JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

HYDROLOGY AND HYDRAULIC ENGINEERING CHAIR

MSc.-Thesis on

"GIS Based Surface Irrigation Suitability Analysis of Birr River Catchment, Abbay Basin, Ethiopia"

By

Animut Aschale Belayneh

This Thesis is submitted to Graduate School of Jimma University Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Hydraulic Engineering

November, 2015

Jimma, Ethiopia

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Advisor: Brook Abate (PhD)

Co-Advisor: Sifan Abera (Msc.)

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

Animut Aschale

Signature------------------------------------ date--

I will submit this thesis examination with my approval as university supervisor

Dr. Brook Abate (PhD)

Signature-------------------------------------- date---

Co-Advisor: Sifan Abera (Msc.)

Signature-------------------------------------- date--

DEDICATION

Memorial to all people who enslaved themselves

To God.

ABSTRACT

Although Ethiopia has a large potential to develop irrigation, only 7.84% of the 3.7 million hectares of land potentially available has been developed. To examine the underlying causes, this study evaluates the suitability of surface water irrigation in Birr River catchment. Birr River catchment is located at the South west Gojjam part of the Abay River Basin. The study area covers an area of about 3191 square kilometers. The investigation of available land and water resources for irrigation is important for planning their use. This study was initiated with the objective of analyzing the water and land resources potential of river catchments in this River basin for irrigation development and generating geo-referenced map of these resources by using Geographic Information System. Watershed delineation, identification of potential irrigable land, estimation of irrigation water requirement and surface water resources of river catchments were the steps followed to analyze this irrigation potential.

The investigation includes data like topography, climate, soil, land use pattern, water availability and agricultural practices. Furthermore the irrigation suitability criteria were defined based on these variables and weighted using pairwise comparison technique. With the purpose to evaluate units for irrigation suitability stream networks were characterized and soil types as well as land use were mapped. Crop development with respect to the prevailing conditions is integrated within this situation.

Integrating all the aggregate suitability variables, the potential capacity of irrigable land was identified and mapped as well. The result indicates that nearly 36.54% of the River catchment is suitable for surface irrigation. However, by analyzing 20 years of river discharge, less than 1.3% of the potential irrigable area (or less than 0.47% of the River catchment area) could be irrigated consistently by run-off-the river-systems in the driest period which is March. Other months which are recommended as irrigation period have greater potential than month March. Thus, the irrigation potential in the Birr River catchment can only be met by increasing dry season flows (if proven feasible) and by supplying water from future reservoirs or by using water from underground. The capacity of low flow as well as 80% and 90% time of exceedance flow of the available surface water in the respective sub watersheds was also estimated. The area that can be irrigated with this flow was computed for the selected cropping pattern which is Maize. The discharges at un-gauged sites were estimated from gauged sites by applying regionalization method using SWAT model and results were obtained on monthly bases. Hence, the minimum simulated stream flow at the outlet of drainage basin was 1.69m^3/s occurred on the month of March.

Keywords: Birr River, catchment, GIS, Irrigation suitability analysis, Abbay Basin, Simulation using SWAT.

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ACRONYMS

ABIDMPP	Abbay Basin Integrated Development Master Plan Project
Alpha_Bf	Alpha Base Flow Separator
CA	Comprehensive Assessment of water management for agriculture
CN	Curve Number
CNES	Centre National d'Études Spatiales
CUP	Calibration Uncertainty Programme
DEM	Digital Elevation Model
DEW02	Dew Point Temperature Calculator
DFID	Department for International Development
EMA	Ethiopian Mapping Agency
DMC	Double Mass Curve
ESCO	Soil Evaporation Compensation Factor
ESRI	Environmental Systems Research Institute
ETc	Crop Evapotranspiration
ETo	Reference Crop Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
FDC	Flow Duration Curve
GLCN	Global Land Cover Network
GPS	Global Positioning System
GW_REVAP	The groundwater Revap coefficient
GWQMN	Threshold Water Depth in the shallow aquifer for flow
HRU	Hydrological Response Units
HSG	Hydrologic Soil Groups
IFAD	International Fund for Agricultural Development
IWR	Irrigation Water Requirement
JIT	Jimma Institute of Technology
LUPRD	Land Use Planning and Regulatory Department
MoA	Ministry of Agriculture
MoWR	Ministry of Water Resources

NASA	National Aeronautics and Space Administration
NGA	National Geospatial intelligence Agency
NLCD	National Land Cover Dataset
NMSA	National Meteorological Services Agency
PCCs	Physical Catchment characteristics
R^2	Regression coefficient
SCS	Soil Conservation Service
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
SUFI2	Sequential Uncertainty Fitting version 2
UNESCO	United Nations Scientific and Cultural Organization
WBISPP	Woody Biomass Inventory and Strategy Planning Project
WGEN	Weather Generator WUE – Water Use Efficiency

1. INTRODUCTION

1.1 Background

Ethiopia depends on rain fed agriculture with limited use of irrigation for agricultural production. It is estimated that more than 90% of the food supply in the country comes from low productivity rain fed smallholder agriculture and hence rainfall is the single most important determinant of food supply and the country's economy (Belete, 2006). The major problem associated with the rainfall-dependent agriculture in the country is the high degree of rainfall variability and unreliability. Due to this variability, crop failures due to dry spells and droughts are frequent. As a consequence, food insecurity often turns into famine with the slightest adverse climatic incident, particularly, affecting the livelihoods of the rural poor. Despite irrigation potential estimated about 3.7 million hectare, only about 290,000 ha (7.84% of the potential) is currently under irrigation which plays insignificant role in the country's agricultural production. Thus to bring food security in the national as well as in house hold level, improvement and expansion of irrigated agriculture must be resorted (MoWE, 2010 and FAO, 2005).

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

The major challenge facing planners and managers is that the physical availability of water and land is fixed; yet their demand is growing (Tariku, 2007). Due to this, the problem is how to balance demand and supply under this increasingly complex and difficult conditions. For many countries, the only solution, therefore, is to manage the available land and water resource in the country in an efficient and sustainable manner. To achieve this reliable information base is necessary, which can identify the resources available, their allocation, use or misuse, the components involved, their abilities and limitations and the infrastructure on hand. Such a database calls for a Geographic Information Systems, in which the information can be easily analyzed and displayed on a map for spatial reference.

Appropriate management and selection of applicable irrigation method is a prerequisite for wise utilization of scarce physical resources, land and water (Wagesho, 2004). To ensure adequate management and design of a particular irrigation system, a well-developed and suitable database is quite important. Thus, it should be able to deal with spatially and temporally varying factors affecting the system. This study concentrates on qualitative as well as quantitative assessment of the existing physical resources those are land and water with respect to its suitability for irrigation. Furthermore, this was supported by development of a suitability database that would help for further investigation on the area. The soil, terrain features (DEM and its derivatives) and land use classification criteria are the basis used to define the suitability. With this respect, the Geographic Information System (GIS) facilities were extensively used. In recognition the above situations, this study focuses on land and soil potential and suitability and using water potential scenarios as well.

1.2 Statement of the problem

Clearly, irrigation can and should play an important role in raising and stabilizing food production, especially in the less-developed parts of Africa south of the Sahara. Although the Ethiopian renewable surface and groundwater amounts to 123 and 28 billion cubic meters per annum, respectively, its distribution in terms of area and season does not give adequate opportunity for sustainable growth to the economy (MoWE, 2010). Among all the factors that hinder meeting the required food supply, moisture deficit in agricultural soil plays the leading role. Hence, the improvement of soil moisture availability at the required amount and time calls for the need of irrigated agriculture (Girma, 2006).

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

The factors that are involved for irrigation suitability analysis such as soil, land cover/use; land slope and distance between water supply and suitable command area should be weighted and evaluated by the use of GIS according to their suitability for irrigation (Wagesho, 2004). Despite there are a large number of rivers, exploitation of their water resources for irrigated agriculture has remained low in the basin. The efforts to establish small, medium and large-scale irrigation schemes in the basin are constrained by a number of uncertainties. Firstly, stream flows from some of the rivers are not known. Secondly, potential irrigable areas in the basin have not been identified well and matched with the water requirements of some crops commonly grown in the basin.

Therefore, to overcome these uncertainties, this study was carried out by using GIS as a tool for analyzing irrigation potential in Birr River catchment using input data from soil, digital elevation model (DEM), and existing land cover/use and geo-referencing and mapping of the analysis result in the context of surface irrigation development in the study area. Furthermore, the study attempted to estimate water resource potential of the river catchments in the catchment and the irrigation water requirements of the identified irrigable areas for cultivating the selected crop in the area.

1.3 Objectives of the Study

1.3.1 General objective:

The main objective of this thesis work is to identify suitable area for surface irrigation using GIS techniques in Birr river catchment.

1.3.2 Specific Objectives:

- To provide integrated geo-referenced irrigation suitability database that can be used for identifying potential irrigation investment opportunities.
- To estimate potentially usable available physical resources; land and water and establish irrigation suitability map of the study area.
- To estimate the dependable surface flow from the gauged and ungauged catchments for irrigation and check its sufficiency for the irrigation suitable area.

1.4 Research Questions

- Is it possible to establish geo-referenced database of irrigation availability in the study area?
- What are the potential physical resources for surface irrigation in Birr River catchment?
- How much minimum flow is available for surface irrigation over the study area?

1.5 Significance of the Study and Scope

The study is believed to contribute to the efforts working towards attaining technically feasible and socially desirable use of irrigation water and land and to the initiatives striving to identify better strategies for irrigated production. These contributions will have application to already irrigated and further irrigable lands, and the ultimate beneficiaries of the study are primarily the poor rural community.

This study can also provide a good input at times of planning for future irrigation projects aimed at foreseeing their future development and impacts. Available water resource and the irrigation land need to be well documented for planning purposes.

This study concentrates on qualitative as well as quantitative assessment of the existing physical resources those are land and water with respect to its suitability for irrigation. The study also focuses on surface water resources and does not include other criteria's rather than land and water resources.

1.6 Limitations of the study

The problem encountered in the course of this thesis includes finance and time constraints that hindered looking at the issues in more detail. There was also a problem of data adequacy and reliability. Model performance can be also considered as limitation because models can not represent exactly the real world situation. The study considers only available minimum water resources for irrigation. Thus, the storage requirements and the place where it is located were not determined. When calculating crop water requirement, only one crop sample was taken and this is also the limitation of the study. Since there is no current data for the location of rural villages, this study did not include the settlement areas of the rural village as criteria to identify suitable land for surface irrigation.

2. LITERATURE REVIEW

2.1 Irrigation and Irrigation Potential

Irrigation is the supply of water to agricultural crops by artificial means, designed to permit farming in arid regions and to offset the effect of drought in semi-arid regions. Even in areas where total seasonal rainfall is adequate on average, it may be poorly distributed during the year and variable from year to year. Where traditional rain-fed farming is a high-risk enterprise, irrigation can help to ensure stable agricultural production. The definition of irrigation potential is not straightforward and implies a series of assumptions about irrigation techniques, investment capacity, national and regional policies, social, health and environmental aspects, and international relationships, notably regarding the sharing of waters. However, to assess the information on land and water resources at the river basin level, knowledge of physical irrigation potential is necessary. The area which can potentially be irrigated depends on the physical resources 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate. Therefore, physical irrigation potential represents a combination of information on gross irrigation water requirements, area of soils suitable for irrigation and available water resources by basin (FAO, 1997).

2.2 Irrigation potential in Ethiopia

Ethiopia has vast surface water resources which are estimated in 123 billion cubic meters with annual ground water recharge of 28 billion cubic meters (MoWE, 2010). Moreover, the potential irrigable land is estimated to be about 3.7million hectare. However, only about 5.6 billion cubic meters of water resource and 290,000 hectare of land which is 7.84 percent of the potential is utilized so far (MoWE, 2010 and FAO, 2005).

2.3 Irrigation development in Ethiopia

According to Dejen et al (2012), in Ethiopia, about 90% of the irrigation potential in terms of land and water resources has not been developed so far. However, there have been many ongoing medium and large-scale irrigation developments in recent years. While about 47% of the developed area is under large-scale public irrigation schemes, mainly industrial crops such as Cotton, Sugarcane and various fruits are grown. About 65% of the irrigated area is under small-scale irrigation schemes, either modern or traditional. Traditional irrigation schemes are those developed by farmers themselves and are without permanent water diversion, conveyance, and control and distribution facilities. Modern schemes are those equipped with basic irrigation infrastructure such as water diversion and flow control structures and conveyance and distribution systems. Modern small-scale schemes account for about 18% of irrigated area to date. Small-scale schemes are operated and managed by the water users themselves with little involvement of government agencies in some cases.

2.4 Irrigation Land Suitability Evaluation Factors

Land suitability is the fitness of a given type of land for a defined use. The land may be classified in its present condition or after improvements for its specified use. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976). Land evaluation is primarily the analysis of data about the land –its soils, climate, vegetation, and etc. in terms of realistic alternatives for improving the use of that land. For irrigation, land suitability analysis, particular attention is given to the physical properties of the soil, to the distance from available water sources and to the terrain conditions in relation to methods of irrigation considered (FAO, 2007). In addition to these factors, land cover/land use types are considered as limiting factors in evaluating suitability of land for irrigation (Haile Gebriel, 2007; Meron, 2007). As extensively discussed in FAO land evaluation guidelines (FAO, 1976, 1983, 1985), the suitability of these factors for surface irrigation method and for the given land utilization types can be expressed corresponding to the following suitability classes.

Order S – suitability: - The classes under this order are:

•S1 (highly suitable) - land having no significant limitation to sustained application of a given use.

•S2 (moderately suitable) - land having limitation which in aggregate are moderately severe for a sustained application of a given use.

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

Order N suitability classification

•N1 (temporarily not suitable) - land having limitations which may be surmountable in time but which cannot be corrected with existing knowledge at currently acceptable cost.

•N2 (Permanently not suitable) - land having limitations which appear as severe as to preclude any possibilities of successful sustained use of the land of a given land use.

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

2.4.1. Slope

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

2.4.2. Soils

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

2.4.3. Land cover or land use

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

2.4.4. Water availability

It is important to make sure that there will be no lack of irrigation water. If water is in short supply during some part of the irrigation season, crop production will suffer, returns will decline and part of the scheme's investment will lay idle (FAO, 2001). Therefore, water supply (water quantity and seasonality) is the important factor to evaluate the land suitability for irrigation according to the volume of water during the period of year which it is available (FAO, 1985). Quantifying the amount of water available for irrigation and determining the exact locations to which water can be economically transported are important in the decision to expand its use. Where possible, the water source preferred to be located above the command area so that the entire field can be irrigated by gravity. It is also desirable that the water source be near the center of the irrigated area to minimize the size of the delivery channels and pipelines. Therefore, distance from water sources to command area, nearness to rivers, is useful to reduce the conveyance system (irrigation canal length) and thereby develop the irrigation system economical (Silesh, 2000).

2.5 Overview of GIS Application

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

2.5.1. 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. 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.

2.5.2. Weighted overlay analysis

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

2.5.3. Watershed delineation

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

2.5.4. GIS as a tool for irrigation potential assessment

In the past, several studies have been made to assess the irrigation potential and water resources by using GIS tool (FAO, 1987; FAO, 1995; FAO, 1997; Melaku, 2003; Negash, 2004; Hailegebriel, 2007; Meron, 2007; Kebede, 2010).

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

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

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

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

Wagesho (2004) conducted a study on irrigation suitability analysis in Ethiopia a case of Abaya-Chamo lake basin. It was a Geographical Information System (GIS) based and had taken into consideration soil, slope, and land use and water resource availability in perennial rivers in the basin to identify potential irrigable land. Ganole (2010) conducted a study on Irrigation potential assessment using GIS techniques in Gale Woreda, Sidama Zone, SNNPRS. The study considered slope, soil, land cover/use, water resources and climate factors in assessing surface irrigation potential.

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

2.6 Hydrological Models

A hydrologic model is an approximation of the actual system, with a structure that is a set of equations linking measured inputs and output variables (Chow et al., 1988)**.** Hydrologic models can be categorized in to two broad classes. (1) Physically-based models that are based on solving governing equations such as conservation of mass and momentum equations. (2) Conceptual models that use simple mathematical equations to describe the main hydrologic processes such as evapotranspiration, surface storage, percolation, snowmelt, base flow, and runoff. The other classification is deterministic and stochastic hydrological models. The deterministic hydrological model as it is the most commonly used modeling approach in hydrology, it can be further classified as lumped, and semi distributed and distributed models (Aghakouchak, 2010 and Nethanet, 2013).

1. *Lumped models*: Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins. The parameters often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. These models are not usually applicable to event-scale processes. If the interest is

primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models.

2. *Distributed models:* Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation runoff behavior. Distributed models generally require large amount of (often unavailable) data. However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy.

3. *Semi-distributed models:* Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin in to a number of smaller sub-basins. The main advantage of these models is that their structure is more physically-based than the structure of lumped models, and they are less demanding on input data than fully distributed models. SWAT, HEC-HMS, HBV are considered as semi-distributed models.

Generally for this study, semi-distributed models are selected because of their structure is more physically-based than the structure of lumped model, and they are less demanding on input data than fully distributed models. Therefore, three selected semi-distributed models were reviewed (Table 2.1).

Table2. 1 Description of three selected semi-distributed hydrological models

Description	SWAT	HEC-HMS	HBV
Model type	Semi-distributed Physically-based	Semi-distributed Physically-based	Semi-distributed Conceptual model
Model Objective	Predict the impact of land management practices on water and sediment	Simulate the rainfall runoff process of watershed	Simulate rainfall runoff process and floods
Spatial scale	Medium +	Flexible	Flexible
Process Modeled	Continuous	Continuous & event	Continuous & event
Cost	Public domain	Public domain	Public domain

2.7 SWAT model description

The Soil and Water Assessment Tool (SWAT) is a physical process based model to simulate continuous-time landscape processes at catchment scale (Arnold et al., 1998; Neitsch et al., 2005). The catchment is divided into hydrological response units (HRU) based on soil type, land use and slope classes. The hydrology computation based on daily precipitation, runoff, evapotranspiration, percolation and return flow is performed at each HRU. The SWAT model has two options for computing surface runoff: (i) the Natural Resources Conservation Service Curve Number (CN) method (USDA-SCS, 1972) or (ii) the Green and Ampt method (Green and Ampt, 1911). Similarly, there are two options available to compute peak runoff rate: (i) the modified rational formula (Kuichling, 1989) or (ii) the SCS TR-55 method (USDA-SCS, 1986). The flow routing in the river channels is computed using the variable storage coefficient method (Williams, 1969), or Muskingum method (Chow, 1959). SWAT includes three methods for estimating potential evapotranspiration: (i) Priestley-Taylor (Priestley and Taylor, 1972), (ii) Penman-Monteith (Monteith, 1965) and (iii) Hargreaves (Hargreaves and Riley, 1985).

SWAT employs the Modified Universal Soil Loss Equations (MUSLE) to compute HRU-level soil erosion. It uses runoff energy to detach and transport sediment (Williams and Berndt, 1977). The sediment routing in the channel (Arnold et al, 1995) consists of channel degradation using stream power (Williams, 1980) and deposition in channel using fall velocity. Channel degradation is adjusted using USLE soil erodibility and channel cover factors.

SWAT is used worldwide and has been chosen by the environmental protection Agency to be one of their better assessment science integrating point and non-point sources models (LENAHART et al, 2002).

The land phase of the hydrological process is simulated based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad \text{.............................. (2.1)}$$

Where SW_t is the final soil water content (mm water)

SW_0 is the initial soil water content on day (mm water)

Tt is time (day)

R_{day} is the amount of precipitation on day I (mm water)

Q_{surf} is the amount of surface runoff on day I (mm water)

E_a is the amount of evapotranspiration on day I (mm water)

W_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom on day i (mm water), and

Q_{gw} is the amount of return flow on day i (mm water)

SWAT is imbedded in arc-GIS called Arc-SWAT. Arc- SWAT integrates various spatial data including soil, land cover, climate and topographic features. SWAT can analyze both small and large watersheds by subdividing the area in to homogeneous parts called hydrological Response Units (HRU). As a physically based model, SWAT model uses Hydrological Response Units (HRUs) to describe special heterogeneity in terms of land cover, soil type and slope with in a watershed.

2.7.1 Application of SWAT

SWAT can be used to simulate a single watershed or a system of multiple hydrological connected watersheds. Each watershed is first divided in to sub basins and then in hydrologic response units (HRUs) based on the land use and soil distribution. Hence, it is applicable for:

- Simulation of processes at land and water phase
- Spatially distributed (different scales)
- Simulation of changes (climate, land use, management etc.)
- Estimation of water quantities, including different runoff components
- Water quality: nutrients, sediments, pesticides, etc.

All the above descriptions are daily time step and at different spatial scales and more or less readily available data sets.

2.8 Review of Commonly Used GIS Data

Geographic Information System (GIS) can integrate Remote Sensing and different data sets to create a broad overview of potential irrigable area (FAO, 1987). While the remotely sensed image of an area gives a true representation of an area based on land cover / use, grid interpolated climate data can serve many purposes and used as climatic data base where meteorological data from gauging networks are not adequate. The topographic and hydrologic attributes of land and landscape such as slope, aspect and watershed modeling can be derived directly from the DEM. They are point elevation data stored in digital computer files. The detailed review of these data is provided in the following sections.

2.8.1. Spatially interpolated climate data on grids

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

2.8.2 Digital elevation model (DEM)

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

2.9. Assessment of Water Resources

Assessment of water resources can only be done at basin level (FAO, 1997). According to the (CA, 2007), "river basins are the geographic area contained within the watershed limits of a system of streams and rivers converging toward the same terminus, generally the sea or sometimes an inland water body. Tributary sub-basins or basins more limited in size (typically from tens of square kilometers to 1,000 square kilometers) are often called watersheds (in American English), while catchment is frequently used in British English as a synonym for river basins, watershed being more narrowly defined as the line separating two river basins. An important consideration in water resource assessment is to estimate how much flow is available at the outlet of river catchment. The volume of water reliably available on an annual or seasonal basis can be determined from the available data in case of gauged rivers and a number of approaches are currently available for prediction of ungauged catchments flows. Methods appropriate include direct estimates of parameters for ungauged catchments using theoretical understanding of (small-scale) soil physics (Koren et al., 2000), transferring calibrated gauged model parameters to neighboring ungauged catchment (Vandewiele and Elias, 1995) while the most common approach relates model parameters to catchment characteristics by means of statistics (see Seibert, 1999; Merz and Blöschl, 2004 and Booij et al,. 2007, among others).

In a case, calibrated model parameters of gauged catchments are transferred to ungauged catchments to predict catchment runoff. Parameters are transferred based on spatial proximity, catchment area ratio and catchment characteristics while in addition also default parameters and a combination of default plus averages of highly sensitive parameter are adapted to all ungauged catchments to simulate the runoff. Parameter transfer based on physical catchment characteristics (PCCs) referred as regionalization is a technique that relates hydrological phenomena to physical and climatic characteristics of a catchment, or region (Young, 2005). The approach has four distinct steps.
Namely:

- Selection of representative catchments and catchment characteristics
- Modeling of the gauged catchments
- Establishing the regional model
- Estimation of model parameters and predicting discharge at the ungauged catchments

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1 Location

The Birr River catchment is a part of Upper Blue Nile Basin and located in South Gojjam sub-basin, and lies on 8^0 15‘ and 11^0 06‘N, and $32^0$11‘ and 37^0 23‘E as shown in Fig 3.1. This River catchment is part of South Gojjam sub basin which is one of the 16 sub basins in the Abay basin. The study area covers a total area of 3191km² with the altitude range of 3435 m in the headwaters to about 1029 m downstream. It flows in the direction of South West Gojjam which is opposite to Gilgel Abbay sub basin. The River catchment is part of the second right bank tributary of Upper Blue Nile and parallel to Belese river catchment. This area covers majorly of West Gojjam Administrative Zone and some parts of Awi Zone is incorporated in the study area.

The sub-basin originates at the southern part of Adama Mountain. It is named after its major river, Birr & the mountain, Adama. The area includes 91% of Jabi Tehnan, 76% of Dembecha, 51% of Sekela, 45% of Quarit, 44% of Burrie and 39% of Degadamot Woredas (MoWR, 1995). The major crops grown in the area are barley, potatoes, wheat, faba beans, field pea, Teff, Maize, Niger seed, chickpea, pepper, onion etc…

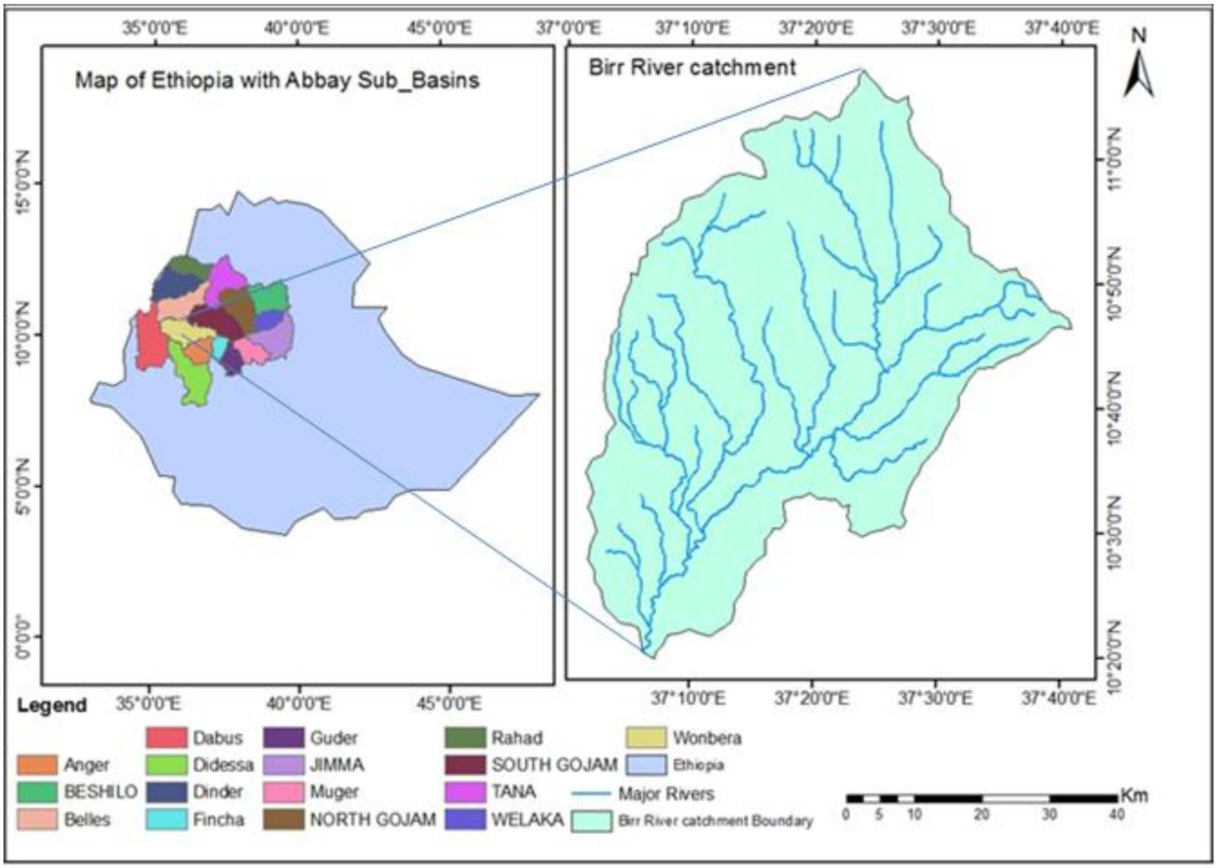

Figure3. 1: Location map of the study area (source: MoWE)

3.1.2. Agro-ecology

According to MoA (2000) classification, agro-ecology of Ethiopia is classified as: Wurch, Dega, Weina-dega, Kolla, and Bereha. Similarly, the landform in Birr River catchment also shows variations in agro-ecology as Dega, Woina–dega and Kola. Generally, Dega, Woina dega and Kola constitute 6.89%, 84.3% and 8.8%, of the total area of the basin respectively. This agro- ecological variation in landforms has had a significant influence on climatic condition of the area.

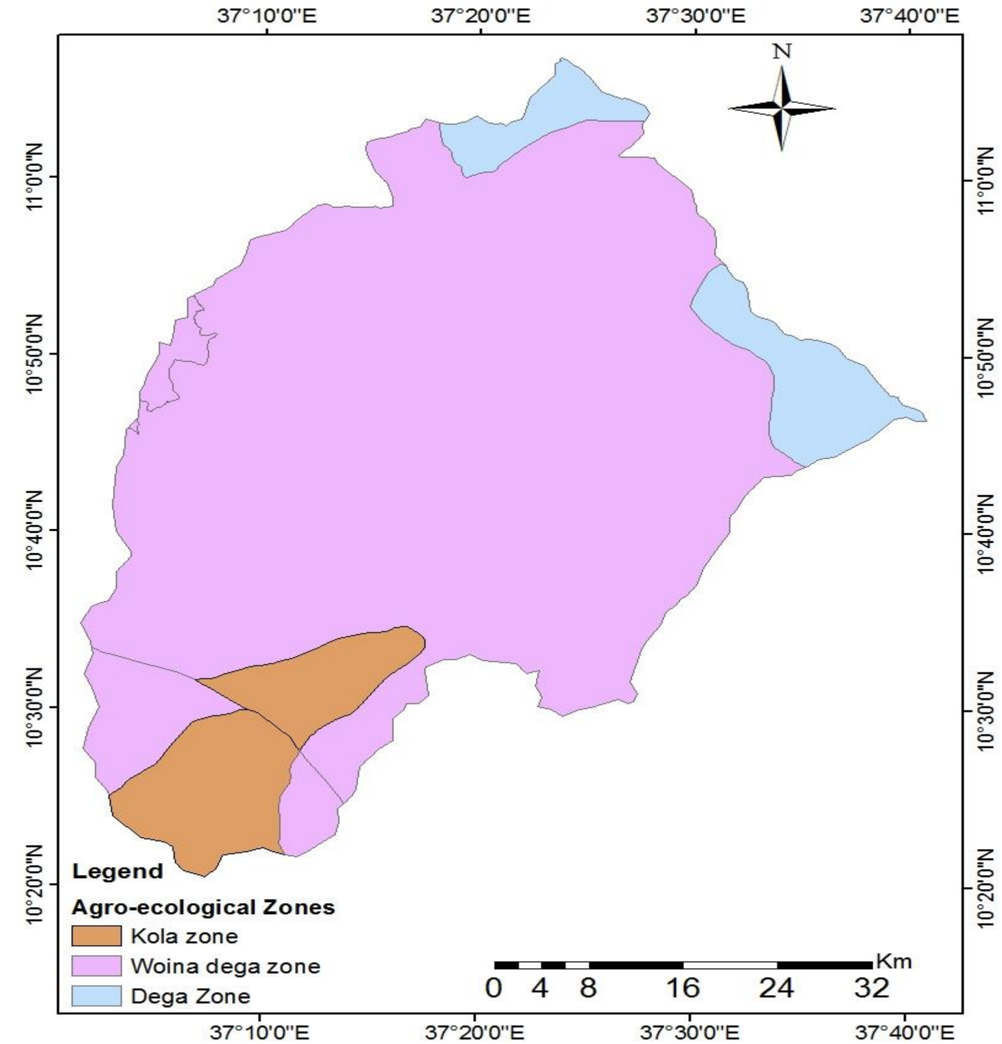

Figure3. 2: Agro-ecological map of the study area

3.1.3 Climate of the study area

The River catchment Region, in spite of being located near the equator, has a comparatively mild climate because of its high and low elevation 3435 m and 1029m amsl respectively. The annual climate may be divided in a rainy and dry season. The rainy season may be divided into a minor rainy season in April and May and a major rainy season from June through September. The dry season occurs between October and March. The long-term mean annual rainfall (1993−2012) at Laybire Station south of the catchment is estimated to be 1055 mm while 1432 mm is estimated at Gundil Station north of the catchment.

There is diurnal difference in temperature, but the temperature is comparatively uniform throughout the year with a mean annual temperature of 20.25 Cº at Laybire and 19.6 Cº at

Gundil (1993-2012). The annual average daily maximum and minimum temperature (1993−2012) at Laybire are 29.5 Cº and 11.2 Cº respectively, and these at Gundil are 27.2 and 10.9 respectively. The mean annual relative humidity (1993−2012) at Laybire is 55.74%.

3.2. Materials

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

Soil data

FAO/UNESCO- Soil Map of East Africa (1997), available in Arc/Info format with scale of 1:10000000 and soil laboratory results of Abay river basin were obtained from GIS and Remote Sensing Department, Ministry of Water Resources. These data were used for soil suitability analysis for irrigation.

DEM (Digital Elevation Model)

DEM data was obtained from MoWR GIS database and was used as input data in ArcGIS to delineate watersheds, used as an input for SWAT model simulation and to derive slope maps of the study area for irrigation suitability analysis.

Meteorological data

Meteorological data of Birsheleko (Laybire), Feres bet, Gundil, Fenote selam, Sekela, Dembecha and Quarit stations were collected from NMSA. These data were used to simulate stream flow using SWAT model and to estimate irrigation water requirements of the selected crop using CROPWAT8.0. In addition, the rainfall data was used to calculate average areal rainfall using Thiessen polygon extension in ArcGIS.

Stream flow data

Discharges of the gauging stations such as Lah at Finote selam, Chereka at Yechereka, Birr near Jiga and Leza near or at Jiga were obtained from Hydrology Department of the Ministry of Water Resources. The stream flow data was used to assess both water resources potential of the gauged and un-gauged sites for irrigation purpose. For regionalization purpose, only the stream flow data of Birr near Jiga station was used.

Software's

The software's that were used to prepare and analyze data are ArcGIS 9.3, ArcSWAT2009, SWAT CUP2012, CROPWAT 8.0 and others which are related to excel.

3.3 Study period

The study was conducted from June, 2015 to November, 2015 in Birr River catchment, mainly covers West Gojjam Administrative zone, in Amhara region, which is located at the North West of Ethiopia.

3.4 Study design

The area of inquiry for this study includes Different Zones and many perennial Rivers in the Birr River catchment. The present study was undertaken using a case study design emanated for the investigation. In line with this, the process of study employed both qualitative and quantitative data, in which the Basin has been chosen on the bases of availability of perennial Rivers, productive area of land and availability of data. As the study's main objective is suitability analysis, suitability–based analysis was used to identify the problems based on the formulated objectives.

3.5 Data collection process

3.5.1 Primary Data Collection

Primary field data collection activities included field observation, pictures and GPS points.

3.5.2 Secondary data collection

The Secondary data included crop types, hydrological data, cropping pattern, climatic data, land cover/use, topographic data and soil characteristics prominent for evaluating the irrigation suitability. Secondary data sources like Adet Research Center, Amhara Water Resource Development Bureau, Amhara Agriculture Bureau, Ministry of Water Resources, Ministry of Agriculture and National Meteorological Services Agency were communicated and the collected data was used in the study work**.** In addition, Internet sources were employed.

3.6 Data pre- processing and analysis

After collection of the valuable data from various sources for the respective River catchment under investigation**,** the analysis was extend to hydrological and meteorological data to prepare input data for water resources assessment and irrigation water requirement estimation using the SWAT model and CROPWAT8.0 respectively**.**

1. Consistency of stream flow and rainfall data

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

r = 1: direct linear correlation

0.6 ≤ r <1: good direct correlation

-0.6 < r <0: insufficient – reciprocal correlation

-1 < r <0.6: good reciprocal correlation+

r = -1: reciprocal linear correlation

The stream flow and rainfall data are relatively consistent if the periodic data are proportional to an appropriate simultaneous period, and of these data, which are inconsistent, can be adjusted by proportioning, using correlation coefficient, between the stations (Selesh, 2000, Moutaz, 2001 and Yarahmad, 2003). Fortunately all the data were consistent and adjustment has not been done as presented in Appendix Figure (1, 2, 3, 4 and 5).

2. Filling missing rainfall data

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

$$P_X = \frac{1}{N}\left(\sum \frac{Px}{Pi} * Pg\right) \text{-------------------------------} (3.1)$$

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

The monthly maximum and minimum temperature values at Dembecha, Laybire, Feres Bet and Gundil stations have been averaged into maximum and minimum long term monthly values. These values were used as input data for evapotranspiration computations. Other climatic data such as sunshine duration, relative humidity and wind speed data of Laybire station has been also averaged into long term mean monthly values and used for evapotranspiration calculation.

3.6.1 Developing DEMs and Derivatives

The Digital Elevation Models (DEMs) are point elevation data stored in digital computer files. These data consists of x, y grid locations and point elevation or z variables. They are generated in a variety of ways for a different map resolutions or scales. The point elevation data are very useful as an input to the GIS. The data can further be processed to yield important derivative products such as slope, aspect, flow accumulation, flow direction, curvature, etc... These data were derived and used for suitability analysis.

3.6.2 Identification of potential irrigable sites

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

3.6.2.1. Slope suitability analysis

Land slope is the most important topographical factor influencing land suitability for irrigation. To derive slope suitability map of the study area, the slope map of the Birr River basin was derived from the available DEM with 90 meters resolution using the Spatial Analysis tool in raster form. Then slope maps of the watersheds were derived using the "Spatial Analysis Slope" tool in ArcGIS. The Slope derived from the DEM was classified based on the classification system of FAO (1994) using the "Reclassification" tool, which is an attribute generalization technique in ArcGIS. The three suitability ranges (S1, S2, and N) were also classified for surface irrigation as shown in Table3.1.

Table3. 1: Slope suitability classification for surface irrigation

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

Source: FAO (1994).

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 have been performed to make a clearer slope suitability map.

This slope map is the basic map for all other land evaluation due to the fact that it is being the critical limiting factor for irrigation implementation even if other evaluation parameters namely water availability and proximity, land cover, suitable soil and agro-climatic conditions are suitable. The slope variation in the study area rages up to 75.313% as shown in Figure 3.2.

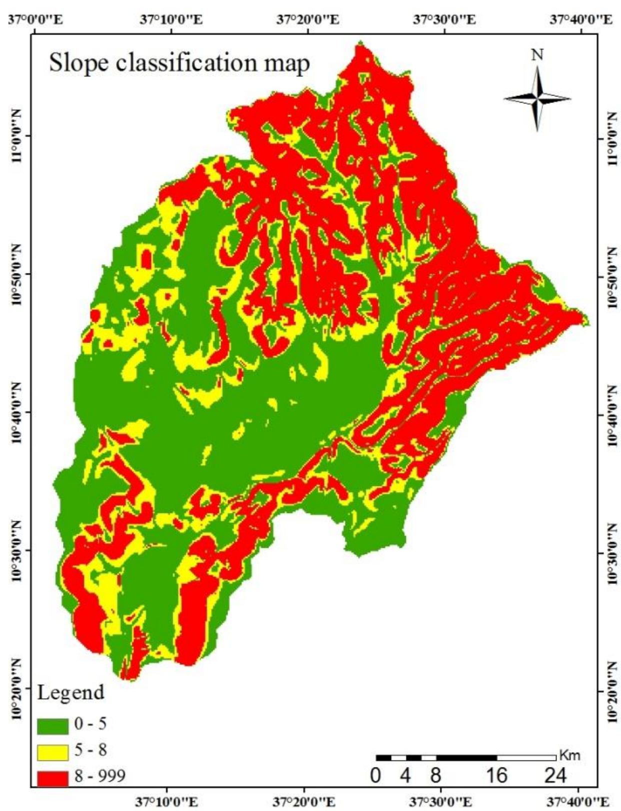

Figure3.3: Slope classification of Birr River catchment derived from the DEM

3.6.2.2. Soil suitability analysis

To assess soil suitability for irrigation, FAO/UNESCO- soil map of east Africa (1997) was used. It is available in ARC/INFO format with scale of 1:1000000. The major soil groups classified in the study area were: Eutric Cambisols, Eutric Fluvisols, Eutric Leptosols, Eutric Vertisols, Haplic Alisols, Haplic Luvisols, Haplic Nitisols, Lithic Leptosols, Dystric Leptsols, Urban and Water. Chemical and physical properties of those soil groups were used for irrigation suitability analysis. The chemical and physical properties of soil map used in this study work are adapted from the Abay River Basin Integrated Development Master Plan Project. It is made available from the Metadata Base Department of the Ministry of Water Resource in soft copy form that can be easily manipulated using the Arc GIS environment. The following soil suitability rating was used based on the FAO guidelines for land evaluation (FAO, 1976, 1979, 1990, 1991) and FAO (1997) land and water bulletin and adapted from the ARBIDMPP study.

Table3. 2: Soil suitability factor rating

Factors	Factor Rating		
	S1	S2	N
Drainage class	Well	Moderately well-Imperfectly drained	Imperfectly-poorly drained
Soil depth (cm)	>100	50-100	<50
Soil texture	L-SiCL, C	SL	-
Salinity	<8 mmhos/cm	8-16 mmhos/cm	
Alkalinity	<15 ESP	15-30 ESP	

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

Further, the soil vector layer was converted into raster layer using conversion tool "To Raster or Feature to Raster module". The rasterized soil map of the study area was then reclassified based on their soil type name, texture, and depth and drainage class. Using overlay tool in Arc GIS 9.3 Spatial analyst, weighted overlay analysis of these factors were performed to determine their suitability for surface irrigation.

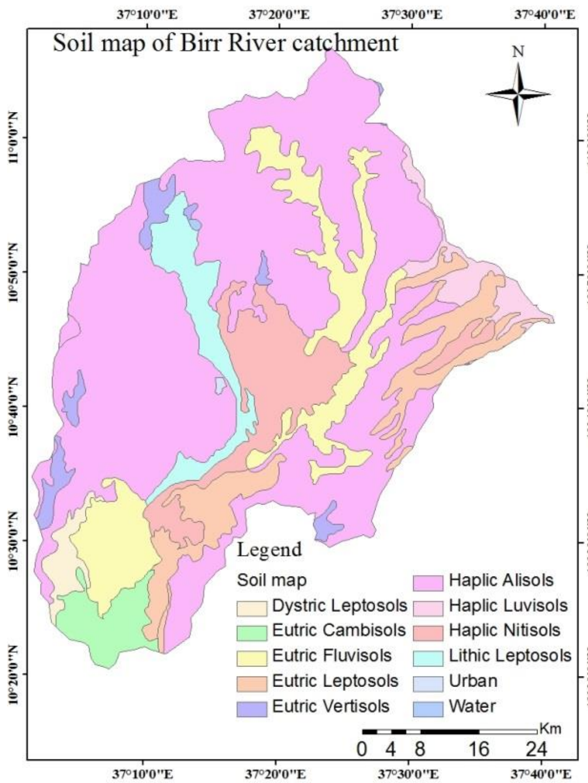

Figure3. 4: Soil classification map of study area

3.6.2.3. Land cover/use

Land cover/use of the study area is also the other factor, which was used to evaluate the land suitability for irrigation. In this research, the 1:250,000 scale land cover map is adapted from the ARBIDMPP, which used the Land Sat imagery as the base data for the land cover mapping. A land cover classification was prepared by ARBIDMPP, using the Land Use Planning and Regulatory Department and Woody Biomass Inventory and Strategic Planning Project legends with some modifications for the entire Abay River basin and this existing land cover map was used to estimate potential irrigable land. The land use class that includes, grass land, cultivated land and bush and shrub land were highly suitable and not suitable category includes forest land, built up (urban) areas, water bodies and marsh lands. There is no land cover/use under categories of moderately suitable class.

Table3. 3: Land use/cover suitability classification

Category	Suitability class	Description of Land Cover types
S1	Highly Suitable	Cultivated---Dominantly, Moderately Grassland--- Open, Bushed, Shrub
S2	Moderately Suitable	Woodland ----Open, Riparian Forest --------- Open
N	Not Suitable	Wood land ---- Dense Forest --------- Dense Urban area Water bodies and marsh lands

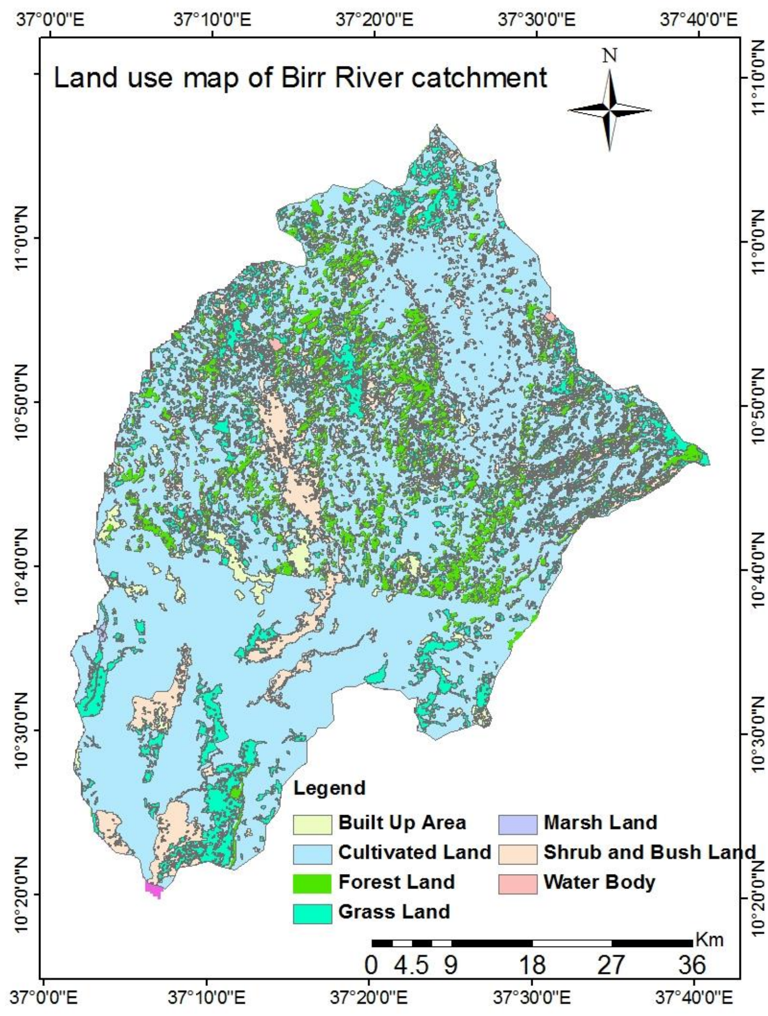

Figure3. 5: Land use map of study area

3.6.2.4. Proximity from water supply (source)

The suitability class of a land parcel with respect to River proximity was determined by its distance in relation to the perennial Rivers. To identify irrigable land close to the water supply (rivers), straight-line (Euclidean) distance from the River center was calculated by projecting the location to a Mercator (UTM) zone 37N using DEM of 90m×90m cell size and reclassified. The reclassified distance as shown in Figure 3.6 was used for weighted overlay analysis together with other factors.

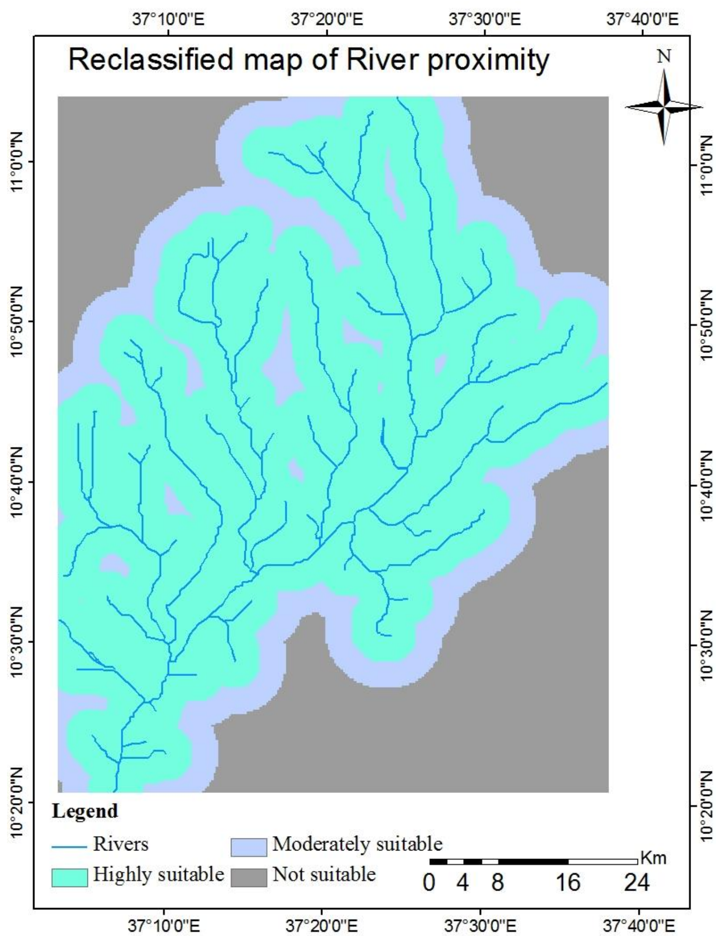

Figure3. 6: Reclassified River proximity map of study area

3.6.2.5. Weighing of irrigation suitability factors to find potential irrigable sites

Weighting of decision factors can be determined based on the importance of each variable in determining the irrigation potential and are mainly based on expert knowledge as presented by Wale et al., (2013). In this study, two types of weighting approaches are applied: the ranking technique and pair wise comparison technique. The ranking involves ordering of decision factors in their relative order of importance (Rossiter et al., 1999). To calculate the weights, the pair wise matrix was prepared comparing factors head-to-head using pairwise comparison scale (Saaty, 1977). The overall weights of the factor maps were then distributed to the suitability classes by equal interval ranges technique. The reclassified and weighted factor maps were overlain and a preliminary surface irrigation area suitability map was computed for two different weighting scenarios by the Weighted Overlay tool of ArcGIS Spatial Analyst Toolbox. Using Equation 3.2, the preliminary suitable area was mapped.

$$S = \sum_{i=1}^{n}(f_i w_i) - (3.2)$$

Where S: is the pixel value in the preliminary suitability map, fi: factor map and wi: weight of the factor map, n: number of factors.

Furthermore, to find suitable site for surface irrigation, a suitability model was created using model builder in Arc-tools box and tools from spatial analysis tool sets. Then, after their individual suitability was assessed, the irrigation suitability factors which are considered in this study, such as slope factor, soil factor, land cover /use factor and water source distance factor were used as the input for irrigation suitability model to find the most suitable land for surface irrigation as shown in Figure 3.7.

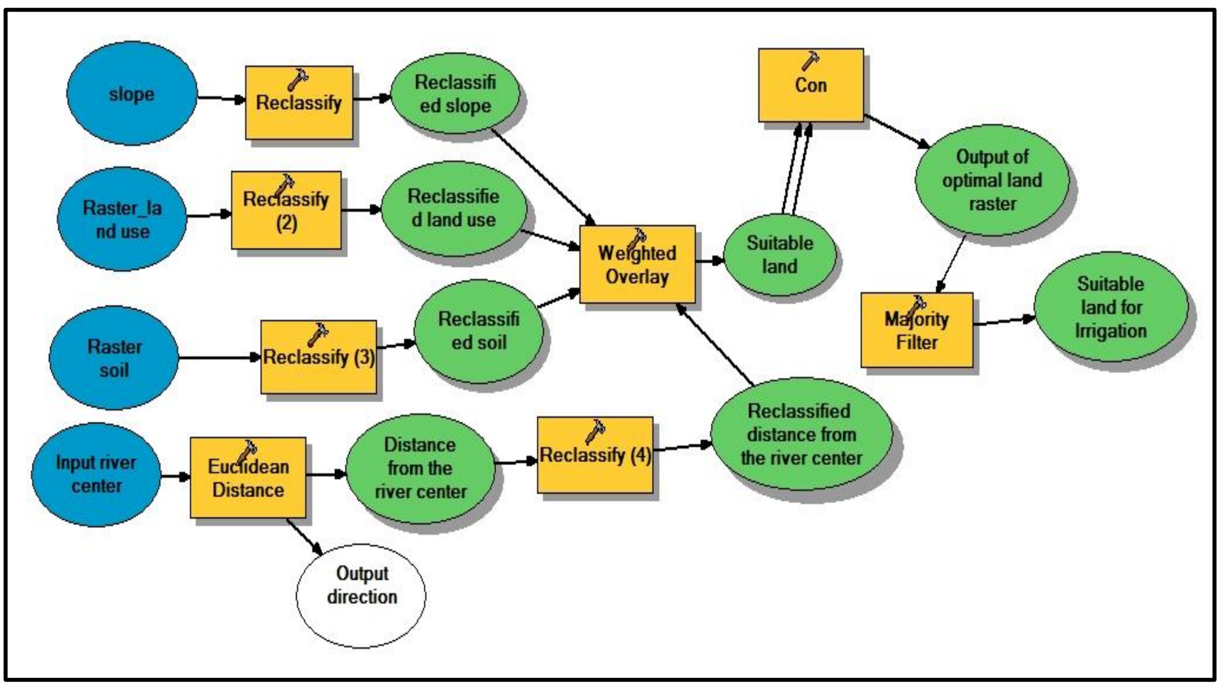

Figure3. 7: Irrigation suitability model

3.6.3. Computing irrigation water requirements

In order to estimate irrigation water requirements of the selected crop in the potential irrigable sites, definition of area of influence of the climatic stations using Arc-GIS inside and around the watershed were performed.

To obtain a spatial coverage of climate data over the study area, each station was assigned to an area of influence using the Thiessen polygons method (FAO, 1997) as presented in Figure 3.7. This method assigns an area of 'nearest vicinity' to each climate station. Laybire climatic station was taken to calculate irrigation water requirement of the identified irrigable area due to the fact that other stations do not have complete climatic records and it is more representative to the suitable land than using FAOCLIM for creation of database to the other stations. The recorded data of this station was taken for creation of data base. Then based on cropping pattern of the study area that was obtained from Zonal agricultural department, the dominant crop having the maximum value of the crop coefficient which is Maize was selected to estimate the water demand on monthly basis. Planting dates for the selected crop was chosen in such a way that the planting dates coincided with the local cropping calendar at the nearby meteorological stations. Then, ETO and other climatic data were derived from the computation for crop water requirement estimation. According to FAO '56' (Richard 1998), the maximum value of the crop coefficient for the dominant crop is 1.15. In the calculation of the consumptive use, by considering the evaporation of the crop (Maize in this case), inefficiencies in irrigation water application and water requirements for special application such as land preparation and leaching were taken into account. Irrigation efficiency considering all losses was assumed 65% of the total crop water requirement. The crop evapotranspiration is computed using Penman-Monteith by multiplying the reference crop evapotranspiration by 1.15 (crop coefficient of Maize at the mid-season) which is the maximum value. Thus, crop evapotranspiration can be computed as:

$$ETc = ETo * Kc \text{ -- } (3.3)$$

Where: ETc = crop evapotranspiration (mm/day)

ETo= reference crop evaporation (mm/day) and Kc = crop coefficient.

And the irrigation water requirement was computed as follows:

$$IWR = ETc - P_{ef} \text{ -- } (3.4)$$

Where: IWR= Irrigation water requirement (mm)

P_{ef} = effect rainfall (mm)

The effective rainfall used for calculation of crop water requirement was estimated using the SCS curve number method.

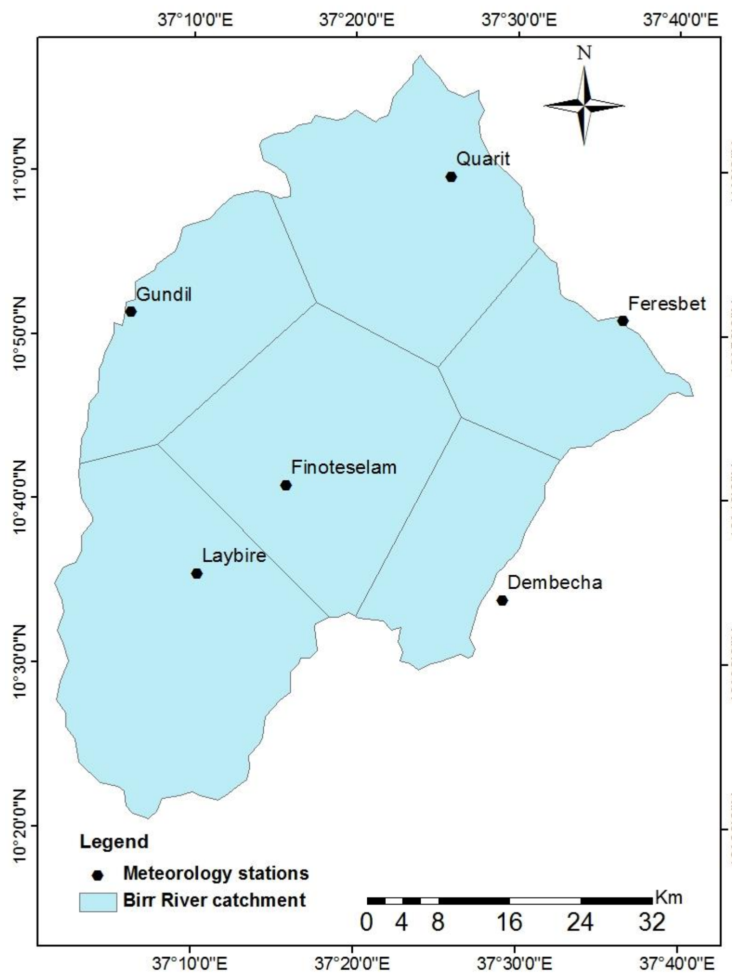

Figure3.8: Thiessen polygons showing area of influence of climatic stations in the study area

3.6.4. Estimating surface water resources potential of river catchments

The available surface water of the catchments was estimated using stream flow discharges (obtained from Ministry of water and Energy) and rainfall data (obtained from National Meteorological Service Agency). The stream flows that were used as input to determine discharges at ungauged sites were organized at the gauging stations inside and around the study area. Lah at Finote-selam, Birr near Jiga and Leza near or at Jiga Hydrometric stations were used based on their data consistency, the station with longest record and proximity of the study area criteria's.

Table3. 4: Hydrometric stations inside and around study area

No	River Name	Site	starting Date	End Date	Latitude (m)	Longitude (m)	Area coverage(km2)
1	Birr	Near Jiga	1985	2010	322797.32	1177743.3	978
2	Leza	Near Jiga	1985	2010	317338.6	1179984.6	175
3	Lah	At Fenote selam	1984	2009	310780.27	1181126.8	288

Estimated potentially irrigable area was compared to the available minimum flow and different level of percentage exceedance of the river. Percentage exceedance computation was done using the 80% and 90% exceedance flow and the respective area to be irrigated was estimated.

3.6.4.1 Estimating discharges at un-gauged sites

The discharge of Unguaged Rivers was estimated using the Regionalization method. Regionalization is the process of transferring information from comparable catchments to the catchment of interest, the choice of catchments from which information to be transferred is usually based on some sort of similarity measure, i.e. one tends to choose those catchments that are most similar to the site of interest. One common similarity measure is spatial proximity, based on the rationale that catchments that are close to each other will have a similar runoff regime as climate and catchment conditions will only vary smoothly in space (Merz and Blöschl, 2004). An alternative similarity measure is the use of catchment attributes such as land use, soil type and topographic characteristics.

In Birr River basin there are 4 gauged catchments that cover 47% of the catchment area. From these catchments one representative catchment was selected to transfer model parameters to the ungauged catchments by considering availability of reliable daily flow data and satisfactory performance of the catchment model by model calibration.

In this study different physical catchment characteristics were used to estimate flow characteristics of ungauged catchments. Generally, physical catchment characteristics can be classified into four major groups as: climate, geography, soil and land use and cover condition. A total of 16 PCCs were derived to represent the above major groups. PCCs are climate index, average slope of catchment, percentage of forest land, grassland, cultivated land, bush and shrub land, marsh land, water bodies, urban, Alisols, Luvisols, Leptosols, Nitisols, Vertisols, Fluvisols, Cambisols and Percentage of water. To estimate ungauged stream flow using this regionalization technique, SWAT Model was selected.

3.6.5 Hydrological Model Selection Criteria

There are multiple criteria which can be used for choosing the "right" hydrologic model. These criteria are always project-dependent, since every project has its own specific requirements. Among the various selection criteria, there are four common, fundamental ones that must be always answered (Cunderlik et al 2003):

- Required model outputs important to the project and therefore to be estimated by the model (Does the model predict the variables required by the project such as long-term sequence of flow?),
- Hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating single-event or continuous processes?),
- Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?),
- Price (Does the investment appear to be worthwhile for the objectives of the project?

Generally, the reasons behind for selecting SWAT model for this study are:

- Physical based model: It is based on readily observed and measure information and it attempts to simulate many hydrological components.
- The model was applied for characterization of PCCs and flow estimation in different parts of the world.
- It is public domain with for free and online access.
- Its compatibility with ArcGIS interface: for ease of data base management.
- It's easy linkage to sensitivity, calibration and uncertainty analysis tools.
- Its smart and coordinated user groups.

3.6.6 Arc-SWAT Model Approach

Watershed can be subdivided in to sub watersheds and further in to hydrological response units (HRUs) to account for difference in soils, land use, crops, topography, weather etc. The model has a weather generator that generates daily values of precipitation, air temperature, solar radiation, wind speed, and relative humidity from statistical parameters derived from average monthly values. The model computes surface runoff volume either by using modified SCS curve number method or the Green and Ampt infiltration method. Flow is routed through the channel using variable storage coefficient method or the Maskingum routing method. SWAT has three options for estimating potential evapotranspiration: Hargreaves, Pristly-Taylor, and Penman Montieth. The model also includes controlled reservoir operation and ground water flow model.

3.6.7 Model set-up

The model set-up involved five steps: (1) data preparation, (2) sub basin discretization, (3) HRU definition, (4) parameter sensitivity analysis and (5) calibration and uncertainty analysis. A predefined digital stream network layer was imported and superimposed onto the DEM to accurately delineate the location of the streams. The land use/land cover spatial data were reclassified into SWAT land cover/plant types. The watershed delineation process include five major steps, DEM set-up, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub basin parameters. For the stream definition, the threshold-based stream definition option was used to define the minimum size of the sub basin. The land use, soil and slope datasets were imported, overlaid and linked with the SWAT databases. Subdividing the sub watershed into hydrological response units (HRU's), which are areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrological conditions for different land covers,

The daily precipitation and maximum and minimum temperature data at six stations interpolated spatially over the catchments were used to run the model. Most of the stations were either established recently or had a lot of missing data. Therefore, a weather generator based on monthly statistics was used to fill in the gaps. Relative humidity, solar radiation and wind speed were generated by the weather generator. The model was run daily for 20 years; the period from 1995 to 2005 was used for calibration whereas the period from 2006 to 2010 was used for validation. Monthly flow discharge was used to calibrate and validate the model at upper Birr River basin gauging station, located at Addis Ababa to Fenote-selam Asphalt road. Sensitivity analysis was carried out to identify the most sensitive parameters for model calibration using One-factor-At-a-Time (LH-OAT), an automatic sensitivity analysis tool implemented in SWAT (van Griensven et al., 2006). Those sensitive parameters were automatically calibrated using the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspouret et al., 2004; Abbaspour et al., 2007).

3.6.8 SWAT Model Input

Digital elevation model (DEM) of a 90m by 90m resolution DEM was obtained from Ministry of Water and Energy department of GIS. The DEM was used to delineate the watershed and to analyses the drainage patterns of the land surface terrain. Sub-basin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length and width were derived from the DEM.

3.6.8.1 Weather Generator

SWAT includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. The occurrence of rain on a given day has a major impact on relative humidity, temperature and solar radiation for the day. The weather generator first independently generates precipitation for the day. Once the total amount of rainfall for the day is generated, the distribution of rainfall within the day is computed if the Green and Ampt method is used for infiltration, maximum temperature, minimum temperature, solar radiation and relative humidity are then generated based on the presence or absence of rain for the day. Finally, wind speed is generated independently. For this study Laybie weather station was selected to generate missing weather data in SWAT simulation model. For data generation weather parameters were developed by using the weather parameter calculator FORTRAN WXGenParm (Williams, 1991) and Dew point temperature calculator Dew02 (LIERSCH, 2003).

The weather generator program reads daily value of solar radiation (calculated from sunshine hours), maximum and minimum temperature, relative humidity, and wind speed and precipitation data. From this data inputs the program calculates monthly averages and standard deviations of all the input variables as well as probability of wet and dry days, skew coefficient, average number of days of precipitation in month and average annual rainfall. The Dew point temperature calculator (Dew02) program reads daily values of maximum and minimum temperatures and relative humidity values and it calculates monthly average dew point temperatures. Detail of weather generator parameters used and their values are shown in Appendix Table 2 and 3 respectively.

3.6.8.2 Soil Data

SWAT model requires different soil textural and physico-chemical properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. The soil data is obtained mainly from the following sources: Abbay river basin Integrated Development Master Plan Project—Semi detailed Soil Survey and the Soils of upper Blue Nile Basin Area, Ethiopia (SCRP, 2000). These sources were utilized to extract the necessary soil properties in relation to the major soil type map developed by Ethiopian ministry of water resources. The different sources have been helped in correlating and verification of the soil properties.

3.6.8.3 Land Use

Land use is one of the most important factors that affect runoff, evapotranspiration and surface erosion in the study area. The land use map of the study area was obtained from ministry of water resources Ethiopia. The land use of the area was reclassified based on the available topographic map (1:250,000) scale and this land cover map is adapted from the ARBIDMPP, which used the Land Sat imagery as the base data for the land cover mapping. The reclassification of the land use map was done to represent the land use according to the specific land cover types.

3.6.8.4 Weather Data

In this study, the weather variables used for driving the hydrological balance are daily precipitation, minimum and maximum air temperature, wind speed, sunshine hour and relative humidity for the period 1993–2012. The data is obtained from Ethiopian National Meteorological Service Agency (NMSA) for stations located within and around the Basin.

3.6.8.5 River Discharge

Daily River discharge values for upper Birr River basin outflow were obtained from the Hydrology Department of the Ministry of Water Resources of Ethiopia. These monthly river discharges data were used for model calibration (1995–2005) and validation (2006–2010). Figure 3.9 shows that the River gets its peak flow during the month of August.

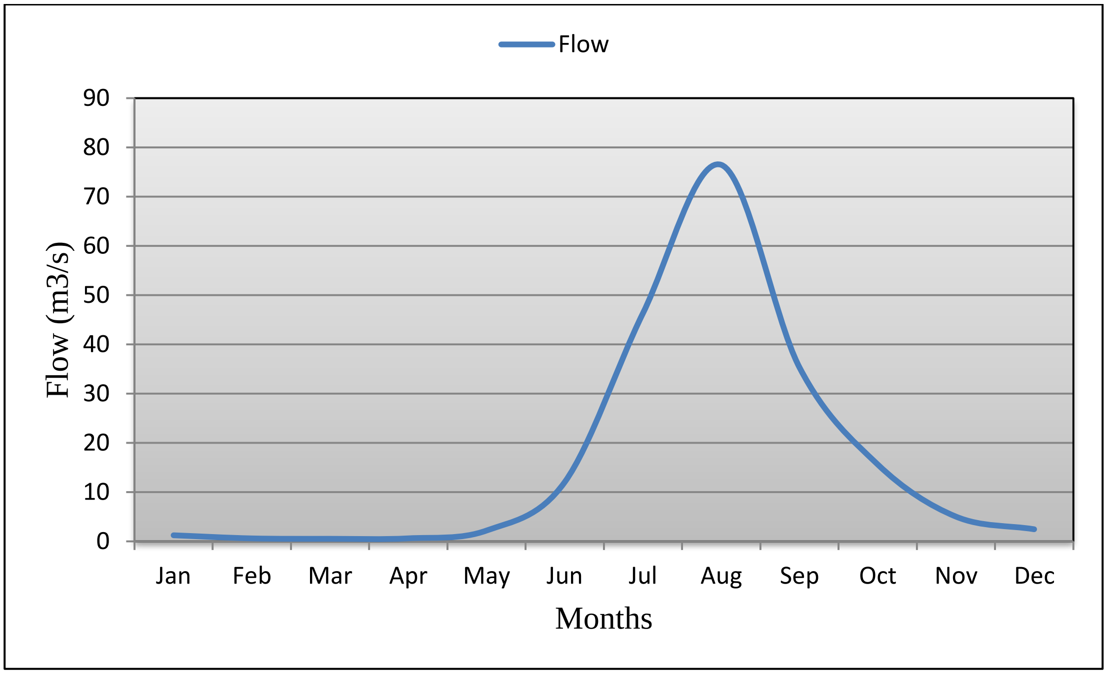

Figure3. 9: Mean monthly observed flow of upper Birr River at gauge station.

3.6.8.6 Digital Elevation Model (DEM)

Topography is defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. In other words, the Digital Elevation Model (DEM) is any digital representation of a topographic surface and specifically to a raster or regular grid of spot heights. It is basic input of the Arc-GIS integrated SWAT hydrological model to delineate watersheds and river networks. The 90X90m DEM for Ethiopia and also Abbay basin was obtained from Ministry of Water Resource (MoWR), GIS and Remote Sensing Branch, and it was extracted by mask using spatial analysis tool of Arc GIS. The DEM was converted in the grid format using conversion tool of ArcGIS 9.3 software. It was also projected in to coordinate system of WGS 1984_UTM_Zone_37N.

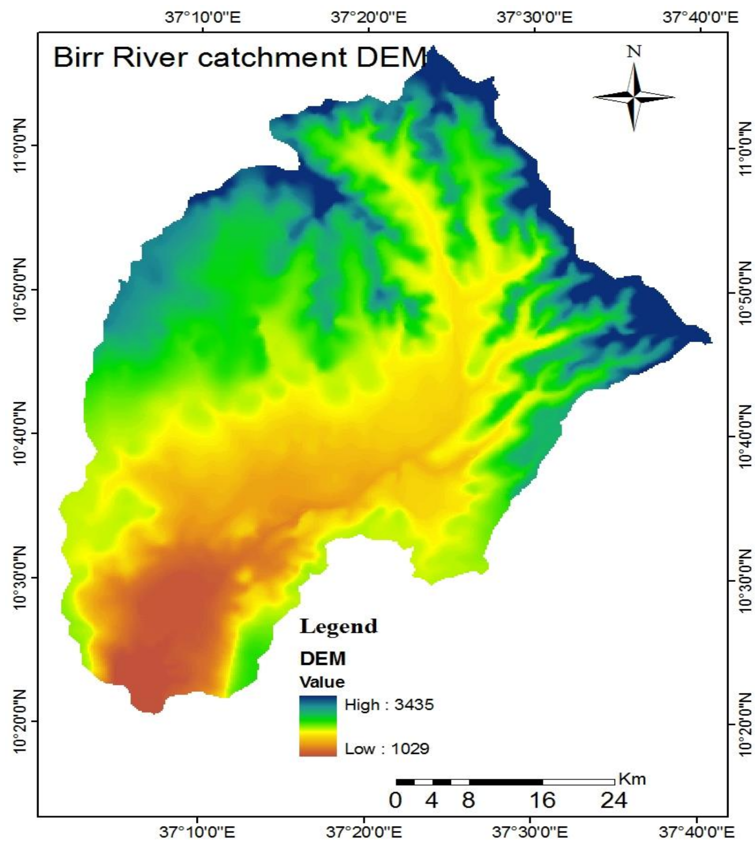

Figure3. 10: Digital elevation model (DEM) of the study area

3.6.8.7 Model Sensitivity analysis, calibration and Validation

Sensitivity analysis is a method of minimizing the number of parameters to be used in the calibration step by making use of the most sensitive parameters largely controlling the behavior of the simulated process. Twenty seven hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. The details of all hydrological parameters are found in Winchell *et al*. (2007). After the analysis, the mean relative sensitivity (MRS) of the parameters was used to rank the parameters, and their category of sensitivity was also defined based on the LENHART et al (2002), classification. He divided sensitivity in to four classes such as very high, high, medium and small. Delnesaw (2006) indicated that there can be a significant variation of hydrological process between individual watersheds. Therefore, justified the need for sensitivity analysis made for in the study area.

Table3.5: Sensitivity classes by Lenahart et al., (2002).

S.no.	Class	Index	Category of Sensitivity
1	I	0.00≤I≤0.05	Small to negligible
2	II	0.05≤I≤0.2	Medium
3	III	0.2≤I<1	High
4	VI	I≥1	Very high

Model simulations were evaluated by using two objective functions; coefficient of determination (R2) and the Nash Sutcliffe efficiency (NSE) (Nash and sutclife1970).

Coefficient of determination (R2) and the Nash Sutcliffe efficiency (NSE)

The coefficient of determination is the square of the Pearson product-moment correlation coefficient and describes the proportion of the total variance in the observed data that can be explained by the model. The closer the value of R^2 to 1, the higher is the agreement between the simulated and the measured flow. Nash and Sutcliffe efficiency, NSE indicates the degree of fitness of the observed and simulated plots with the 1:1 line (SANTHI et al, 2001). They are calculated using the following equations.

$$R^2 = \left[\frac{\sum_{i=1}^{N}(Oi-\overline{O})(OPi-\overline{P}i)}{\left[\sum_{i=1}^{N}(Oi-\overline{O})\right]^{0.5}\left[\sum_{i=1}^{N}(OPi-\overline{P}i)\right]^{0.5}}\right]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Oi-\overline{P})^2}{\sum_{i=1}^{N}(Oi-\overline{O})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Where N: Number of compared values

$\overline{O}$ is observed mean

O_i: is observed data

P is simulated data

$\overline{P}i$: is simulated mean

NSE Have values ranging from $-\infty$ to 1. If the simulation is accurate, NSE is equal to one. If the accuracy of the simulation result is smaller than the average value of measured variables, then NSE

Percent difference (D)

The percent difference for a quality (D) over a specified period with total days calculated from measured and simulated values of the quantity in each model time step as:

$$D = 100\% * \left[\frac{\sum_{i=1}^{n} Q_0 - \sum_{i=1}^{n} Q_s}{\sum_{i=1}^{n} Q_0}\right] \quad (3.7)$$

Where, Q_o = Observed flow, Q_s = Simulated flow

The percent difference (D) can vary b/n ∞ and -∞ but it performs best when a value of zero is generated. A percent deference between +5% and -5% indicates the model performs well while percent deference b/n +5% and +10% and -5% and -10% indicates a model with reasonable performance (Demelash, 2011).

SWAT developers in Santhi et.al, (2001) assumed an acceptable calibration for hydrology at R^2 >0.6 and NSE > 0.5.These values were also considered in this study as adequate statistical values for acceptable calibration. Both observed and simulated stream flow should be separated into base flow and surface flow. Surface runoff should be calibrated until average measured and simulated surface runoff within ± 15% and the model performance statistics should be D<±25%, R^2 >0.6 and NSE > 0.5 for monthly simulation period.

The data for period 1995-2005 calibration and from 2006 to 2010 were used for validation of the model for this study. Periods 1993–1994 were used as 'warm-up' periods for calibration purposes. The warm-up period allows the model to get the hydrological cycle fully operational.

The calibration and uncertainty analysis were done using SUFI-2 algorithms. These methods are chosen for their applicability from simple to complex hydrological models. Sequential uncertainty fitting—*SUFI-2* is the calibration algorithm developed by Abbaspour et al. (2004, 2007) for the calibration of SWAT model. In SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g. rainfall), parameters, conceptual model and measured data (e.g. observed flow). After the validation processes the stream flow of the intended sub watersheds and the whole catchment were estimated.

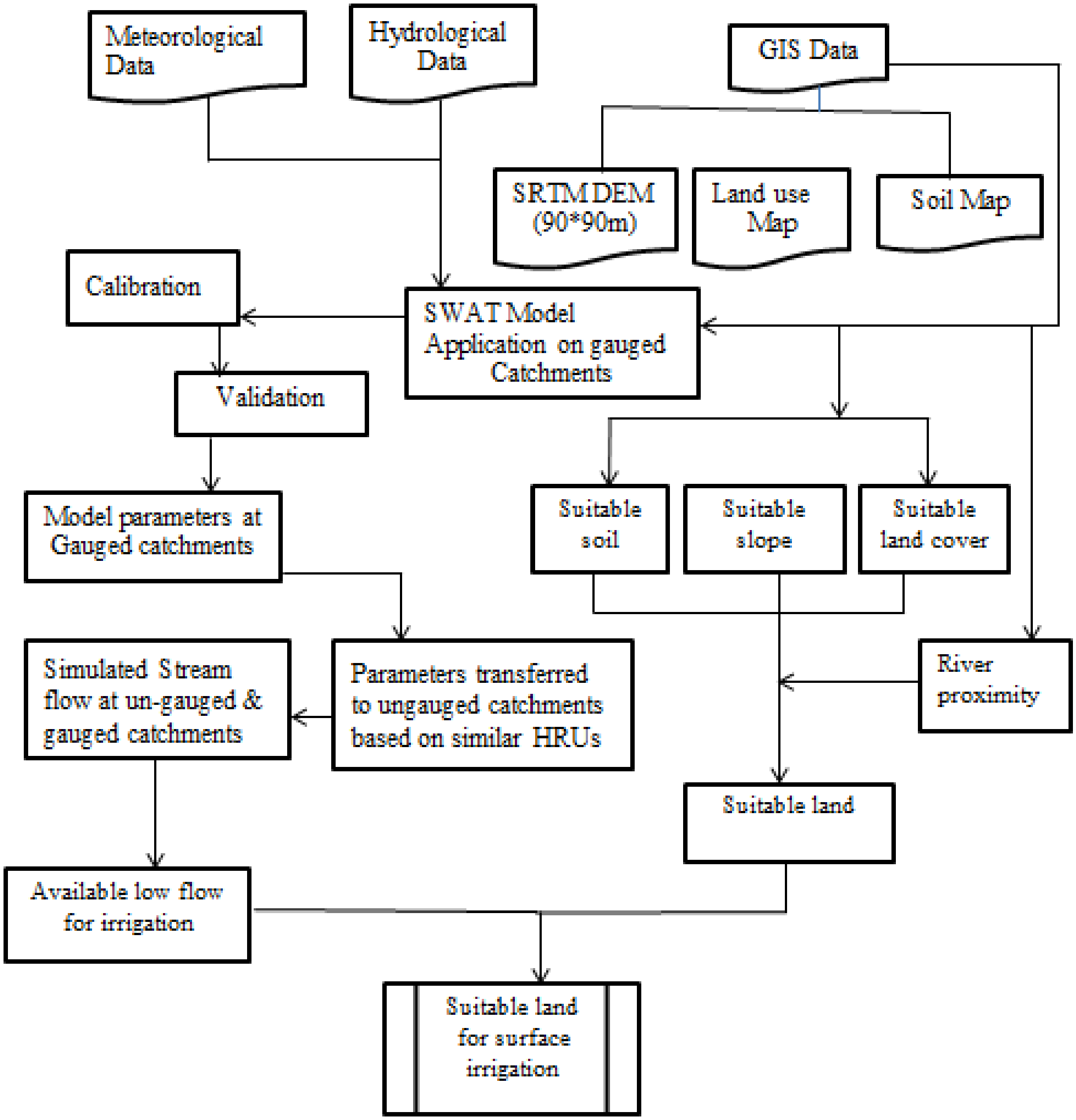

Figure 3.11: Simplified flow chart of the Methodology adopted in the research

4. RESULTS AND DISCUSSIONS

4.1 Checking Consistency

A time series observation data is relatively constant and homogeneous if the periodic data are proportional to an appropriate simultaneous period. This proportionality can be tested by double mass curve analysis (DMCA) in which accumulated rainfall data is plotted against the mean value or the sum of all stations. In DMC analysis the graph is plotted between the cumulative rainfalls of a single station as ordinate and the average cumulative rainfall of the other stations as abscissa. Using the double mass curve, the consistency change in the time series (in particular jumps) that may have been originated from a change in observer, in rain-gauge type, etc can be identified. Any inflection point in the double mass curve shows inconsistency of the data series and it can be adjusted in to consistent values by proportionality. In this study the double-mass curve analysis revealed that there is good direct correlation between the cumulative stream flow records of all stream flow and rainfall gauging stations with the cumulative average stream flows and rainfall records of other stations respectively. This indicates that both the stream flow and rainfall data at all gauging stations are consistent. The correlation coefficients of each station indicated that there is good direct correlation between the stations' records and their corresponding base stations. Therefore, it was concluded that the stream flow and rainfall data from all stations can be used for further application. The double mass curve plot is made for all of the selected stream flow and rainfall gauge stations as presented in Appendix Figures (1, 2, 3, 4, and 5).

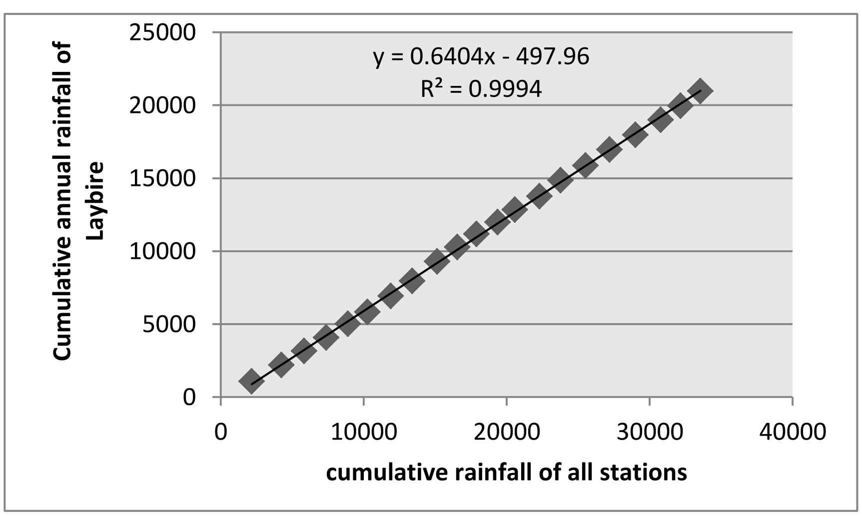

Figure 4.1: Double mass curve of Laybire rainfall station.

The rainfall analysis result showed that there were missing rainfall records of all stations. Therefore, to use these data for further application, missing values were filled by normal ratio method. In case the normal annual rainfall at any of the neighboring stations varies considerably (i.e. more than 10%) from the normal annual precipitation at target stations, then the normal ratio method (equation 3.1) was used to calculate the missing value. Therefore, missing rainfall records of stations presented in Table 4.1 were filled using the normal ratio method.

Table 4.1: List of missing Rainfall data filled by normal ratio method

	List of missing rainfall data records			
No.	Rainfall stations	Year	Months	Days of missed records
1	Finote selam	1993	April	from 1-8
		1996	December	from 11-30
		2014	March	From 2-13
2	Feres bet	1994	March	From 1-9
		1996	June	From 1-19
3	Quarit	1994	January	From 1-13
		1994	June	From 3-13

4.2 Delineation of gauged and ungauged catchments

A Digital Elevation Model (DEM) of 90m resolution from Shuttle Radar Topography Mission (SRTM) (Obtained from MoWRE) has been used to delineate the gauged and ungauged catchments by using SWAT and hydro-processing tools in GIS software. The extracted gauged catchments and ungauged catchments are shown in Figure 4.2. The watershed delineation showed that one main watershed which indicates the whole River catchment and four sub watersheds in the study area. Lower Birr River catchment is the major one and covers 3191 km2. The others such as Upper Birr, Lower Lah, Middle Birr and Silala are sub-watersheds of Lower Birr River catchment each covering area of 978 km2, 510 km2, 585 km2 and 1466 km2, respectively.

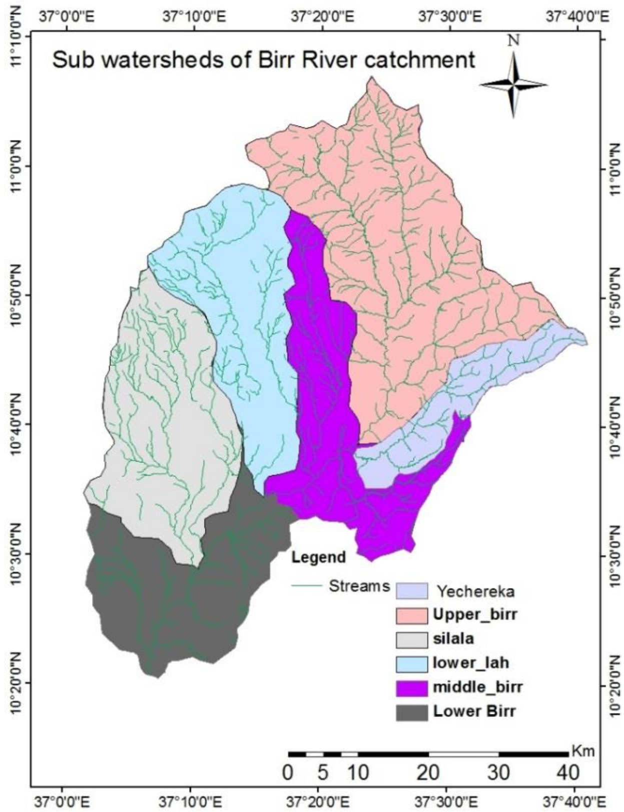

Figure 4.2: Lower Birr (including Gauged and ungauged catchments) in the study area.

4.3 Irrigation Suitability Evaluation

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

4.3.1 Slope Suitability

The slope map of the study area was derived from the available DEM using the Spatial Analysis tool in raster form. In Arc GIS Spatial Analysis "slope" tool identifies the steepest downhill gradient for a location on a surface. It is the maximum rate of change in elevation over each raster cell and its eight neighbors. This raster data was converted to vector shape file, with its slope ranges, to simplify slope map for the evaluation purpose.

There are many literatures on suitable land slope for different types of irrigation method. The land slope ranges used for this project is the one followed by FAO in land and water bulletin (Irrigation potential in Africa A basin approach, 1994). The suitable order was divided in two classes Highly Suitable (S1) for slope up to 5% and Moderately Suitable (S2) for slope range between 5% and 8%. Land slope >8% was classified in general as not suitable for surface irrigation.

This slope map is the basic map for all other land evaluation due to its being the critical limiting factor for irrigation implementation even if other evaluation parameters namely water availability, land cover, suitable soil and agro-climatic conditions are suitable. The slope variation in the study area rages up to 73.313% as shown in Figure 4.3.

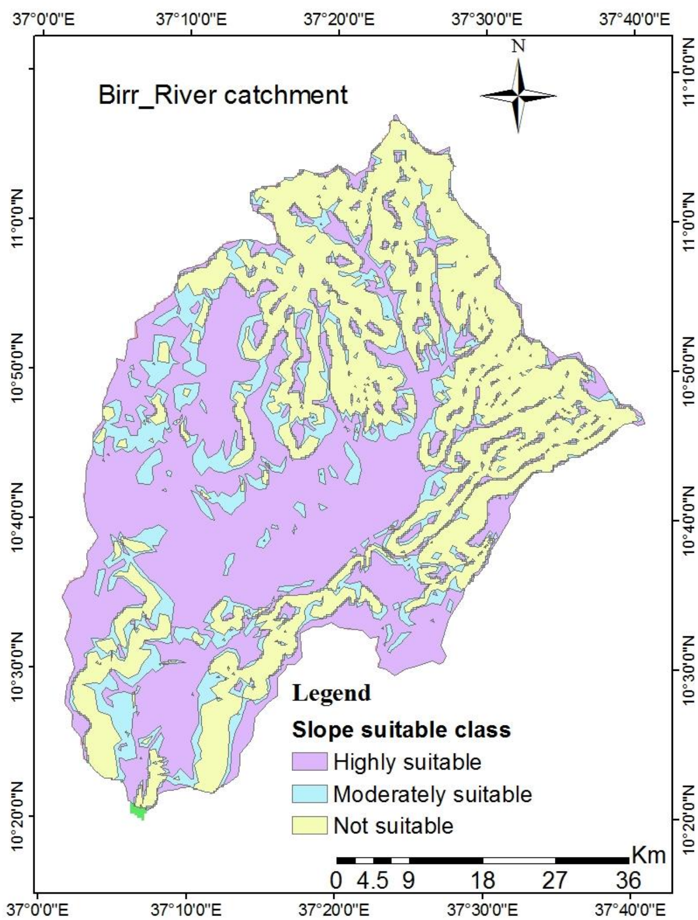

Figure 4.3: Slope suitability map of the study area for surface irrigation

Table4.2: Slope suitability range of the study area for surface irrigation

No.	Slope Range (%)	Area(km2)	Percentage (%)	Suitability class
1	0-5	1383.7	43.36	S1
2	5-8	553.2	17.34	S2
3	8-999	1254.1	39.30	N
	Total	3191.0	100.00	

The result shows that 60.7% of the total study area ranges highly suitable to moderately suitable for surface irrigation system with respect to slope whereas the remaining 39.3% of the area is not suitable. Hence, the majority of the study area is highly to moderately suitable for surface irrigation in terms of slope suitability.

4.3.2 Land cover/use Suitability

Land cover/use classes that includes, grass land, cultivated land and bush and shrub land were classified as highly suitable for irrigation with the assumption that these land cover classes can be irrigated without limitations. These land classes covers 91.1% of the study area. Not suitable categories were included forest land, built up (urban) areas, water bodies and marsh lands. It is obvious that land cover classes such as forest land, urban areas, water bodies and marsh land cover classes are restricted to use for irrigation. These land units covers about 8.9% of the total study area. However, the study established that there are no land cover/use types that can be categorized as S2 (moderately suitable) for surface irrigation.

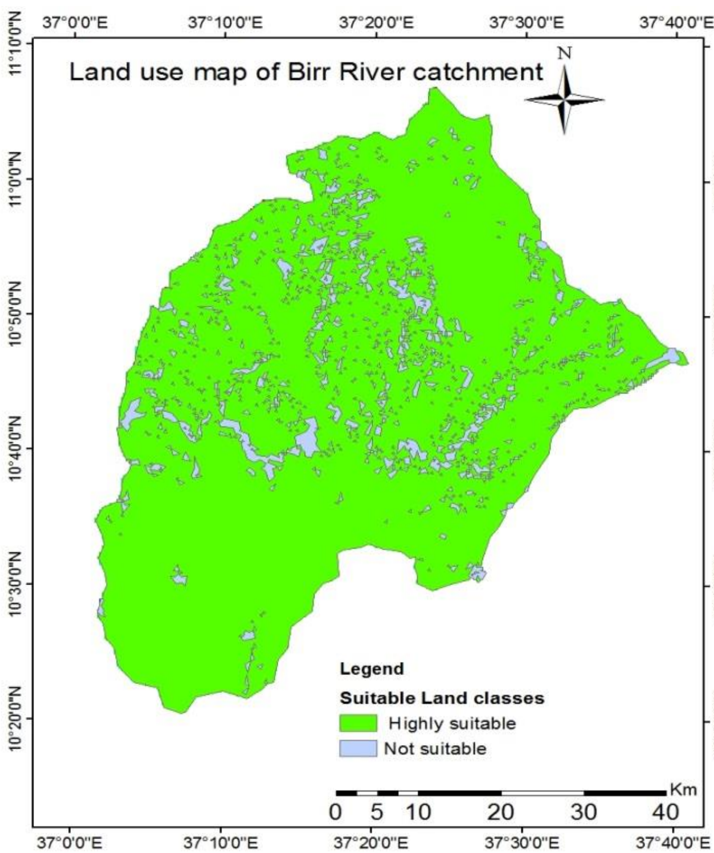

Figure 4.4: Land cover/use map of the study area

Table4.3: Area coverage of land cover/use and suitability classes of the study area

No.	Land cover type	Area(km2)	Percentage (%)	Suitability class
1	Built Up Area	51	1.6	N
2	Cultivated Land	2214	69.4	S1
3	Forest Land	225	7.1	N
4	Grass Land	375	11.8	S1
5	Marsh Land	2	0.1	N
6	Shrub and Bush Land	321	10.1	S1
7	Water Body	3	0.1	N
	Total	3191	100.0	

Grassland

This category is subdivided further for better understanding. Open grassland is defined where the area is dominated by grass with very few shrubs or bushes. Bushed/Shrub grassland consists of grassland with frequent patches of shrubs and/or bushes. Wooded grassland has, in addition, dispersed trees throughout the unit. These three units of land that is grassland, bushed/shrub land covers 21.9% of the study area.

Forest

Forest consists of a multi storied tree community, and is described by the major type (deciduous or coniferous) and degree of disturbance. This land covers an area of 7.1% of the total area of the river catchment.

Cultivated land

Cultivation is in a sense self-explanatory, being that land which is being cultivated. Rain fed, state farm, perennial crops and irrigated lands are sub divisions of the cultivated class included. This land cover type is dominant as compared to the other land cover types in the study area. It covers 69.4% of the total area of the river catchment. This land cover type is found throughout different agro-ecological zones of the study area.

Water body

This land unit covers 0.1% of the study area and located mainly the upper or northern part of the river catchment.

Marsh land

This land unit mostly consists of wetlands (swampy areas). It is found near the outlet of The River catchment at south western part of the study area. It covers an area of 0.1% of the total area of the River catchment.

Settlement

This land cover class covers urban areas or zonal, woreda and kebele level towns covering an area of 1.6% of the total area of the River catchment.

4.3.3 Soil Suitability

The soil map of the major soil groups of the catchment classified as per the FAO soil group was used for this study. This map was obtained from the GIS department of MoWRE. The dominant soils are described below. The "dissolve" tool in the "Data management tool" of Arc GIS was used to simplify this layer. The new soil map divides all the soils in to the major groups (Alisols, Nitisols, Vertisols, Leptosols, Cambisols, Fluvisols, Luvisols, Urban and Water).

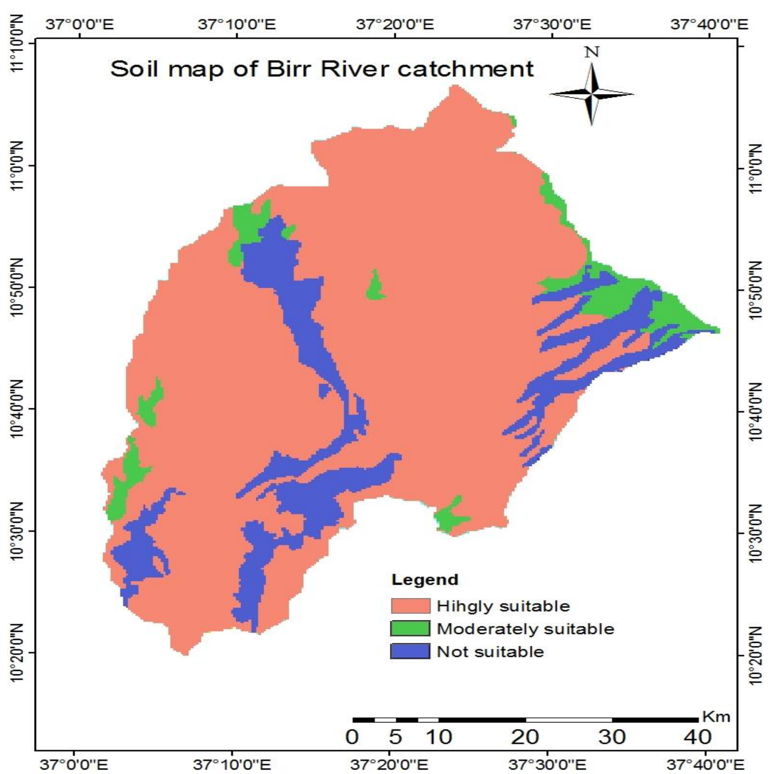

Figure 4.5: soil suitability class for irrigation

The results of this analysis shows that the study area can be generally classified into three irrigation suitability classes based on soil suitability as a factor: S1 (highly suitable), S2 (moderately suitable) and N (not suitable). Alisols, covering an area of 1,794 square kilo meters which accounts 56.2% of the total area, was classified as highly suitable (S1) for surface irrigation. This soil is characterized by deep to very deep soil, clay/clay loam/silt clay texture, well drainage condition and no salinity and alkalinity hazards. Fluvisols and Nitisols are also categorized as highly suitable class and covers 9% and 11.8% respectively. Vertisols, Cambisols and Luvisols are categorized as moderately suitable for their poor drain ability, moderate soil depth and limited by sandy loam textures respectively. Leptosols, Urban and water bodies are categorized as not suitable for their shallow depth.

In general, about 77% of the soil in the study area can be categorized as highly suitable (S1 class), 14.8% moderately suitable (S2 class) and 8.2% not suitable (N class) for surface irrigation. These soils are classified based on classification system of FAO (1983).

Table 4.4: Soil suitability evaluation criteria for Irrigation

No.	Soil type	Texture	Depth(cm)	Drainage	Salinity (ds/m)	Alkalinity(ESP)	Irrigation suitability	Area (km2)	Percentage (%)
1	Leptosols	C/L	shallow to very shallow	well			N	465	14.6
2	Cambisols	SC	moderately deep	well			S2	99	3.1
3	Fluvisols	C/SC/CL	deep to very deep	well			S1	377	11.8
4	Vertisols	C	deep to very deep	imperfect to poor	0.1	4.93	S2	77	2.4
5	Alisols	C/CL/SC	deep to very deep	well			S1	1794	56.2
6	Luvisols	SL	deep to very deep	well	0.1	4.83	S2	86	2.7
7	Nitisols	C/CL/SC	deep to very deep	well	0	0.43	S1	288	9
8	Urban						N	3	0.1
9	Water						N	2	0.1

NB: C= Clay, CL= Clay Loam, SL = Sandy Loam, SC= silty clay, L= loam

4.4 Suitable Land for Surface Irrigation

Before building the model, the pairwise matrix was constructed. It consists of the first five columns in Table4.5. Four factors are listed ranging from soil to slope. The pair wise matrix compares the importance for surface irrigation of each of the factors on the left to another factor on the top. Thus, 'river proximity' is much more important factor than land use for determining the suitability of a particular piece of land for irrigation. Hence, assigning the value of 4 (the highest number but the actual value is arbitrary) at the intersection of the row of 'river proximity' and the column of land use. Conversely, 'land use' on the left of the Table is much less important than 'river proximity' on the top and was assigned the reciprocal of 4 (i.e. 1/4) to the intersection of these two factors. River proximity is the most important factor since it has all integer values followed by slope that only has one value less than 1 in its row and that is in the column with river proximity. The least important factor in considering surface water irrigation is land use with all values in the land use row being less than 1. Next, the weights were computed by pairwise weighting according to Saaty (1977) and ranking method by Rossiter et al. (1999) and as described above. These calculated weights are listed in the last two columns of Table 4.5 where the greater the value, the more important the factor. The sum of each of the last two columns is 100. Both weighting approaches ranked the factors in the same order: river proximity was the most important factor followed by slope and soil of the land. Land use as expected was the least important factor. The factors River proximity and slope were judged as very important because they are the most limiting factors and associated with a large initial investment than others. The factors' weights in pairwise comparison have a greater standard deviation than ranking technique (14.3 and 12.9 respectively).

Table 4.5: Weighting by Pairwise comparison matrix and ranking technique

Factors	Soil	Land use	River proximity	Slope	Pair wise weighting	Ranking weighting
Soil	1	2	1/2	1/2	18	20
Land use	1/2	1	1/4	1/3	10	10
River proximity	2	4	1	2	43	40
Slope	2	3	1/2	1	29	30

The weights of each factor in the last two columns of Table 4.5 are further subdivided into three intervals for each map pixel to indicate how favorable the pixel is in determining the irrigation suitability.

Furthermore, potential irrigable land was obtained by creating irrigation suitability model analysis which involved weighting of values of all data sets such as soil, slope, land cover and distance from the water supply. Figure 4.6 shows the identified potential irrigable lands in the main watershed among the main and tributary perennial rivers. The main and tributary rivers are referring to the main and sub-watersheds obtained by watershed delineation. Finally moderately suitable classes (S2) can be transferred to not suitable classes since it is restricted by the most limiting factor which is River proximity.

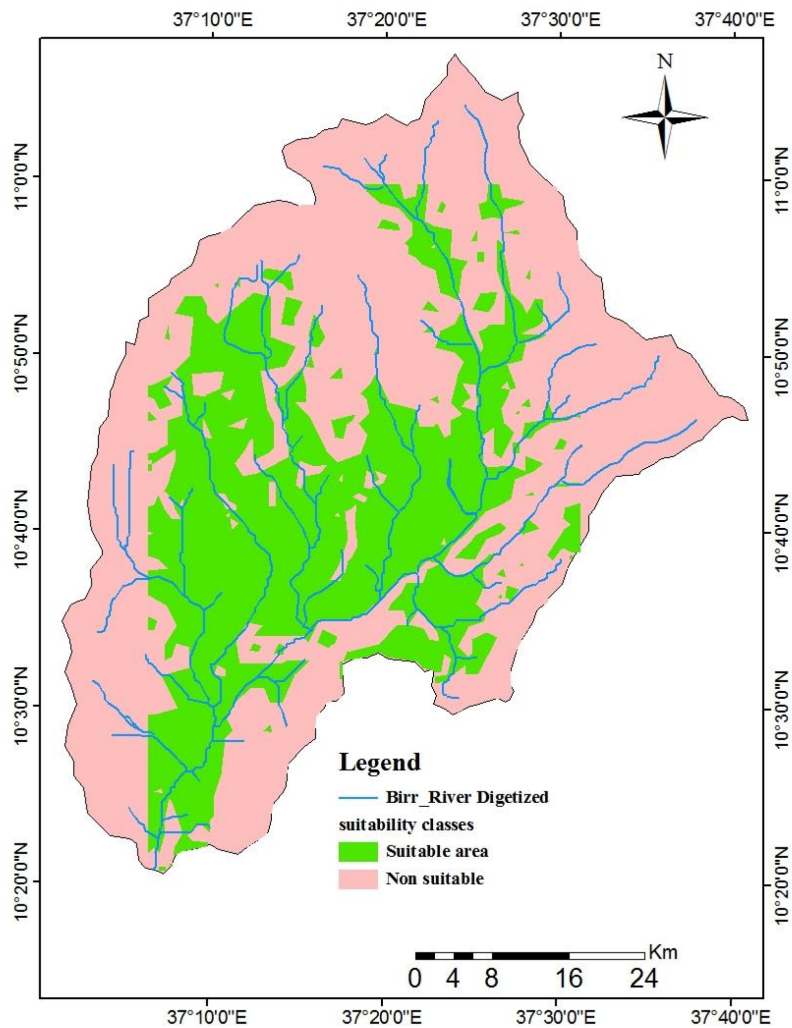

Figure 4.6: Suitable land for surface irrigation in Birr River catchment

Table 4.6: Identified suitable area for irrigation

No.	Watersheds (river name)	Total area coverage(km2)	potential command area(km2)	Percentage (%)
1	Upper Birr	978	236	24.13
2	Lower Lah	510	249	48.82
3	Middle Birr	1466	500	34.11
4	Silala	585	306	52.31
5	Lower Birr(Total)	3191	1166	36.54

For verification the previous identified suitable areas studied by Abbay basin master plan project was referred. The existing command area can irrigate by constructing two dams at the middle and lower Birr River. The lower Birr reservoir includes Lah River. These existing identified areas lie on the identified areas by this thesis work which is suitable for surface irrigation as shown in Figure 4.7.

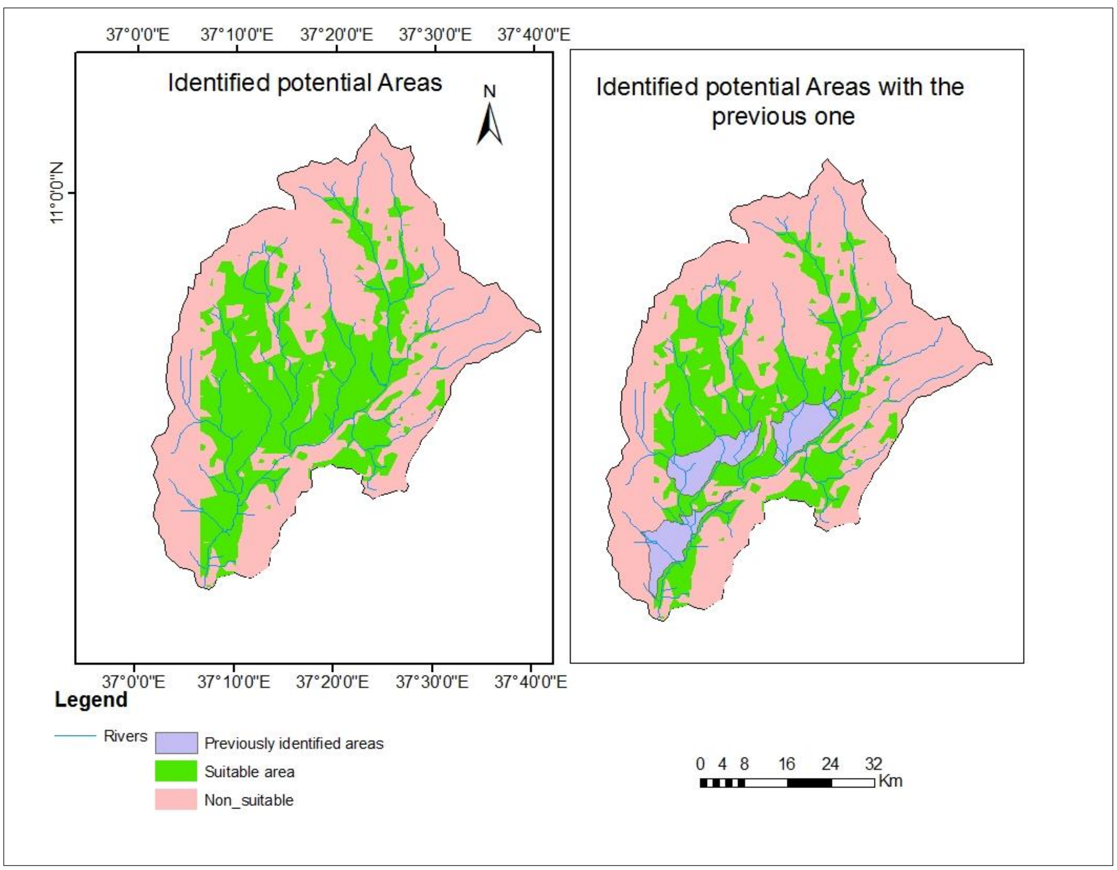

Figure 4.7: Verification of Suitable land for surface irrigation in Birr River catchment (from the previous identified command areas)

4.5. Irrigation Water Requirements of the Identified Command Areas

To calculate the irrigation water requirement a reference crop evaporation rate was calculated by Penman-Moenteith approach and it ranges from 2.9 mm in August (cold and rainy) to 6.5 mm in March (the warmest and driest month). The total irrigation water requirement computed on monthly basis with (Equation 3.4) ranges below zero mm/day in the rainy season to a maximum of 7.3 mm/day in dry season. The rainfall in the wet season June through September is well above crop evapotranspiration. So, in the rainy season there is no need for irrigation.

The irrigation potential of the different level of percent exceedance and minimum available water was computed by dividing the available water by the irrigation water requirement during a single irrigation water application time. This is so by maintaining about 25% of the flow for the downstream ecological balance as presented by Wagesho (2004).

The result indicated, October has the maximum irrigation potential of each sub watershed and March has the minimum potential. Computation was done for the month of March which has minimum potential using the 80 %, 90% exceedance and minimum available flow. Therefore, the respective minimum areas to be irrigated for all sub watersheds were estimated as shown in Table 4.7.

Table 4.7: Area irrigated with different percentage exceedance and minimum flow

No.	River Basin	Area Irrigated (ha) with different percent reliability level of flow		
		80%	90%	Minimum flow
1	Lah	443.84	257.42	186.41
2	Upper Birr	701.26	576.99	470.47
3	Middle Birr	994.19	878.79	790.03
4	Silala	461.59	213.04	168.66
5	Lower Birr	2157.04	1659.95	1500.16

4.5.1 Flow duration curve

The 80 and 90 percentile available flow is determined by making flow-duration curve (FDC). FDC provides the percentage of time (duration) of a daily or monthly stream flow is exceeded for the 18 year period from 1993 to 2010 (Vogel and Fennessey 1994). The FDC graph of logarithmic monthly river flow vs. exceedance frequency is plotted for the main River catchment and sub watersheds as shown in Figure 4.7. FDC of the sub basins and the whole drainage basin indicated no distinct dry season, all months for the study period have no zero flow and it has relatively medium variability in stream flow.

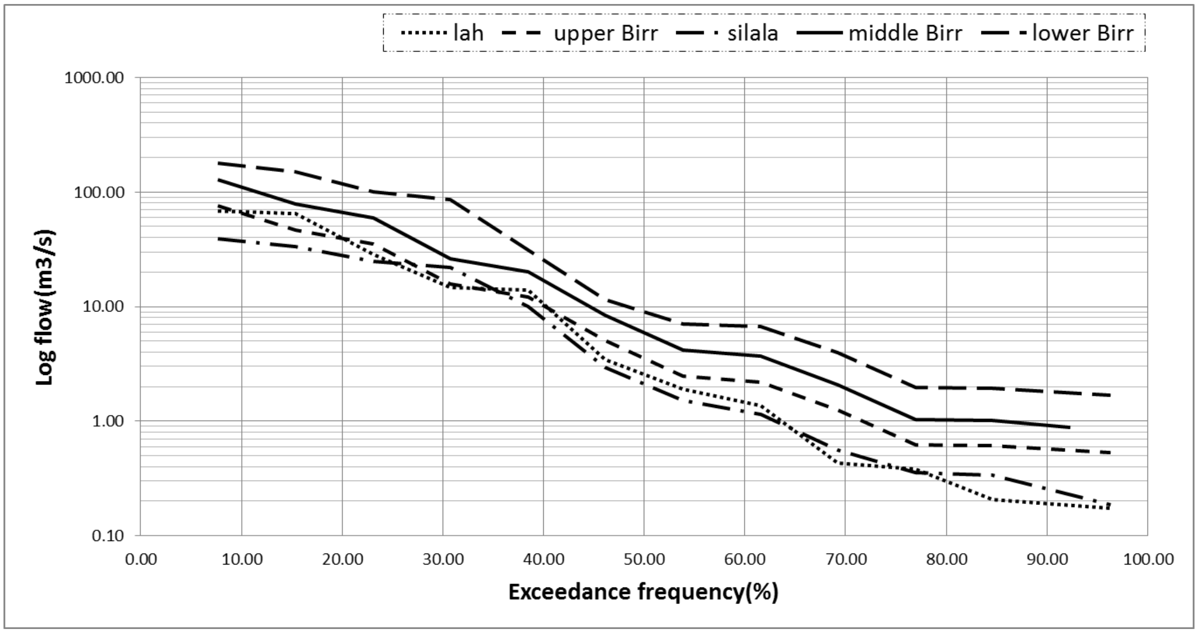

Figure 4.8: Monthly flow duration curves for sub watersheds and the whole drainage basin.

4.6. Water Resources Assessment

Prior to estimating stream-flows at the un-gauged sites from gauged sites, watersheds above both gauged and un-gauged sites were characterized. Taking the watershed similarities into account, stream flows at un-gauged sites were estimated from the gauged sites through regionalization technique by applying SWAT model.

4.6.1. Gauged and un-gauged watersheds similarities

Slope, soil and land covers

Before transferring the stream flow data from gauged to ungauged catchments, similarities of Climate, Geography, Soil and Land use and cover condition were checked from the SWAT model results. This result indicates that there is a good correlation of slope, soil and land cover conditions between gauged and ungauged catchments as described below.

Table 4.8: soil correlation of gauged and ungauged catchments

	upper birr gauged	silala ungauged	lah ungauged	middle birr ungauged	lower birr ungauged
upper birr gauged	1				
silala ungauged	0.97314	1			
lah ungauged	0.80367	0.88832	1		
middle birr ungauged	0.96102	0.96808	0.89229	1	
lower birr ungauged	0.98120	0.98375	0.87737	0.99384	1

Table 4.9: slope correlation of gauged and ungauged catchments

	upper birr gauged	silala ungauged	lah ungauged	middle birr ungauged	lower birr ungauged
upper birr gauged	1				
silala ungauged	0.99583	1			
lah ungauged	0.99708	0.99988	1		
middle birr ungauged	0.99940	0.99838	0.99912	1	
lower birr ungauged	0.99666	0.99995	0.99998	0.99888	1

Table 4.10: land covers correlation of gauged and ungauged catchments

	upper birr gauged	silala ungauged	lah ungauged	middle birr ungauged	lower birr ungauged
upper birr gauged	1				
silala ungauged	0.9696	1			
lah ungauged	0.9117	0.8156	1		
middle birr ungauged	0.7908	0.6648	0.9723	1	
lower birr ungauged	0.8746	0.7758	0.9926	0.9836	1

Climate

- **Standard annual average rainfall**

The most commonly used characteristic is the standard annual average rainfall (SAAR) with respect to the climatic PCCs. For this characteristic the data are frequently available. However this is not commonly applied in other studies but in Deckers (2006) it proved to be a good indication for climatic variability. In this study there is a good similarity between the catchments.

- **Mean precipitation wet season and dry season**

It is observed that there are two clear seasons for precipitation in the region, with high rainfall during June to September and low rainfall during October to May. Hence average daily rainfall in the dry season and the wet season was selected separately as climate PCCs. This condition also has good relation between gauged and ungauged catchments as presented in Appendix Table 5 and 6 respectively.

- **Average annual evapotranspiration**

The average annual evapotranspiration also has significant distribution over the catchment and varied from 1043 to 1194 mm/year. Kim (2008) has used this characteristic for the upper Blue Nile river basin and got reasonable relation with model parameters used in his study. In this study average annual evapotranspiration was used as PCCs and the result indicates reasonable relation with gauged and ungauged catchments as described in Appendix Table 4.

4.6.2 SWAT Hydrological Model Result

5.6.2.1 Flow Simulation

For simulation of flow the whole watershed is divided in to 19 sub basins based on threshold area 3191km^2. Hundred seven HRUs were generated and each HRU composes of land use, soil type and slope parameters. The land use of the basin consists of seven land use types. The dominant land use in the basin is cultivated land. Marsh land is the smallest land use type within the River catchment.

Table 4.11: Aerial coverage of land use in Birr River catchment

No.	SWAT code	Land cover	Area(km2)	Percentage (%)
1	URBN	Built Up Area	51	1.6
2	AGRC	Cultivated Land	2214	69.4
3	FRST	Forest Land	225	7.1
4	RNGE	Grass Land	375	11.8
5	SPAS	Marsh Land	2	0.1
6	RNGB	Shrub and Bush Land	321	10.1
7	WATR	Water Body	3	0.1
		Total	3191	100.0

Soil type is the second component of HRUs and the watershed has 11 soil types. The dominant soil type in the basin is Haplic Alisols. Water is the smallest soil type within the River catchment.

Table 4.12: Aerial coverage of soil type in Birr River catchment

No.	Soil type	Symbol code of SWAT	Area(km2)	Percentage (%)
1	Dystric Leptosols	LPd	49	1.5
2	Eutric Cambisols	Cme	99	3.1
3	Eutric Fluvisols	Fle	377	11.8
4	Eutric Leptosols	Lpe	267	8.4
5	Eutric Vertisols	Vre	77	2.4
6	Haplic Alisols	Alh	1794	56.2
7	Haplic Luvisols	LVh	86	2.7
8	Haplic Nitisols	NTh	288	9.0
9	Lithic Leptosols	LPq	149	4.7
10	Urban	U	3	0.1
11	Water	W	2	0.1
	Total		3191	100.0

Slope discrimination is another important parameter of HRUs. The slope of the River catchment was divided in to three categories such as; class1:0-5% covers 43.36% watershed area, clas2: 5-8% covers an area of 17.34% and class3: 8-9999% covers an area of 39.3 of the study area.

4.6.2.2 Sensitivity analysis

Sensitivity analysis for stream flow at the gauging point for the period of 20 years which contains both calibration and set up periods has been shown that 27 parameters are considered in the analysis. These parameters with 10 intervals of sampling (totally 270 iterations) were used for sensitivity analysis and only 7 of them showed meaningful effect on the monthly flow simulation of the study area. As shown in Table 4.12, the first seven parameters indicate a relative sensitivity, being the Alpha base flow separator (Alpha_Bf), Soil evaporation compensation factor (Esco) and Threshold Water Depth in the shallow aquifer for flow (Gwqmn) are high sensitive. Hence, the most sensitive parameters controlling stream flow in the basin are Alpha base flow separator (Alpha_Bf), Soil evaporation compensation factor (Esco) and Threshold Water Depth in the shallow aquifer for flow (Gwqmn).

Table 4.13: Adjusted parameter values of the flow calibration.

Rank	Parameter	Description	Lower bound	Upper bound	Mean value	Fitted value	Category of Sensitivity
1	Alpha_Bf	Alpha base flow separator	0	1	0.19	0.633	High
2	Esco	Soil evaporation compensation factor	0	1	0.19	0.65	High
3	Gwqmn	Threshold Water Depth in the shallow aquifer for flow	0	5000	0.15	750	High
4	Cn2	Initial SCS CN2 value	-25%	25%	0.07	12%	Medium
5	Sol_Z	Total soil depth(mm)	0	3000	0.05	150	Low
6	Gw_Revap	Groundwater “revap” coefficient	0.02	0.2	0.05	0.06	Low
7	Sol_Awc	Soil available water capacity (mm WATER/mm soil	0	1	0.05	0.1666	Low

4.6.2.3 Flow Calibration

SWAT simulation by the default value of parameters at the gauging stations has shown a weak hydrograph in matching the simulated and observed stream flows of SWAT2009 model. In computing the efficiency, both the first and the second years of simulated model result was excluded, because it is a warm period, which means the influence of the initial conditions such as soil water content will be minimized. Afterwards manual Swat-cup (sufi-2) calibration for average annual and monthly water balance and stream flow was done. Once the model is calibrated for average annual conditions it can be repeated for monthly basis. As shown in Figure 4.9 the calibration results have been indicated that there is a good agreement between the observed and simulated monthly flow relationships. This is demonstrated by objective functions; the correlation coefficient (R^2 = 0.81) and the Nash_sutclife (1970) efficiency (NSE=0.73).

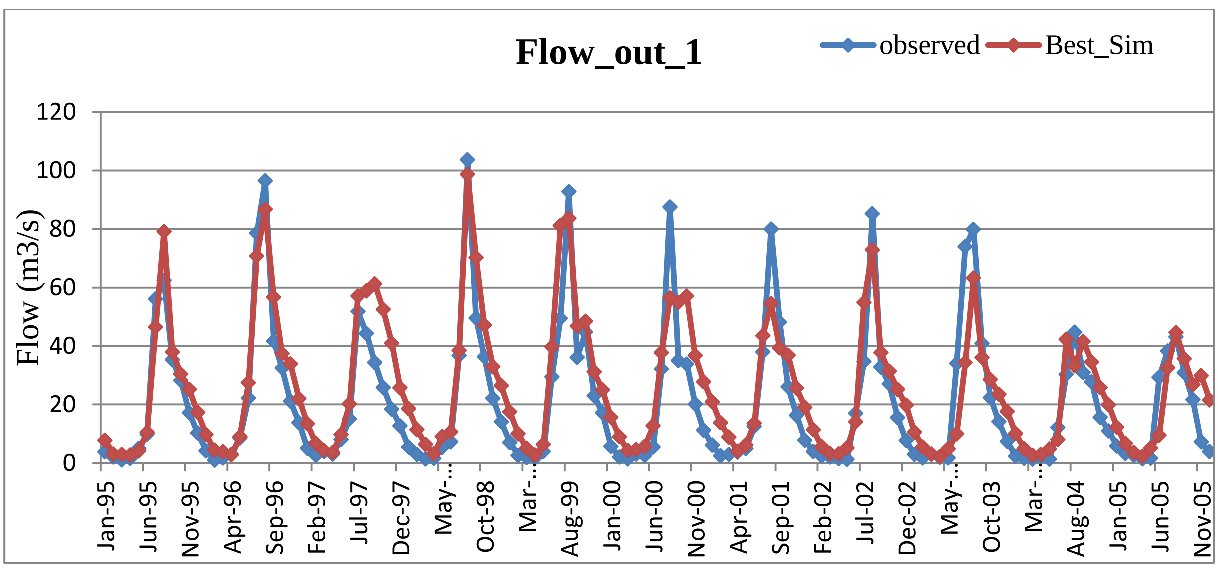

Figure 4.9: Calibration results of average monthly simulated and gauged flows at the outlet of upper Birr River catchment.

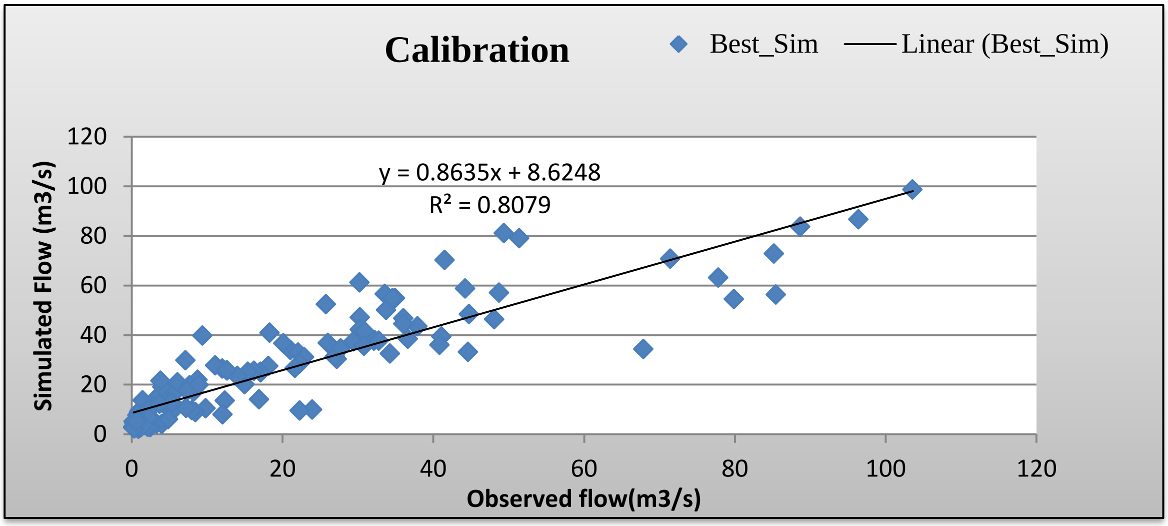

Figure 4.10: Scatter plots of monthly simulated and gauged flows at the outlet of gauged area.

4.6.2.4 Flow Validation

The purpose of model validation is to cheek weather the model can predict flow for another range of time period or conditions than those for which the model calibrated for. Model validation involves re-running the model using input data independent of data used in calibration, differing time period, but keeping the calibrated parameters unchanged. In this study the validation was carried out 5 years from January 1st 2006 to December 31st 2010. The correlation coefficient during validation period was (R^2 = 0.75) and the Nash_Sutclife (1970) Simulation coefficient (NSE = 0.70). The validation period shows a good agreement between the simulated and gauged flow of the outlet of the gauged area.

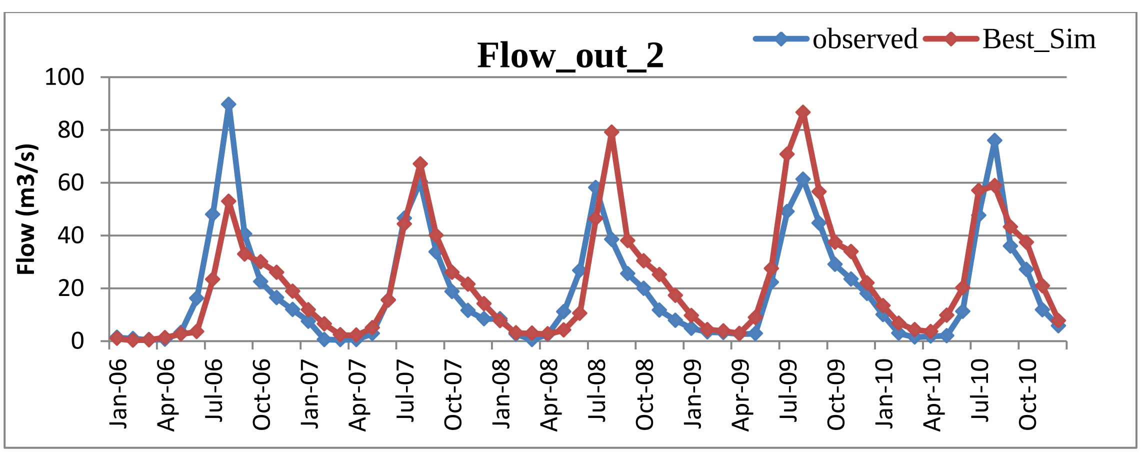

Figure 4.11: Validation results of average monthly simulated and gauged flows at the outlet of upper Birr River catchment.

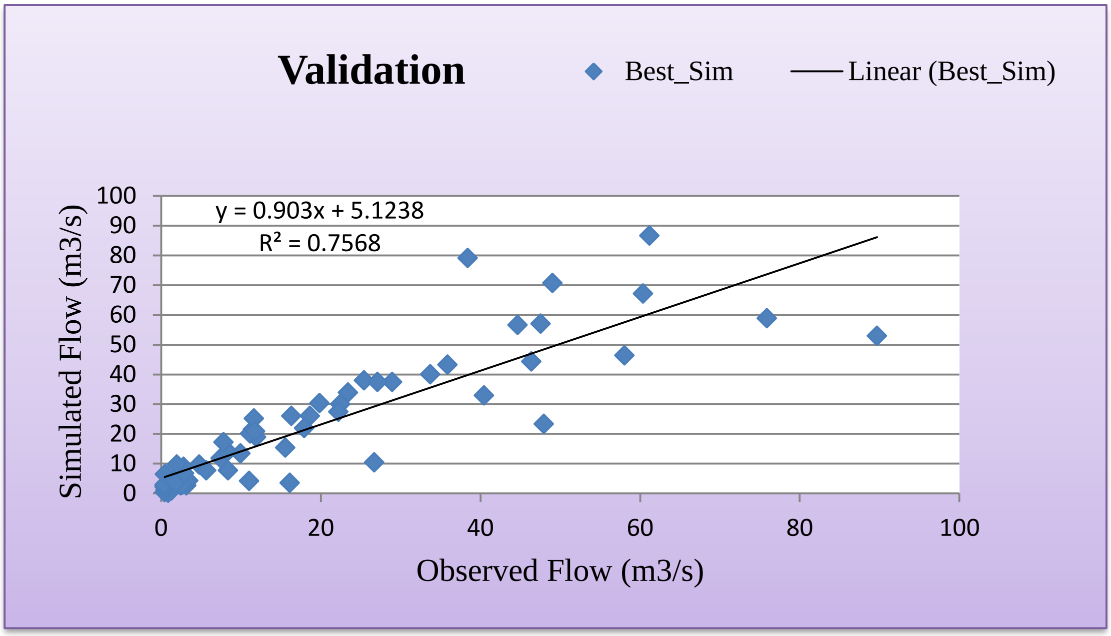

Figure 4.12: Scatter plots of monthly simulated and gauged flows at the outlet of upper Birr River catchment.

4.6.3. Stream flows at un-gauged sites

Referring to section 4.6.1, the characteristics of watersheds above the un-gauged sites on Lower Lah, Silala, Middle Birr and Lower Birr river catchments have similar Climate, Geography, Soil and Land use and cover condition with the watershed above the gauged site (Upper Birr) river catchment. Similarly, the distances between these gauged and un-gauged sites were found to be less than 50 kilometers. Hence, the requirements suggested by Merz and Blöschl, (2004) to use the regionalization method were met and thus mean monthly discharges at the un-gauged sites from gauged sites were estimated by transferring the best parameters fitted values without changing and the gauged stream flow data to the whole basin. After transferring the data simulation was done again for the total River catchment or the study area. Therefore, the simulated stream flows of each sub basin were estimated from SWAT model simulated results from the whole drainage basin as presented in Table 4.14.

Table4.14: Mean monthly simulated stream flows of un-gauged river catchments

	River catchments flow in m3/s			
Months	Lower lah River	Middle Birr River	Silala River	Lower Birr River
Jan	0.429	2.089	0.564	3.968
Feb	0.175	1.023	0.357	1.944
Mar	0.208	0.889	0.186	1.689
Apr	0.382	1.041	0.337	1.977
May	1.890	3.707	1.152	7.040
Jun	25.035	20.258	21.826	101.053
Jul	37.086	77.919	33.125	177.044
Aug	27.035	128.550	38.912	150.533
Sep	17.365	59.415	24.831	86.096
Oct	3.275	26.276	10.062	31.241
Nov	1.673	8.464	2.953	11.468
Dec	2.267	4.142	1.510	6.733

Irrigation potential of the river catchments in the study area was obtained by comparing irrigation requirements of the identified land suitable for surface irrigation and the available minimum mean monthly flows in the river catchments and considering 25% for downstream ecological balance based on the method suggested by FAO (1997). Table 4.15 present the net irrigation demands of the selected crop commonly grown in the study area (Maize) and the available minimum mean monthly flows of the corresponding river catchments. Results of these analyses revealed that monthly irrigation requirements of Maize are much greater than the available minimum mean monthly flows of all River catchments from the month of November to May. Upper Birr, Lah and Middle Birr River catchments mean monthly flows are greater than the command area while the mean monthly flows of Silala and Lower Birr Rivers are slightly less than the irrigation water requirements of crop at their corresponding command area on the month of October. This implies that surface irrigation potential of these River catchments is limited by water to be fully irrigated. From the dry seasons, month March is the most critical period so that the 80 and 90 percent exceedance was done for this month to estimate the minimum potential irrigable land in the study area by considering the maximum crop water requirement for all these dry seasons which is recommended as irrigation period.

Table 4.15: Connection of irrigation demands and available flows of river catchments in the study area for Maize

River Name	Command area(ha)	Monthly flows available in each river catchment and net irrigation demand m3/s												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upper Birr	23,600	Available flows (m3/s)	0.93	0.46	0.40	0.46	1.65	9.04	34.77	57.35	26.51	11.72	3.78	1.85
		Net irr.Req (m3/s)	12.02	15.30	19.94	17.21	9.01	2.19	0.00	0.00	3.00	7.92	11.20	11.47
Lah	24,900	Available flows (m3/s)	0.32	0.13	0.16	0.29	1.42	10.42	50.92	48.72	21.42	11.11	2.58	1.03
		Net irr.Req (m3/s)	12.68	16.14	21.04	18.16	9.51	2.31	0.00	0.00	3.17	8.36	11.82	12.10
Middle Birr	50,000	Available flows (m3/s)	1.57	0.77	0.67	0.78	2.78	15.19	58.44	96.41	44.56	19.71	6.35	3.11
		Net irr.Req (m3/s)	25.46	32.41	42.25	36.46	19.10	4.63	0.00	0.00	6.37	16.78	23.73	24.31
Silala	30,600	Available flows (m3/s)	0.42	0.27	0.14	0.25	0.86	16.37	24.84	29.18	18.62	7.55	2.21	1.13
		Net irr.Req (m3/s)	15.58	19.83	25.85	22.31	11.69	2.83	0.00	0.00	3.90	10.27	14.52	14.88
Lower Birr	116,600	Available flows (m3/s)	2.98	1.46	1.27	1.48	5.28	75.79	132.78	112.90	64.57	23.43	8.60	5.05
		Net irr.Req (m3/s)	59.38	75.57	98.52	85.02	44.53	10.80	0.00	0.00	14.84	39.14	55.33	56.68

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The suitability analysis has been carried out for Birr River catchment to evaluate and estimate irrigable land without considering the social, environmental and economic constraints as evaluation parameters. The evaluation of these constraints is very crucial for the overall suitability results that help in decision making for the implementation of irrigation agriculture.

The suitability of the water resource evaluation focuses on the quantitative availability only, taking the quality being suitable. Because the main river, Birr and its tributaries, in the River catchment found in rainy part of the country the availability of water in ample amount is shown, but its nearness or accessibility and infrastructural availability identification needs detail site specific investigation.

The slope, soil, land cover data and River proximity layers were used for the GIS analysis. Each layer was categorized in to different class of suitability (Highly, Moderately, and Not suitable) using different criteria considering land qualities required by surface irrigation method from the slope, soil, land cover and River proximity aspect. After checking and correcting each layer for their accuracy and reliability; the weight of each factor were given by using the pair wise comparison technique. Then, the overlaying analysis procedures were carried out using the suitable model builder the GIS environment.

Based on the analysis, surface irrigation land suitability analysis indicate that 91.8 % of soil and 60 .7 % of slope in the study area are in the range of highly suitable to moderately suitable for surface irrigation system whereas the remaining 8.2% (soil) and 39.3% (slope) in the area are not suitable. In terms of land cover/use, land covered by settlement, forest, wetland and water body covering 8.9% of the study area were restricted from irrigation development. The rest 91.1% of land cover/use areas are highly suitable for surface irrigation. When these factors were weighted using weighted overlay suitable model in Arc GIS, the potential irrigable land for surface irrigation was reduced to 36.54% which is 116,600 ha of land. This implies that, if more factors are considered in the evaluation process and weighted, the total irrigable land is expected to reduce more thereby giving accurate estimate of the land potential for surface irrigation.

By dividing available mean monthly flows from each watersheds to the irrigation water requirement, their minimum surface irrigation potential on the month of March was obtained as: Lah (186.41 ha), Upper Birr (470.47 ha), Middle Birr (790.03 ha), Silala (168.66 ha) and Lower Birr (1500.16). The potential irrigable land estimated using the 80 and 90 percent exceedance were greater than the above command areas. From the analysis result, the available minimum flows of Rivers in the dry period are much smaller than their command area monthly irrigation demand. This implies that surface irrigation potential of these River catchments is limited by water to be fully irrigated. This does not mean that the total annual flow capacity is less than the irrigation water demand. There is large amount of river flow as well as run off during the peak flow periods, which is able to satisfy the demand of irrigated area and even for some other energy generating options.

The water resource assessment at ungauged parts of the River catchment was carried out through regionalization technique by using the SWAT model and the simulated results were presented on monthly basis. This implies that the estimated amount of flow is available for each month and varies from month to month.

The SWAT model is a good approach to determine the hydrological parameters, at the initial stage before calibrating the model efficiency is poor, finally by adjustment of parameters affecting the stream flow a good result was found. The calibration of these parameters was done using SWAT_CUP Sufi2.

A SWAT hydrological model simulation has shown that the model is able to simulate the observed stream flow in the basin reasonably. This was proved during calibration and validation period of the model performance criterion such as coefficient of determination and Nash-Sutclife used to evaluate the model are in the range of 0.70 to 0.81 in both calibration and validation period. Stream flow model efficiency by coefficient of determination and Nash-Sutcliffe was 0.81 and 0.73 for calibration and 0.75 and 0.7 in validation respectively. This shows that the SWAT model simulates well or good agreement for stream flow in Birr River catchment.

5.2. Recommendations

Based on the results of this study the following points are recommended for further consideration:

- The data generated for the purpose of the this research work such as estimated discharges at ungauged sites, evapotranspiration data close to identified potential irrigable sites, land cover/use, soil, and slope maps of river catchments can assist local or regional planners to facilitate preliminary surveys and prepare irrigation projects in the study area.
- The surface irrigation potential was carried out in this research by considering only distance from water sources, soil, slope, and land cover/use factors. But the effects of other factors such as environmental, economic and social terms should be assessed to get sound and reliable result.
- Surface irrigation land suitability analysis result indicates that the main limitation for surface irrigation in the study area is the available water. Future estimates of irrigation potential should take into account building of reservoirs, or sustainable use of groundwater if available.
- Soil and water conservation works should be done to increase the potential of surface and ground water resources.
- The reliability of the analysis results depends on the existing GIS data set used for the overlaying process. The results can be improved by updating the GIS database using new technologies like remotely sensed images interpretation, when it is available.
- The estimation of irrigation water requirement of identified command areas was carried out by selecting one crop type only. But the future research should select several crops to calculate irrigation requirements of identified potential irrigable land among river catchments.
- SWAT model calibrated using observed flow data at gauging station. In order to improve the model performance, the weather stations should be improved both in quality and quantity. Hence, it is highly recommended to establish a good network of both hydrometric and meteorological stations.

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APPENDIX:

Appendix Table 1: Meteorological stations and their location (UTM)

ID	Station Name	X_coordinate	Y_coordinate	ELEVATION
1	Laybire	299997	1171348	1707
2	Dembecha	334346	1168288	2117
3	Feres bet	347839	1199634	3000
4	Gundil	292626	1200706	2587
5	Finote selam	310012	1181246	1840
6	Quarit	328571	1215875	2147

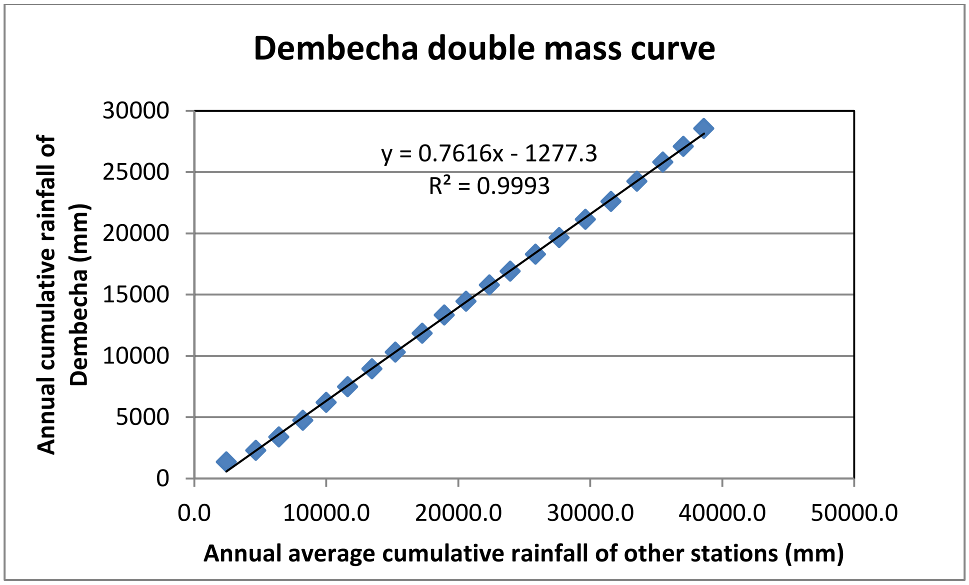
Appendix Table 2: Symbols and description of Weather Generator Parameters (WGEN) used by the SWAT model

Symbol	**Description**
TMPMX	Average or mean daily maximum air temperature for month (ºC).
TMPMN	Average or mean daily minimum air temperature for month (ºC).
TMPSTDMX	Standard deviation for daily maximum air temperature in month (ºC).
TMPSTDMN	Standard deviation for daily minimum air temperature in month (ºC).
PCPMM	Average or mean total monthly precipitation (mm H2O).
PCPSTD	Standard deviation for daily precipitation in month (mm H2O/day).
PCPSKW	Skew coefficient for daily precipitation in month.
PR_W1	Probability of a wet day following a dry day in the month.
PR_W2	Probability of a wet day following a wet day in the month.
PCPD	Average number of days of precipitation in month.
RAINHHMX	Maximum 0.5 hours Rainfall in entire period of record for month (mm)
SOLARAV	Average daily solar radiation for month (MJ/m2/day).
DEWPT	Average daily dew point temperature in month (ºC).
WNDAV	Average daily wind speed in month (m/s).

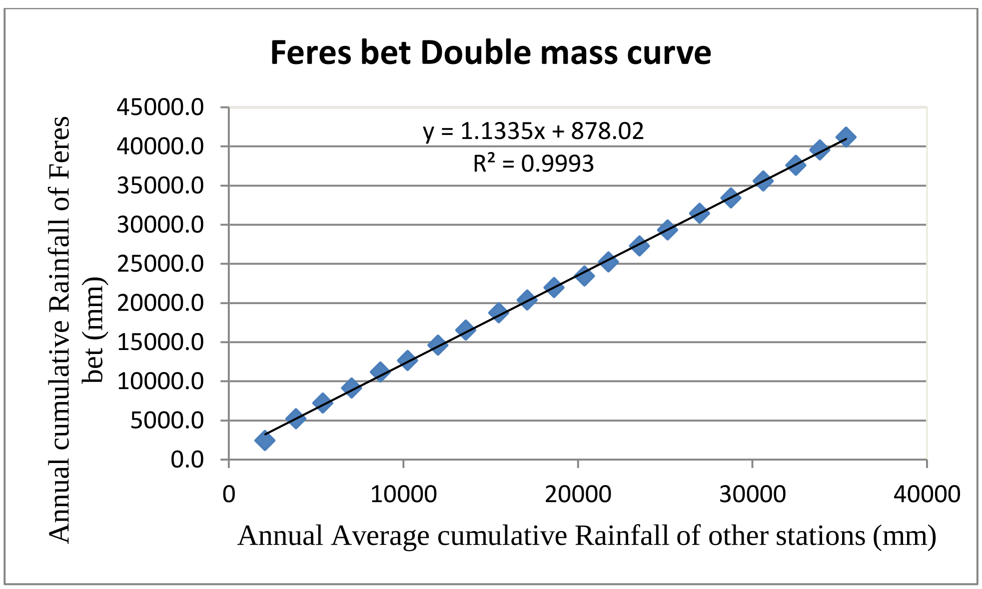
Appendix Table 3: Weather generator station and data baseline period

ID	STATION	WLATITUDE	WLONGITUDE	WELEV	RAIN_YRS	
1	WLAYBIR	1171348	299997	1707	20	

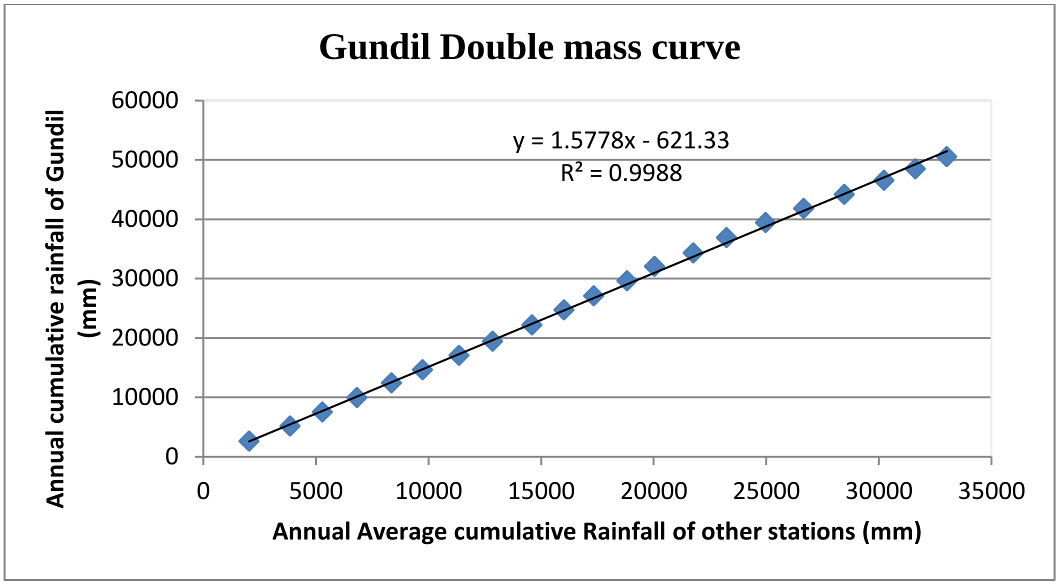
months	TMP.MAX	TMP.MIN	StdDev of TMP.MAX	StdDev of TMP.MIN	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD	RAINHH_MAX	SOLARAV	DEWPT	WND AV
Jan.	31.08	10.04	1.33	1.96	4.68	0.88	7.33	0.04	0.39	1.90	0.20	20.72	10.78	1.05
Feb.	32.78	11.53	1.12	2.14	5.01	0.98	7.37	0.05	0.41	2.55	0.20	21.85	9.63	1.88
Mar.	33.10	13.64	1.40	2.00	22.72	2.48	5.85	0.13	0.56	7.35	0.60	21.57	10.79	11.08
Apr.	32.63	14.59	2.22	2.19	44.46	4.15	4.60	0.18	0.62	10.25	0.70	20.89	10.52	3.05
May.	31.01	14.73	2.69	2.24	104.55	6.93	3.76	0.31	0.67	15.55	1.30	20.10	12.61	1.39
Jun.	26.68	13.68	2.13	2.26	161.58	7.28	2.56	0.63	0.82	24.25	1.00	17.83	14.01	1.17
Jul.	23.96	13.22	1.78	2.27	245.92	10.18	2.89	0.85	0.88	28.05	1.90	14.88	15.01	0.78
Aug.	24.04	13.14	1.49	2.29	187.91	7.41	2.22	0.86	0.87	28.05	1.00	15.15	15.10	0.65
Sep.	25.57	12.84	1.52	1.82	133.99	6.63	3.29	0.69	0.80	24.25	1.30	17.88	14.88	0.66
Oct.	27.63	12.11	1.54	1.92	79.61	6.06	4.33	0.25	0.60	13.10	1.20	20.27	13.78	0.66
Nov.	29.12	10.66	1.34	2.00	27.16	3.42	6.07	0.11	0.49	6.05	0.80	20.36	11.97	22.77
Dec.	29.92	9.42	0.99	1.77	11.68	1.67	6.73	0.09	0.41	4.25	0.40	20.34	10.87	15.45



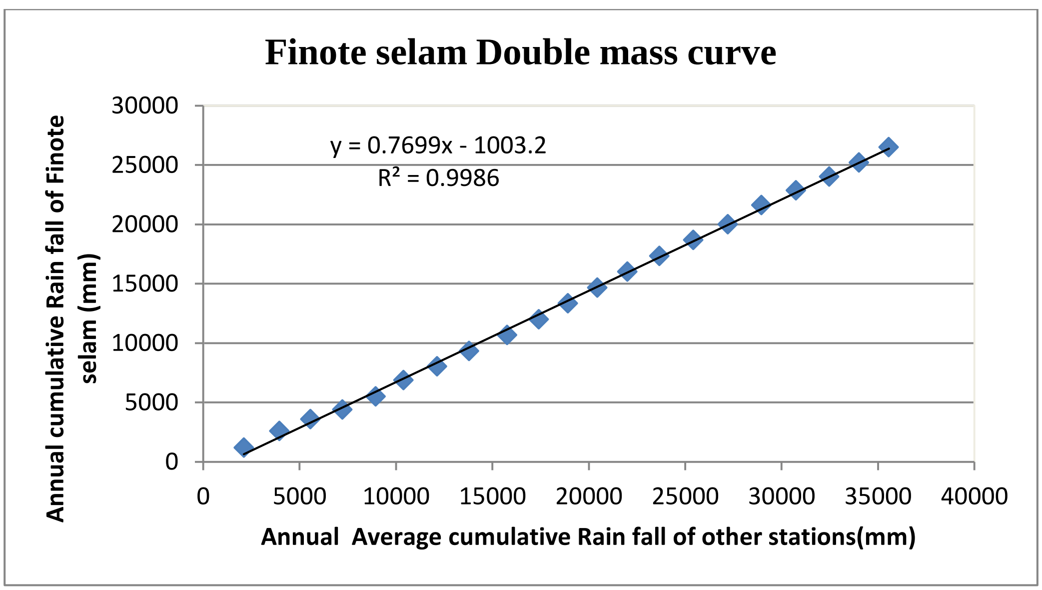
Appendix Figure 1: Double mass curve of Dembecha rainfall station



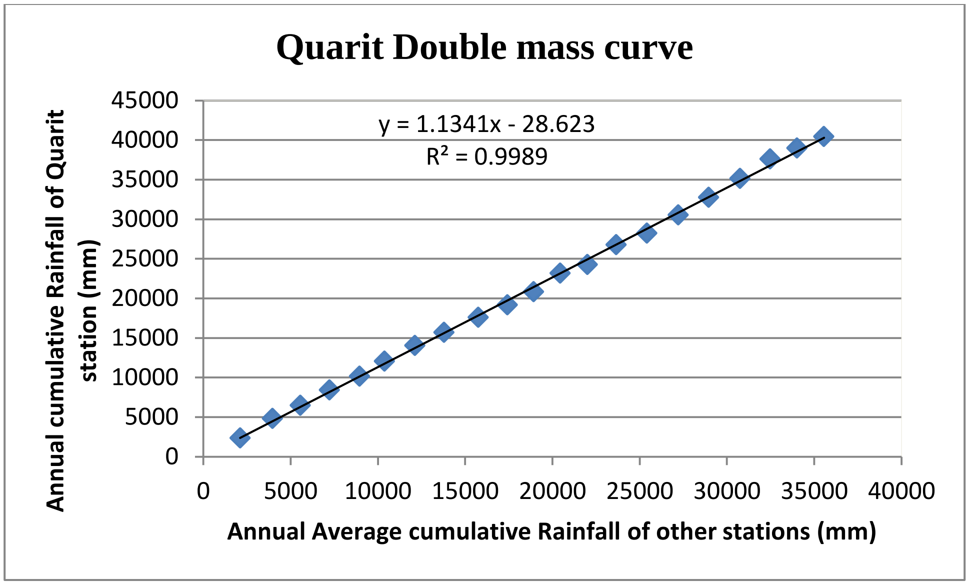
Appendix Figure 2: Double mass curve of Feres bet rainfall station



Appendix Figure 3: Double mass curve of Gundil rainfall station



Appendix Figure 4: Double mass curve of Finote selam rainfall station



Appendix Figure 5: Double mass curve of Quarit rainfall station

Appendix Table 4: Average Annual PET (mm/year)

	Sub-Basins				
Year	Middle Birr	Lower Lah	Upper Birr	Lower Birr	Silala
1993	1168.39	1172.95	1161.56	1194.10	1185.85
1994	1151.92	1199.37	1097.75	1177.26	1212.57
1995	1169.69	1035.02	1118.26	1195.42	1046.40
1996	1151.74	1002.90	1092.07	1177.08	1013.93
1997	1171.58	1020.19	1093.38	1197.35	1031.41
1998	1103.52	964.34	1018.82	1127.80	974.95
1999	1122.06	987.05	1061.95	1146.75	997.91
2000	1109.59	967.19	1058.87	1134.00	977.83
2001	1179.02	1027.96	1084.06	1204.96	1039.27
2002	1237.84	1072.64	1136.69	1265.07	1084.44
2003	1123.73	1003.55	1079.92	1148.45	1014.59
2004	1162.85	1040.30	1133.08	1188.43	1051.74
2005	1191.20	1085.67	1149.28	1217.41	1097.61
2006	1157.64	1041.97	1112.72	1183.10	1053.43
2007	1188.79	1060.10	1126.35	1214.94	1071.76
2008	1235.32	1075.26	1123.97	1262.50	1087.09
2009	1203.27	1050.70	1133.13	1229.74	1062.26
2010	1084.06	939.64	1003.14	1107.91	949.98
2011	1202.20	1061.77	1145.25	1228.64	1073.45
2012	1214.50	1063.34	1108.89	1241.22	1075.04

Appendix Table 5: Annual Precipitation in Dry Season (mm/year)

Sub -Basins					
Year	Middle Birr	Lower Lah	Upper Birr	Lower Birr	Silala
1993	183.23	214.83	215.23	177.73	210.53
1994	189.00	240.16	240.61	183.33	235.36
1995	163.40	213.30	213.70	158.50	209.04
1996	163.65	207.52	207.90	158.74	203.37
1997	163.90	283.03	283.55	158.98	277.37
1998	209.58	228.99	229.41	203.29	224.41
1999	173.19	228.91	229.34	167.99	224.33
2000	181.72	226.16	226.57	176.27	221.63
2001	148.84	226.43	226.85	144.38	221.90
2002	177.96	228.99	229.41	172.62	224.41
2003	182.98	228.91	229.34	177.49	224.33
2004	171.43	226.16	226.57	166.29	221.63
2005	205.32	226.43	226.85	199.16	221.90
2006	230.67	222.92	223.34	223.75	218.46
2007	195.78	220.37	220.78	189.90	215.96
2008	196.78	207.39	207.78	190.88	203.24
2009	187.49	197.09	197.46	181.87	193.15
2010	191.76	132.46	132.70	186.01	129.81
2011	170.93	172.94	173.26	165.80	169.48
2012	196.03	187.89	188.23	190.15	184.13

Appendix Table 6: Annual Precipitation in Wet Season (mm/year)

Sub -Basins					
Year	Middle Birr	Lower Lah	Upper Birr	Lower Birr	Silala
1993	874.97	1069.70	1071.68	848.72	1048.30
1994	869.20	954.48	956.25	843.12	935.39
1995	801.43	944.56	946.31	777.39	925.67
1996	872.46	1045.95	1047.89	846.29	1025.03
1997	848.12	1328.80	1331.26	822.67	1302.22
1998	911.87	1105.05	1107.09	884.51	1082.95
1999	842.85	1113.34	1115.40	817.56	1091.07
2000	926.68	1111.39	1113.45	898.88	1089.16
2001	779.85	1112.11	1114.17	756.45	1089.87
2002	745.71	1113.67	1115.73	723.34	1091.39
2003	660.37	1113.34	1115.40	640.56	1091.07
2004	773.32	1111.39	1113.45	750.12	1089.16
2005	804.70	1112.11	1114.17	780.55	1089.87
2006	1106.64	1061.50	1063.47	1073.44	1040.27
2007	959.81	959.94	961.72	931.02	940.74
2008	1026.07	1154.00	1156.14	995.29	1130.92
2009	776.33	922.78	924.49	753.04	904.33
2010	873.47	666.24	667.47	847.26	652.92
2011	828.04	765.93	767.35	803.20	750.61
2012	773.82	819.97	821.49	750.61	803.57

Country: Ethiopia and Station: Laybire

Altitude: 1707 meter(s) a.m.s.l.

Latitude: 10.59 Deg. (North) and Longitude: 37.17 Deg. (East)

Appendix Table 7: Estimated ETo

Month	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (km/day)	Sunshine (hours)	Radiation (MJ/m²/day)	Eto (mm/day)
January	10	31.1	46	91	9.2	20.7	3.86
February	11.5	32.8	40	162	9	21.8	4.88
March	13.6	33.1	40	353	8.1	21.6	6.48
April	14.6	32.6	40	263	7.4	20.9	5.97
May	14.7	31	49	120	7.1	20.1	4.62
June	13.7	26.7	64	101	5.8	17.8	3.75
July	13.2	24	76	67	3.8	14.9	2.95
August	13.1	24	77	56	3.8	15.2	2.92
September	12.8	25.6	72	57	5.7	18	3.36
October	12.1	27.6	62	57	7.8	20.2	3.7
November	10.7	29.1	53	86	8.8	20.3	3.77
December	9.4	29.9	49	87	9.4	20.4	3.69
Average	12.4	29	56	125	7.2	19.3	4.16

Appendix Table 8: Estimated Effective Rainfall

months	Rain (mm)	Eff. Rain (mm)
January	5.1	0
February	5.1	0
March	22.1	3.3
April	44.5	16.7
May	104.5	59.6
June	161.6	105.3
July	256	180.8
August	177.8	118.2
September	134	83.2
October	79.6	39.7
November	27.2	6.3
December	11.7	0
Total	1029.2	613.1

Appendix Table 9: Crop water requirement result

Month	Decade	Stage	Kc _ coeff	Etc (mm/day)	Etc (mm/dec)	Eff rain(mm/dec)	Irr. Req. (mm/dec)
Nov	1	Init	0.3	1.12	10.1	4.5	5.1
Nov	2	Init	0.3	1.13	11.3	0.9	10.5
Nov	3	Deve	0.33	1.22	12.2	0.6	11.7
Dec	1	Deve	0.55	2.06	20.6	0.1	20.5
Dec	2	Deve	0.82	3.03	30.3	0	30.3
Dec	3	Deve	1.1	4.14	45.5	0	45.5
Jan	1	Mid	1.24	4.71	47.1	0	47.1
Jan	2	Mid	1.24	4.78	47.8	0	47.8
Jan	3	Mid	1.24	5.2	57.2	0	57.2
Feb	1	Late	1.24	5.61	56.1	0	56.1
Feb	2	Late	1.05	5.1	51	0	51
Feb	3	Late	0.78	4.22	33.7	0.1	33.6
Mar	1	Late	0.51	3.12	31.2	0.4	30.7
Mar	2	Late	0.35	2.34	2.3	0.1	2.3
Total					456.6	6.6	449.6

Appendix Table 10: Lah Sub-watershed monthly irrigation potential

months	IWR (mm/day)	Available flow(m3/s)	25% of flow	Remaining flow (m3/s)	potential Area (ha)
Jan	4.4	0.43	0.11	0.32	403.15
Feb	5.6	0.18	0.04	0.13	129.08
Mar	7.3	0.21	0.05	0.16	120.21
Apr	6.3	0.38	0.10	0.29	257.57
May	3.3	1.89	0.47	1.42	2186.91
Jun	0.8	13.90	3.47	10.42	31052.46
Jul	0	67.90	16.97	50.92	
Aug	0	64.96	16.24	48.72	
Sep	1.1	28.56	7.14	21.42	68544.31
Oct	2.9	14.81	3.70	11.11	21330.45
Nov	4.1	3.45	0.86	2.58	3660.47
Dec	4.2	1.37	0.34	1.03	1390.76

Appendix Table11: Upper Birr Sub-watershed monthly irrigation potential

months	IWR (mm/day)	Available flow(m3/s)	25% of flow	Remaining flow (m3/s)	potential Area (ha)
Jan	4.4	1.24	0.31	0.93	1166.86
Feb	5.6	0.61	0.15	0.46	448.18
Mar	7.3	0.53	0.13	0.40	305.96
Apr	6.3	0.62	0.15	0.46	417.94
May	3.3	2.21	0.55	1.65	2552.12
Jun	0.8	12.05	3.01	9.04	26928.30
Jul	0	46.35	11.59	34.77	
Aug	0	76.47	19.12	57.35	
Sep	1.1	35.35	8.84	26.51	84829.06
Oct	2.9	15.63	3.91	11.72	22509.05
Nov	4.1	5.04	1.26	3.78	5348.75
Dec	4.2	2.46	0.62	1.85	2494.97

Appendix Table12: Silala Sub-watershed monthly irrigation potential

months	IWR (mm/day)	Available flow(m3/s)	25% of flow	Remaining flow (m3/s)	potential Area (ha)
Jan	4.4	0.56	0.14	0.42	529.34
Feb	5.6	0.36	0.09	0.27	262.82
Mar	7.3	0.19	0.05	0.14	107.47
Apr	6.3	0.34	0.08	0.25	227.58
May	3.3	1.15	0.29	0.86	1333.11
Jun	0.8	21.83	5.46	16.37	48769.82
Jul	0	33.13	8.28	24.84	
Aug	0	38.91	9.73	29.18	
Sep	1.1	24.83	6.21	18.62	59595.59
Oct	2.9	10.06	2.52	7.55	14489.93
Nov	4.1	2.95	0.74	2.21	3136.66
Dec	4.2	1.51	0.38	1.13	1528.65

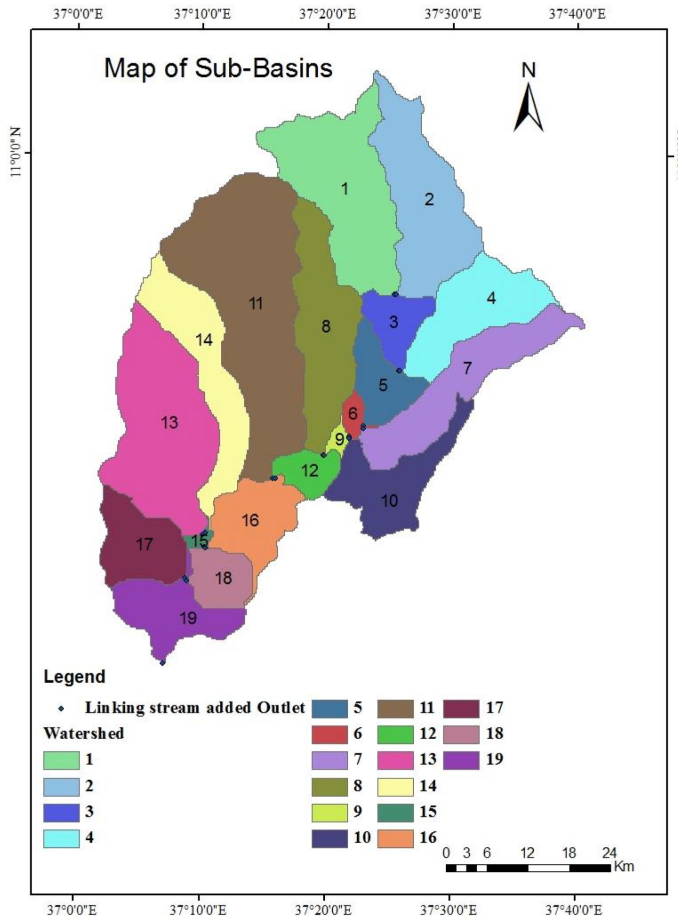
Appendix Table13: Middle birr Sub-watershed monthly irrigation potential

months	IWR (mm/day)	Available flow(m3/s)	25% of flow	Remaining flow (m3/s)	potential Area (ha)
Jan	4.4	2.09	0.52	1.57	1961.46
Feb	5.6	1.02	0.26	0.77	753.39
Mar	7.3	0.89	0.22	0.67	514.31
Apr	6.3	1.04	0.26	0.78	702.56
May	3.3	3.71	0.93	2.78	4290.06
Jun	0.8	20.26	5.06	15.19	45265.97
Jul	0	77.92	19.48	58.44	
Aug	0	128.55	32.14	96.41	
Sep	1.1	59.42	14.85	44.56	142596.09
Oct	2.9	26.28	6.57	19.71	37837.30
Nov	4.1	8.46	2.12	6.35	8991.15
Dec	4.2	4.14	1.04	3.11	4194.01

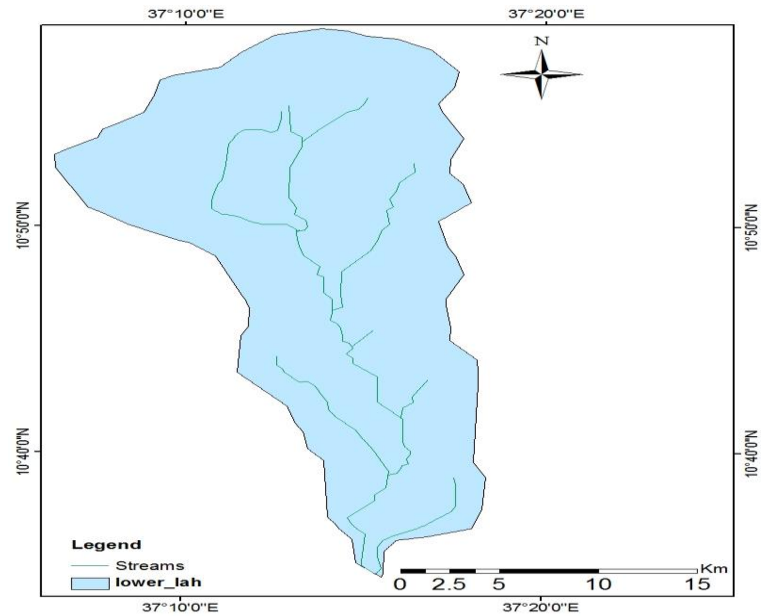
Appendix Table14: Lower Birr River catchment monthly irrigation potential

(the whole study area)

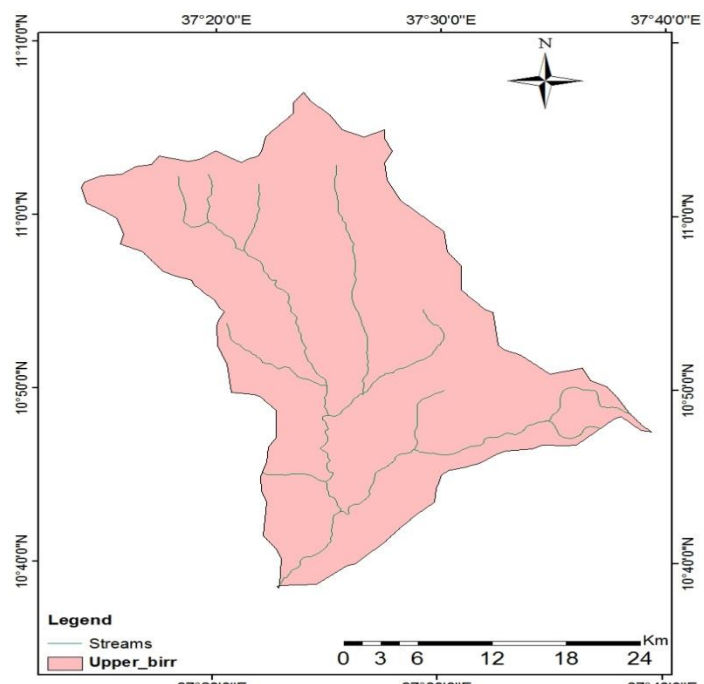
months	IWR (mm/day)	Available flow(m3/s)	25% of flow	Remaining flow (m3/s)	potential Area (ha)
Jan	4.4	3.97	0.99	2.98	3726.06
Feb	5.6	1.94	0.49	1.46	1431.17
Mar	7.3	1.69	0.42	1.27	977.01
Apr	6.3	1.98	0.49	1.48	1334.60
May	3.3	7.04	1.76	5.28	8146.29
Jun	0.8	101.05	25.26	75.79	225801.93
Jul	0	177.04	44.26	132.78	
Aug	0	150.53	37.63	112.90	
Sep	1.1	86.10	21.52	64.57	206630.67
Oct	2.9	31.24	7.81	23.43	44986.96
Nov	4.1	11.47	2.87	8.60	12182.66
Dec	4.2	6.73	1.68	5.05	6817.63



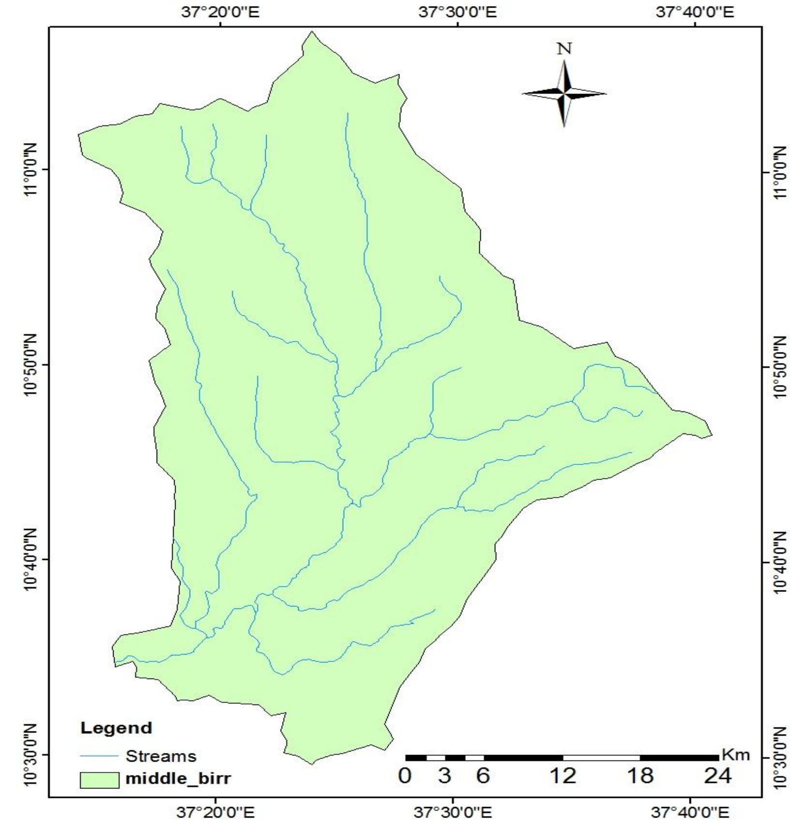
Appendix Figure 6: Map of sub-watersheds from SWAT result in the study Area



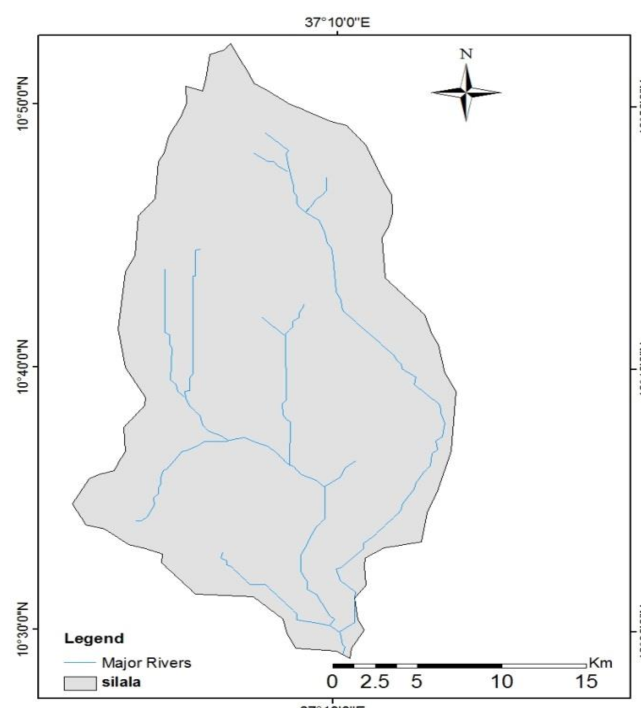
Appendix Figure 7: Lah sub watershed (ungauged)



Appendix Figure 8: Upper Birr sub watershed (guauged)



Appendix Figure 9: Middle Birr sub watershed (ungauged)



Appendix Figure 10: Silala sub watershed (ungauged)