finding optimal site for irrigation requires weighting of factors such as land cover, slope and soil (Yang, 2003). To prioritize the influence of these factor values, weighted overlay analysis uses evaluation scale from 1 to 9 by 1. For example, a value of 1 represents the least suitable factor in evaluation while, a value of 9 represents the most suitable factor in evaluation. Weighted overlay only accepts integer raster's as input, such as a raster of land cover/use, soil types and slope to find suitable land for irrigation (Janssen, 1990).

2.8.2. GIS as a Tool for Irrigation Potential Assessment

In the past, several studies have been made to assess the irrigation potential and water resources by using Geographic Information System tools.

FAO (1987) conducted a study to assess land and water resources potential for irrigation in Africa on the basis of river basins of countries. It was one of the first GIS based studies of its kind at a continental level. It proposed natural resource-based approach to assess irrigation potential. Its main limitations were in the sensitivity of criteria for defining land suitability for irrigation and in water allocation scenarios needed for computation of irrigation potential.

FAO (1997) has studied the irrigation potential of Africa taking into consideration the above limitations. It focused mainly on quantitative assessment based on physical criteria (land and water), but depend on information collected from the countries.

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

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

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

Dagnenet (2013) conducted a study on assessment of irrigation land suitability and development of map for the Fogera catchment using GIS in South Gonder. It was based on the basis of stoniness, soil salinity, soil alkalinity, soil depth and groundwater quality and 72 percent S, 28 percent N due to different reasons: Such as drainage limitation, flood hazard, texture and slope factors.

2.9. Application of MCE and GIS in Irrigable Land Suitability Analysis

The integrated application of the Geographic Information System and the Multi–Criteria Evaluation helps land-use planners to improve decision-making processes (Malczewski, 1999, Mustafa et al., 2011).GIS based MCE tool found to be a promising tool to identify the suitability/potential and strength and limitation to grow different types of crops in different areas of the globe (Tienwong et al., 2009).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

Sibilu River catchment is found in the Sululta district, Oromia Specialized Zone Surrounding Addis Ababa, Oromia Regional National State, to the North of Addis Ababa to Fitche highway. It is one of the tributary of Muger River, which is the main tributary of Abay Basin. It is found between geographical coordinates of 8° 50' 0"- 9° 20' 0"N latitude, 38° 34' 30"- 38° 55' 30"E longitude. It is 2530 m above sea level and meanders in the flat topography of Sululta plain. The economy of the study area is mainly dominated by agriculture. It is located about 45 km east of Addis Ababa. The study area covers about 45645 ha.

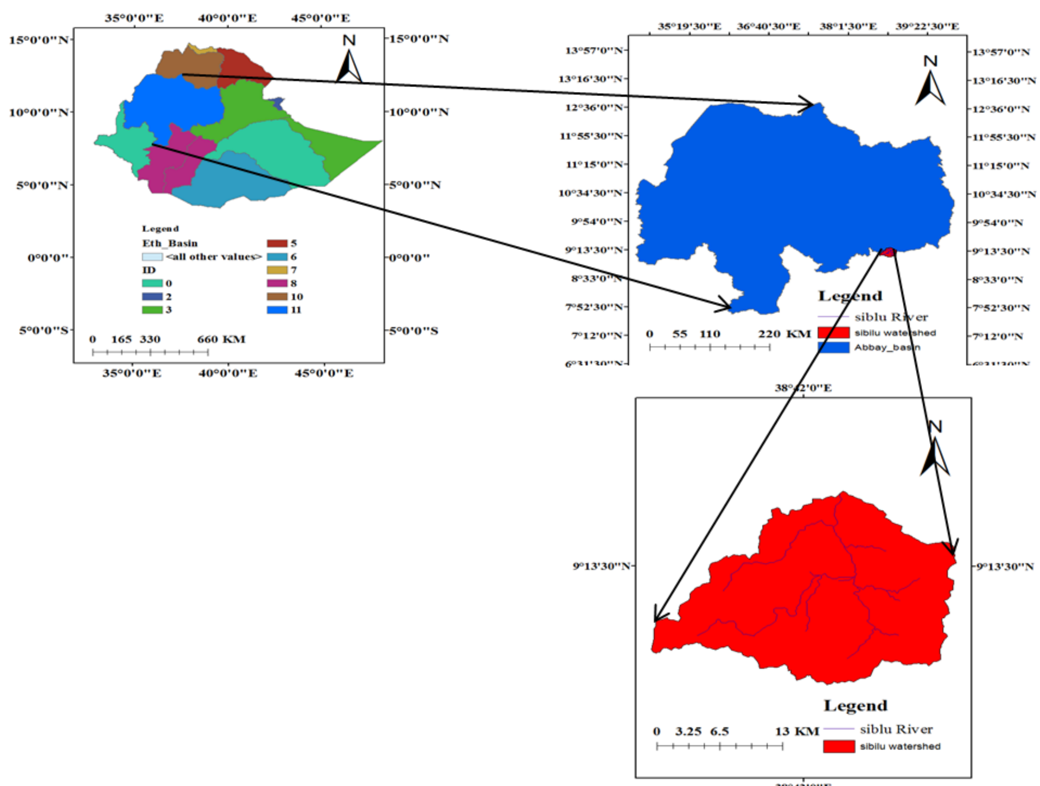

Figure 3.1: Map of the study area

3.1.2. Topography

The topography of the area varies from chains of mountains around Entoto ridge in the south to plain lands in the East, North-West and North. The average elevation in the study area is 2530 m above mean sea level (Hawi, 2017).

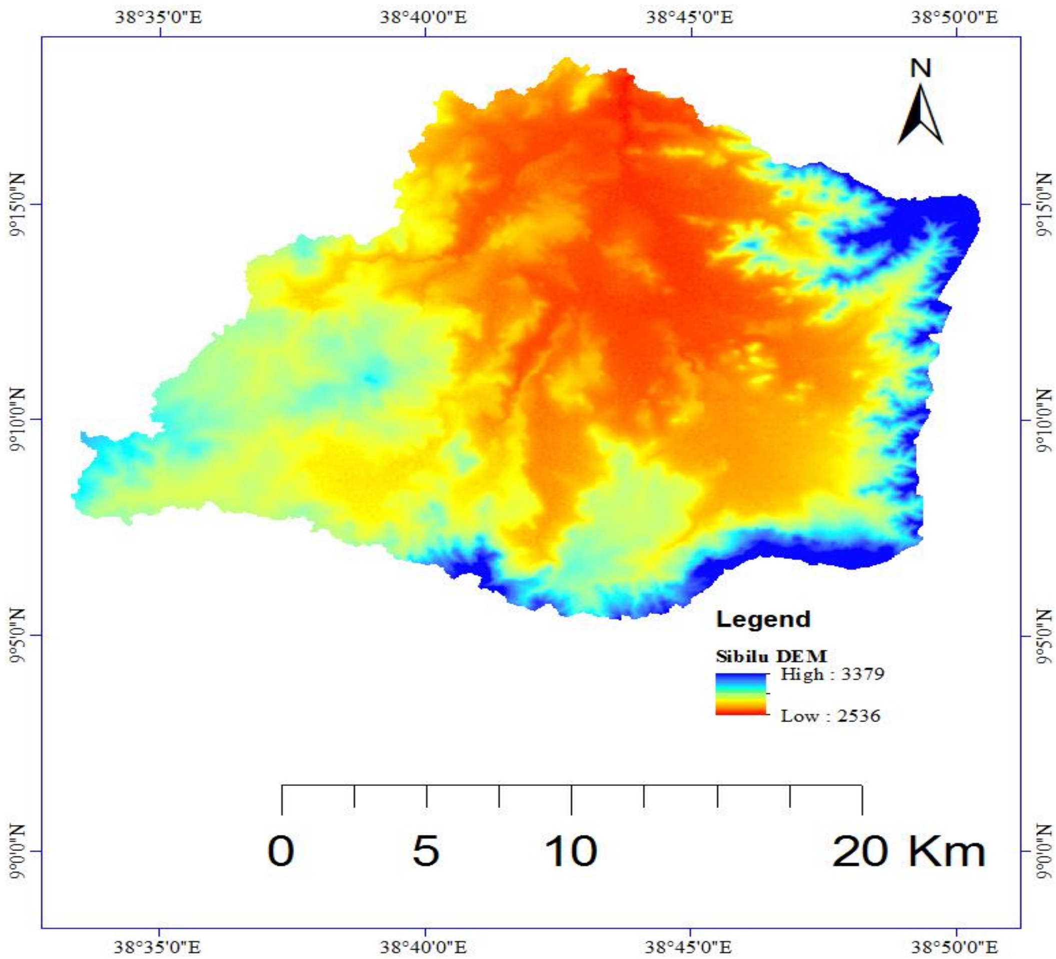

Figure 3. 2: Digital Elevation Model of Sibilu River

3.1.3. Climate

The climate of the Ethiopia is mainly controlled by the seasonal migration of the Inter-tropical Convergence Zone (ITCZ), which is conditioned by the convergence of trade winds of the northern and southern hemisphere and the associated atmospheric circulation (Merga, 2012). It is also highly influenced, regionally and locally, by complex topography of the country. The study area is the part of tropical humid climatic region, which is characterized by warm temperature and agro-climatic zone.

3.1.3.1. Rainfall (mm)

The rainfall of the study area has a bi-modal pattern (Debebe, 2005). The main rainy season is from June to September. Highest rainfall was observed in the month of July. The short rainy season from November to February. The lowest rainfall was observed in the month of December.

Rainfall data was available from 1998 to 2017 and recorded from three stations, such as: from Addis Ababa Bole, Addis Ababa Observatory and Sululta. Annual Average rainfall for Addis Ababa Bole, Addis Ababa Observatory and Sululta were 1023mm, 1231mm and1236mm respectively. The mean monthly rainfalls of different stations in the study area were given graphically in Figure 3.3.

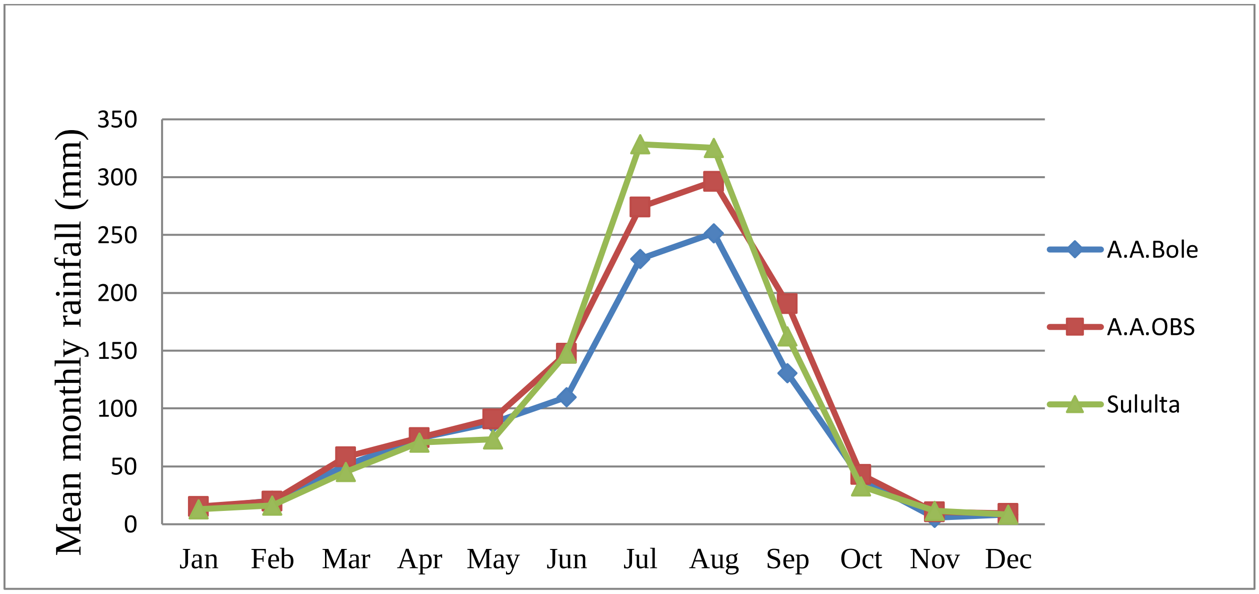

Figure 3.3: Average monthly rainfall of different stations in the study area

3.1.3.2. Temperature (℃)

Temperature data were taken from three stations, Addis Ababa Bole, Addis Ababa Observatory and Sululta. Based on the recorded data the mean annual minimum and maximum temperature of the study area were 8.1℃ and 25.9℃ at Addis Ababa Observatory, whereas the average monthly minimum and maximum temperature were 4.7℃ and 24.4℃ at Sululta station. Generally, months of February, March, and April had the highest temperature while June July, August and September had the lowest temperature.

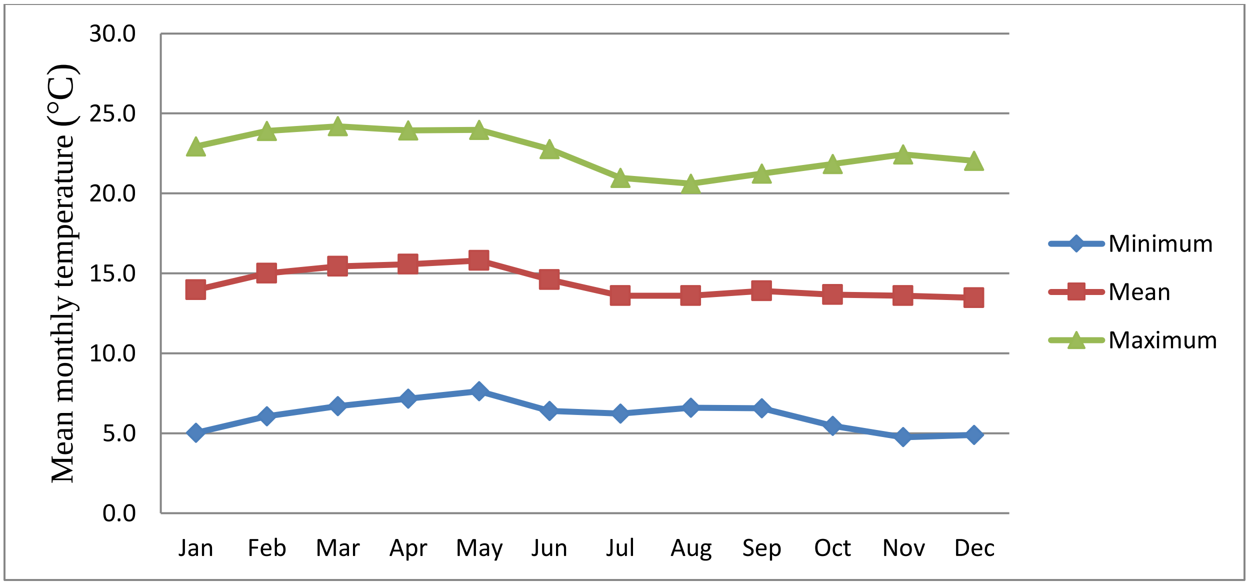

Figure 3.4: Average monthly temperature of Sululta

3.1.3.3. Relative Humidity (%)

Relative humidity is the relative measure of the amount of moisture in the air to the amount needed to saturate the air at the same temperature (Shaw, 1988). It varies from time to time, depending on variation in rainfall and air temperature. The mean monthly relative humidity attains the maximum in the months of July, August and September and the minimum value is during February. In general, this change is related to the rainy season and dry season of the country in which it raises during summer. According to (Table 3.1), the mean monthly relative humidity attains the maximum in the months of July, August and September and the minimum in the month of February.

Table 3.1: Monthly mean relative humidity at the study area

Location	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A.Bole	52.4	47.2	46.1	46.8	53.1	63.5	72.7	76.9	70.1	54	52.5	50.8
A.A.Obs	43.9	40.5	43.3	42.2	47.3	56.9	63.9	68.5	62.1	47.3	44.7	44.2
Sululta	54.9	49.2	54.5	60.9	57.6	68.4	87.1	87	78.6	64.8	58.1	55.8

3.1.2.4. Sunshine Hour (hr)

A sunshine hour of the study area varied from 3.8 to 8 hours per day. Low sunshine hours were during rainy seasons.

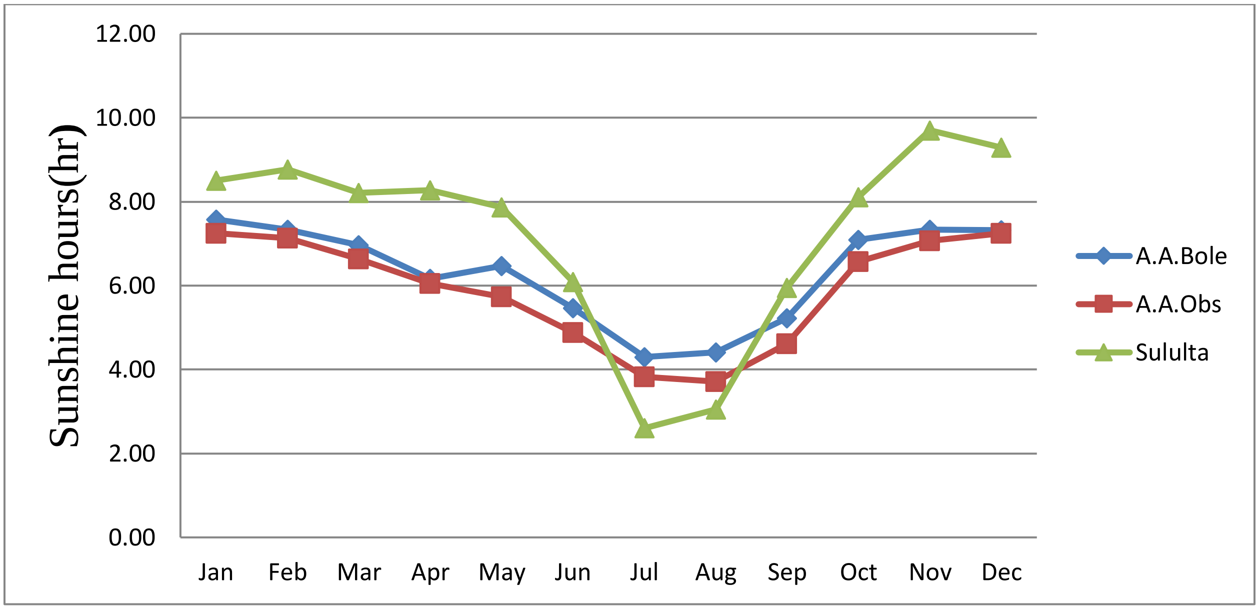

Figure 3.5: Monthly average Sunshine hours of stations

3.1.3.5. Wind Speed (m/s)

The wind speed of the study area were obtained from (1998-2017) years from National Metrological Agency. Wind speed of the study area ranged from 0.95 to 1.77m/s. Low wind speed was on rainy season.

3.1.4. Soil Type

According to the soil map (source: BCEOM 1999), there were different types of soil in the study area. Eutric Cambisols, Eutric Vertisols, Eutric Leptosols and Chromic Luvisol. Most of the study areas were mostly covered by Eutric vertisol and Eutric Luvisol.

3.1.5. Land use/Land cover

Land use land cover of the catchment includes the cultivated land, grazing land, forest land and settlement land. The cultivation land dominated in the different types of the study area. Wood and grazing land were found in the lower parts of the catchment. The land use land cover of the study area was highly dominated by cultivated land.

3.1.6. Population

Sululta is the one where high rate of population growth is observed as a result of different pushing factors. Despite the serious problems of overcrowding, sub-standard housing, crime and burden for the government to manage and fairly allocate the resource (Merga, 2012).

3.1.7. Socio-Economic Activity

The economy of the high land of Ethiopia is dependent on mixed agriculture (Hirko, 2017). The study area also depends on similar condition. Crop production is the major agricultural practice in the study area. The agricultural activity of the study area is mainly rain-fed.

3.2. Data Collection and Sources

The data gathering techniques used for this study were secondary data. These secondary data were collected from different organization such as: MOWIE, NMA and EMA.

Different types of data were used for analyzing the irrigation potential of the Sibilu river catchment to attain the objectives illustrated .Such data were:

Spatial data (DEM, LULC and Soil)

Hydrological data (Stream flow)

Metrological data (Rainfall, temperature, relative humidity and solar radiation)

3.2.1. Digital Elevation Model (DEM)

DEM of 30 m x 30 m spatial resolution was obtained from the Ministry of Water, Irrigation and Electricity. It was used to delineate a watershed and to derive slope maps of the study area for irrigation suitability analysis using ArcGIS 10.6.

3.2.2. Land Use Land Cover

Land use land cover map of the study area were collected from the Ethiopian Mapping Agency. This data were used for land suitability analysis of the Sibilu river catchment.

3.2.3. Soil Data

The soil data for this study area were collected from the Ministry of Water, Irrigation and Electricity. In case the data was not available in the MOWIE, FAO soil classification map was used. The soil data were used for developing soil map and suitability analysis for irrigation of the study area.

3.2.4. Stream Flow Data

The stream flow data of the Sibilu River catchment were collected from Ministry of Water, Irrigation and Electricity office. The records of discharge used for this study were obtained from fifteen years daily data (1996-2011) for Sibilu River at Chancho gauging station. This data were very essential for identification of surface water resource potential.

3.2.5. Metrological Data

Twenty years (1998-2017) daily data of the meteorological data for all stations were collected from NMA.These data were used to estimate irrigation water requirements for crop using CROPWAT 8.0 software.

3.3. Materials and Softwares

The tools used to assess the irrigation potential of this study were: GIS, Excel work sheet and CROPWAT.These data analysis were represented by graphs and table.

Softwares used for this study were: Microsoft excels for rearranging data inputs, ArcGIS 10.6 for map making and suitablity analysis and CROPWAT 8.0 for estimating ETO and crop water requirements.

3.4. Methods

3.4.1. Data Processing and Analysis

Collected data can contain errors due to failures of measuring device or the recorded. So, before using the data for specific purpose, the data were checked and errors were removed.

3.4.1.1. Consistency checking for rainfall data

To prepare the rainfall data for further application, their consistency were checked using double mass curve analysis. A plot of accumulated rainfall data at site of interest against the accumulated average at the surrounding stations is generally used to check consistency of rainfall data (Nemec, 1973).

The mean annual cumulative rainfall of twenty years of each station were drawn in y-axis and the mean annual cumulative rainfall of reference stations were drawn in the x- axis to check the consistency of each rainfall stations using double mass curve. As the results of the test shown graphically in Figure 3.6, the precipitation data is consistent with (R^2 = 0.9995) for Addis Ababa Bole, (R^2 = 0.9992) for Addis Ababa Observatory and, (R^2 = 0.9998) for Sululta stations.

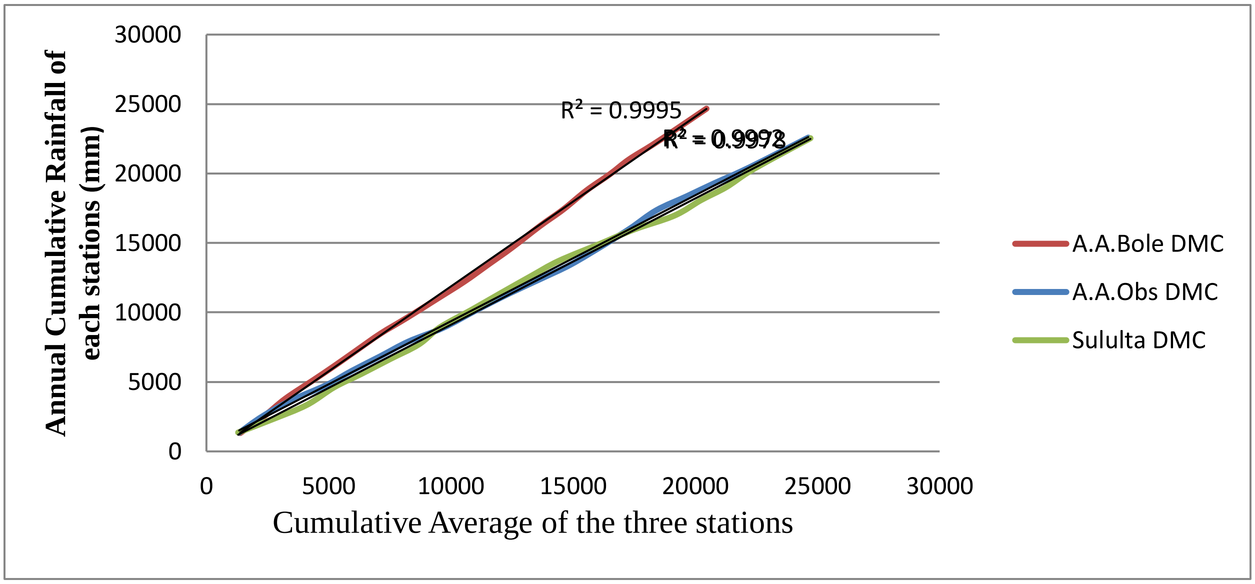

Figure 3.6: Double Mass Curve of three stations

3.4.1.2. Filling in Missing Metrological Data

Missing data is a common problem in hydrology. To perform hydrological analysis and simulation using data of long time series, filling in missing data is very important. The missing data can be completed using metrological hydrological stations located in the nearby stations. Missing records of the stations for this study were filled by using normal ratio method which is recommended to estimate missing data in regions where annual rain falls among stations differ by more than 10% (Dingman, 2002).

This approach enables an estimation of missing rainfall data by weighting the observation at N gauges by their respective annual average rainfall values as expressed by below (Yemane, 2004).

$$Px=\frac{1}{N}\left(\sum\frac{Px}{Pi}\cdot Pg\right) \quad (3.1).$$

Where: Px=Missing data, PX=the annual average precipitation at the gauge with the missing data, Pi=the annual average values of neighboring station, Pg =Monthly rainfall data in station for the same month of missing station, N=the total number of gauge under consideration. The monthly maximum and minimum temperature, sunshine duration, relative humidity and wind speed data were used for estimation of reference evapotranspiration calculation.

3.4.2. Watershed Delineation

DEM of the study area were extracted from Abay basin DEM using ArcGIS 10.6. Using the fill tool in ArcGIS 10.6, Abay DEM was filled. Then flow direction raster map was generated from the filled raster map. From the flow direction raster map flow accumulation map was generated. On the flow accumulation map, outlet Point of Sibilu River (the point where it joins Abay River) was found and this was changed to point shape file. Snap pour point was created from this point shape file. Then using this pour point and flow accumulation raster, Sibilu watershed was delineated. Sibilu watershed raster map was converted to polygon shape file map. Using raster processing tool, Abay filled DEM, and Sibilu watershed polygon, DEM for Sibilu watershed was extracted.

3.4.3. Identification of Potential Irrigable Sites

Identification of suitable sites for irrigation were carried out by considering the slope, soil and land cover/use. The individual suitability of each factor was first analyzed and finally weighted to get potential irrigable sites.

3.4.3.1. Slope Suitability Analysis

Slope is very important parameter for soil formation and management because of its influence on runoff, drainage and erosion control and also it is a critical limiting factor for irrigation suitability. The slope of the study area was derived from DEM 30-meter by using Arc GIS 10.6 spatial analyst tool. Then, on spatial analyst tool reclassified digital map of slope were produced. The slope derived from the DEM was classified based on the classification system of FAO (1990) using the “Reclassification” tool, which is an attribute generalization technique in ArcGIS. Slope has been considered as one of the evaluation parameters in irrigation suitability analysis. Based on the four slope classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N) for surface irrigation (FAO, 1990).

Table 3.2: Slope suitability classification for surface irrigation (FAO, 1990).

Slope (%)	Factor rating	Description
0-2	S1	Highly suitable
2-5	S2	Moderately suitable
5-8	S3	Marginally suitable
>8	N	Not suitable

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

The land having slope gradient less than two percent is highly suitable for surface irrigation without limitation with respect to slope. This type of land does not need much cost for construction of canals for waterway. Surface irrigation follows the slope, which does not need great energy for distribution of water with the irrigation field. The land having slope greater than eight percent is not suitable for surface irrigation. This type of land need much cost for construction of canal (FAO, 1990).and also it needs diversion of rivers.

3.4.3.2. Soil Suitability Evaluation

Soil is a major factor in the suitability of land for surface irrigation. Its influence is on the productive capacity, but it also influences production and development costs. Soil texture, soil drainage, soil depth and soil type are the major physical properties of soil which are very important for evaluation of irrigation potential of the study area. They affect the root growth of plant, infiltration of water in to the soil and the production of crops. Suitable soil for potential surface irrigation is obtained creating weighted overlay analysis which involved all data sets of soil physical properties.

The soil vector layer were converted into raster layer using conversion tool" to raster or feature to raster module", the rasterized soil map of the study area were reclassified based on their soil type, depth, texture and drainage class. Using overlay tool in ArcGIS 10.6 spatial analyst, weighted overlay analysis of these factors were performed to determine their suitability for surface irrigation (FAO, 1976). Then, the new values were re-assigned for each soil factor in order of their irrigation suitability rating based on common evaluation scale from S1-N available in weighted overlay analysis for land evaluation to the factor classes. A value (S1) represent highly suitable factor in evaluation, while value (N) represent not suitable factor in evaluation. The following soil suitability rating was used based on the FAO guidelines for land evaluation (FAO, 1997).

Table 3.3: Soil suitability factor for drainage class, soil depth and soil texture (FAO, 1976).

	Factor rating			
Factors	S1	S2	S3	N
Soil texture	L-SiCL,C	SL	-	-
Soil depth	≥100	80-100	50-80	<50
Drainage class	Well	Moderately	Imperfect	Poor

1. Soil type

According to BCEOM (1999) soil types of the study area were classified as Chromic Luvisol, Eutric cambisol, Eutric leptosol and Eutric vertisol.

Cambisols are soils with initial stage of soil formation or developing soils relating to their parent material. Most Cambisols are medium-textured soils with high porosity, good water holding capacity.Leptosols is soils with an incomplete solumn and without clearly expressed morphological features. They are particularly common in hilly to mountainous area of the southern fringe of the study area and it covers a small proportion of the area. They are free drainage and have low water holding capacity (FAO, 2001).

Luvisol represent soils having an argic subsurface horizon. They are most common in flat or gently sloping land. Luvisol with good internal drainage were potentially suitable for wide range of agricultural uses because of their moderate stage of weathering and high base saturation.

Vertisols are soil type characterized by, having a uniform particle size distribution.Vertisols are soils with good water holding property and have high catio exchange and base saturation. Thus, it is good for irrigation (FAO, 2001). According to FAO (1979), the suitability of soil type for irrigation was as follows: Chromic Luvisol and Eutric Vertisol (S1), Eutric Cambisols (S2) and Eutric Leptosols (N).

Table 3.4: Major soil types in the study area

Soil type	Area (ha)	Area (%)
Eutric Cambisols	15370.34	33.57
Eutric Vertisols	17707.64	38.68
Chromic Luvisol	8843.1	19.31
Eutric Leptosols	3863.4	8.44

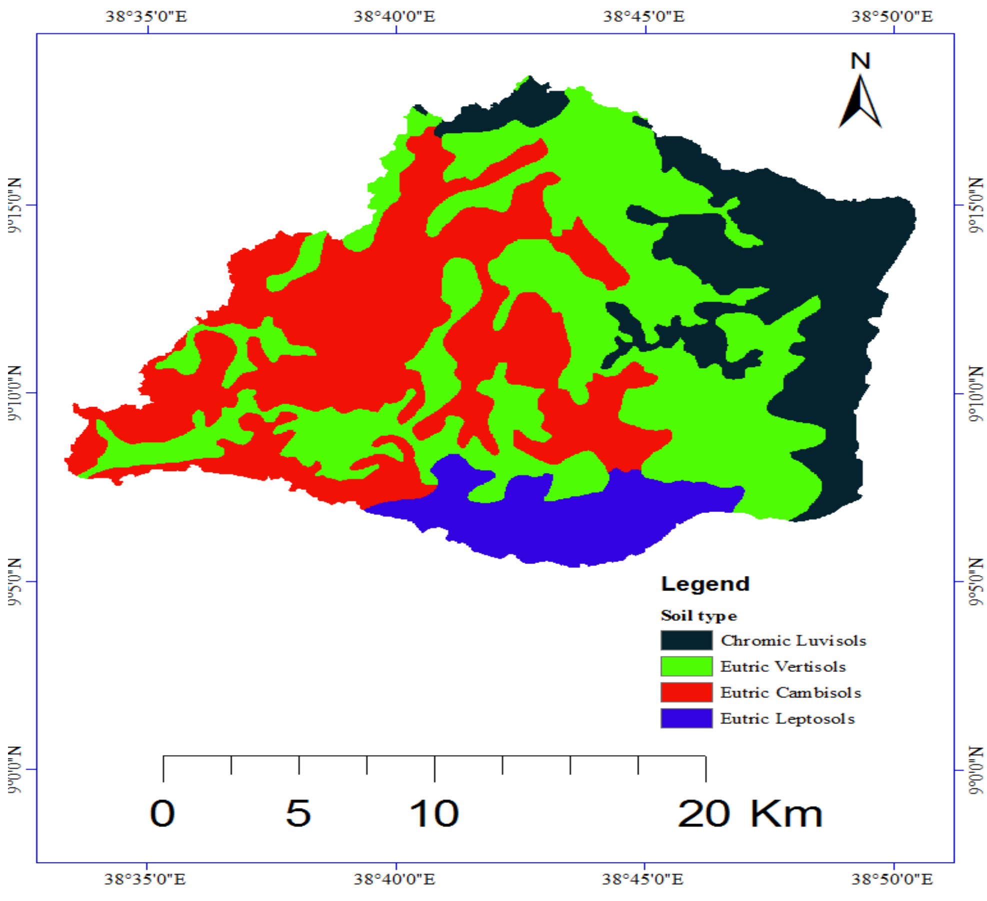

Figure 3.7: Soil map of study area

2. Soil Texture

Texture influences the movement of water through the soil, how much water can be stored in the soil, and how much of the stored water is available to plants. It determines the rate at which water should be applied, how much should be applied and how often irrigation should occur (FAO, 1999).According to FAO guidelines soil texture of the study area were classified into clay, clay loom, loam and Sandy clay. Clay has important effects on the physical properties of soil and has low water absorption capacity. Clay loam is medium textured soil which has a high absorption capacity for water (Thorne and Peterson, 1949). The map of soil texture of study area was shown in Figure 3.8. Infiltration (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 the subsoil, the permeability will greatly influence the basic intake rate of the soil.

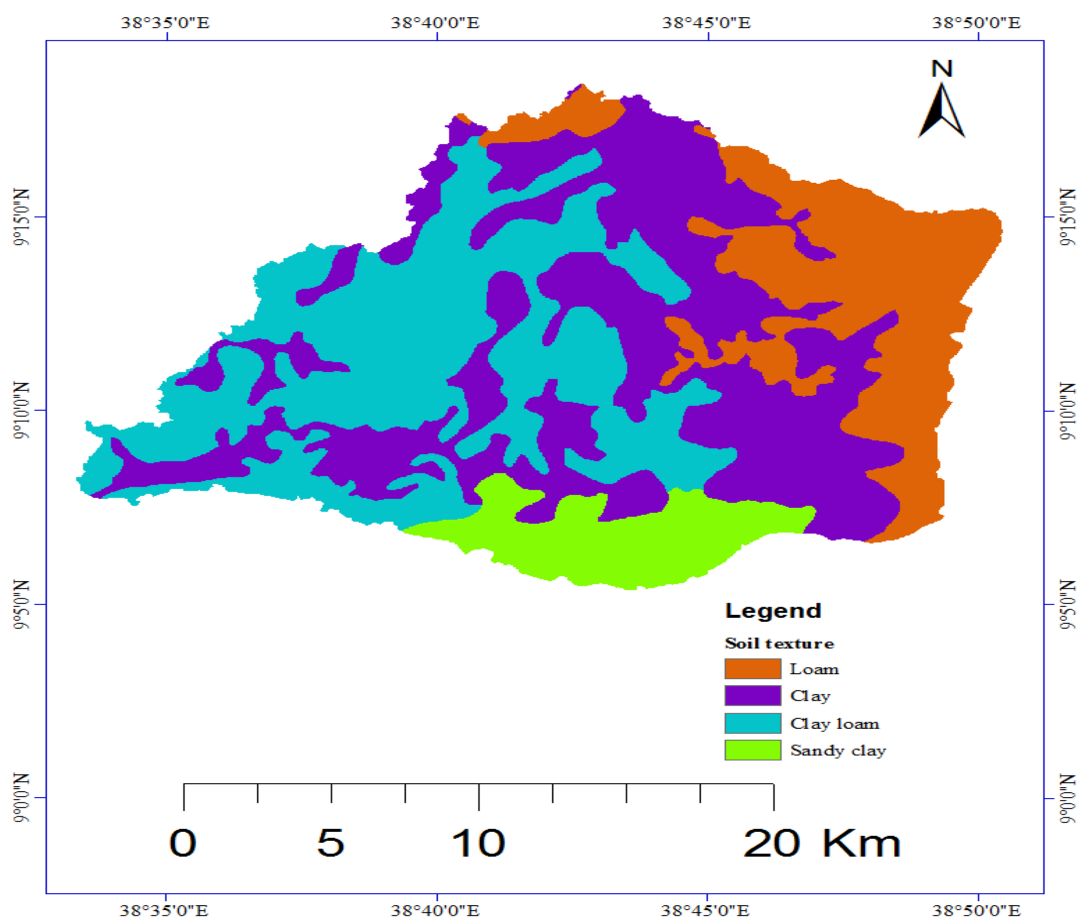

Figure 3.8: Soil texture map of the study are

3. Soil depth

Soil depth refers to the thickness of the soil materials. Soil depth provides structural support, nutrients, and water for plants. (Jamshid, 2003). The soil depth is one factor which is used to determine irrigation suitability. The soil depths of the study area were divided in to four classes to select surface irrigation potential. Rating factor was given for the value of soil depth and weighting them to evaluate the suitability of surface irrigation potential of the study area it was shown in the Figure 3.9.

Table 3.5: Factor rating for suitability of soil depth (FAO, 1991)

Factor	factor rating			
	S1	S2	S3	N
Soil depth (cm)	≥100	80-100	50-80	<50

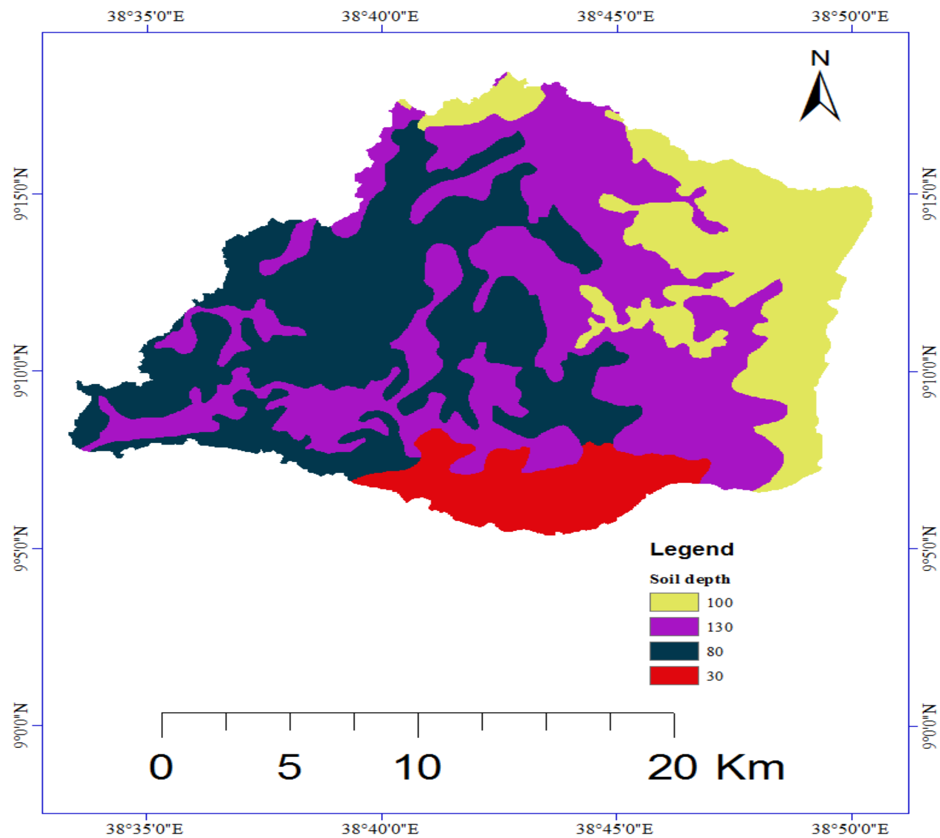

Figure 3. 9: Soil depth map of the study area

4. Soil drainage

Soil drainage requirement is a critical element in selecting land for irrigation, particularly with diversified upland crop production (FAO, 1997). Adequate soil drainage is essential to ensure sustained productivity and to allow efficiency in farming operations. According to (FAO, 1997) guideline soil drainage was divided in to four classes. These classifications were: well drained, moderately drained, poor drained and imperfectly drained. Therefore the soil drainage of the study area was classified in to well drained, imperfectly drained and poorly drained as shown in Figure 3.10.

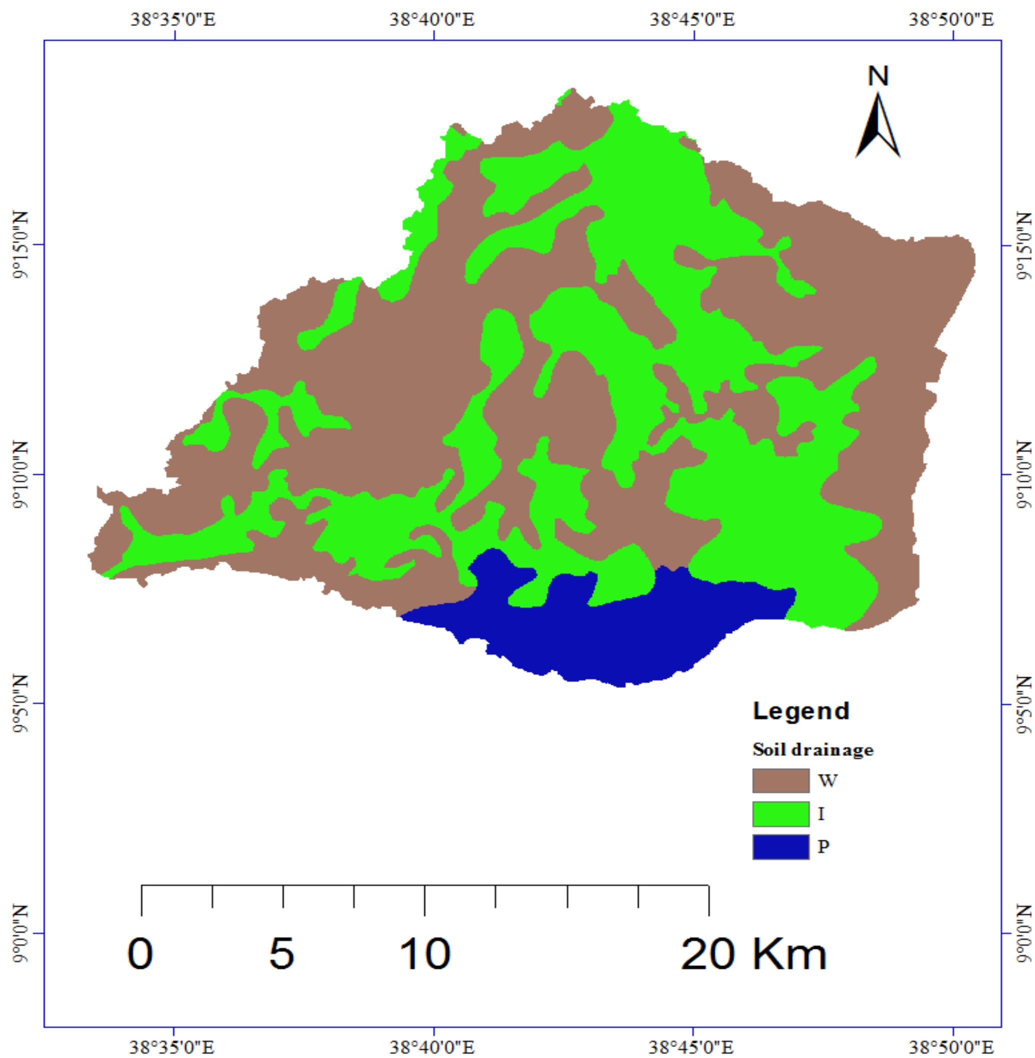

Figure 3. 10: Soil drainage map

3.4.3.3. Land Use/ Cover Analysis

Land use/ cover of the study area were also the factor, which were used to evaluate the land suitability for irrigation. Land use map of the study area was obtained from the Ethiopian Mapping Agency. Land use/ cover types of the study area were ranked based on their suitability for irrigation potential. Land use/cover influences on the cost of irrigation practice to prepare the land for agriculture. The types of land use/cover in the study are included perennial crop. Annual crop grass land, moderate forest mixed forest woodland wet land, closed grass, settlement Figure 3.11.

Perennial Crops: This land use type was covered an area of 4754.97 ha of the total study area. It is speeded throughout the study area. It was found as dominant in the most part of the study area. Land use/Landover classes of this study were classified as highly suitable for irrigation with the assumption that these land cover classes can be irrigated without limitations.

Annual Crop: This land use type was accounts an area of 25160.67 ha of total study area which includes the scattering cultivation, shifting cultivation and recession farming following the dried out water or wetland areas. Land uses/cover classes of this type were classified as highly suitable for irrigation with the assumption that these land cover classes can be irrigated without any limitation.

Woodland: This land cover type was representing an open wood land having the tree coverage of less than 50% ground cover including open bush and shrub lands. This land cover accounts about 47.52 ha.

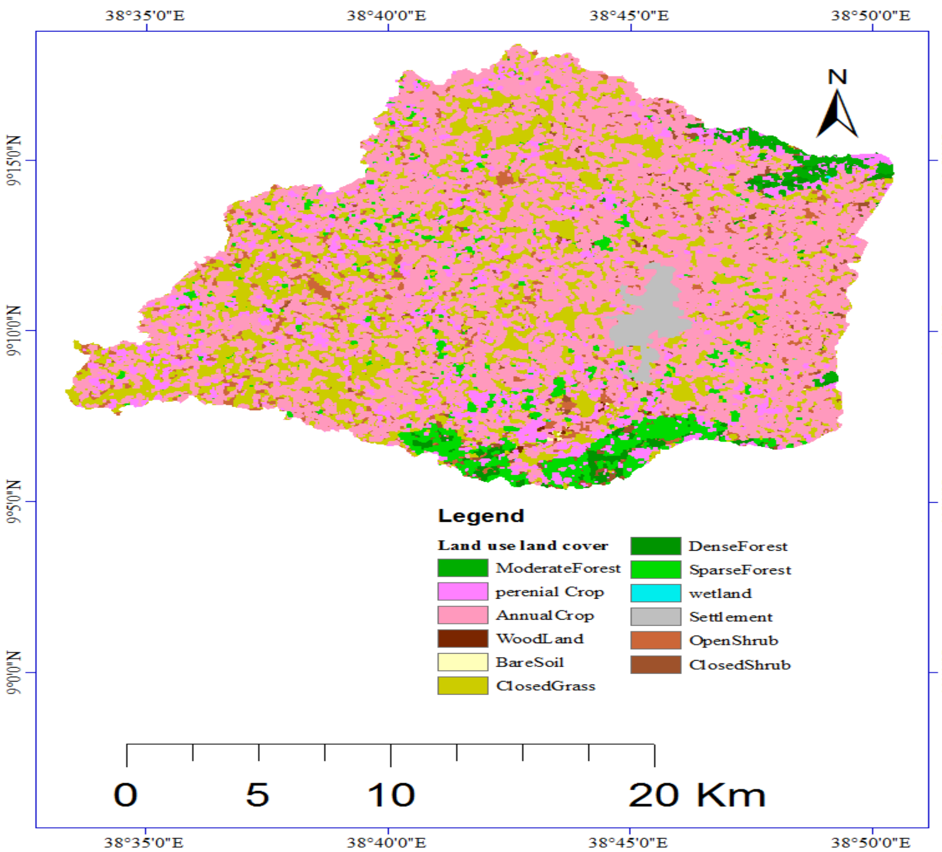

Figure 3. 11: Land use land cover map

3.4.4. Developing the Pairwise Comparison

Pair wise comparisons were evaluated to find suitable alternatives to estimate associated absolute numbers from 1 to 9 is selected and allocated for each factor. Team where a maximum score implies that the row was more important than the column. The diagonal of the matrix was allocated a score of 1.Now proceeding column wise the value in the corresponding column just below the diagonal was just inverse of the score in the corresponding row.

The score given in the matrix was the fundamental scale for making judgments; which means: 1 is Equal, 2 is between equal and Moderate, 3 Moderate, 4 Between Moderate and Strong, 5 Strong, 6 Between Strong and Very Strong, 7 Very Strong, 8 Between Very Strong and Extreme, 9 Extreme Decimal judgments, such as 3.5, are allowed for fine tuning, and judgments greater than 9 may be entered, though it is suggested that they be avoided. Consistency Ratio calculation was described with formula from the matrix goal calculation.

$$CR=\frac{CI}{RI} \quad (3.2).$$

Where, CI= Consistency Index and R= Random Consistency Index, Moreover, Consistency Index was computed as follows: CI = $\frac{(\lambda\max - n)}{(n-1)}$ (3.3).

Where: λmax= maximum Eigen value and n = numbers of criteria or sub-criteria in each pair wise comparison matrix. The bigger the matrix is the higher the inconsistency level.

3.4.5. Weighing of Irrigation Suitability Factors to find Potential Irrigable Sites

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

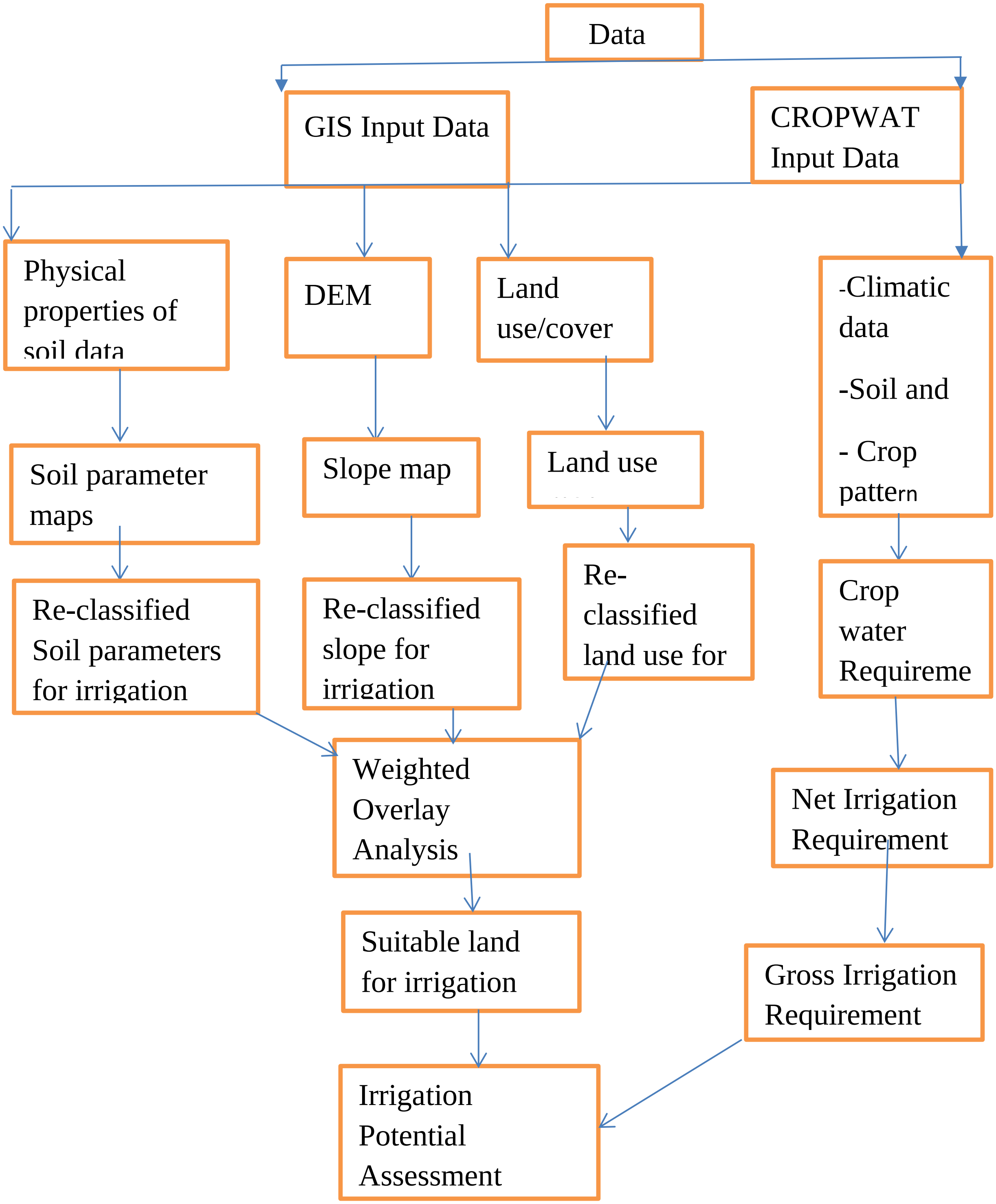

Figure 3.12: Work flow of the study area

3.4.6. Computing Irrigation Water Requirements

The assessment of the irrigation potential, based on soil and water resources can be done by assessing the irrigation water requirement FAO 1987.According to FAO, (2001), ETc can be derived from ETO using the equation

$$ETC=ETO*KC \quad (3.4).$$

Where, Kc is crop coefficient, ETC= crop evapotranspiration (mm/day), ETO=Reference evapotranspiration (mm/day).

Reference Evapotranspiration ETO

ETO is climatic parameters that it is affected by climatic factors only. It was calculated by using FAO penman-montheith method with the help of CROPWAT 8.0 software.

Net Irrigation Water Requirement (NIWR)

It is the depth of moisture that must be supplied by irrigation to satisfy evapotranspiration need of the crop minus effective rainfall. According to FAO (2002) net irrigation requirement can be expressed as:

$$NIR=ET-Pe \quad (3.5).$$

Where Pe=effective rainfall, ET=crop water requirement

Gross Irrigation Water Requirement (GIWR)

Gross irrigation water requirement is the net irrigation requirement divided by irrigation efficiency. It is described according to FAO (2002).

$$GIWR=NIR/ E \quad (3.6).$$

Where E=Irrigation Efficiency

According to (FAO, 1997) recommendations on the irrigation schemes, irrigation efficiency for Ethiopian highlands is given as 50%.

4. RESULTS AND DISCUSSIONS

4.1. Irrigation Suitability

The analysis results of surface irrigation suitability factors were described by considering: slope, soil physical properties and land use land cover factors.

4.1.1. Slope Suitablity

Results obtained from slope analysis of the study area were classified in to four suitability classes (S1, S2, S3 and N) shown in Table 4.1.

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

Slope range (%)	Area coverage (ha)	Area coverage (%)	Suitablity Classes	Suitability class name
0-2	25877.79	56.5	S1	Highly suitable
2-5	12825.81	28	S2	Moderately suitable
5-8	4906.44	10.72	S3	Marginally suitable
>8	2175.03	4.75	N	Not suitable

As the results obtained in Table 4.1 revealed that 56.6% (25877.79 ha) area was highly suitable, 28% (12825.81 ha) area was moderately suitable, 10.72% (4906.44 ha) area was marginally suitable and 4.75% (2175.03 ha) area was not suitable for surface irrigation system. Hence, in terms of slope suitability, the major parts of the study area were highly to marginal suitable for surface irrigation development. After the reclassification of the slope of the study area, slope suitability map of the area was developed for surface irrigation in Figure 4.1.The land having slope less than two percent, the green one (S1) in Figure 4.1 is suitable for surface irrigation without limitation because it did not need much cost. While the land which had slope greater than eight percent was not suitable for surface irrigation due to high cost.Slpoe which was suitable fort surface irrigation in terms of its work efficiency and cost for land leveling, canal construction and cost for pumping system.

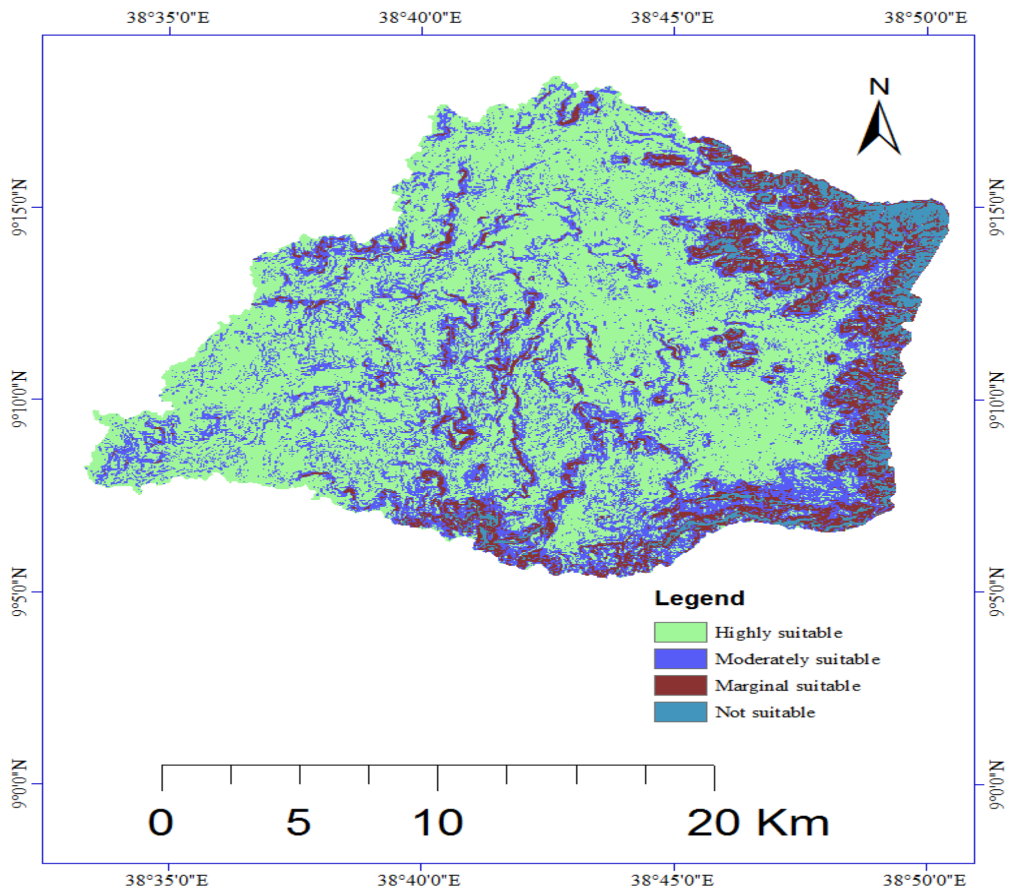

Figure 4.1: Slope suitablity map of the study area

4.1.2. Evaluation of Soil Suitable for irrigation

The results of soil suitability analysis of the study area for surface irrigation were presented in terms of soil physical properties such as soil texture, soil type, and soil depth and soil drainage. They affect the root growth of plant, infiltration of water in to the soil and the production of crops.

1. Soil Texture

The soil textures in the study area were found in the Table 4.2 with their distributions. Results of soil texture analysis indicate that the study area could be classified in to two irrigation suitability classes, highly suitable (S1) and moderately suitable (S2).

Table 4.2: Soil texture suitability of study area.

Soil Texture	Area (ha)	Area (%)	suitability class
Clay, Loam and clay loam	41824.08	91.61	Highly suitable
Sandy clay	3830.4	8.39	Moderately suitable

Based on Table 4.2, the soil texture classes of study area were developed. Clay, clay loam and loam were classified as highly suitable with area of 91.61% (41824.08 ha) and sandy clay was moderately suitable covering 8.39% (3830.4 ha) area for irrigated. Generally, the soil textures of the study area were dominated by clay, clay loam, loam and sandy clay soil. The advantage of clay soil in irrigated agriculture is that in clay soil more water can be stored than in sandy clay soil and also clay soil is good in water holding capacity and rich in nutrients. Thus clay soil was considered as highly suitable for surface irrigation in terms of soil texture suitability.

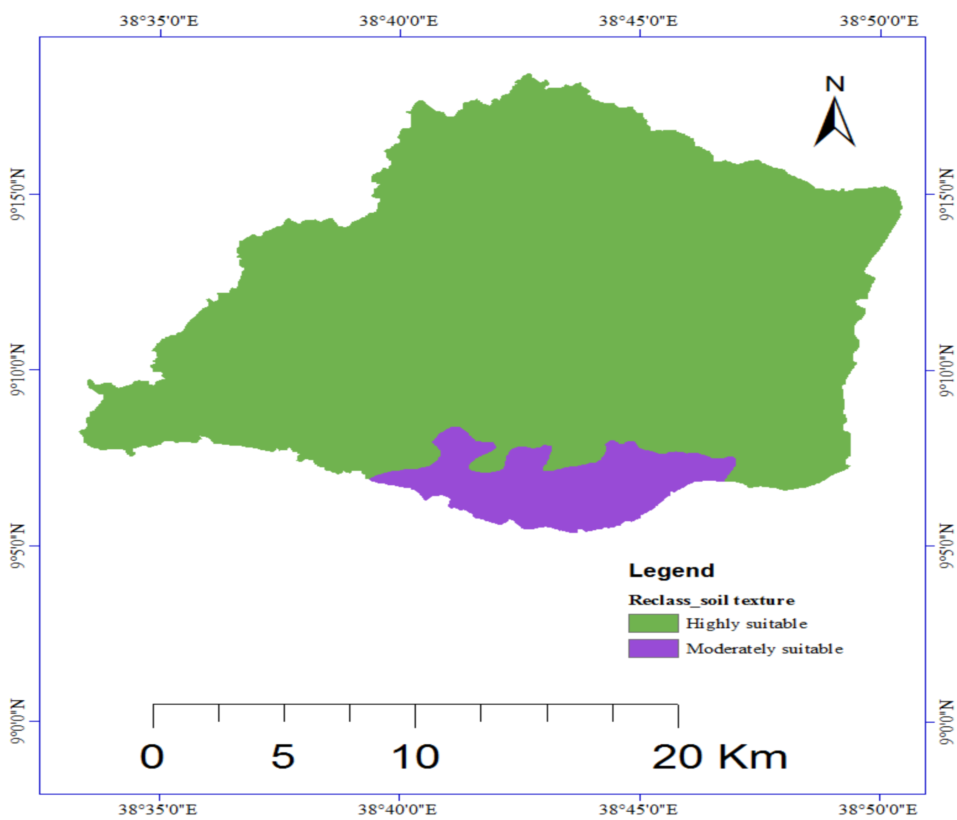

Figure 4.2: Soil texture suitability map of the study area.

2. Soil Type

Soil types of the study area were generally classified into three irrigation suitability classes based on soil suitability: S1 (highly suitable), S2 (moderately suitable), N (not suitable) in Table 4. 3. vertisols and Luvisol covering an area of 58% (26485.74 ha) of the study area, they are soils with natural fertility and suitability for wide range of agriculture uses and very productive were classified as highly suitable (S1) for surface irrigation, Cambisols covers an area of 33.6% (15338.34 ha) of the study area has good natural fertility and considerable for agricultural was classified as moderately suitable (S2) and Leptosols covers an area of 8.39% (3830.4 ha) with low moisture holding capacity, low production potential, rocky soil, poor fertility and poorly drained was also classified as not suitable (N) for surface irrigation. Hence, most of the study area was highly suitable for surface irrigation.

Table 4.3: Soil type suitablity of study area

Soil Type	Area (ha)	Area (%)	Soil suitablity	Suitability classes
EutricVertisol,Chromic Luvisol	26485.74	58.01	S1	Highly suitable
Eutric Cambisols	15338.34	33.6	S2	Moderately suitable
Eutric Leptosols	3830.4	8.39	N	Not suitable

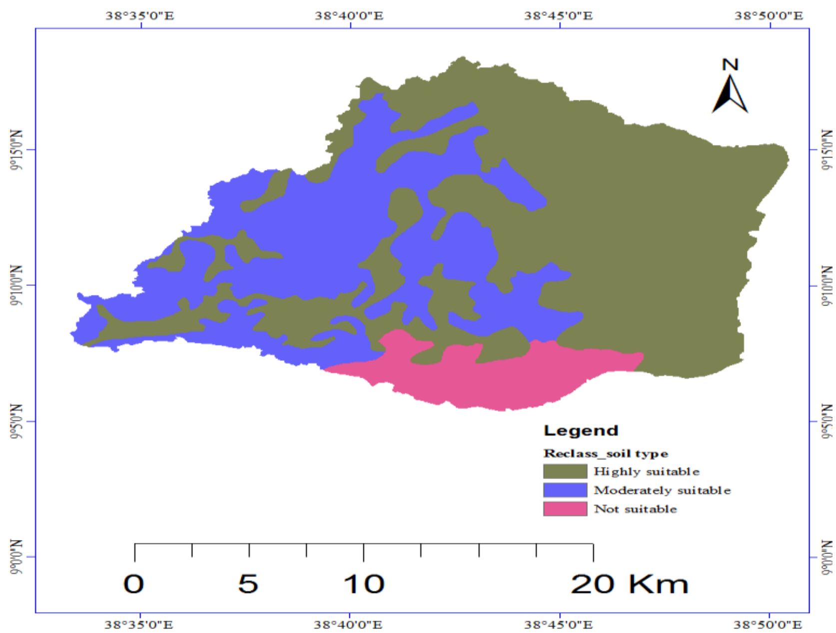

Figure 4. 3: Suitability map of soil type of the study area

3. Soil Depth

The thickness of soil depth gives structural support, nutrients and water for crops. The soil depth properties of the Sibilu river watershed were classified in to highly suitable, moderately suitable and not suitable for surface irrigation. It was found in Table 4.4.

Table 4.4: Soil depth suitability of the study area

Soil Depth	Area (ha)	Area (%)	Suitability rating	Suitability class
130,100	27956.4	61.23	S1	Highly suitable
80	16396.5	35.91	S2	Moderately suitable
30	1301.58	2.85	N	Not suitable

As obtained in Table 4.4 the study area can be classified into three irrigation suitability classes based on soil depth suitability as a factor: 61.23% (27956.4 ha) of the total area was classified as highly suitable,35.91% (16396.5 ha) was moderately suitable and 2.85% (1301.58 ha) area was not suitable for surface irrigation.

Based on the given weighting factors for each soil depth of the study area, soil depth suitability map of the study area for surface irrigation potential was developed in Figure 4.4 most of the upper part of the study area were highly suitable while the lower part of the study area were not suitable for surface irrigation suitability.

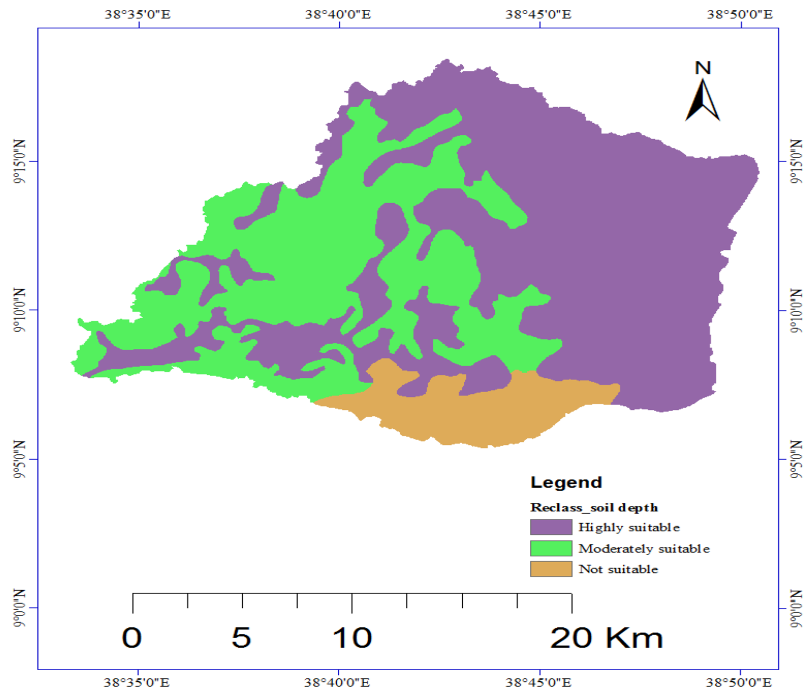

Figure 4. 4: Suitability map of soil depth of the study area.

4. Soil Drainage

Soil drainage of the study area was divided in to three classes. These were well drained, imperfectly drained and poorly drained. Most of the study area was in well drained in drainage soil suitability.

Table 4.5: Soil drainage of the study area.

Soil drainage	Area (ha)	Area (%)	Suitability factor	Suitability class
Well drained	24148.44	52.89	S1	Highly suitable
Imperfectly drained	17675.64	38.72	S3	Marginally suitable
Poorly drained	3830.4	8.39	N	Not suitable

The soil suitability classes as presented in Table 4.5 show that 52.89% (24148.44 ha) was well drained, which classified as highly suitable, 38.72% (17675.64 ha) was imperfectly drained and marginally suitable and the remains 8.39% (3830.4 ha) was considered as not suitable for surface irrigation. Hence, majority of the study area were highly suitable for surface irrigation development. Based on the soil type the Luvisol was well drained due to its high water holding capacity, whereas Leptosol has low water holding capacity and poor nutrient, so it was poorly drained. From the rasterized soil map of the study area, the suitability map of soil drainage was developed in Figure 4.5.As indicated in Figure 4.5 soil drainage map; most parts of the study area were highly suitable for surface irrigation.

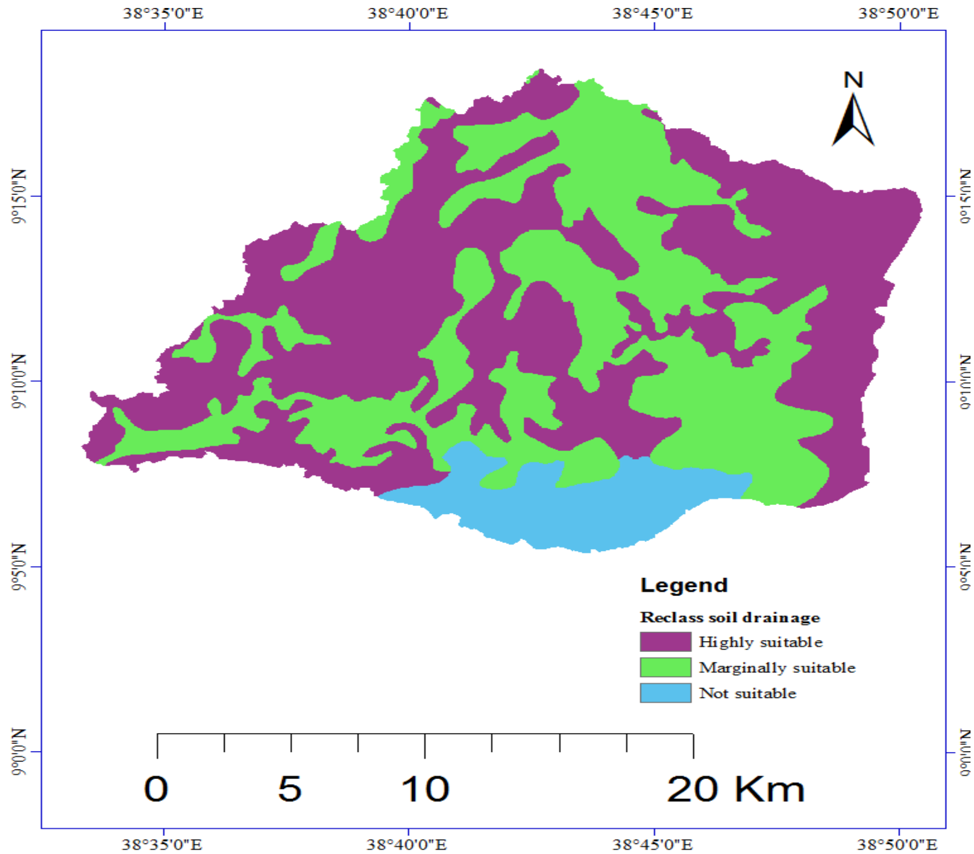

Figure 4.5: Suitability map of soil drainage of the study area.

4.1.3. Land Use/ land Cover Suitability

Land use map of the study area was obtained from the Ethiopian Mapping Agency. Land use land cover of the study area, such as cultivated and grass land were classified as highly suitable for irrigation with the assumption that these land cover classes can be irrigated without limitations. They cover 89.82% (41008.5 ha) of the study area other land use such as wood and grazing land were ranked as marginally suitable with area of 6.05% (2760.48 ha) and forest and settlement area were not suitable for surface irrigation with the area of 4.42 %.(2015.55 ha).Hence, the majority of the study area was in the range of highly to marginal suitable for surface irrigation in terms of land use land cover suitability. Around 41008.5 ha of land use land cover of the study area were highly suitable for surface irrigation as found in Table 4.7.

Table 4.7: Major land use/land cover types of the study area

Land use/cover factor	Area(ha)	Area (%)	Suitability factor	Description
Cultivated and grass land	41008.5	89.82	S1	Highly suitable
Wood and grazing land	2760.48	6.05	S3	Marginally suitable
Forest and settlement	2015.55	4.42	N	Not suitable

As obtained from Table 4.7 the cultivated land was considered as highly suitable for surface irrigation due to there will not be land clearing preparation cost and there will not be deforestation of forests**.** And also these land cover classes be irrigated without or with limited cost for land clearing and farm preparation.

Wood and grazing land classified as marginally suitable for irrigation due to their work efficiency, cost for land clearing and land preparation for irrigation.

Forest and settlement were considered as not suitable for surface irrigation due to they are restricted to use for irrigation and there is no irrigation practice in the land cover.

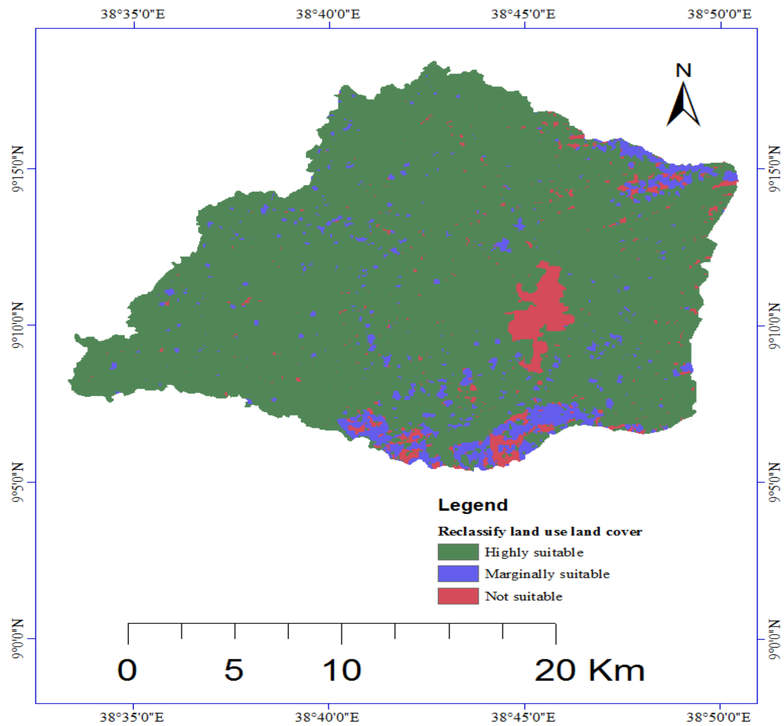

Figure 4.6: Suitability of Land use land cover map of the study area

4.2. Irrigation Water Requirement for Suitable Irrigable Land

The river discharge and gross irrigation water requirements of cabbage, potato and pepper for the potentially irrigable site in Table 4.8 indicates that the irrigation needs cabbage, potato and pepper crops exceeds the minimum stream flow discharge in all cases in Table 4.8.Thus,the existing water resources can irrigate only small portion of the irrigable land. The irrigation efficiency for the study area was found to be 50%.

4.3. Irrigation Potential of Sibilu River Catchment

Irrigation potential of the river catchment in the study area was obtained by comparing irrigation requirements of the identified land suitable for surface irrigation and the available mean monthly flows in the river catchments.

Irrigation potential of the Sibilu River was obtained by comparing water demand of the three crops grown in the study area cabbage, potato and pepper, considering the identified suitable land for irrigation and the 90% dependable monthly flow of Sibilu River.

The maximum water irrigation requirement was found in the month of May, which was 0.30l/s/ ha (Table 4.8), whereas the minimum available flow in the month of May found to be 0.08m^3/s (Table 4.8), the command area that can be irrigated using the available flows in the study area

Table 4.8: Gross Irrigation Requirement of different crops in the study area.

month	Type of Crops			NIW	Area	GIWR (m^3/s/ha)	90%of exceedance flow
	cabbage	potato	pepper	l/s/ha	ha		
Jan	8.8	7.6	0	0.02	2,525.00	$4*10^{-5}$	0.101
Feb	75.7	63.1	0	0.17	179.40	$3.4*10^{-4}$	0.061
Mar	71.1	83.1	6.9	0.18	133.3	$3.6*10^{-4}$	0.048
Apr	70	90.5	15	0.21	176.2	$4.2*10^{-4}$	0.074
May	83.6	80.5	76.2	0.30	133.3	$6*10^{-4}$	0.08
Jun	14.9	7.2	23.4	0.06	1,333.3	$1.2*10^{-4}$	0.16
Jul	0	0	0	0	-	0	7.128
Aug	0	0	0	0	-	0	29.236
Sep	0	0	0	0	-	0	7.741
Oct	0	0	0	0	-	0	0.702
Nov	0	0	0	0	-	0	0.309
Dec	0	0	0	0	-	0	0.154

The results obtained in Table 4.8, indicated that the minimum net irrigation water requirements was found in the months of January, which was 0.02 l/s/ha,where as it had maximum area coverage (25,25 ha).

4.4. Weighting of Factors and Suitable area for Irrigation

The pair-wise comparison matrix was used to weigh the factors. Weighing of irrigation suitability factors including slope, soil and land use land cover were needed. Based on relative importance of each factor the results were given in Table 4.9.

Table 4.9:Pair-wise comparison scoring for irrigation suitability factor.

	Slope	Soil Type	Soil Texture	Soil Depth	Soil Drainage	Land use / cover
Slope	1.00	4.00	2.00	2.00	3.00	5.00
Soil Type	0.25	1.00	2.00	0.50	0.75	1.20
Soil Texture	0.50	0.50	1.00	0.67	1.00	1.50
Soil Depth	0.50	2.00	1.50	1.00	2.00	1.67
Soil Drainage	0.33	1.33	1.00	0.50	1.00	1.20
Land use land cover	0.20	0.83	0.50	0.80	0.83	1.00
sum	2.78	9.67	8.00	5.47	8.58	11.57

Then the table was formulated for normalization based on Table 4.9, by dividing each value of a cell of column to total column. The average of each row in this table was the weights of each factor. The weight of the factors was calculated by multiplying average of each row by 100.

Table 4.10: Normalized Value

	Slope	Soil type	Soil texture	Soil depth	Soil drainage	Land use land cover	Weight
Slope	0.36	0.41	0.25	0.37	0.35	0.43	0.36
Soil type	0.09	0.10	0.25	0.09	0.09	0.10	0.12
Soil texture	0.18	0.05	0.13	0.12	0.12	0.13	0.12
Soil depth	0.18	0.21	0.19	0.18	0.23	0.14	0.19
Soil drainage	0.12	0.14	0.13	0.09	0.12	0.10	0.12
Land use land cover	0.07	0.09	0.06	0.15	0.01	0.09	0.01

Calculate the consistency ratio by calculating lambda, lambda was calculated by dividing row to its weights. Therefore, first the row and then lambda were calculated.

Table 4.11: Computing lambda

Rows	Value	Approximate lamda
Row(R1)	2.271	6.277
Row (R2)	0.744	6.153
Row (R3)	0.742	6.14
Row (R4)	1.177	6.229
Row (R5)	0.723	6.247
Row(R6)	0.573	6.245
Average		6.215

$$CI=(\lambda - n)/(n-1) \quad (4.1).$$

Where, CI=consistency index, λ =maximum lambda and n=number of irrigation factors that computed=6, CI= (6.215-6)/ (6-1) =0.043

CI=0.043

$$CR=CI/RI \quad (4.2).$$

Where, CR=consistency ratio, CI=consistency index and RI=random consistency index.

CR=CI/RI=0.043/1.24= 0.034, CI=0.034, RI=1.24 for n=6 as it was shown in the appendix table.

The calculation for consistency ratio was found to be 0.034; this was less than the maximum allowable 0.1. This indicates that the comparisons of each factor were perfectly consistent, and the relative weights were suitable for use in the GIS multi-factor evaluation.

4.5. Suitable Land for Irrigation

Potential irrigable land was obtained by creating irrigation suitability model analysis which involved weighting of values of all suitability factors such as slope, soil and land use land cover.

The results obtained in Figure 4.8 show that most parts of the study area were ranged in terms of overall suitability analysis, the study area were classified as highly suitable to moderately suitable for surface irrigation potential developments.

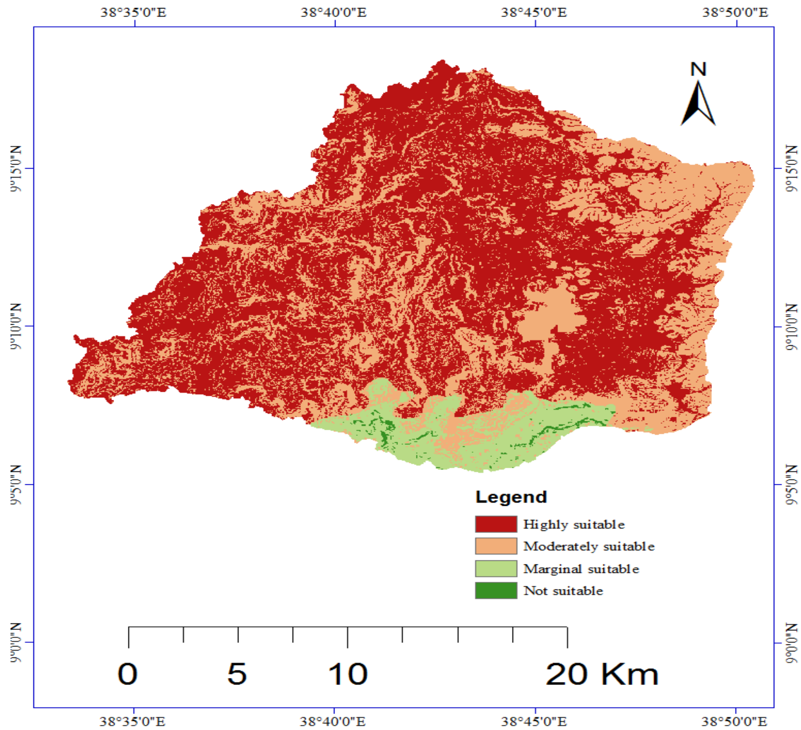

Figure 4.7: Final irrigable land suitability map of Sibilu river catchment

As shown in Table 4.12 the overall irrigation suitability results were described. Highly suitable area for surface irrigation covered area of 57.53% (26247.33 ha), moderately suitable was 35.89% (16373.43 ha), marginally suitable area covered 6.17% (2813.13 ha) and 0.42% (191.7 ha) of the study area categorized as not suitable for surface irrigation. Therefore, most of the study areas were ranged as highly suitable to moderately suitable for surface irrigation in terms of overall suitability.

Table 4.12: Overall surface irrigation suitability

Area ha	Area (%)	Suitability factor	Description
26247.33	57.53	S1	Highly suitable
16373.43	35.89	S2	Moderately suitable
2813.13	6.17	S3	Marginal suitable
191.7	0.42	N	Not suitable

5. CONCLUSIONS AND RECCOMMENDATIONS

5.1 CONCLUSIONS

From the results obtained and discussed in the above sections, the following conclusions were made: The irrigation suitability study was conducted for Sibilu river catchment. It had been carried out to suitable irrigable land in the study area and developed final suitability map. The main irrigation suitability factors undertaken during the study were slope, soil type, soil texture, soil depth, soil drainage and land use land cover.

The tools used to assess the irrigation potential of this study were: Geographic Information System, Excel work sheet and CROPWAT. Secondary data were collected from Ministry of Water, Irrigation and Electricity, National Metrological Agency and Ethiopian Mapping Agency. The collected data were checked for inconsistency using double mass curve and the missing metrological data were filled by normal ratio method.

Irrigation suitability was evaluated based on FAO guideline such as highly suitable (S1), moderately suitable (S2), marginal suitable (S3)and not suitable (N).Based on the analysis 56.5% of slope, 19.3% of soil and 89.82 % of land use land cover of the study area were identified to be in the range of highly suitable for surface irrigation. Whereas 4.75% of slope, 8.39% of soil and 4.42% of land use land cover were classified as not suitable for surface irrigation. When these factors were weighted using overlay in Arc GIS, the potential irrigation lands for irrigation were as follows: 57.53% highly suitable, 35.89 % moderately suitable, 6.17% marginally suitable and 0.42% not suitable for irrigation development.

Irrigation water demand of cabbage, potato and pepper crops were computed climatic data input using FAO penman-Monteith in CROPWAT 8.0 software. The irrigation demand of the irrigable land for each catchment was evaluated with 90% stream flow and showed that the existing water resource potential could irrigate a small portion of the land in the study area.

The main limitation for surface irrigation in the study area was the available water not the land for irrigation. In general, the study area was ranged as highly to marginal suitable for surface irrigation potential in terms of land suitability factors.

5.2. RECOMMENDATIONS

The finding indicated that, from the result obtained about 133 ha potentially irrigable land could be irrigated within the available flow in the river at the dry season. Therefore, ground water should be utilized during dry season to increase the irrigable land if possible.

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

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

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APPENDIX

Appendix Table: 1 Average monthly Temperature of Addis Ababa Bole station

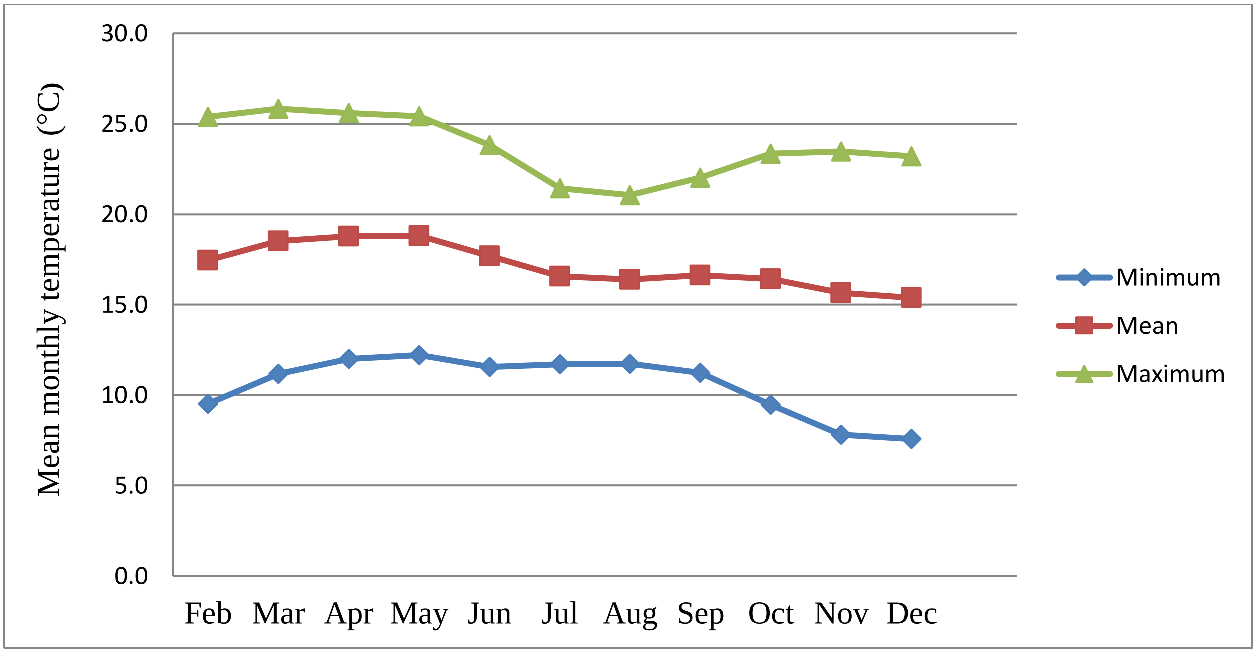
Temp (℃)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	24.0	25.4	25.8	25.6	25.4	23.8	21.4	21.1	22.0	23.4	23.5	23.2
Minimum	8.4	9.5	11.2	12.0	12.2	11.5	11.7	11.7	11.2	9.5	7.8	7.6
Mean	16.2	17.5	18.5	18.8	18.8	17.7	16.6	16.4	16.6	16.4	15.6	15.4

Appendix Table 2. Average monthly Temperature of Addis Ababa Observatory station

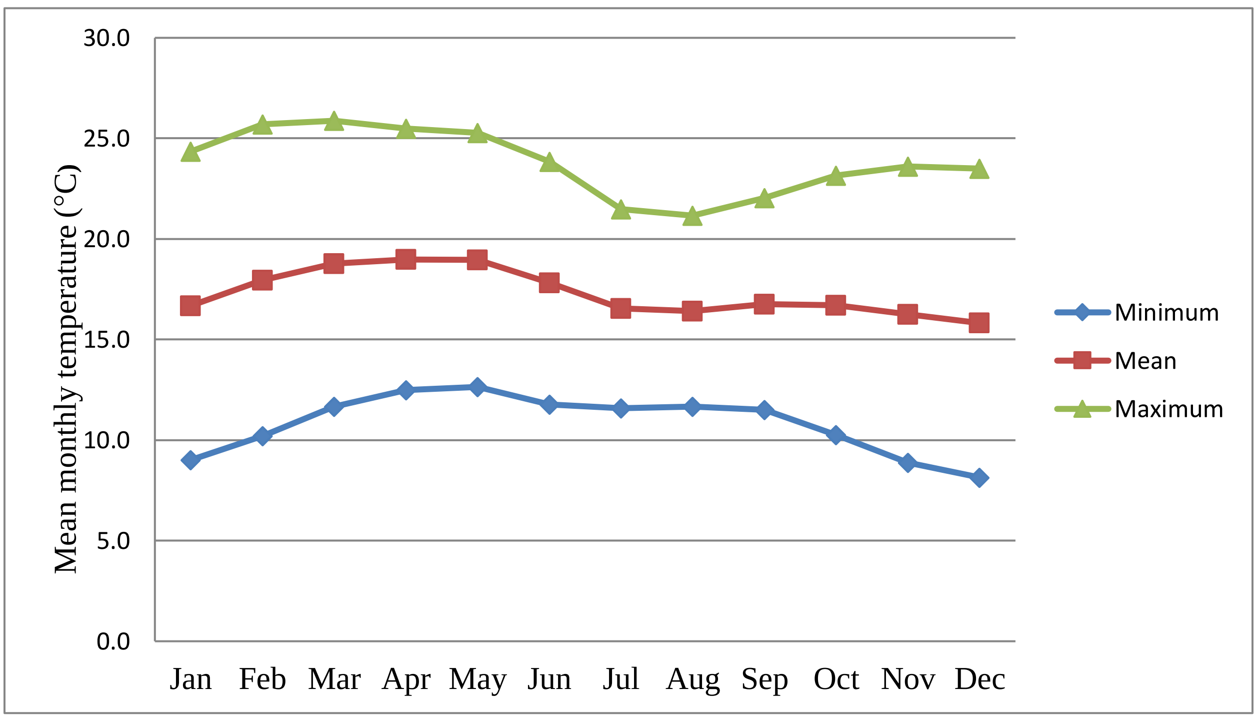
Temp(℃)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	9.0	10.2	11.7	12.5	12.6	11.8	11.6	11.7	11.5	10.3	8.9	8.1
Maximum	24.4	25.7	25.9	25.5	25.3	23.8	21.5	21.2	22.0	23.2	23.6	23.5
Mean	16.7	18.0	18.8	19.0	19.0	17.8	16.5	16.4	16.8	16.7	16.2	15.8

Appendix Table 3. Average monthly Temperature of Sululta station

Temp(℃)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	22.9	23.9	24.2	23.9	24.0	22.8	21.0	20.6	21.2	21.9	22.4	22.1
Minimum	5.0	6.1	6.7	7.2	7.6	6.4	6.2	6.6	6.5	5.5	4.7	4.9
Mean	14.0	15.0	15.4	15.6	15.8	14.6	13.6	13.6	13.9	13.7	13.6	13.5



Appendix Figure 4: Average monthly temperature of Addis Ababa Bole



Appendix Figure 5: Average monthly temperature of Addis Ababa Observatory

Appendix Table 6. Corrected monthly rainfall at Addis Aaba.Bole (mm)

Year	Jan	Feb	March	Apr	May	jun	Jul	Aug	Sep	Oct	Nov	Dec
1998	66.60	40.00	43.80	99.80	197.70	111.60	270.70	236.80	173.40	139.40	0.00	0.00
1999	4.40	0.00	35.00	17.80	30.50	104.60	294.00	270.50	62.80	127.10	0.00	0.00
2000	0.00	0.00	17.60	87.80	95.20	102.10	192.90	221.90	157.50	19.60	7.50	0.00
2001	0.00	10.30	174.30	14.80	116.70	166.00	289.40	207.30	113.30	10.60	0.00	0.00
2002	30.60	25.90	79.40	36.60	49.60	115.50	213.90	233.60	72.60	0.50	0.00	32.80
2003	4.80	41.50	48.90	111.50	18.00	111.00	204.30	238.40	130.20	4.60	0.00	33.30
2004	26.52	11.70	32.40	118.20	7.00	114.50	240.60	230.10	122.10	50.00	0.60	0.00
2005	55.40	14.10	41.80	116.20	164.60	159.10	174.30	248.00	77.60	25.80	7.20	0.00
2006	2.00	36.60	107.80	93.90	37.80	115.10	313.20	331.10	132.50	35.90	0.00	0.00
2007	9.90	21.30	61.10	86.80	134.00	157.60	191.30	305.40	130.90	37.20	0.10	0.00
2008	0.00	0.00	0.00	34.00	75.30	73.10	295.10	259.10	192.70	22.20	53.10	0.00
2009	40.90	0.00	12.40	46.10	52.00	77.50	238.20	269.50	86.10	42.40	2.00	79.90
2010	0.40	115.20	75.60	159.50	94.70	107.20	320.20	138.80	105.00	0.00	13.80	15.70
2011	3.40	13.60	27.90	51.20	86.00	148.00	183.10	296.50	141.30	0.00	11.90	0.00
2012	0.00	0.00	34.50	75.10	58.50	72.80	228.80	281.60	176.90	1.20	0.00	9.80
2013	0.00	0.00	63.50	114.40	78.50	101.40	157.60	270.20	126.70	45.30	3.20	0.00
2014	0.00	41.70	29.70	33.70	62.10	41.80	179.70	253.60	95.10	34.80	0.00	0.00
2015	0.00	0.00	21.30	22.80	96.55	174.35	218.00	274.35	123.50	2.70	11.15	0.10
2016	37.65	16.00	43.95	137.50	124.10	104.40	162.90	226.60	132.00	17.60	3.40	0.00
2017	0.00	20.70	66.10	33.10	174.30	44.10	217.00	241.70	260.50	171.30	0.00	0.00
mean	14.13	20.43	50.85	74.54	87.66	110.09	229.26	251.75	130.64	39.41	5.70	8.58

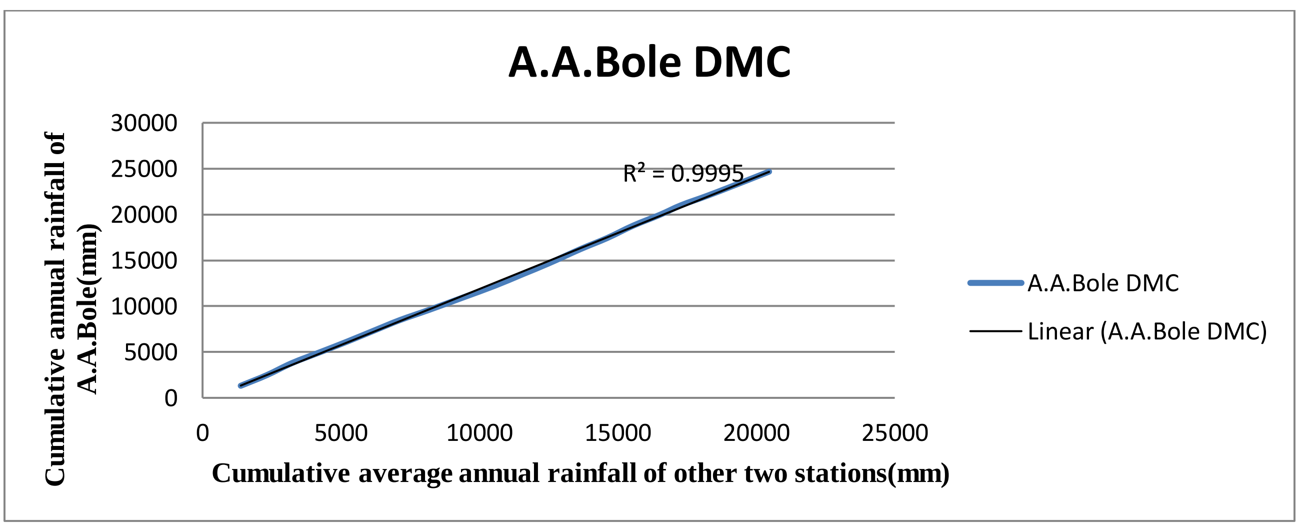
Appendix Table 7: Corrected monthly rainfall at Addis Ababa Observatory (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998	55.20	20.50	49.00	48.50	154.20	124.40	285.40	260.00	213.60	126.90	0.00	0.00
1999	2.90	0.30	28.80	16.30	23.80	119.60	281.90	305.30	88.40	75.40	0.00	0.00
2000	0.00	0.00	17.60	49.90	110.00	144.50	244.80	306.20	250.60	46.40	21.10	0.00
2001	0.00	12.20	210.80	25.00	168.00	216.20	428.00	246.40	131.70	13.70	0.00	0.00
2002	14.70	21.00	90.20	56.30	63.10	172.50	256.90	215.90	108.80	0.20	0.00	10.50
2003	10.50	53.30	62.60	99.30	20.20	151.80	291.80	233.30	193.30	0.80	1.50	54.90
2004	24.80	20.30	49.50	139.90	30.10	141.90	238.50	272.60	164.00	76.90	0.00	0.00
2005	45.90	51.60	83.20	160.90	133.70	179.80	246.00	315.20	162.50	25.05	4.40	0.00
2006	0.70	11.20	135.25	78.90	74.60	150.10	356.30	243.60	239.10	54.00	0.30	8.00
2007	51.30	19.10	59.80	73.80	120.10	174.77	261.80	381.20	147.60	24.80	0.00	0.00
2008	0.00	13.00	0.00	49.40	94.30	88.90	277.00	360.90	256.70	88.20	79.40	22.90
2009	21.30	2.70	28.40	80.60	58.90	82.60	349.90	388.30	112.70	45.80	4.40	65.00
2010	2.60	79.80	55.50	97.80	74.40	271.10	313.90	205.80	237.80	1.80	25.70	15.00
2011	14.10	13.10	44.30	22.80	66.10	182.00	180.90	340.80	146.00	0.00	42.30	0.00
2012	0.00	0.00	15.80	74.09	50.20	69.40	324.20	298.00	215.50	2.30	0.00	9.80
2013	4.40	0.00	57.36	92.30	85.00	153.20	232.36	353.20	202.36	58.40	22.30	0.00
2014	1.70	47.40	61.50	26.20	93.60	66.70	219.90	262.40	264.70	35.00	1.70	0.00
2015	0.00	0.00	27.20	136.17	111.80	214.06	217.00	309.90	148.90	0.00	7.70	0.10

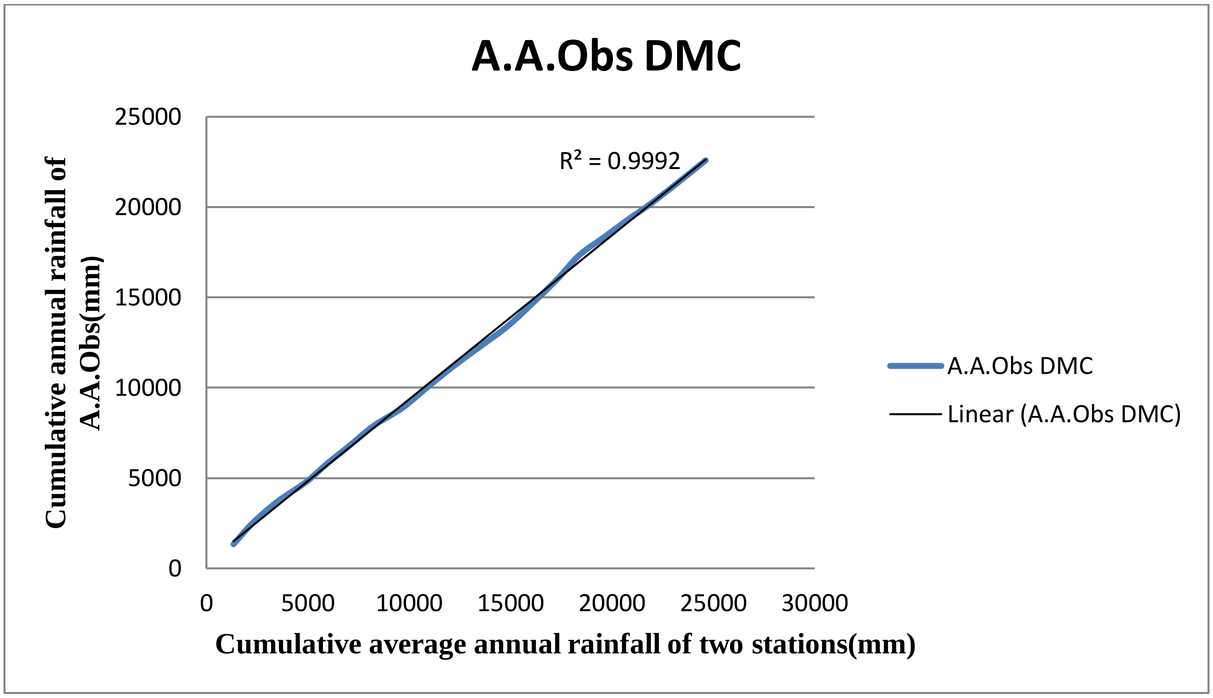
2016	59.80	12.10	47.90	136.80	132.70	187.30	182.80	299.90	141.80	15.50	3.60	1.90
2017	0.00	20.70	36.60	33.70	152.50	64.50	290.40	329.80	386.00	171.30	0.00	0.00
mean	15.50	19.92	58.07	74.93	90.86	147.77	273.99	296.44	190.60	43.12	10.72	9.41

Appendix Table 8.Corrected average monthly rainfall at Sululta (mm)

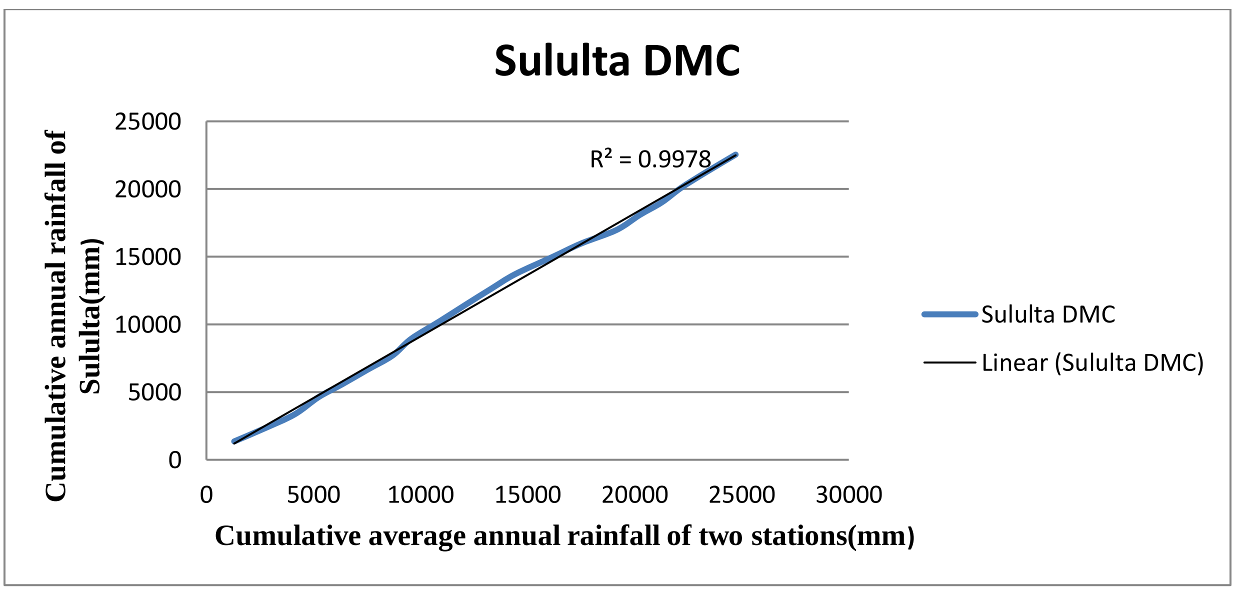
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998	68.50	20.10	6.00	76.90	120.30	190.20	301.60	248.40	193.50	72.40	0.00	0.00
1999	24.20	12.90	28.50	16.00	46.90	189.40	400.70	443.00	146.80	78.70	5.90	0.00
2000	0.00	0.00	7.50	95.80	80.90	164.40	469.90	422.30	138.00	7.00	23.60	13.30
2001	3.60	0.50	164.20	45.30	107.30	166.90	336.90	215.40	79.30	5.10	0.00	0.00
2002	35.60	24.60	97.30	54.50	25.20	153.50	302.30	289.10	81.20	2.50	0.00	35.60
2003	4.10	14.00	32.70	87.00	6.50	162.90	365.40	343.10	139.70	2.00	0.00	8.90
2004	10.10	10.10	36.60	96.50	4.70	127.60	279.40	393.10	165.80	46.50	7.40	1.80
2005	9.60	3.50	33.30	73.90	17.90	41.70	257.70	250.20	155.30	24.30	13.70	0.00
2006	2.50	20.30	82.20	74.50	70.80	178.60	385.50	272.80	185.20	26.40	0.00	14.10
2007	38.60	5.80	60.45	80.30	127.05	163.35	226.55	343.30	139.25	31.00	0.05	0.00
2008	0.00	19.30	11.90	40.10	66.50	89.30	398.90	287.40	132.80	32.90	102.20	0.00
2009	24.30	1.35	5.20	13.20	55.45	126.50	361.50	328.90	99.40	44.10	3.20	72.45
2010	11.30	117.90	56.80	59.70	117.10	267.80	440.90	374.30	243.00	11.00	22.40	10.10
2011	2.60	5.30	73.80	79.60	76.05	228.40	321.90	375.50	180.80	0.80	13.60	0.00
2012	0.00	0.00	37.10	176.30	92.60	124.10	481.80	423.60	301.10	1.75	0.60	9.80
2013	6.20	0.30	29.10	59.50	51.30	153.90	252.50	340.40	145.50	33.40	13.70	0.50
2014	0.00	25.20	46.00	65.80	81.00	60.40	261.10	309.00	128.20	46.80	0.85	0.50
2015	0.00	0.00	18.70	78.35	83.80	134.80	219.00	238.80	98.10	5.40	14.60	0.10
2016	15.50	19.90	40.00	96.70	105.60	145.85	172.85	325.30	171.30	16.55	9.00	0.95
2017	0.00	20.70	41.80	46.30	130.70	88.80	332.80	285.75	323.25	171.30	0.00	0.00
mean	12.84	16.09	45.46	70.81	73.38	147.92	328.46	325.48	162.38	33.00	11.54	8.41



Appendix Figure 9. Double mass curve for Addis Ababa Bole station



Appendix Figure 9.Double mass curve for Addis Ababa Observatory station



Appendix Figure 9.Double mass curve for Sululta station

Appendix Table 11: Mean monthly discharge flow data from Sibilu River

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	0.254	0.189	0.188	0.162	0.141	2.008	23.933	37.027	17.045	1.854	0.475	0.299
1997	0.162	0.087	0.084	0.243	0.095	0.150	7.193	19.764	5.565	0.776	0.579	0.252
1998	0.271	0.111	0.108	0.103	0.183	0.934	17.692	42.576	16.826	4.598	0.649	0.262
1999	0.162	0.078	0.102	0.085	0.079	0.319	11.016	36.769	14.442	2.490	0.463	0.231
2000	0.138	0.072	0.043	0.086	0.123	0.186	7.304	37.882	10.050	1.802	0.474	0.299
2001	0.158	0.096	0.169	0.172	0.286	1.402	21.670	31.384	11.302	0.848	0.346	0.192
2002	0.162	0.088	0.125	0.113	0.093	0.167	12.865	28.037	5.989	0.590	0.203	0.148
2003	2.630	6.637	7.069	6.594	4.231	0.465	24.598	40.275	19.459	1.566	0.351	0.122
2004	0.103	0.060	0.039	0.347	0.122	0.343	11.510	35.681	13.916	1.254	0.311	0.158
2005	0.107	0.061	0.057	0.139	0.546	0.352	15.481	37.020	18.753	1.134	0.323	0.179
2006	0.076	0.078	0.105	0.237	0.158	0.442	26.674	30.036	16.436	1.594	0.341	0.204
2007	0.140	0.125	0.069	0.103	0.097	2.621	18.688	42.503	12.644	2.065	0.323	0.247
2008	0.098	0.063	0.052	0.066	0.068	1.364	24.498	40.689	16.303	1.360	2.003	7.680
2009	0.181	0.080	0.054	0.080	0.081	0.107	6.002	34.912	13.546	0.544	0.562	0.232
2010	0.164	0.206	0.113	0.257	1.332	2.125	30.676	39.364	24.094	1.264	0.307	0.204
2011	0.122	0.061	0.058	0.062	0.131	0.547	7.031	33.391	8.910	0.929	0.346	0.177
mean	0.308	0.506	0.527	0.553	0.485	0.846	16.677	35.457	14.080	1.542	0.503	0.681

Appendix Table 12: Average Random Consistency Index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Appendix Table 13. ETO and climatic data for Sululta metrological station

Monthly ETo Penman-Monteith - C:\Users\gutu\Desktop\Input data of cropwat\eto sululta.pem

Country: Ethiopia Station: Sululta

Altitude: 2610 m. Latitude: 9.18 °N Longitude: 38.73 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	5.0	22.9	55	178	8.5	20.0	4.00
February	6.1	23.9	49	191	8.8	21.7	4.59
March	6.7	24.2	54	183	8.2	21.9	4.63
April	7.2	23.9	61	181	8.3	22.3	4.53
May	7.6	24.0	58	156	7.9	21.1	4.38
June	6.4	22.8	68	127	6.1	18.1	3.63
July	6.2	21.0	87	122	2.6	13.1	2.56
August	6.6	20.6	87	108	3.0	14.0	2.63
September	6.5	21.2	79	117	5.9	18.4	3.33
October	5.5	21.9	65	171	8.1	20.9	3.95
November	4.7	22.4	58	185	9.7	21.9	4.16
December	4.9	22.1	56	181	9.3	20.6	3.94
Average	**6.1**	**22.6**	**65**	**158**	**7.2**	**19.5**	**3.86**

Appendix Table 14. Effective rainfall of Sululta

Monthly rain - C:\Users\gutu\Desktop\Input data of cropwat\Sululta effective rainfal...

Station: Sululta Eff. rain method: Fixed percentage

	Rain	Eff rain
	mm	mm
January	12.8	10.2
February	16.1	12.9
March	45.5	36.4
April	70.8	56.6
May	73.4	58.7
June	147.9	118.3
July	328.5	262.8
August	325.5	260.4
September	162.4	129.9
October	33.0	26.4
November	11.5	9.2
December	8.4	6.7
Total	**1235.7**	**988.6**

Appendix Table 15. Crop Water Requirement of cabbage

Crop Water Requirements

ETo station: Sululta | Crop: CABBAGE Crucifers

Rain station: Sululta | Planting date: 29/12

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Dec	3	Init	0.70	2.78	8.3	0.7	8.3
Jan	1	Init	0.70	2.79	27.9	3.0	24.9
Jan	2	Init	0.70	2.80	28.0	3.4	24.6
Jan	3	Init	0.70	2.94	32.3	3.7	28.6
Feb	1	Deve	0.71	3.10	31.0	3.4	27.7
Feb	2	Deve	0.76	3.48	34.8	3.3	31.5
Feb	3	Deve	0.81	3.75	30.0	6.3	23.7
Mar	1	Deve	0.87	4.02	40.2	9.6	30.6
Mar	2	Deve	0.93	4.32	43.2	12.2	30.9
Mar	3	Deve	1.00	4.58	50.4	14.4	36.0
Apr	1	Mid	1.06	4.83	48.3	17.2	31.1
Apr	2	Mid	1.07	4.86	48.6	19.7	28.9
Apr	3	Mid	1.07	4.80	48.0	19.7	28.4
May	1	Mid	1.07	4.75	47.5	17.5	30.0
May	2	Mid	1.07	4.70	47.0	16.9	30.1
May	3	Late	1.06	4.40	48.4	24.4	24.0
Jun	1	Late	1.00	3.89	38.9	30.2	8.8
Jun	2	Late	0.96	3.50	3.5	3.5	3.5
					656.5	209.2	451.5

Appendix Table 16. Crop Water Requirement of pepper

Crop Water Requirements

ETo station: Sululta | Crop: Sweet Peppers

Rain station: Sululta | Planting date: 29/12

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Dec	3	Init	0.60	2.38	7.1	0.7	7.1
Jan	1	Init	0.60	2.39	23.9	3.0	20.9
Jan	2	Init	0.60	2.40	24.0	3.4	20.6
Jan	3	Deve	0.61	2.57	28.3	3.7	24.6
Feb	1	Deve	0.73	3.21	32.1	3.4	28.8
Feb	2	Deve	0.87	3.99	39.9	3.3	36.6
Feb	3	Deve	0.99	4.58	36.6	6.3	30.3
Mar	1	Mid	1.08	4.98	49.8	9.6	40.3
Mar	2	Mid	1.08	5.02	50.2	12.2	37.9
Mar	3	Mid	1.08	4.98	54.8	14.4	40.4
Apr	1	Mid	1.08	4.95	49.5	17.2	32.3
Apr	2	Late	1.06	4.79	47.9	19.7	28.2
Apr	3	Late	0.98	4.39	43.9	19.7	24.3
May	1	Late	0.93	4.14	8.3	3.5	8.3
					496.5	120.2	380.5

Appendix Table 17. Crop Water Requirement of potato

Crop Water Requirements

ETo station: Sululta | Crop: Potato

Rain station: Sululta | Planting date: 28/12

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Dec	3	Init	0.50	1.98	7.9	0.9	7.9
Jan	1	Init	0.50	1.99	19.9	3.0	16.9
Jan	2	Init	0.50	2.00	20.0	3.4	16.6
Jan	3	Deve	0.61	2.58	28.4	3.7	24.7
Feb	1	Deve	0.85	3.75	37.5	3.4	34.2
Feb	2	Deve	1.08	4.97	49.7	3.3	46.3
Feb	3	Mid	1.18	5.45	43.6	6.3	37.3
Mar	1	Mid	1.18	5.47	54.7	9.6	45.1
Mar	2	Mid	1.18	5.48	54.8	12.2	42.6
Mar	3	Mid	1.18	5.45	59.9	14.4	45.5
Apr	1	Late	1.17	5.35	53.5	17.2	36.3
Apr	2	Late	1.06	4.79	47.9	19.7	28.1
Apr	3	Late	0.92	4.13	41.3	19.7	21.6
May	1	Late	0.81	3.60	21.6	10.5	12.8
					540.7	127.4	415.9

Appendix Table 18.Crop irrigation schedule for cabbage

Crop irrigation schedule

ETo station: Sululta | Crop: CABBAGE Crucifers | Planting date: 28/12 | Yield red. 0.0 %

Rain station: Sululta | Soil: Heavy (clay) | Harvest date: 09/06

Table format

- (•) Irrigation schedule
- ( ) Daily soil moisture balance

Timing: Irrigate at critical depletion

Application: Refill soil to field capacity

Field eff. 70 %

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
6 Jan	10	Init	0.0	1.00	100	47	26.0	0.0	0.0	37.1	0.43
18 Jan	22	Init	0.0	1.00	100	48	29.3	0.0	0.0	41.9	0.40
30 Jan	34	Init	0.0	1.00	100	45	30.4	0.0	0.0	43.4	0.42
11 Feb	46	Dev	0.0	1.00	100	46	33.4	0.0	0.0	47.7	0.46
24 Feb	59	Dev	0.0	1.00	100	49	38.6	0.0	0.0	55.2	0.49
9 Mar	73	Dev	0.0	1.00	100	46	39.7	0.0	0.0	56.7	0.47
22 Mar	86	Dev	0.0	1.00	100	45	42.0	0.0	0.0	60.0	0.53

Totals

Total gross irrigation	611.7	mm	Total rainfall	256.1	mm
Total net irrigation	428.2	mm	Effective rainfall	217.3	mm
Total irrigation losses	0.0	mm	Total rain loss	38.8	mm
Actual water use by crop	653.2	mm	Moist deficit at harvest	7.7	mm
Potential water use by crop	653.2	mm	Actual irrigation requirement	435.9	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	84.8	%
Deficiency irrigation schedule	0.0	%			

Yield reductions

Appendix Table 19.Crop irrigation schedule for pepper

Crop irrigation schedule

ETo station	Sululta	Crop	Sweet Peppers	Planting date	29/12
Rain station	Sululta	Soil	Light (sand)	Harvest date	01/05

Yield red. 0.0 %

Table format
- (•) Irrigation schedule
- ( ) Daily soil moisture balance

Timing: Irrigate at critical depletion
Application: Refill soil to field capacity
Field eff. 70 %

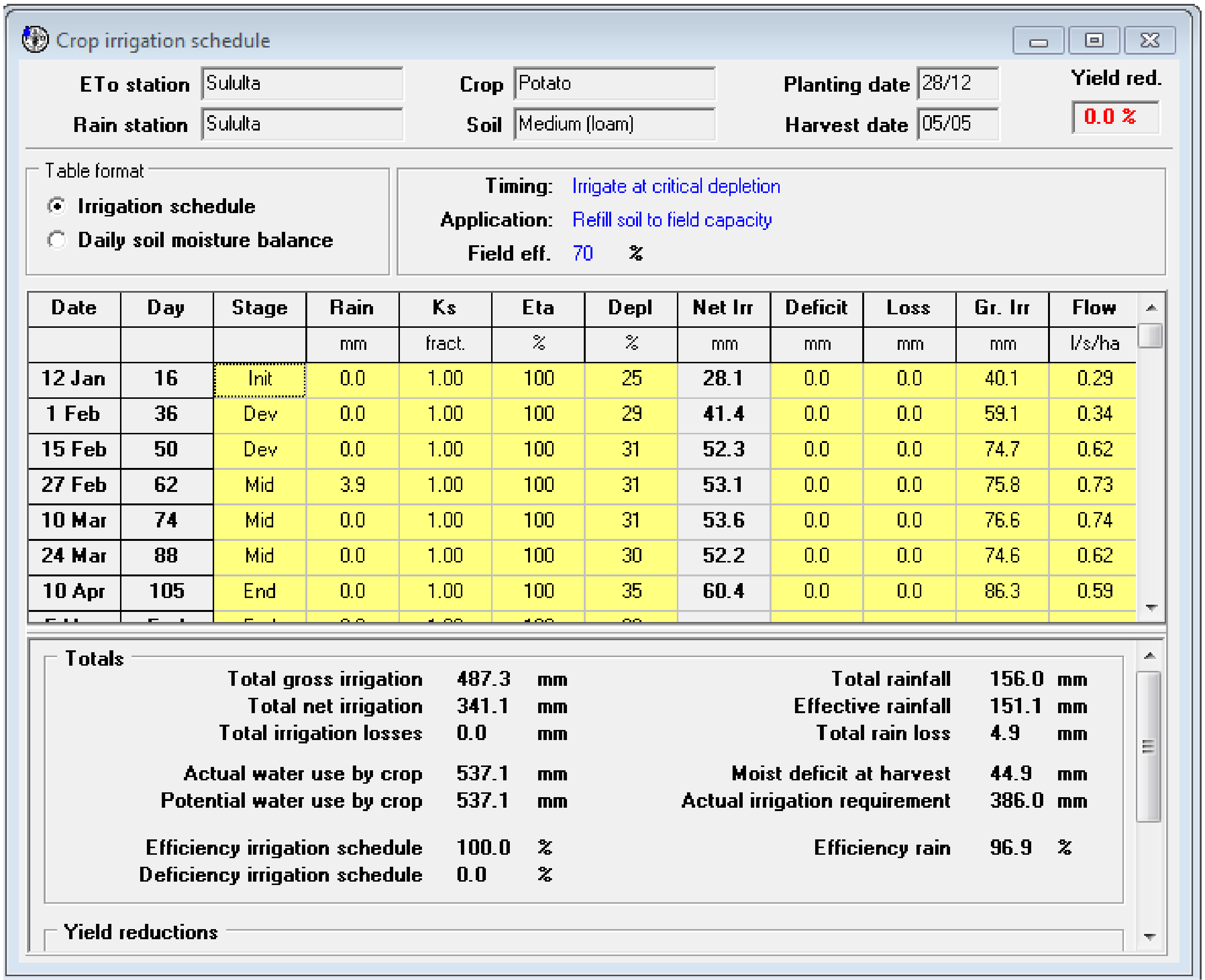
Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
30 Dec	2	Init	0.0	1.00	100	30	4.8	0.0	0.0	6.8	0.39
1 Jan	4	Init	0.0	1.00	100	28	4.8	0.0	0.0	6.8	0.39
4 Jan	7	Init	0.0	1.00	100	28	5.3	0.0	0.0	7.5	0.29
6 Jan	9	Init	0.0	1.00	100	24	4.8	0.0	0.0	6.8	0.40
8 Jan	11	Init	0.0	1.00	100	23	4.8	0.0	0.0	6.8	0.40
10 Jan	13	Init	0.0	1.00	100	22	4.8	0.0	0.0	6.8	0.40
12 Jan	15	Init	0.0	1.00	100	21	4.8	0.0	0.0	6.9	0.40

Totals

Total gross irrigation	548.5	mm	Total rainfall	145.0	mm
Total net irrigation	383.9	mm	Effective rainfall	85.8	mm
Total irrigation losses	0.0	mm	Total rain loss	59.2	mm
Actual water use by crop	492.4	mm	Moist deficit at harvest	22.6	mm
Potential water use by crop	492.4	mm	Actual irrigation requirement	406.5	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	59.2	%
Deficiency irrigation schedule	0.0	%			

Yield reductions

Appendix Table 20.Crop irrigation schedule for potato



Crop irrigation schedule

ETo station	Sululta	Crop	Potato	Planting date	28/12
Rain station	Sululta	Soil	Medium (loam)	Harvest date	05/05

Yield red. 0.0 %

Table format
- Irrigation schedule (selected)
- Daily soil moisture balance

Timing: Irrigate at critical depletion
Application: Refill soil to field capacity
Field eff. 70 %

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
12 Jan	16	Init	0.0	1.00	100	25	28.1	0.0	0.0	40.1	0.29
1 Feb	36	Dev	0.0	1.00	100	29	41.4	0.0	0.0	59.1	0.34
15 Feb	50	Dev	0.0	1.00	100	31	52.3	0.0	0.0	74.7	0.62
27 Feb	62	Mid	3.9	1.00	100	31	53.1	0.0	0.0	75.8	0.73
10 Mar	74	Mid	0.0	1.00	100	31	53.6	0.0	0.0	76.6	0.74
24 Mar	88	Mid	0.0	1.00	100	30	52.2	0.0	0.0	74.6	0.62
10 Apr	105	End	0.0	1.00	100	35	60.4	0.0	0.0	86.3	0.59

Totals

Total gross irrigation	487.3	mm	Total rainfall	156.0	mm
Total net irrigation	341.1	mm	Effective rainfall	151.1	mm
Total irrigation losses	0.0	mm	Total rain loss	4.9	mm
Actual water use by crop	537.1	mm	Moist deficit at harvest	44.9	mm
Potential water use by crop	537.1	mm	Actual irrigation requirement	386.0	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	96.9	%
Deficiency irrigation schedule	0.0	%			

Yield reductions

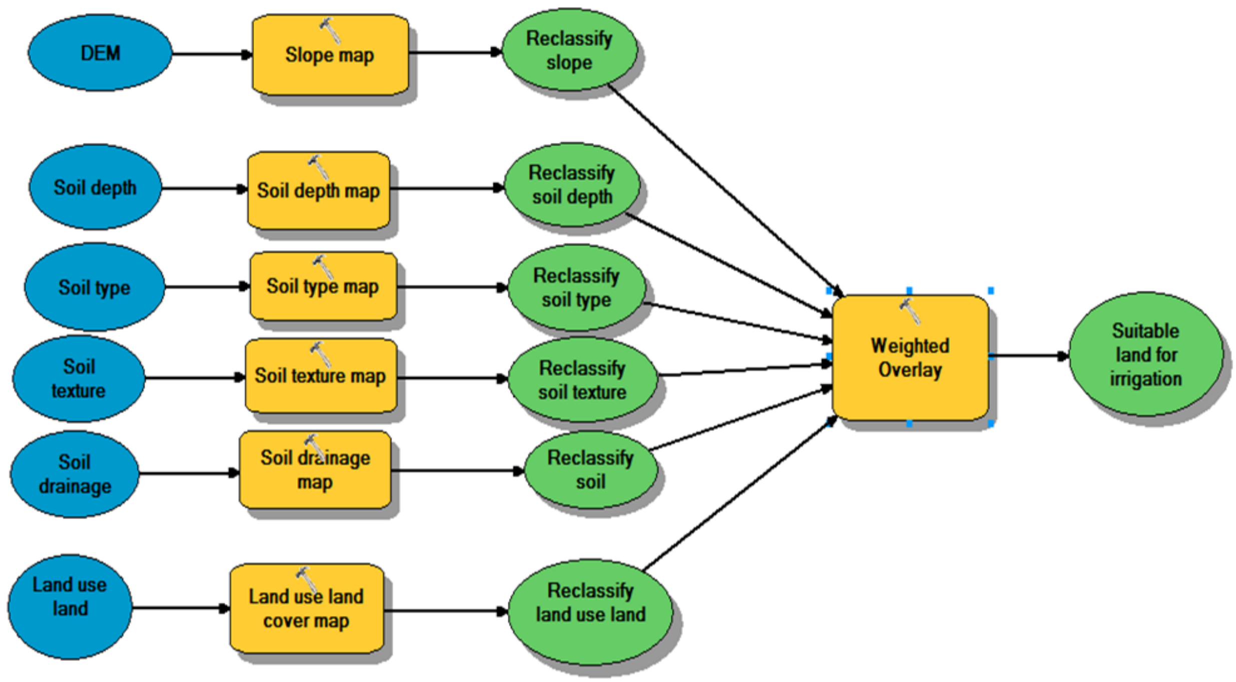


Figure 21: Model for irrigation suitability analysis