



Addis Ababa University

Addis Ababa Institute of Technology

School of Graduate Studies

School of Civil and Environmental Engineering

**Assessment of Surface Water Potential and Demands in
Tekeze River Basin, Northern Ethiopia**

By

Setogn Abate Getu

**Main-Advisor: - Dr.Ing. Geremew Sahilu, School of Civil and Environmental
Engineering, Addis Ababa University, Ethiopia**

**Co-Advisor - Professor Lars Ribbe, Cologne University of Applied Science,
Germany**

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Tekeze River Basin, Northern Ethiopia**

A thesis submitted and presented to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the Degree of Masters of Science in Civil and Environmental Engineering (Hydraulic Engineering Major)

By

Setogn Abate

Approval by Board of Examiners

Advisor	Signature	Date
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External examiner	Signature	Date
Chairman (Department of Graduate Committee)	Signature	Date

DECLARATION

This is to certify that this thesis entitled “**Assessment of Surface Water Potential and Demands in Tekeze River Basin, Northern Ethiopia**” is my original work and Submitted in partial fulfillment of the requirements for the degree of Master of Science in Hydraulic Engineering at Addis Ababa University.

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ABSTRACT

Tekeze river basin is located in the northern part of Ethiopia. The objective of this paper is to assess surface water potential using SWAT model and estimation of water demands using the Water Evaluation and Planning (WEAP) model in the Tekeze River Basin.

According to the result obtained from SWAT model, the basin receives a mean annual rainfall of 976.4 mm which is 80.9BM³. The mean annual actual evapotranspiration is 9.5BM³ or 11.8% of the mean annual rainfall of the basin. The mean annual surface runoff that leaves from the basin is 7.8BM³ which corresponds to 93.97 mm. Out of the mean annual rainfall of 80.9BM³; the remaining 40.1BM³ is lost due to percolation for the recharging of the aquifer and 23.5BM³ as lateral flow or subsurface flow.

For calibration, the model was run for a period of five years and the monthly calibration results for R² and NS were 0.82 and 0.81 respectively which are beyond the acceptable ranges. According to SWAT developers in Santhi et al (2001), the daily stream flow calibration result (i.e. R²=0.54 and NS= 0.53) was found to be unsatisfactory which failed to meet especially the requirement of R² > 0.6

For model validation, the model was run for a period of three years and the model validation results on monthly time step shows a good relationship between measured and simulated results and the results of R² and NS values were 0.7 and 0.63 respectively. However, unsatisfactory performance of SWAT model in daily validation was obtained which failed to meet statistical model efficiency criteria with R² and NS values of 0.47, 0.41 respectively.

The water demand estimation portion of this study was done for one water supply, three hydropower and four irrigation large scale projects in the basin. The model results showed that, for the reference scenario from year 2012 to 2030 are 18.4Bm³, 18.3267Bm³ and 73.3 Mm³ for water demand, supply delivered and unmet demand respectively. The annual average water demand, supply delivered and unmet demand are 969Mm³, 965.14Mm³, and 3.86 Mm³ respectively for the proposed large scale projects.

Generally, comparing assessment of surface water potential result (i.e. average annual of 7.8BM³) and average annual water demand (i.e. 969Mm³); the basin has sufficient surface water potential that can be used for the selected planned and ongoing large scale projects.

Keywords: Water Evaluation and Planning, Soil and Water Assessment Tool, Water Demand, surface water potential, Tekeze River Basin

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LIST OF ABBREVIATIONS

Cumecs	Cubic meter per second
CWR	Crop Water Requirement
ETcrop	Crop Evapotranspiration
ETo	Reference Crop Evapotranspiration
FAO	Food and Agricultural Organization
GIS	Geographic Information System
GPS	Global Positioning System
Ha	Hectare
IRg	Gross Irrigation Requirement
IWR	Irrigation Water Requirement
Kc	Crop coefficients
MCM	million cubic meters
MOWR	Ministry of Water Resource
NIR	Net Irrigation Requirement
RH	Relative humidity
RF	Rainfall
ICID	International commission on irrigation and drainage
LPCD	liter per capita per day
Kcal	Kilo calorie
amsl	above mean sea level
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur
SOL_K	Saturated hydraulic conductivity

SOL_ZMX	Maximum rooting depth of soil profile
GW_DELAY	Groundwater delay
SOL_ALB	Moist soil albedo
BIOMIX	Biological mixing efficient
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur
SOL_AWC	Available water capacity of the soil layer
CN2	SCS runoff curve number
EPCO	Plant uptake compensation factor
ESCO	Soil evaporation compensation factor
SOL_Z	Depth from soil surface to bottom of layer
GW_REVAP	Groundwater "revap" coefficient
ALPHA_BF	Base flow alpha factor

CHAPTER ONE

1.1. General Introduction

Ethiopia has abundant surface water resources that can be used for different purposes. There are 12 major river/drainage basins seven of which are transboundary. The total annual runoff from these basins is estimated to be about 124.25 billion cubic meters (Seleshi et al, 2010). The major rivers carry water and sediments and drain mainly to the arid regions of neighboring countries. There are also eleven major lakes with a total area of 750,000 ha. Although Ethiopia's water resource is large, very little of it has been developed for agriculture, hydropower, industry, water supply and other purposes. To date only about 160,000 ha (about 4%) of the potential irrigable land has been developed. Based on available information the potential irrigable land in the country is about 3.7 million ha (Ministry of Water Resources, 2001).

Knowing the potential and availability of surface water, currently the government of Ethiopia is undertaking a huge investment on water resource investigation and development for various uses. This would help to increase the productivity of micro dams, to improve ways and means of the traditional irrigation management system, to increase potable water supply and also to increase the hydroelectric power generation of the country (Nata, 2006).

An integrated management of water resources at river basin level ensures that social, environmental, technical dimensions as well as economic implications of water allocation are taken into account. The need for integrated water resources management system includes utilization and development of water resources in an efficient, environmentally sound, equitable and reasonable manner in order to satisfy society's demand for water, water-related goods and services as well as to safeguard the ecological functions of water resources. Effective management of water resources at the basin permits some anticipation of how water

resources are going to change in the future under the influence of both natural and man-made changes.

The purpose of appraising water resources is to determine the source, extent and dependability of supply and the character of water on which an evaluation of their future control and utilization is to be based. Integrated water resources management (IWRM) system in the Tekeze basin is important for effective management of water resources, allowing for economic development and the protection of ecosystems. For sustainable integrated water resources management (IWRM) system, assessment of total water resource potential and demands in the basin is essential. Surface water is available on the surface of the earth in the form of rivers, lakes, ponds, canals, etc. However, rivers comprise the most important source of surface water in the Tekeze basin. Surface water assessment portion of this study focused on surface water that can be stored in TK 5 hydropower dam reservoir and in different rivers as a form of runoff whereas water demands assessment portion of this study includes irrigation, domestic and hydropower water demands from large scale projects in the basin.

1.2. Statement of the Problem

For sustainable integrated water resources management (IWRM) system, assessment of total water resource potential and their monthly or annually distributions in the basin is essential. Before planning any project on water resources in a certain river basin, first it is essential to identify and evaluate the total available water resource of that basin. Full utilization of all these available water potential is not possible due to the topographical, hydrological, the need for allowing certain amount of water to flow in the river for maintaining the river regime and other constraints. The main problems for integrated water resource management system in Tekeze river basin are the uncertainty in the information available regarding updated surface

water resource potential, surface water requirements for different uses, estimated future water demand and water supply and demand interactions in the basin.

Therefore, this research work covered the estimation of surface water potential, future water requirements for various uses from large scale projects, investigating impacts of planned large scale projects on future water supply and demand and the relation between water supply and demand situations in the basin for a better integrated water resources management system.

1.3. Research Questions

This research contains the following research questions:

- How much surface water is available in the Tekeze River basin and how is the availability changing with respect to time and what are the critical factors that affect surface water quantity, supply and demand in the basin?
- How much surface water is required for planned and ongoing large scale projects for different water use requirements (i.e. irrigation, hydropower and domestic) for the next 16 years (i.e. 2015-2030) in the basin?
- Is there sufficient surface water potential for planned and ongoing large scale projects, which can fulfill different water use activities (i.e. for irrigation, hydropower and domestic) and what is the relation between water supply and demand for large scale projects in the basin?

1.4. Objective

1.4.1. General Objective

The major objectives of this research are to conduct surface water potential assessment, estimation of water demands and to investigate the interaction between water supply and demand situations in the Tekeze river basin for a better integrated water resources management system.

1.4.2. Specific Objectives

The main specific objectives of this research are:-

- ✓ To estimate surface water availability and to identify the critical factors that affect surface water quantity and water demands in the basin
- ✓ To estimate future surface water demands for planned and ongoing large scale projects during the periods from 2015 to 2030 for irrigation, hydropower and domestic water demands.
- ✓ To investigate the relation between water demands with the available surface water supplies in order to identify whether there is surplus or deficit of water by considering the supply as constant for the next 16 years (i.e. 2015-2030)

1.5. Scope of the Study

Due to time constraint and data availability, the scope of this research has been limited to assess surface water potential and water demands for various requirements (i.e. irrigation, domestic and hydropower) from large scale projects, investigation on the potential factors that affect surface water quantity, demand and supply and the possible impacts of large scale planned water resources schemes on the availability of surface water potential and future water demands in the basin.

1.6. Outline of the Thesis

Generally, this thesis has six chapters and the main concepts of each chapter are summarized below.

Chapter One: is an introduction, which gives background information on assessment of surface water potential, water demands, statement of the problem, objectives, research questions and scope of the study.

Chapter Two: contains detail description of literature review of assessment of surface water potential and demands in the basin.

Chapter Three: this chapter includes brief description of the study area, sources of hydro meteorological data, meteorological data analysis, meteorological data gap filling, selection of representative meteorological stations, hydrological data analysis, materials used, description of SWAT and WEAP model, model selection criteria, descriptions of SWAT input data, watershed delineation, description of model calibration and validation and assessment of water demands from large scale projects for domestic, irrigation and hydropower water demands.

Chapter Four: contains model results and discussion, comparison of the result with previous studies and model performance on calibration and validation results, summaries on different water requirements for various uses

Chapter Five: this chapter summarizes the recommendation and conclusion portion of this research.

At the end, this paper contains lists of references which were used during the study and appendixes which contains some tables, computer out puts and data used in this research.

CHAPTER TWO

2. Literature Review

2.1. Surface Water Potential

Water is the single most important element of the environment. The availability of water largely determines the spatial pattern of the Earth's terrestrial biomes (forest, grasslands and deserts); it covers 71% of the Earth's surface providing habitat for fresh and saltwater ecosystems; water is a major controlling element of the Earth's climate, and it is water that is largely responsible for sculpting the Earth's surface into the infinitely complex associations of erosional and depositional landforms. Water makes life on Earth possible, and, to a large extent, water makes the Earth itself.

Water is the most abundant substance on earth. It is very vital to the survival of all living things and is instrumental to the proper functioning and maintenance of the ecosystem throughout the whole world. Globally, there is wide awareness of the contribution of water in maintaining the environmental services and ecosystem. The importance of water in rural and urban settlements cannot be overemphasized. Human beings cannot live for more than a few days without water, shorter than without any other source of sustenance except fresh air. The quality, quantity, and accessibility determine the level of public health, food production, energy, and other aspects of life (Niel et al, 1995). It is essential for all social economic developments in all parts of the world and it is difficult to think of a resource more essential to the health of human communities or their economies than water. The eradication of poverty and hunger in rural areas is closely related to a fair and equitable access for the most vulnerable people to basic livelihood assets (including land and water) for most domestic and productive uses (UN, 2006).

Earth's surface water is held in two different kinds of water bodies: Salt water bodies and Fresh water bodies. Fresh water is defined as water that contains less than 0.5 parts per

thousand (ppt) of dissolved salt. 99 % of the fresh water is locked up in snow and ice or in lakes, while rivers and other surface fresh water bodies make up 0.01 % of all the water in the world. When the surface water level is high enough, ground water comes to the surface naturally, like springs and may form lakes, ponds and rivers (Nata, 2006).

Fresh-water is a finite; naturally, renewable resources received by way of precipitation, but are significantly unevenly distributed in time and space and the hydro-climatologically conditions of a region set the limit for its availability. Countries or regions are generally considered water stressed when the annual per capita availability is between 1000-2000 m³. With availability below 1000 m³, a county is deemed 'water scarce'. In 1990, eighteen countries in the world were 'water scarce', a number that could swell to 30 by the year 2025. Most of these are located in Asia and Africa, and are already faced food shortage (ICID, 2000).

Surface water is water that is on the Earth's surface, such as in a stream, river, lake, or reservoir. Surface water is a valuable resource which can be used for public, industrial and agricultural supply purposes. Surface water courses also provide important natural habitats and environmental and leisure resources. Therefore, understanding surface water resources is a key aspect of water resource assessment and evaluation.

In order to properly state the available water resource potential of a certain river basin it is first essential to determine the amount of water available in that system. Accordingly, that requires understanding of the hydro-system and its interaction with the environment and to be able to properly describe the water flow, 'in and out', of the basin. Information and data regarding the basin such as runoff, evaporation and rainfall, for example, are some of the components that would be necessary in describing the water movement or circulation (Daniel, 2007).

2.2. Factors Affecting Surface Runoff

Apart from rainfall characteristics (i.e. rainfall intensity, amount, duration, distribution over the drainage basin, and other meteorological and climatic conditions that affect evapotranspiration, such as temperature, wind speed, relative humidity and season), there are a number of site specific factors which have a direct bearing on the occurrence and volume of runoff. The major factors are reviewed below.

2.2.1. Soil Type

Soil functions essentially as medium that provides a large number of passageways for water. Water flow in soil depends on the size and permanency of the pores. The size of the conduits depends on the size of the soil texture, the degree of aggregation and the arrangements of particles and aggregates (Silveira et al., 2000). The infiltration capacity is among others dependent on the porosity of a soil which determines the water storage capacity and affects the resistance of water to flow into deeper layers. Porosity differs from one soil type to the other. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have smaller infiltration capacities. The infiltration capacity depends further more on the moisture content prevailing in a soil at the onset of a rainstorm. The initial high capacity decreases with time (provided the rain does not stop) until it reaches a constant value as the soil profile becomes saturated (Finkel et.al, 1995).

2.2.2. Vegetation

The amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage. More significant is the effect the vegetation has on the infiltration capacity of the soil. Dense vegetation shields the soil from the rain drop impact and reduces the crusting effect. In addition, the root systems as well as organic matter in the soil increase the soil porosity thus allowing more water to infiltrate. Vegetation also retards

the surface flow particularly on gentle slopes, giving more time to infiltrate and to evaporate (Finkel et.al, 1995).

2.2.3. Slope and Catchment Characteristics

The volume and peak rate of runoff increases with catchment area. However, for the same rainfall event, a long narrow catchment would be expected to have a lower peak rate of runoff than a more compact or circular one of the same area. In the longer catchment, it takes more time for the runoff from the most remote part of the catchment to reach the outlet (Carey et al., 2004). The runoff efficiency (volume of runoff per unit of area) increases with the decreasing size of the catchment i.e., the larger the size of the catchment the larger the time of concentration and the smaller the runoff efficiency. Investigation on experimental plots has shown that steep slope plots yield more runoff than those with gentle slopes. In addition, it was observed that the quantity of runoff decreased with slope length to some extent (Ben Asher et al, 1988).

2.3. Water Resources in Ethiopia

2.3.1. Surface Water Resources: Lakes and Reservoirs in Ethiopia

Ethiopia has 11 fresh and 9 saline lakes, 4 crater lakes and over 12 major swamps or wetlands. Majority of the lakes are found in the Rift Valley Basin. The total surface area of these natural and artificial lakes in Ethiopia is about 7,500 km². The majority of Ethiopian lakes are rich in fish. Most of the lakes except Ziway, Tana, Langano, Abbaya and Chamo have no surface water outlets, i.e., they are endhoric. Lakes Shala and Abiyata have high concentrations of chemicals and Abiyata is currently exploited for production of soda ash.

2.3.2. Surface Water Resources: River Basins in Ethiopia

The geographical location of Ethiopia and its endowment with favorable climate provides a relatively higher amount of rainfall in the region. Much of the water, however, flows across the borders being carried away by the Transboundary Rivers to the neighboring countries.

Ethiopia has 12 river basins. The total mean annual flow from all the 12 river basins is estimated to be 124.25 billion cubic meters (Seleshi et al, 2010). The idea of a river basin, despite its physical or natural attributes, is more than an engineering concept and encompasses the magnitude and dynamics of a resource that must be harnessed for the common good (Molle, 2006). It has often been advocated that the most logical unit for water resources planning and optimum utilization of available water resources is the river basin.

All major river basins in Ethiopia have an integrated development master plan study, and their potential in terms of economic development be known. The surface runoff potential of all the river basins is shown in table 1 and figure 1 shows the map of Ethiopian River Basins.



Figure: 1: Ethiopian river basins map

Table 1: Surface water potential and coverage area of Ethiopian river basins

River Basin	Area (Km ²)	Surface runoff (Bm ³)	River Basin	Area (Km ²)	Surface runoff (Bm ³)
Tekeze	82,350	8.2	Afar /Denakil	74,002	0.86
Abbay	199,812	54.8	Awash	112,696	4.9
Baro –Akobo	75,912	23.6	Aysha	2,223	-
Omo- Ghibe	79,000	16.6	Ogaden	77,121	-
Rift valley	52,739	5.6	Wabi- Shebele	202,697	3.16
Mereb	5,900	0.65	Genale dawa	171,042	5.88

Source: (Seleshi et al, 2010)

The knowledge of surface water availability in the Tekeze basin is very scanty, despite the fact that measurement started 28 years ago. Often, however, not enough flow measurements were taken, or measurements did not cover a large enough part of the flow range to make rating curves. The flow data scarcity problem had already been identified at the start of the project and much effort has been put into simulating rehabilitation and upgrading of the network. The Tekeze basin consists of three sub-basins: Tekeze, Angereb and Goang River sub-basins whose estimated annual surface runoff flow is about 8.20 Bm³ (Tekeze River Basin Master Plan, 1998).

Integrated water resources management is a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromise the sustainability of vital ecosystems.

The overall aim of the national water resources management policy is to enhance and promote all national efforts towards the efficient, equitable, and optimum utilization of the available water resource of Ethiopia for significant Socio-Economic development on substantial basis (MOWR, 2002).

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998), a well-known distributed hydrological model, has been widely used for hydrological modeling and water resources studies in large watersheds (Arnold et al, 1996; Arabi et al., 2007; Schuol et al., 2008; Setegn et al., 2010).

In order to know the potential and availability of surface waters, the government of Ethiopia is currently undertaking a huge investment on water resource investigation and development for various uses. This would help to increase the productivity of micro dams, to improve ways and means of the traditional irrigation system, to increase potable water supply and also to increase the hydroelectric power generation of the country (Abeyou, 2014).

Water resources development and utilization have integrated with Ethiopian overall socio-economic development objectives. One of the actions included in the strategy encourages undertaking of assessment and development of the country's surface water resources by-

- Making inventory of the available surface water in the country in both quantity and quality.
- Applying suitable methodologies to assess the available surface water both in time & in space.
- Developing strategic mechanisms for suitable development and utilization of surface water in all water using sectors.

2.4. Previous Related Studies on Surface Water Potential

According to Nata, (2006), the curve number and runoff coefficient methods were used for surface water potential estimation for Hantebet basin, Tigray, Northern Ethiopia. The two methods were selected based on the absence of water level observations and flow measurements conducted in the basin due to lack of hydrometric station in any one of the rivers in the entire basin to analyze the runoff of the basin by computer models or scale

models. According to him, other methods like the unit hydrograph and flood frequency analyses were also not used because of their requirements of historical records.

The curve number method is based on the potential maximum retention (S) of the watershed, which is determined by wetness of the watershed that is antecedent moisture condition (AMC) and physical characteristics of the watershed. The curve number method calculations are shown below:

$$S = \frac{25400 - 254}{CN} \text{-----2.1}$$

$$Q = \frac{(P - 0.2S)^2}{P - 0.8S} \text{-----2.2}$$

Where

S is maximum potential retention of the watershed, mm:

CN is Curve number:

Q is runoff of depth (mm):

P is rainfall (mm): and,

$I = 0.2S$ which is initial abstraction rainfall by soil and vegetation.

The volume of surface runoff from the basin was also computed by using the runoff coefficient method, which employed the following formula.

$$Q = K.P.A \text{-----2.3}$$

Where

Q is runoff, m^3 :

K is a constant also called runoff coefficient depends up on the imperviousness of the drainage area:

P is precipitation (mm): and,

A is area of the basin (m^2).

After the surface water potential was estimated using the two methods, Nata concluded that: since the curve method takes into account a number of hydrologic parameters than the runoff coefficient method, the calculated value of the curve method is taken as a representative of the basin.

2.5. Water Demand

Water demand is defined as the volume of water requested by users to satisfy their needs. Water demand forecasting is a process achieved through several techniques and is typically used to predict future water requirements for different uses including hydropower, domestic and agriculture water demands. The type of technique used depends on the availability of the data needed, the general scope of the region for which the forecast is being conducted, and the resources available to the organization for which the forecast is being conducted. For all intensive purposes future water demand is derived from basic functions. For instance, municipal demand is generally projected using population size and the number of households, industrial demand is often based on number of employees, and agricultural demand commonly relies on crop type and irrigated land (Water Resources Planning (Dzurik, 1996).

The key variables such as population growth, urbanization, increasing irrigation water consumption, changes in cropping patterns, increasing productivity of rain fed agriculture and the water demand for environment and pollution controls were considered in estimating future water demand.

The accelerating growth of human population, the rapid advances made in industry and agriculture have resulted in a rapidly increasing use of water by man, to the extent that the availability of water as well as the control of excessive water has become a critical factor in the development of every regions of the world (Williams, 2010).

Over the decades, water supply management has proved to be insufficient to deal with strong competition for water with growing per capital water use, increasing population, urbanization

pollution and storages (Wang Xiao – Jun et al, 2009). Also, the need for domestic, industrial and agricultural water supply is growing, but the absence of demand management strategies means that the increase in demand will likely outstrip the available supply, hence water scarcity is occurred (UNESCO, 2006).

The issue of water scarcity in the world and its implication on development of new political and economic relations among countries may result to crisis in the future. The management of water resources as a common resource would require trade-off among countries and water users (Yang et al, 2007).

Over the years, population growth and urbanization, industrialization and the expansion of irrigated agriculture are arresting rapidly increasing in demands and pressure on the water resources, besides contributing to the rising of water pollution (Global Water Partnership, 2000)

Water demand is an important technical design parameter. It can be measured (for an existing project scheme) or calculated using local data or, more typically, established norms and standards. Such calculations also take into account the number and type of users to be served, the anticipated population growth rate and the expected life span of the infrastructure being provided. It is also important to take into account the seasonal influence on water demand (Paw, et.al, 2002).

The demand for water is growing rapidly as population, industrial activities expand and irrigated agriculture continues to increase. Water is used for the day-to-day life activities and hence the demand for it varies widely. Total water consumption for all purposes varies very significantly and there is no noticeable relationship between size of population served and consumption per capita. A fundamental consideration for the sizing of any water system, or its component parts, is an estimate of the amount of water expected to be used by the customers on the system (Twort, 1985).

Water demand is affected by a number of socio-economic implications such as the legal system, the institutional framework, customs and traditions, religious beliefs and economic and financial considerations prevailing in any country. Climate is another factor affecting water demand: dry areas will require more water than humid ones. Finally, water demand is influenced by water quality; thus, water containing a high percentage of salt will not be of great domestic or agricultural use (Dante, 1992).

The amount of water that people use depends on minimum needs, amount of water available for use, level of economic development and extent of urbanizations. There are three categories of fresh water use globally: for agriculture, industry and domestic (personal, household and municipal) of which agriculture dominates (Gleik, 1996).

Although Ethiopia's water resource is large, very little of it has been developed for agriculture, hydropower, industry, water supply and other purposes. National coverage of potable water supply stood at 26% by 1992 while coverage of sanitation services is only 7%, which is low by even the Sub-Saharan standards. There is also a wide divergence in the water supply coverage between urban (76%) and rural (18.8%) areas (Seleshi, 2010).

In order to meet the demands of different users, efforts should be intensified on the efficient use of all water resources (surface water, ground water, and rainfall) and also on water allocation plans that maximize the resultant economic returns to limited water resources and, at the same time, protect the fragile ecosystem.

Over the years, population growth, urbanization, industrialization and the expansion of irrigated agriculture are arresting rapidly increasing in demands and pressure on the water resources, besides contributing to the rising of water pollution (Global Water Partnership, 2000). Water consumption has doubled since 1950 (UNESCO 2003). The direct consumption by the man and animals constitute about 50% of the fresh water use while agriculture (crop production, aquaculture, land and water conservation), which is the predominant user,

accounts for about 70% globally, and up to 95% in several developing countries. In order to cope with the ever expanding demand for food, it has been estimated that in the next 30 years, about 14% more freshwater will be withdrawn for agricultural purposes (Verosmarty *et al.* 2000; UN, 2006). The demand for water resources of sufficient quantity and quality for human consumption, sanitation, agriculture, and industrial uses will continue to intensify as the population increases and global urbanization, industrialization, and commercial development accelerate (Flint *et al.*, 2004). Therefore, water resource management is one of the most important challenges the world is facing today.

Water demand management (WDM) is essential being part of the challenge to sustain the water resources. It is well known that the main principle in water demand management is “efficient use of water in order to maintain vital environment flow and to reduce dependence on costly infrastructure projects”. For instance, a toilet may be flushed clean or laundry washed with one third than the amount of water that is normally used with equal or better efficiency (Wong *et al.*, 2009).

2.5.1. Irrigation Water Demand

Ethiopia has a significant irrigation potential identified from both available land and water resources. Irrigation would provide farmers with sustained livelihoods and improve their general well-being (Belay *et al.* 2013). However, the country's irrigable land has been underutilized, and only 4 to 5% of the potential area has been developed for irrigation (Awulachew *et al.*, 2007). Consequently, the agricultural economy of the country is largely based on rainfed cultivation, but while employing 85% of the population, it only contributes 50% to the gross domestic product (Berry *et al.*, 2003). Ultimately, increasing agricultural production using irrigation is one of the main drivers to end poverty caused by insufficient output from these rainfed systems.

According to the Ministry of Water, Irrigation & Energy of Ethiopia irrigation command areas can be classified into three groups (Awulachew et al., 2005). The first group is small-scale irrigation areas of less than 200 ha, medium-scale between 200 and 3000 ha and large-scale above 3000 ha. For this study, large scale projects are considered based on this classification.

Irrigation is one means by which agricultural production can be increased to meet the growing demands in Ethiopia (Awulachew et al. 2005). One of the best alternatives to consider for reliable and sustainable food security development is expanding irrigation development on various scales, through river diversion, constructing micro dams, water harvesting structures, etc. (Robel, 2005).

Currently, the government is giving more emphasis to the sub-sector by way of enhancing the food security situation in the country. Efforts are being made to involve farmers progressively in various aspects of management of small-scale irrigation systems, starting from planning, implementation and management aspects, particularly, in water distribution and operation and maintenance to improve the performance of irrigated agriculture.

Ethiopia has developed irrigation schemes in many parts of the country at different scales. Data and information are not uniformly available to accurately know the existing irrigation schemes. While it is possible to capture the medium and large schemes data accurately, it is difficult to account for the small-scale irrigation development, particularly, the traditional irrigation development and the privately developed household-based irrigation schemes which use traditional diversions, water harvesting and ground water development.

Water is supplied to agricultural fields in the form of irrigation to satisfy crop water requirement. Crop water requirements are defined as the depth of water needed to meet the water loss through evapotranspiration (ET_o) of disease-free crop, growing in large fields

under non-restricting soil conditions including soil water and fertility and achieving full production under the given growing environment.

ET_o is expressed in mm per day and represents the mean value over that period. For areas where measured data on temperature, humidity, wind and sunshine duration or radiation are available, an adaptation of the Penman-Monteith method is recommended by FAO to estimate reference ET_o (FAO, 1996).

Irrigation requirement of a crop refers to the amount of water needed to apply as to supplement the water received through rainfall and soil profile contribution in meeting the water needs of the crop for optimum growth and yield. Tekeze basin has a potential for three large-scale irrigation sites with an estimated potential irrigable area of 83,368 hectares (Tekeze River basin integrated master plan, 1998).

2.5.2. Domestic Water Demand

Domestic water demand includes water used for basic needs such as drinking, cooking, ablution, washing clothes and utensils and cleaning houses. It is difficult to estimate the exact amount of water needed to maintain the acceptable or minimum living standards. Moreover, different sources use different figures for total water consumption and for water use by sector of economy. According to Gleik's (1996), international organizations and water providers adopt an overall basic water requirement of 50 liter per capita per day (Lpcd) as a minimum standard to meet four basic needs: drinking, sanitation, bathing and cooking. Falkenmark (1996) uses the value of 100 liter of fresh water per capita per day for personal use as a rough estimate of the amount needed for a minimally acceptable standard of living in developing countries not including uses for agriculture and industry. The water required to produce food for people is about 3500 liters/day/adult for a 3000 Kcal diet, or about 70 times more than that needed for other domestic purposes, including safe drinking water (IWMI, 2006).

Different countries have different consumption requirement for domestic use. For instance, in India, there is a large variability of the quantity supplied in urban areas from 10 to 500 Lpcd and in rural areas from 5 to 70 Lpcd. In Iran, the planned demand for food is based on a diet of 2700 Cal per person per day, which is accordance with the FAO, 1996 estimate. Accordingly, some 1600 m³ per person per year of water is required in the root-zone to allow self-sufficient food production (ICID, 2000). According to some feasibility, studies on water supply in Ethiopia per capita per day requirement range from 20-40L (AESL, 1982).

The Policy Letter that was issued by MOWR in January 1996 suggests a design standard of 15-25 liters per person per day for rural water supplies and 35-40 liters per person per day for urban centers. The proposed figures that will be used for predicting the rural water demand within 1999-2009 is 20 liters per person per day and for urban water demand is 40ld (Cited by Abbay River Master Plan, 1998).

In 1995 water demand in the urban area was estimated at 35l/c/d and in the rural area at 20l/c/d. with the improvement of the water supply infrastructure these figures will, in the year 2030, have grown to 60l/c/d in urban and 30l/c/d in rural areas. Multiplying these figures with population totals gives total demand for Tekeze river basin. The total demand in 1995 was 37Mm³ (1.2m³/s) and in 2030 it is expected to be 173Mm³ (5.5m³/s). These figures are rather small compared with the total outflow of the basin of 8,200Mm³ (260m³/s) (Tekeze River basin integrated master plan, 1998).

CHAPTER THREE

3. Materials and Methods

3.1. Description of the Study Area

Tekeze River basin is situated in the northwest of Ethiopia between $11^{\circ} 40'$ and $15^{\circ} 12'$ N, and $36^{\circ}30'$ and $39^{\circ} 50'$ E. It is bordered by the Mereb River basin and by Eritrea in the north, the Atbara River plains in Sudan in the west, the Abbay River basin in the south and Danakil basin in the east.

There are two main tributaries (Angereb and Goang) that contribute to Tekeze River which rises in the central highlands of Ethiopia, and joins the Atbarah River, the lower course of which is a tributary of the Nile. The river basin has a lowest elevation of 539 m and a highest elevation of 4,517 m, which is the highest elevation, in Ethiopia. Tekeze river basin has an area of 82,824.095 Km², covering parts of the Amhara and Tigray regional states.

The Tekeze River basin begins at the springs near Lalibela and flows, generally, in the western direction to the Sudan border. The river slope is quite steep in the mountain stretch, more than 1.5%, and gradually decreases to 0.3% and finally to 0.1% near the Sudan border.

The Tekeze basin consists of three sub-basins: Tekeze, Angereb and Goang River sub-basins. The rivers are quite steep and some have deep gorges, which make ideal dam construction sites. However, the drawbacks are that no steep drops and high flows for the short rainy season and the presence of high variability over years (Tekeze River basin integrated master plan, 1998).

The length of Tekeze River from its source at springs near lalibela down to the Sudanese border is more than 750km. The main tributaries of Tekeze, which originate in the highlands

of the east side of the Semien Mountain, are Zamra, Tserare, Gheba, and Wori (NEDECO, 1998

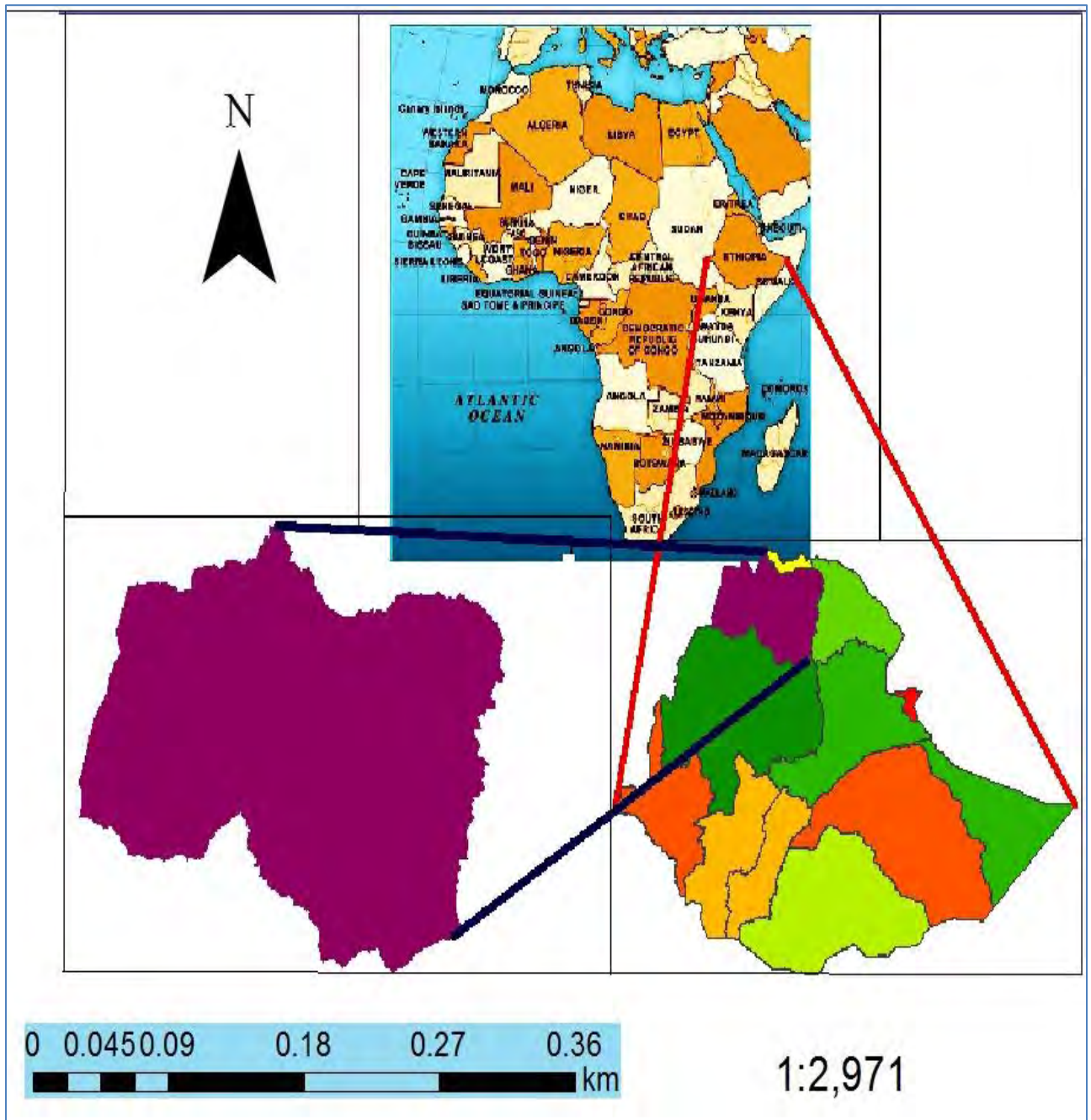


Figure: 2: Location of the study area

3.2. Climate

According to the definition given by the World Meteorological Organization (WMO), Climate is defined as the synthesis of weather condition in a given area characterized by long-term statistics (mean, variance, probabilities of extremes, etc) of the meteorological

elements in an area (NEDECO, 1998). The WMO usually accepts 30 years of statistical data series to define climate. The climate of the Tekeze basin in general, comes under the influence of the Inter Tropical Convergence Zone (ITCZ). The meteorological/climatic elements include rainfall, temperature, wind, radiation, humidity, and sunshine hours.

The conditions of some of climatic elements in the basin are described below.

3.2.1. Rainfall

Rainfall data is an important input in water resources studies, in particular for the study of the rainfall-runoff process through which is determined how much runoff results from a certain amount of precipitation on different catchments. In Ethiopia one differentiates between two distinct precipitation types, the mono- modal and the bimodal type. Each type can again be subdivided into sub-types based on length of the rainy season.

In the west of the basin a monomodal type regime can be recognized and a bimodal type in the east. The study area is characterized by a Bimodal type I (quasi double maximum) rainfall pattern, with a small peak in April and a maximum peak in August. Therefore, the region is dominated by a semi – bimodal peak rainfall pattern (NEDECO, 1998).

The average annual rainfall decreases from south to north from 1,854 to 504 mm in the basin.

The mean annual rainfall in the basin is 976.4 mm. The small rains are from October to May and the main from June to September with a marked increase in July and August.

3.2.2. Temperature

The mean annual temperatures in the basin vary from 13.6°C in the highlands and to 27.6°C in the lowlands. Minimum and maximum temperature ranges are 2.1-23°C and 20-46°C respectively.

3.2.3. Relative Humidity, Sunshine Hours and Wind Speed

Minimum mean monthly relative humidity values occur in the dry period (October-March) and can be as low as 40%. High values occur in the main rainy season (July-August) in which mean monthly values for many stations are above 70%. Mean monthly sunshine hours for the different stations range between 6.5 and 8.5hrs/day. High monthly values up to 10hrs/day occur during the dry period. Low values to below 4hrs/day occur during the rainy season especially in the months of July and August. Mean Monthly wind speeds up to 300km/day occur during the rainy season (June-August). Low values occur during the dry season, sometimes below 100km/day (NEDECO, 1998). For wind speed, sunshine hours and relative humidity, the recorded available data are for short period of time and it was impossible to fill and extend the missing data and due to scarcity of data it was impossible to use the measured data for the SWAT model.

3.2.4. Topography and Slope

Slope is an important characteristic of a catchment as it gives an indication of the kinetic energy available for water to move towards the basin outlet, and it has been found to be related to total runoff and base flows (Bullock, 1988). Slope is highly variable within a basin, ranging from 0%- 376.549%.

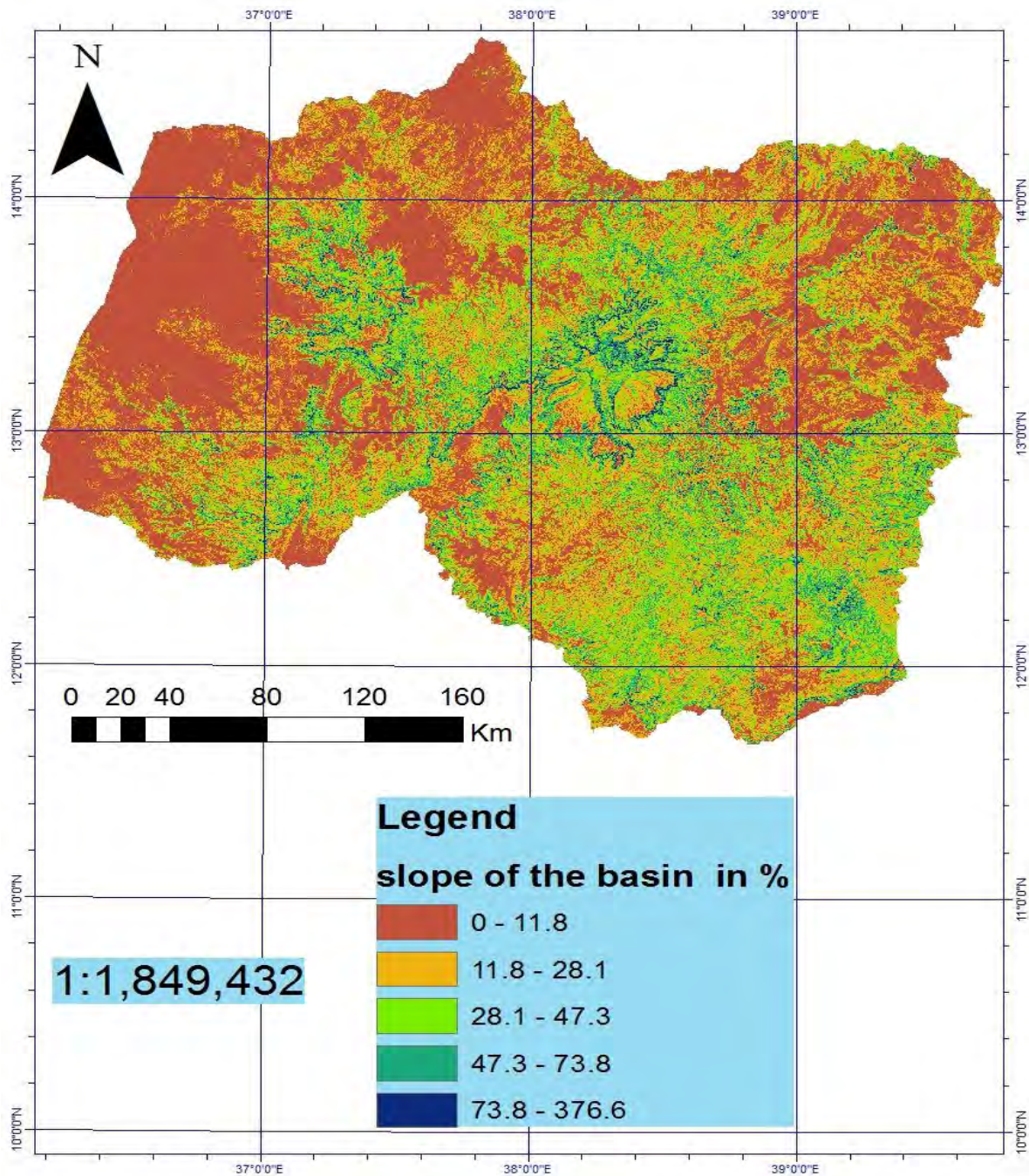


Figure: 3. Slope map of the basin

3.2.5. Land Use and Land Cover

The land use land cover data, which was collected from the Ministry of Water Resource, was done before 16 years ago and the land use description was not available. Different research papers and design documents were collected from Ethiopian Ministry of Water resources, Amhara and Tigray Water Resources Energy and Mining bureaus. Using these documents,

the land use land cover types, which were in year 2008, were identified and land use land cover map were prepared. Since the study area is too large, it was difficult to get the land use image data from USGS GLOVIS earth explorer. It is impossible to get one scene/ image/ land use land cover data for large area. Because, each land sat scene covers an area of 172km by 185 km, which cannot cover the whole study area. Therefore, eight land sat image data have been downloaded from USGS GLOVIS earth explorer for the year 2008 and each image was mosaicked to a single image using Arc GIS and both image classification techniques were applied and lastly supervised classification technique was selected for the image classification.

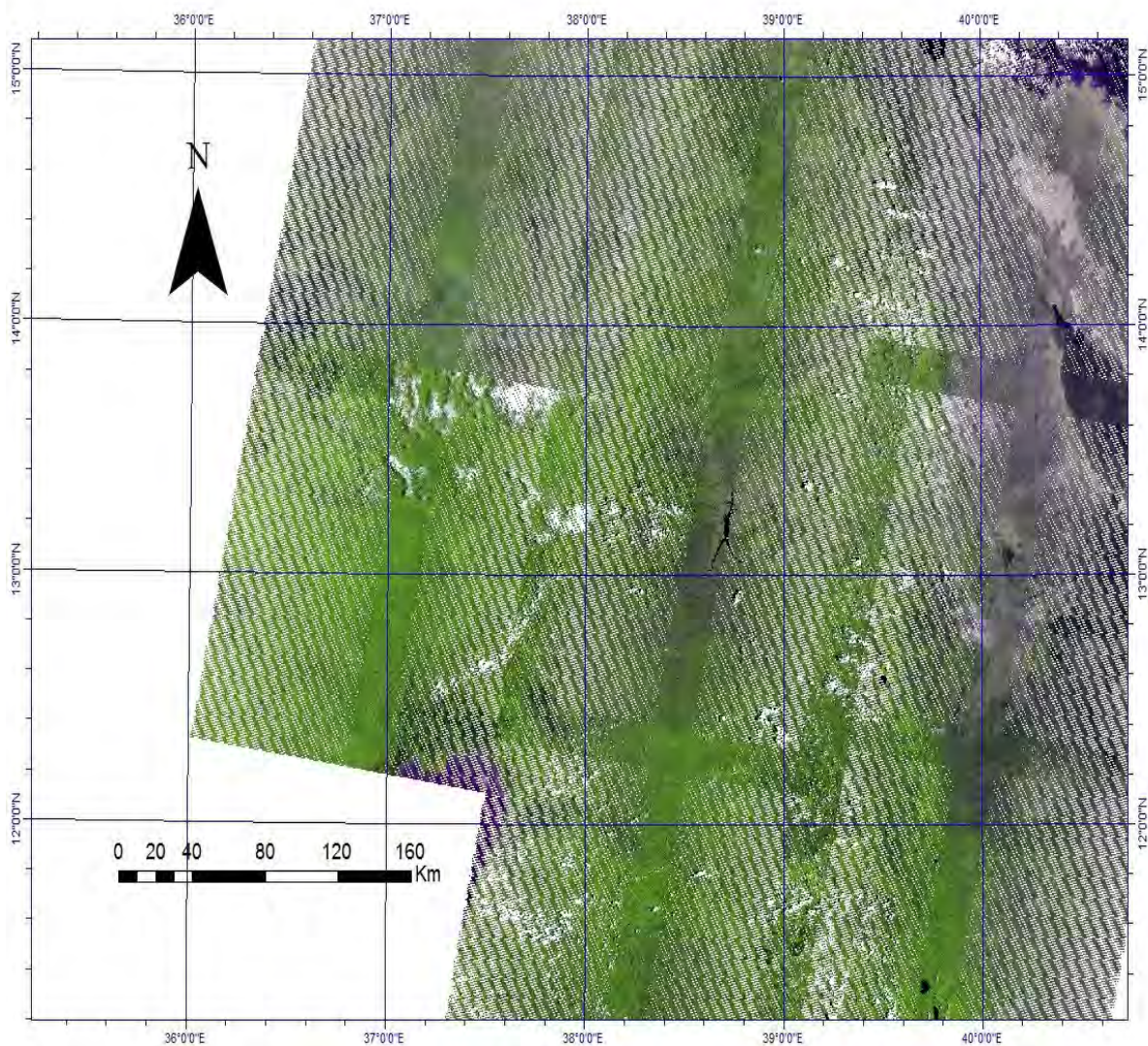


Figure: 4. Mosaicked land sat image

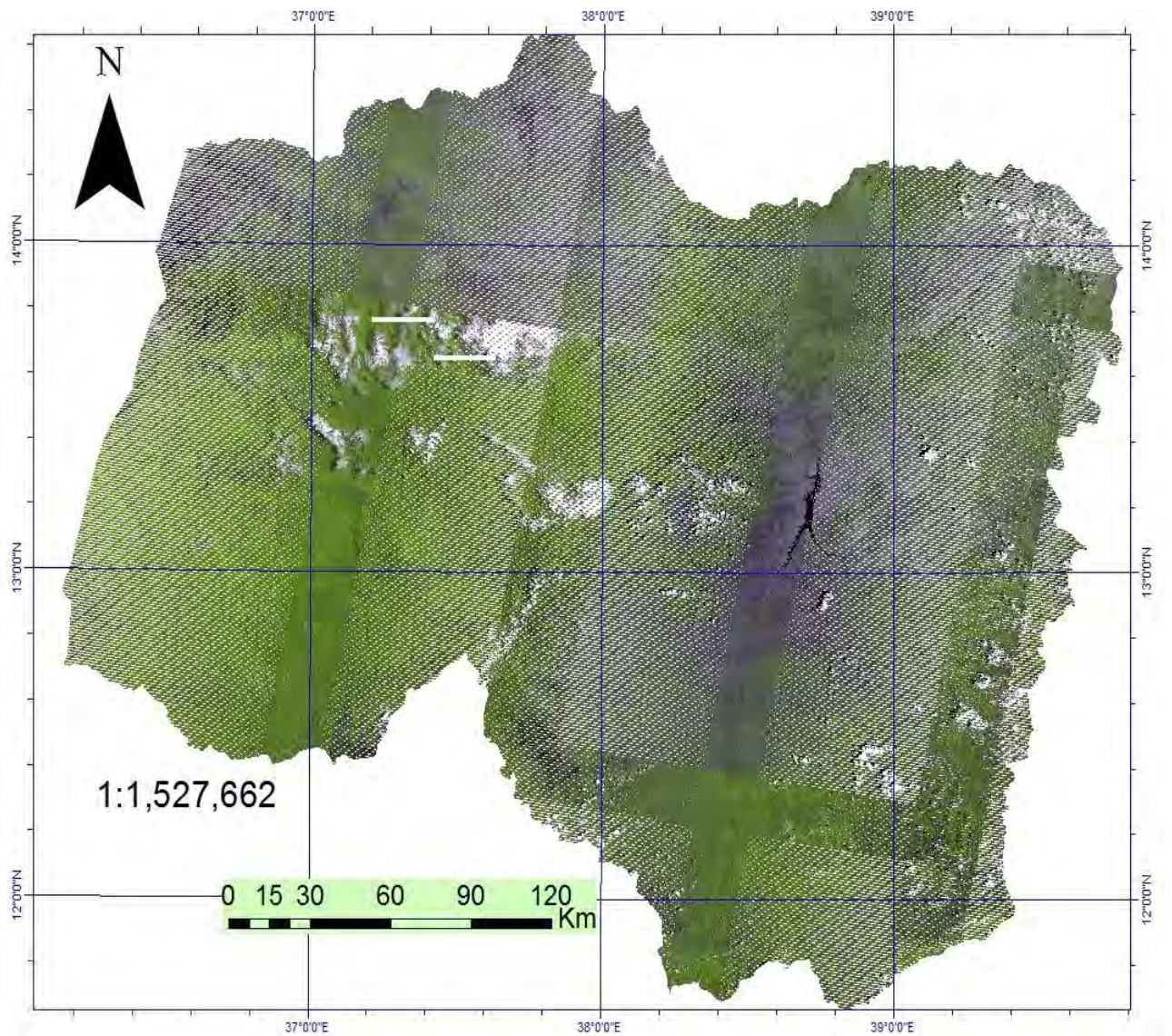


Figure: 5. Clipped land use image

3.2.6. Soil Types

Among the inputs to any catchments water yield estimation models, soil data is one of the essential input parameters for the hydrologic model. Soil properties influence the process of generation of runoff from rainfall and they must be considered in methods of runoff estimation. For this research work, soil data that was obtained from “GIS-based hydrological zones and soil geo-database of Ethiopia (Belete et al, 2013) was used. The soil data basically contains information of hydrological soil group, coverage area in the basin along with the

percentage of spatial coverage. The Dominant soil groups in the basin are the four soil types i.e. Eutric Vertisols, Eutric Leptosols, Haplic Luvisols and Lithic Leptosols which accounts about 80% of the total catchment area. The types of soils in the basin are Eutric Vertisols on the level lands; Eutric Leptosols, Eutric Vertisols, Eutric and Calcric Cambisols and Halpi Luvisols on the sloping lands; Eutric Leptosols on the steep lands; and Leptosols on composite landforms.

Luvisols -these soils are derived from various volcanic and undifferentiated lower complex rocks. They are identified in color as Brown /reddish brown with clay to silty clay texture. These soils are Friable to firm, sticky and slightly plastic. Leptosols-these soils are developed in relatively younger surface and were probably only moderately deep too deep by origin. The top soil has a thickness ranging from 10 to 30 cm, and it is mostly brown /yellowish brown in color and cly loam to clay in texture.

Litic leptosols: are soils limited in depth by continuous hard rock or continuous cemented layer within 10 cm of the surface.

Vertisols-these soils are mostly imperfectly to poorly drained, dark grayish soils, formed on flat to almost flat plains. The clay fraction of these soils is dominant by expansible 2:1 lattice clays. Vertisols are very to extremely hard when dry and very sticky and very plastic when wet.

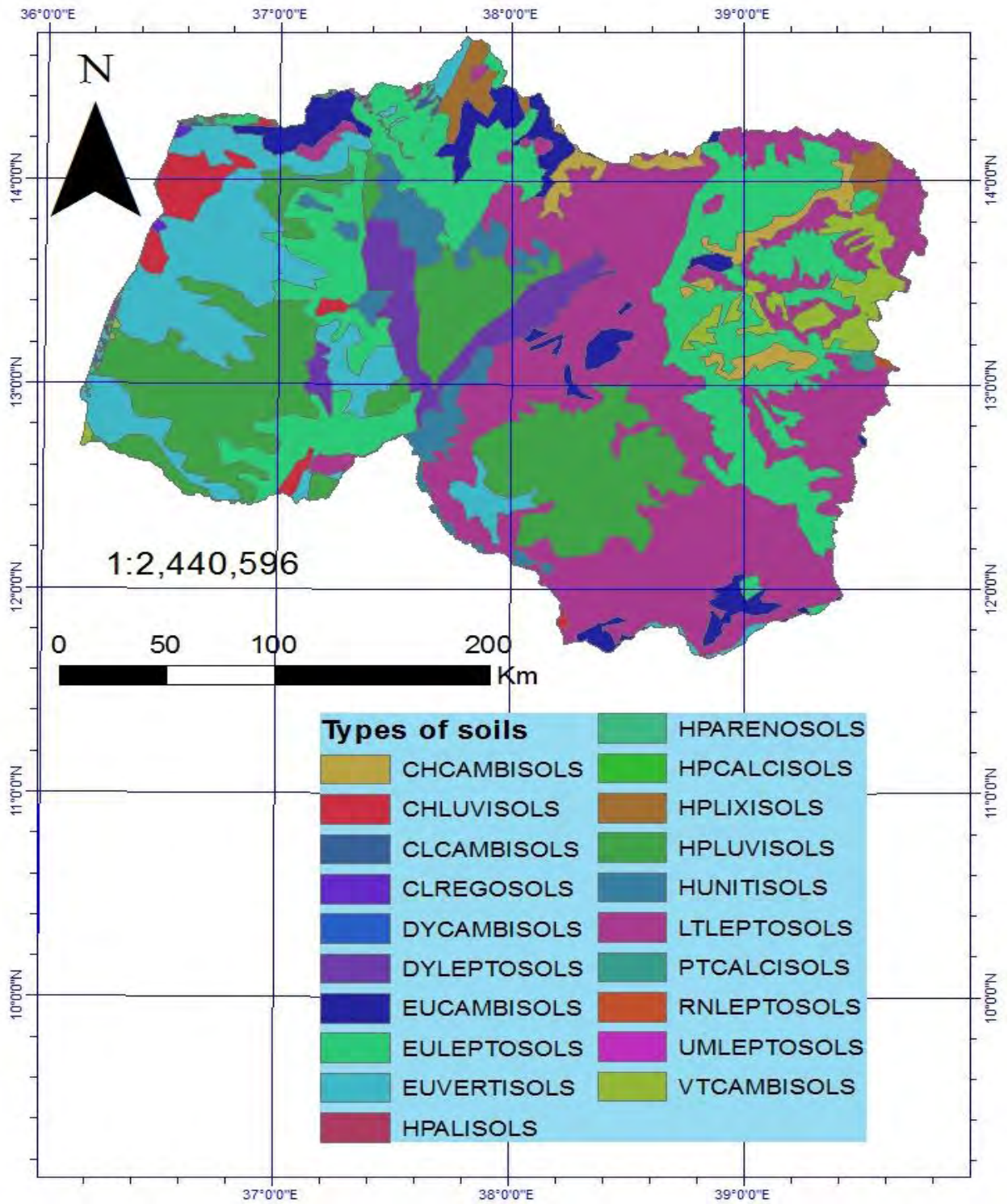


Figure: 6. Soil map of Tekeze River Basin

The following table summarizes the major soil groups, coverage area, texture and assigned hydrological soil group.

Table 2: Major soil group, textures and the respective hydrological soil group

Major Soil Group	Area In Sqr.Km	Percentage	Soil Texture	Hydrological Soil Group
Eutric Vertisols	9301.34	11.16	Clay	D
Eutric Leptosols	17147.19	20.57	Sandy loam	A
Lithic Leptosols	25015.06	30.01	Sandy loam	A
Calcaric Cambisols	152.28	0.18	Sandy loam	A
Umbric Leptosols	4.10	0.00	Loam	B
Eutric Cambisols	3507.49	4.21	Clay	D
Haplic Luvisols	15494.29	18.59	Loam	B
Haplic Arenosols	1.06	0.00	Sand	A
Chromic Luvisols	1474.99	1.77	Loam	B
Haplic Alisols	7.87	0.01	Loam	B
Haplic Calcisols	0.82	0.00	lomy sand	A
Dystric Cambisols	1.39	0.00	Sandy loam	A
Haplic Lixisols	1111.12	1.33	Sandy clay loam	C
Calcaric Regosols	75.13	0.09	Loam	B
Chromic Cambisols	1749.82	2.10	Clay	D
Vertic Cambisols	2025.39	2.43	Clay	D
Rendzic Leptosols	48.16	0.06	Sandy loam	A
Humic Nitisols	2884.21	3.46	Loam	B
Dystric Leptosols	3239.90	3.89	Sandy loam	A
Petric Calcisols	111.40	0.13	lomy sand	A
Eutric Vertisols	9301.34	11.16	Clay	D
Total	83353.00	100.00		

3.3. Methods and Materials Used

3.3.1. Materials Used

Materials used and methodologies applied for the assessment of surface water potential and estimation of water demands from large scale projects are given detail in the respective chapters and summary of them are listed below.

The materials used for this research are:-

- ✚ Hydrological data (stream flow data)
- ✚ Meteorological data (daily Rainfall, Temperature, RH, Sunshine hours, wind speed)
- ✚ 90 by 90m DEM data was used as an input data for Arc GIS and Arc SWAT software
- ✚ Arc GIS 10.2.1 was used to obtain hydrological and physical parameters and spatial information, to locate geographical location of the study area, to classify land use land cover map etc...
- ✚ SWAT software was used to delineate the basin, sub basin and HRUs of the study area and to estimate surface runoff
- ✚ SWAT CUP- was used for sensitivity analysis, calibration and validation of SWAT model
- ✚ WEAP (Water Evaluation And Planning) to estimate water requirements for different uses in the basin

3.3.2. Methods

Methodologies applied for this study include:

- Review of previous studies on the basin
- Secondary data collection from institutions such as Ethiopian Water Resource, Irrigation and Energy Minister, Tigray and Amhara Water Resource, Mines and Energy and Ethiopian National Meteorological Service Agency

- Field observation and collect necessary data and information in the basin
- After collecting all data, filling of missed data and quality checking have been done
- Preparing necessary input data in SWAT format
- Preparing DEM and delineating the watershed of the basin
- Then the SWAT model is used to simulate surface runoff and WEAP was used for estimation of water demands from large scale projects for the basin

3.3.3. Model Selection Criteria

There are a number of criteria which can be used for choosing the right model. These criteria are mainly dependent on the use of the model. Furthermore, some criteria are also user dependent such as: personal preference; computer operation system; input/output management and structure etc. Cunderlik (2003) suggested four criteria for the selection of models. These are: (1) required model outputs for the needed purpose, (2) different hydrological processes that are required to be modeled for the desired purpose, (3) availability of input data and (4) Price

Depending upon the above selection criteria for this research Soil and Water Assessment Tool (SWAT) for assessment of surface water potential was selected because:

- i) SWAT is public or open source domain software actively supported by the USDA (United States Department of Agriculture) – ARS (Agricultural Research Service) at the Grass-land, Soil and Water Research Laboratory in Temple, Texas, USA.
- ii) SWAT is a river basin scale, a continuous time, a spatially distributed model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2005).

iii) SWAT can analyze both small and large watersheds by subdividing the area into homogenous parts. As a physically-based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in terms of land cover, soil type and slope within a watershed. The SWAT system embedded within geographic information system (GIS) that can integrate various spatial environmental data including soil, land cover, climate and topographic features. (Lenhart *et al.*, 2002)

3.3.4. Description of SWAT Model

SWAT is the acronym for **S**oil and **W**ater **A**ssessment **T**ool, a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch *et al.*, 2005).

In recent years, SWAT model developed by Arnold *et al.* (1998), has gained international acceptance as a robust interdisciplinary watershed modeling. SWAT is currently applied worldwide and considered as a versatile model that can be used to integrate multiple environmental processes, which support more effective watershed management and the development of better informed policy decision (Gassman *et al.*, 2005).

SWAT is a basin-scale, continuous-time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management.

In SWAT, a watershed is divided into multiple sub-basins, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management,

and soil characteristics. The HRUs represent percentages of the sub-basin area and are not identified spatially within a SWAT simulation. Alternatively, a watershed can be subdivided into only sub-basins that are characterized by dominant land use, soil type, and management (Gassman *et al.*, 2007).

The Simulation of the hydrology of a watershed is separated into two divisions. One is the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. Hydrological components simulated in land phase of the Hydrological cycle are canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, tributary channels and return flow. The second division is routing phase of the hydrologic cycle that can be defined as the movement of water, sediments, nutrients and organic chemicals through the channel network of the watershed to the outlet (Neitsch *et al.*, 2005).

In the land phase of hydrological cycle, SWAT simulates the hydrological cycle based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad \text{---4.1}$$

where, SW_t is the final soil water content (mm), SW_o is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU

and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

Brief description of some of the key model components are provided in this study. More detailed descriptions of the different model components are listed in SWAT user's manual (Neitsch *et al.*, 2005).

Surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. When water is initially applied to a dry soil, the application rate and infiltration rates may be similar. However, the infiltration rate will decrease as the soil becomes wetter. When the application rate is higher than the infiltration rate, surface depressions begin to fill. If the application rate continues to be higher than the infiltration rate once all surface depressions have filled, surface runoff will start. Surface runoff occurs whenever the rate of precipitation exceeds the rate of infiltration. SWAT offers two methods for estimating surface runoff: the SCS curve number procedure (USDA-SCS, 1972) and the Green and Ampt infiltration method (Green and Ampt, 1911; as cited in Neitsch *et al.*, 2005). Using daily or sub daily rainfall, SWAT simulates surface runoff volumes and peak runoff rates for each HRU. The SCS curve number equation is (SCS, 1972):

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \text{-----4.2}$$

Where, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm); S is the retention parameter (mm).

SCS defines three antecedent moisture conditions: I-dry (wilting point), II-average moisture and III-wet (field capacity). The moisture condition I curve number is the lowest value the daily curve number can assume in dry conditions. The curve numbers for moisture conditions I and III are calculated with the equations 2.3 and 2.4, respectively.

$$CN_1 = CN_2 - \frac{20 \times (100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636 \times (100 - CN_2)])} \text{-----4.3}$$

$$CN_3 = CN_2 \times \exp[0.00673(100 - CN_2)] \text{-----4.4}$$

Where, CN1 is the moisture condition I curve number, CN2 is the moisture condition II curve number, and CN3 is the moisture condition III curve number.

The retention parameter is defined by equation 2.5

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right) \text{-----4.5}$$

SWAT includes two methods for calculating the retention parameter; the first one is retention parameter varies with soil profile water content and the second method is the retention parameter varies with accumulated plant evapotranspiration. The soil moisture method (equation 2.6) over-estimates runoff in shallow soils. But calculating daily CN as a function of plant evapotranspiration, the value is less dependent on soil storage and more dependants on antecedent climate. Runoff will only occur when $R_{day} > 0.2S$. The retention parameter varies with soil profile water content according to the following equation:

$$S = S_{max} \times \left(1 - \frac{SW}{SW + \exp(w_1 - w_2 \times SW)} \right) \text{-----4.6}$$

where S is the retention parameter for a given moisture content (mm), Smax is the maximum value the retention parameter can achieve on any given day (mm), SW is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm of water), and w1 and w2 are shape coefficients.

The maximum retention parameter value, Smax, is calculated by solving equation 2.7 using CN1

$$S_{\max} = 25.4 \left(\frac{1000}{CN_1} - 10 \right) \text{-----4.7}$$

The shape coefficients are determined by solving equation 2.8 assuming that, 1) The retention parameter for moisture condition I curve number corresponds to wilting point soil profile water content, 2) The retention parameter for moisture condition III curve number corresponds to field capacity soil profile water content, and 3) The soil has a curve number of 99 ($S = 2.54$) when completely saturated.

$$w_1 = \ln \left[\frac{FC}{1 - S_3 \times S_{\max}^{-1}} - FC \right] + w_2 \times FC \text{-----4.8}$$

$$w_2 = \frac{\left(\ln \left[\frac{FC}{1 - S_3 \times S_{\max}^{-1}} - FC \right] - \ln \left[\frac{SAT}{1 - 2.54 \times S_{\max}^{-1}} - SAT \right] \right)}{(SAT - FC)} \text{-----4.9}$$

where w_1 is the first shape coefficient, w_2 is the second shape coefficient, FC is the amount of water in the soil profile at field capacity (mm of water), S_3 is the retention parameter for the moisture condition III curve number, S_{\max} is the retention parameter for the moisture condition I curve number, SAT is the amount of water in the soil profile when completely saturated (mm of water), and 2.54 is the retention parameter value for a curve number of 99.

The daily curve number value adjusted for moisture content can be calculated by rearranging equation 2.7 and inserting the retention parameter calculated for that moisture content:

$$CN = \frac{25400}{(S + 254)} \text{-----4.10}$$

Where, CN is the curve number on a given day and S is the retention parameter calculated for the moisture content of the soil on that day.

The moisture condition II curve numbers provided in the tables are assumed to be appropriate for 5% slopes. Williams (1995) developed an equation to adjust the curve number to a different slope:

$$CN_{2S} = \frac{(CN_3 - CN_2)}{3} \times [1 - 2 \times \exp(-13.86 \times slp)] + CN_2 \text{ -----4.11}$$

Where, CN_{2S} is the moisture condition II curve number adjusted for slope, CN_3 is the moisture condition III curve number for the default 5% slope, CN_2 is the moisture condition II curve number for the default 5% slope, and slope is the average percent slope of the sub-basin. Runoff is calculated separately for each sub-basin and routed to obtain the total runoff for the basin.

SWAT calculates the peak runoff rate with a modified rational method. There are many methods that are developed to estimate potential evapotranspiration (PET). Three methods are incorporated into SWAT: the Penman-Monteith method (Monteith, 1965), the Priestley-Taylor method (Priestley et al, 1972) and the Hargreaves method (Hargreaves *et al.*, 1985) and the model will also read in daily PET values if the user prefers to apply a different PET methods.

3.4. SWAT Model Inputs

To achieve the goal of this research using SWAT, data such as DEM of the study area, topography, soil, land use and meteorological data include, daily rainfall, minimum and maximum temperature, relative humidity, solar radiation, and wind speed are required.

3.4.1. Digital Elevation Model

To delineate the watershed and sub-basins and to determine stream networks SWAT uses the digital representation of the topographic surface *i.e.* Digital Elevation Model (DEM). The DEM forms the base to delineate the watershed boundary, stream network and create sub-

basins. Topography was defined by a DEM which describes the elevation of any point in a given area at a specific spatial resolution as a digital file. It was also used to analyze the drainage patterns of the land surface terrain (SWAT 2012 User's Manual). For this research, a DEM with a resolution of 90 m was used, which was sourced from ASTER GDEM of official website, released by ERSDAC (Earth Remote Sensing Data Analysis Center) in collaboration with NASA and collected from Ethiopian Water Resource, Irrigation and Energy Ministry.

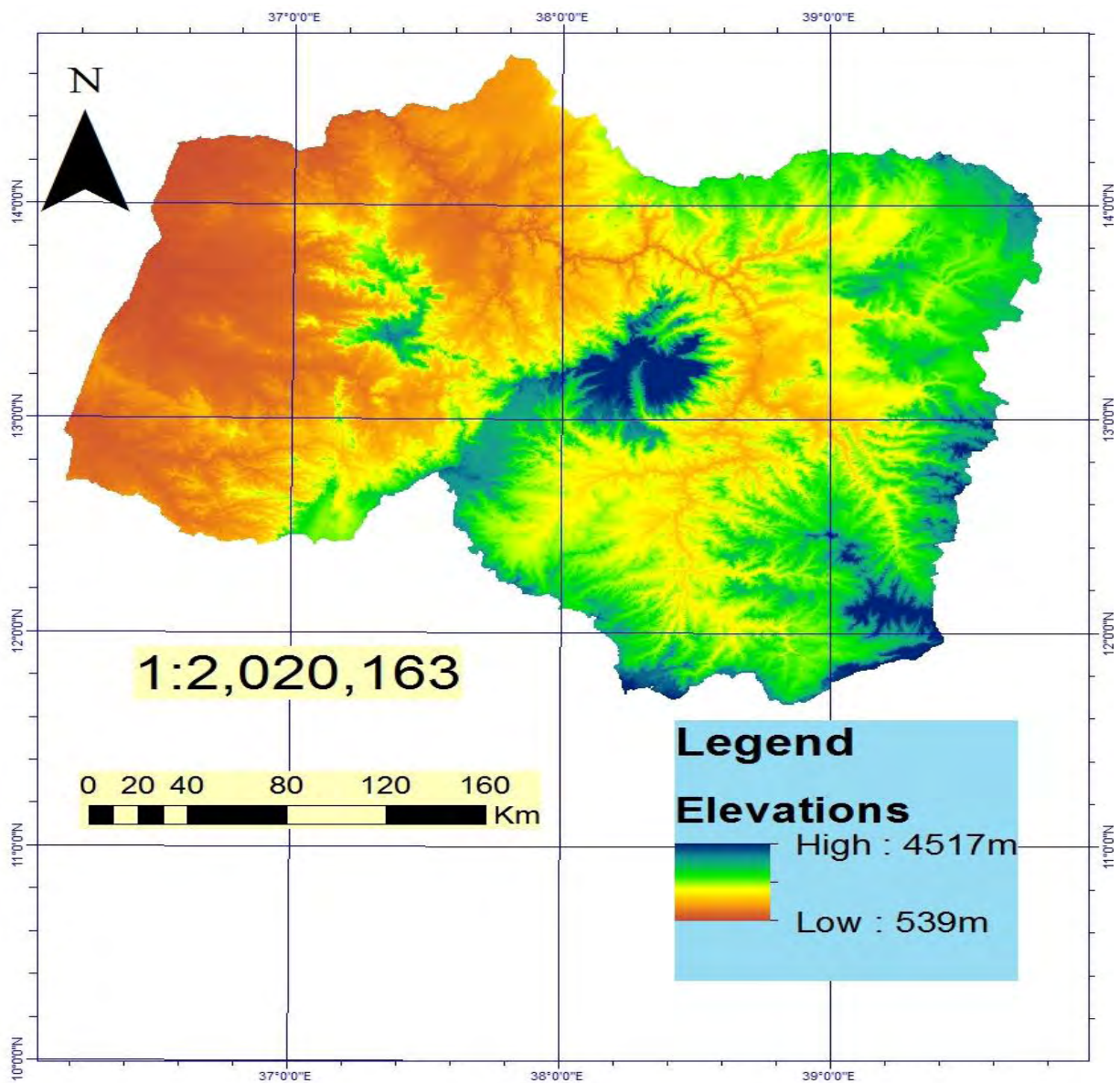


Figure: 7. DEM of the study area

3.4.2. Land Use Land Cover Data

Land use land cover (LULC) data for the basin, which was downloaded from www.earthexplorer.USGS.GLOVIS, and classified using supervised classification technique was used for this research. Ten major land use types were identified in the research papers and different water resource projects which have been done in the basin in the year 2008 and the land use land cover map for the study area was prepared using these major land use types. These are cultivated land, grazing land, deciduous woodland, deciduous shrub land, open grass land with sparse shrubs, bush land, water/reservoirs, rural and urban and bare land. The ground is virtually bare during the dry season. The main land use activities are rain fed cultivation of cereals, oil seeds and pulses and grazing on unimproved pasture and fallow (NEDECO, 1998).

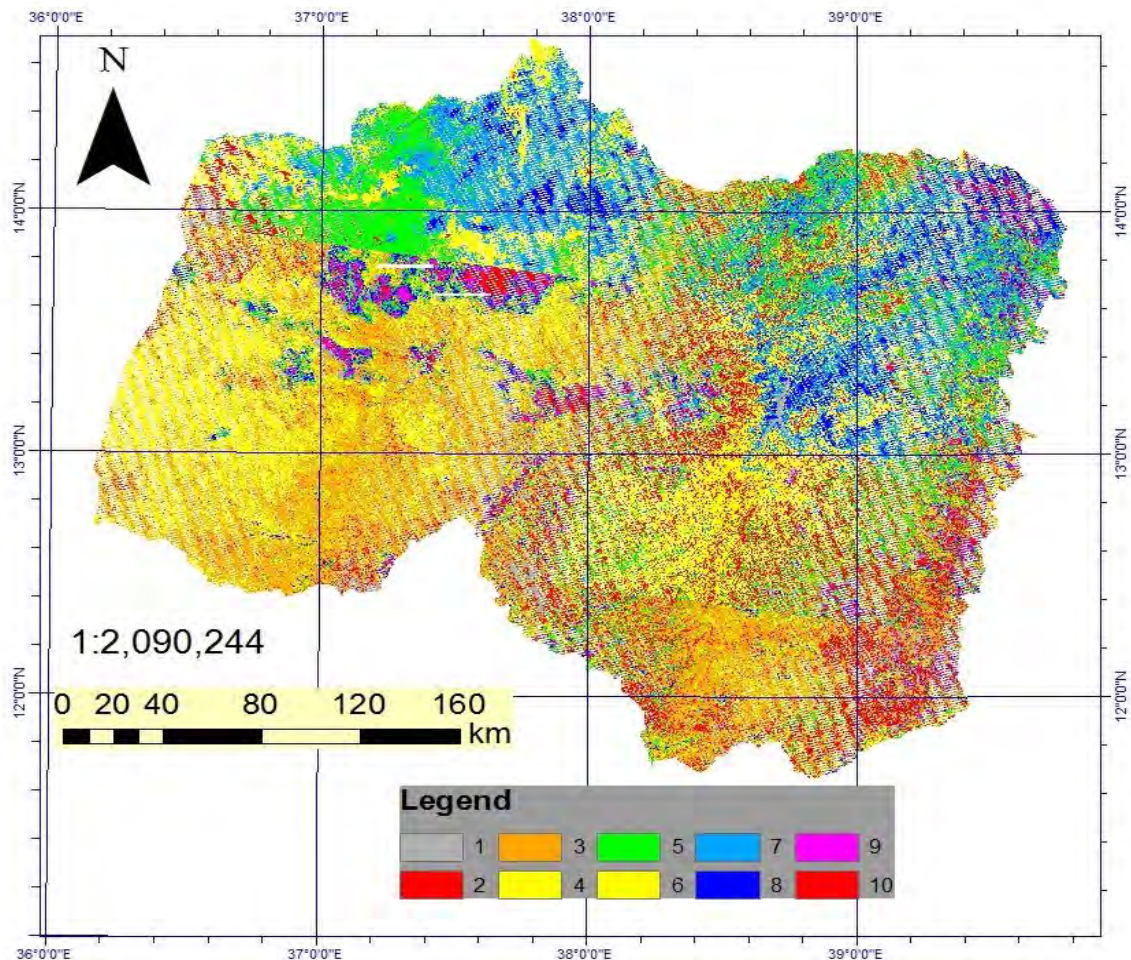


Figure: 8. Land use map classified by unsupervised classification method

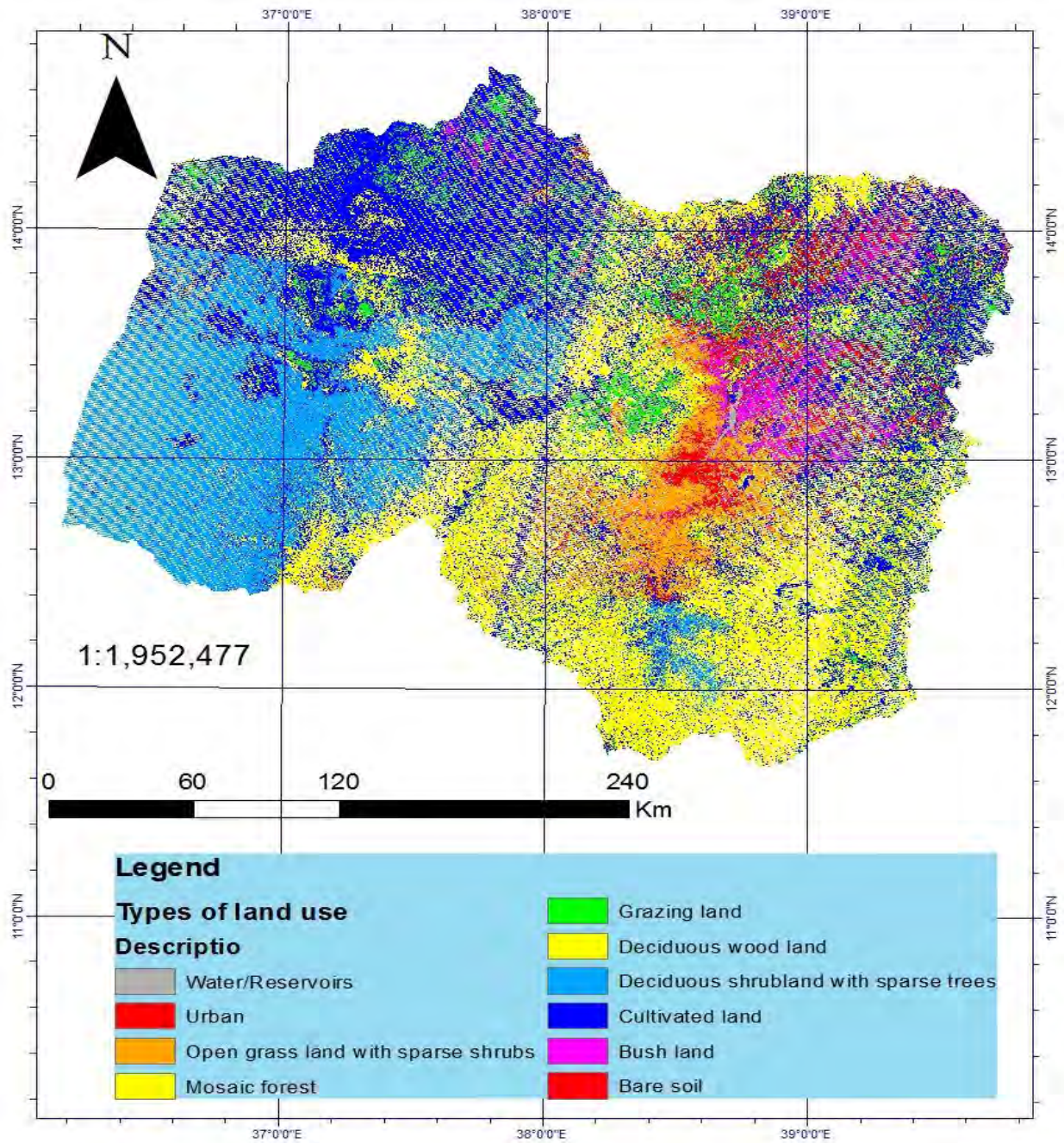


Figure: 9. Land use map classified by supervised classification method

3.4.3. Meteorological Data

The SWAT model requires daily meteorological data that could either be read from a measured data set or be generated by a weather generator model which include daily precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity. Daily precipitation and maximum and minimum temperature data, which were collected from National Meteorological Service Agency (NMSA), were used and for

solar radiation, wind speed and relative humidity, different monthly parameters were estimated using pcpSTAT and Dew point estimation program and sunshine hours was converted in to solar radiation energy (MJ/m²-day) using sunshine hour to radiation conversion tool which was created by Eric White, (2008) using the Angstrom –Prescott equation.

3.4.4. Weather Generator

Lack of full and realistic long period climatic data is the problem of developing countries. Weather generators solve this problem by generating data having the same statistical properties as the observed ones (Danuso, 2002). SWAT requires daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed. The user may choose to read these input from a file or generate the values using monthly average data summarized over a number of years.

SWAT includes the WXGEN weather generator model (Sharpley et al, 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 (Neitsch *et al.*, 2005)

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 (Neitsch *et al.*, 2005).

3.5. Hydrological Data

Daily river discharge data of the Yechila stations with 8 years of record data was obtained from the Hydrology Department of the Ethiopian Water Resource, Irrigation and Energy Ministry. This station was used for performing calibration and validation of the model from 1997-1999 and 2000-2002 respectively.

3.5.1. Outlier Tests for River Flow Data

Outliers are data points that depart significantly from the trend of the remaining data or outliers are peaks that depart substantially from the trend of the remaining peaks. The Water Resources Council method recommends that adjustments be made for outliers. The retention or deletion of these outliers can significantly affect the magnitude of statistical parameters computed from the data, especially for small samples. Procedures for testing outliers require judgment involving both mathematical and hydrologic considerations. According to the Water Resources Council (1981), if the station skew is greater than +0.4, tests for high outliers are considered first; if the station skew is less than -0.4, tests for low outliers are considered first. Where the station skew is between ± 0.4 , tests for both high and low outliers should be applied before eliminating any outliers from the data set (Chow, 1988).

The following frequency equation can be used to detect high outliers:

$$X_H = X_{av} + K_N S, \text{-----} 4.12$$

Where X_H = Logarithmic high-outlier test threshold,

S = standard deviation

K_N = 10-percent significance-level critical value for outlier test statistic for samples of size N from the normal distribution.

If the logarithms of values in a sample are greater than X_H in the above equations, then they are considered high outliers.

According to the Water Resources Council (1981), if information is available that indicates a high outlier is the maximum over an extended period of time, the outlier is treated as historic flood data and excluded from the analysis.

A similar equation can be used to detect low outliers:

$$X_L = X_{av} - K_N S \text{-----} 4.13$$

Where X_L = logarithmic low-outlier test threshold.

Flood peaks considered as low outliers are deleted from the record and a conditional probability adjustment described by the Water Resources Council (1981) can be applied.

During the outlier test for Yechila station, the station skew (G) was found to be -0.31 which is between ± 0.4 , so that tests for both high and low outliers were applied and the following results were obtained.

Table 3: Average annual river flow data at Yechila station

Year	Average flow(m ³ /s)	Logarithmic Value
1997	145.09	2.17
1998	525.01	2.72
1999	377.61	2.58
2000	214.71	2.33
2001	402.88	2.61
2002	108.91	2.04
Average		2.41
skew		-0.31
STDV		0.27

High outlier test, $X_H = X_{av} + K_N S$, $=2.41+2.036*0.272=2.959$, $X_H=10^{2.959}=909 \text{ m}^3/\text{s}$

And for low outlier test, $X_L = X_{av} - K_N S = 2.41-2.036*0.272=1.85$, $X_L=10^{1.85}=71.2 \text{ m}^3/\text{s}$

The outlier test result shows that, the largest recorded value(525 m³/s) does not exceed high outlier test threshold value(909 m³/s) and the smallest recorded value (108.9 m³/s) is not less than the low outlier test threshold value(71.2 m³/s), so both high and low outliers were not detected.

3.6. SWAT Model Set Up

3.6.1. Watershed Delineation

The first step in creating SWAT model input is delineation of the watershed from a DEM.

The SWAT model provides three spatial levels: the watershed, the sub-basins, and the hydrologic response units (HRUs). Each level was characterized by a parameter set and input data.

The watershed and sub-basin delineation was done using DEM data. Even though about one third (1/3) of the minimum suggested threshold area is recommended by the arc swat interface manual for a more detailed analysis of the hydrologic processes, 200ha was used for the delineation of the whole. From a minimum user defined threshold area of 200 ha, 548 sub-basins were delineated in the basin area of 82,824.094 km².

3.6.2. Hydrological Response Units

The HRU Analysis tool in Arc SWAT helped to load land use, soil and slope map to the project for HRU definition. Prepared land use and soil maps were loaded with percentage of overlap 100% and 99.95% respectively. For slope, the multiple slope option (an option which considers different slope classes for HRU definition) was selected. The LULC, soil and slope map was reclassified in order to correspond with the parameters in the SWAT database. After reclassifying the land use, soil and slope in SWAT database, all these physical properties were made to be overlaid for HRU definition and a total of 3,258 HRUs were obtained using 10% threshold value for land use, 5% for soil and 10% for slope.

The soil data base, which was obtained from “GIS-based hydrological zones and soil geo-database of Ethiopia (Belete et al, 2013)” was reclassified using Arc SWAT interface and the reclassified result is given in table 4.

Table 4: Reclassified soil by SWAT model

Soil type	Area(ha)	% of area	Soil type	Area(ha)	% of area
CHCAMBISOLS	6040.01	0.07	CHLUVISOLS	98587.84	1.21
EULEPTOSOLS	1711586.52	21.03	HUNITISOLS	251085.44	3.08
EUVERTISOLS	929848.42	11.42	DYLEPTOSOLS	276649.08	3.40
HPLIXISOLS	98408.27	1.21	CHCAMBISOLS	158082.86	1.94
EUCAMBISOLS	284923.14	3.50	CLREGOSOLS	787.15	0.01
LTLEPTOSOLS	2526309.62	31.04	VTCAMBISOLS	184791.22	2.27
HPLUVISOLS	1608060.04	19.76	PTCALCISOLS	4349.75	0.05

The reclassifications of the LULC in SWAT database were made and the descriptions are shown table 5.

Table 5: Land use and its respective SWAT codes

Land use type	SWAT code	Area(ha)	% ge of area
Agricultural Land-Close-grown	AGRC	1322147.56	16.24
Water	WATR	6245.84	0.08
Forest-Mixed	FRST	577561.32	7.10
Range-Brush	RNGB	1383497.29	17
Pasture	PAST	1256455.64	15.44
Wetlands-Mixed	WETL	500992.88	6.16
Range-Grasses	RNGE	489067.68	6.01
Wetlands-Non-Forested	WETN	226828.38	2.79
Agricultural Land-Generic	AGRL	2055405.87	25.25
Wetlands-Forested	WETF	54953.97	0.68
Residential-Med/Low Density	URML	266352.94	3.27

3.7. Calibration and Validation of SWAT Model

3.7.1. Calibration of Model

Calibration is the process whereby model parameters are adjusted to make the model output match with observed data. There are three calibration approaches widely used by the scientific community. These are the manual calibration, automatic calibration and a combination of the two. The manual calibration approach requires the user to compare measured and simulated values, and then to use expert judgment to determine which variables to adjust, how much to adjust them, and ultimately assess when reasonable results have been obtained (Gassman *et al.*, 2007). Coffey *et al.* (2004) presented nearly 20 different statistical tests that can be used for evaluating SWAT stream flow output during a manual calibration process. They recommended using the Nash-Sutcliffe simulation efficiency ENS and regression coefficients R^2 for analyzing monthly output, based on comparisons of SWAT stream flow results with measured stream flows for the same watershed.

Automated techniques involve the use of Monte Carlo or other parameter estimation schemes that determine automatically what the best choice of values are for a suite of parameters, usually on the basis of a large set of simulations, for a calibration process (Gassman *et al.*, 2007). Automatic calibration involves the use of a search algorithm to determine best-fit parameters. It is desirable as it is less subjective and due to extensive search of parameter possibilities can give results better than if done manually. The manual trial-and-error method of calibration is the most common and especially recommended for the application of more complicated models in which a good graphical representation is a prerequisite (Refsgaard *et al.*, 1996). However, it is very cumbersome, time consuming, and requires experience.

3.7.2. Validation of SWAT Model

In order to utilize any predictive watershed model for estimating the effectiveness of future potential management practices the model must be first calibrated to measured data and should then be tested (without further parameter adjustment) against an independent set of measured data. This testing of a model on an independent data set is commonly referred to as model validation. Model calibration determines the best or at least a reasonable, parameter set while validation ensures that the calibrated parameters set performs reasonably well under an independent data set. Provided the model predictive capability is demonstrated as being reasonable in the calibration and validation phase, the model can be used with some confidence for future predictions under somewhat different management scenarios (Dilnesaw, 2006).

3.7.3. SWAT-CUP

SWAT-CUP (Calibration and Uncertainty Procedures) is developed for integrating various calibration and uncertainty analysis programs of SWAT model. The program links, Sequential Uncertainty Fitting (SUFI-2), Generalized Likelihood Uncertainty Estimation (GLUE), Parameter Solution (PS), Mark chain Monte Carlo²⁰ (MCMC), and Particle Swarm

Optimization(PSO) procedures to SWAT models and it enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT model. For this study, various SWAT parameters related to stream flow discharge was estimated using the SUFI2 technique. SUFI-2 is the algorithm for calibration of SWAT model. GLUE is a common method for the global sensitivity analysis. SUFI-2 can provide the widest marginal parameter uncertainty intervals of model parameters among the five approaches. For this research, SUFI-2 was applied for sensitivity analysis, calibration and validation of the model.

This optimization technique uses the range of the parameters as constraints and seven (7) of the model evaluation coefficients as objective functions during calibration, they are

- 1) A multiplicative form of the square error (mult);
- 2) A summation form of the square error (sum);
- 3) Coefficient of determination (r^2);
- 4) Nash-Sutcliffe (1970) coefficient (NS);
- 5) Chi-squared χ^2 (Chi2);
- 6) Coefficient of determination R^2 multiplied by the coefficient of the regression line (br^2);
- and 7) sum of square of residual (SSQR). Only one objective function is used at a time during calibration time. In SUFI2 all of the objective functions are exist, there is also a possibility to improve the model evaluation coefficients by using different objective functions

3.7.4. SUFI-2

The parameter uncertainty is calculated from all the input and output source uncertainties such as the uncertainty in the input rainfall data, the user land use and soil type, parameters, and observed data, in SUFI 2. The simulation uncertainty is quantified by the 95% prediction uncertainty (95PPU) which is referred to as the p-factor. The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution function of the output variable obtained by Latin hypercube sampling.

The best calibration and parameter uncertainty is measured by the basis of the closeness of the p-factor to 100% (i.e. all the observations bracketed by the prediction uncertainty) and the r-factor to 1 (i.e., achievement of rather small uncertainty band). If the two factors are in satisfactory values, a uniform distribution in the parameter hypercube is explained as the following parameter distribution.

The goodness fit in SUFI-2 is quantified by the ($R^2 > 0.6$) and Nash-Sutcliffe (NS > 0.5) coefficient between the observation data and the best simulation.

3.7.5. Model Performance Evaluation

In order to evaluate the performance of SWAT model to determine the quality and reliability of prediction compared to the observed values, the following methods for goodness-of-fit measures of model predictions were used during the calibration and validation periods.

3.7.5.1. Nash-Sutcliffe Coefficient [NS]

Nash-Sutcliffe coefficient measures the efficiency of the model by relating the goodness-of-fit of the model to the variance of the measured data, Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 corresponds to a perfect match of simulated discharge to the observed data. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < NS < 0$) occurs when the observed mean is a better predictor than the model. Besides, due to frequent use of this coefficient, it is known that when values between 0.6 and 0.8 are generated, the model performs reasonably. A value between 0.8 and 0.9 tells that the model performs well and a value between 0.9 and 1 indicates that the model performs extremely well [Nash and Sutcliffe, 1970].

The formula for Nash Sutcliffe (NS) is:

$$E_{NS} = 1 - \frac{\sum_{i=1}^n (q_{oi} - q_{si})^2}{\sum_{i=1}^n (q_{oi} - \bar{q})^2} \text{-----4.14}$$

Where: E_{NS} : Nash-Sutcliffe coefficient, number of observed data points, q_{si} : simulated flow, q_{oi} : observed flow and q_o : average of observed flow.

3.7.5.2. Coefficient of Determination [R^2]

The coefficient of determination, denoted R^2 , it provides a measure of how well observed outcomes are replicated by the model. The range of R^2 lies between 0 and 1 which described how much of the observed desperation is explained by the prediction. A value of zero means no correlation at all; whereas one means that the desperation of the prediction is equal to that of the observation.

$$r^2 = \frac{\left[\sum_{i=1}^n (q_{si} - \bar{q}_s)(q_{oi} - \bar{q}_o) \right]^2}{\sum_{i=1}^n (q_{si} - \bar{q}_s)^2 \sum_{i=1}^n (q_{oi} - \bar{q}_o)^2} \text{-----4.15}$$

Where: R^2 : coefficient of determination, q_{si} : simulated flow, q_{oi} : observed flow and q_o : average of observed flow (SWAT-CUP 2012 user manual).The calibration and validation were performed using observed data from the year 1995 to 2002 Using SWAT SUFI2.

3.8. Assessment of Water Demands in the Basin

3.8.1. Method of Data Collection

For the assessment of water demands in the basin the following different secondary data were used.

- Rainfall, wind speed, relative humidity, sunshine hours, maximum and minimum temperature were collected from Ethiopian national meteorological service agency ,
- Number of population and annual water use rate for shire and 11 nearby towns were obtained from shire and nearby town water supply feasibility study report which was obtained from Tigray water resources bureau.

Monthly crop water requirement, irrigation area and annual water use rate data for irrigation demand sites are presented in Appendix table 13.

3.8.2. Method of Data Analysis

The various data which were used for the WEAP model to estimate water demands were, population data, total agricultural land area, agricultural monthly variation demands, water requirements per hectare for estimation of future water demands of Metema, Angereb, Humera and Wolkayte irrigation projects, and for existing Tekeze hydropower, head flow, storage capacity, initial storage, volume elevation curve, net evaporation from the reservoir, reservoir zoning, maximum turbine flow, tail water elevation, plant factor and generating efficiency

After collecting all required data, WEAP software was used to estimate for one existing and two planned hydropower water demand and future irrigation and domestic water demands in the basin. In WEAP software, the typical scenario modeling effort consists of three steps. First, a Current Account year, which is chosen to serve as the base year of the model; second, a reference scenario that is established from the current account to simulate likely evolution of the system without intervention; and third “what-if” scenarios created to alter the “reference Scenario” and evaluate the effects of changes in policies and/or technologies.

Geographical information system (GIS) was used to prepare the river networks of the study area.

WEAP model is structured in a way that the water resources system is represented in terms of river, groundwater, reservoirs withdrawals, transmission and wastewater treatment facilities, ecosystem requirements, and return flow. Other representations include flow requirements, runoff river hydrology, water demand sites and pollution (Sieber et al, 2005).

The model also consists of five main views, namely schematic, data, results, overviews and notes.

The raster files were prepared using GIS for the schematic view of the study area and the raster file was imported to the WEAP model as a background for schematic layers. Streams in the area were redrawn by using the interactive drag and drop button on the WEAP model.

Drag and drop method was used to create objects such as demand nodes, reservoir, transmission link, catchments, stream gauges and return flow, which were positioned within the study area.

The current account (baseline) year represent the basic definition of the water system as it currently exists. The year 2012 was selected as the starting year for all scenarios due to data availability for water demand, supply, irrigation and demographical information such as number of population and water needs per capita. As per the final prefeasibility report of shire and 11 nearby towns design document, 42litr/capita/day is needed and the estimated total population was 177, 999 in the year 2012.

Different water uses, including domestic, hydropower and agricultural takes place within the Tekeze basin and as population and economic activities increase, water demand also increases. This study estimated the water demand for medium hydropower water uses and also the study determined future water demands from large scale projects for various uses (i.e. Domestic and irrigation) in the basin.

In this study, Water Evaluation and Planning (WEAP) model is used to estimate future water demands for large scale planned projects in the river basin up to the year 2030. The water

demand estimation part was quantified water demand for irrigation and domestic water demand from planned and ongoing large scale projects in the basin for the next 16 years (i.e. 2015-2030).

The scenario considers constant supply and simulates the future water demand in the basin starting from 2012 to 2030 for Metema, Angereb, Humera, Wolkayte irrigation projects and Shire towns and its 11 nearby towns water supply project. For this research, population growth for domestic and improving irrigation efficiency for irrigation water demand were used for the estimation of future water demands.

3.8.3. Irrigation Water Demand

The agricultural sector is the leading sector in the Ethiopian economy, 47.7 percent of the total GDP, as compared to 13.3 percent from industry and 39 percent from services (World Bank 2005). Though agriculture is the dominant sector, most of Ethiopia's cultivated land is under rainfed agriculture. Due to lack of water storage and large spatial and temporal variations in rainfall, there is not enough water for most farmers to produce more than one crop per year and hence there are frequent crop failures due to dry spells and droughts which have resulted in a chronic food shortage currently facing the country.

Since the mid-1980s, the Ethiopian government has responded to drought and famine through promoting and construction of irrigation infrastructure aimed at increasing agriculture production. These are traditional, small, medium and large-scale irrigation schemes performing at different levels. Irrigation development has positive socio-economic and some negative environmental impacts. Formally accounted overall irrigation development is estimated at some 5 – 6 percent of the developable potential of 3.7 million ha. The irrigation area in year 2002 was 197,000 hectares with a coverage distribution of 38 percent traditional, 20 percent modern communal, 4 percent modern private and 38 percent public schemes (MoWR, 2002).

The revised figure puts the total irrigated area at about 250,000 hectares (Awulachew et al. 2005). This number gives a per capita irrigated area of about 30 m². This value is very small compared to 450 m² globally. The targeted growth expansion (according to the 2001 Water Sector Development Plan), is also not significant and not expected to bring a significant change and the much-needed economic growth.

In Ethiopia, the extent of irrigation development, the locations of developed schemes, their performances, their positive and negative roles and impacts towards food security, poverty alleviation, national economy, environment, etc., are not known.

While obtaining data on the potential of development is relatively easy, obtaining data and information on existing development, particularly for traditional and small-scale irrigation is very difficult, and in many cases not available (Seleshi, 2010).

For this study, it was difficult to get the whole irrigation demand sites due to the absence of one centralized source of information on existing or planned small, medium and large scale irrigation schemes in the basin. Most of the irrigation sites are small scale irrigation schemes that are implemented to attain the food security of rural peasants in the basin and the required data for the WEAP are not well known for all these irrigation schemes.

Since the water demands assessment of this study is limited to large scale projects, four large scale irrigation projects were identified and water demands for these irrigation demand sites were estimated. Currently there is no existing large scale irrigation project in the basin. Agricultural demand was projected to decrease over the next sixteen years as a result of better management of irrigation water in the basin.

3.8.4. Domestic Water Demand

The domestic water demand of the basin is increasing rapidly due to the high population growth in the basin. For domestic water demand estimation, shire and its 11 nearby towns were selected. For most of towns such as Mekele, the source of water supply is ground water.

There are also other water supply projects rivers as the source of water but, it was difficult to get the required data. Population growth rate of 4.3%, which was obtained from the prefeasibility study of shire and its nearby town's water supply project, was taken for the projection of population over the next 16 years. The model result showed that there will be an increase in domestic water demand over the next sixteen years. This is due to continuous population growth and the improvement of the standard of life which will result in an increased per capita use. For this study, the value of 42 liters per person per day proposed by prefeasibility study of shire and its nearby town's water supply project is used for estimating the water requirement for domestic use in the basin.

3.8.5. Hydropower Water Demand

In the basin, one existing hydropower (TK5) is currently available with installed capacity of 300MW and further five mini and medium hydropower projects were identified during the master plan study. Among these planned hydropower projects, two of them were selected based on their hydropower production (medium hydropower) and data availability for the estimation of hydropower water demand.

3.9. WEAP Model Input and Setup

3.9.1. Description of Water Evaluation and Planning (WEAP) Model

Water Evaluation and Planning (WEAP) was developed by the Stockholm Environment Institute (SEI) and is a unique water resources and planning software where it stimulates hydrologic pattern based on climatic input. This is a vital tool to inform the society on the adaptation of climate change towards the policy making. WEAP uses climatic inputs such as precipitation, temperature, humidity, infiltration, and wind speed. All these inputs can be derived from baseline scenarios, and used to predict the amount of precipitation that falls into

a particular area, run-off into streams, recharge of groundwater, or evapotranspiration through vegetation.

WEAP also allows user to build scenarios with scenarios, for instance, increase in temperature or heavier rainfall, along with assumptions towards water demand, infrastructure and regulation. All human activities can be incorporate in WEAP in order to predict water shortage and water quality base on a model scenario.

WEAP can be used to demonstrate the result of water demand quantity is met during a month, the degree of potential water shortage, level of reservoir storage for future use and measurement of water quality. WEAP also assesses the adequacy of environmental water flows, the level of hydropower generation capacity, the evolution of soil moisture, evapotranspiration rates, volume of surface run-off and the rate of groundwater recharge.

The WEAP model has a long history of development and used in the water planning arena (*SEI, 2001*). WEAP applications generally involve the following steps:-

- Problem definition including time frame, spatial boundary, system components and configuration;
- Establishing the ‘current accounts’, which provides a snapshot of actual water demand, resources, and supplies for the system;
- Building scenarios based on different sets of future trends based on policies, technological development and other factors that affect demand, supply and hydrology; and
- Evaluating the scenarios with regards to criteria such as adequacy of water resources, costs, benefits and environmental impacts.

WEAP has two (2) primary functions (*Sieber et al., 2005*):-

- Simulation of natural hydrological processes (e.g., evapotranspiration, runoff and infiltration) to enable assessment of the availability of water resources within a catchment; and
- Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (e.g., consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

3.9.2. WEAP Model Input

In WEAP, models are called “areas”. The background raster data of the study area, which was created by GIS software, was added to the model.

Once the area is open, the years, time steps and units are set. In this study, the current account is set to be year 2012 with the last year scenarios to year 2030. the time steps per year was set to be 12 and the time step boundary “based on calendar month”, starting with the month of January was selected.

The current account is the dataset from which the scenarios are built. A default scenario, the “reference scenario” carries forward the current accounts data into the entire project specified (2012-2030). River path was drawn in WEAP by clicking on the “river” symbol in the element window. Figure 10 shows the schematic view of river networks and demand sites for the study area.

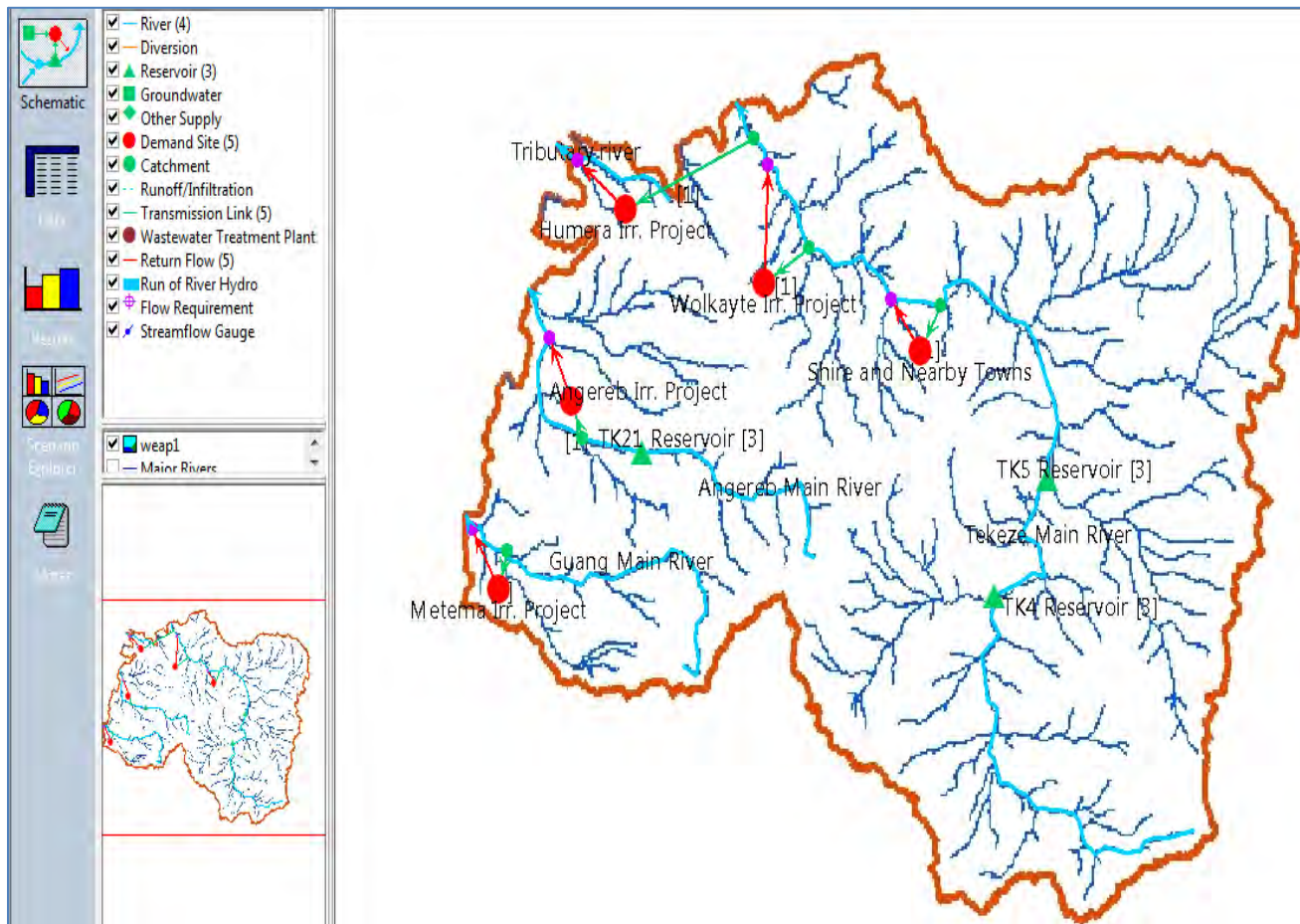


Figure: 10. Schematic view of the study area

3.9.3. Demand Sites

Five demand nodes (their purpose and locations were identified during master plan study) were created and the required data were imported to the model for each demand sites.

3.9.4. Connecting the Demand with Supply

In order to inform WEAP how the demand is satisfied, the water supply source (rivers) was connected to each demand sites. These were accomplished in the schematic view by adding the transmission link. The link was first positioned on the river, then pointing to each five demand nodes.

3.9.5. Creating the Return Flow Links

The return flow routing is the percent of total outflow from a demand node, and then the return flow routing for that link must be 100%. The return flow links were connected back to the rivers and return flow routing was set to be 100% so as to use the return flow for other demands effectively.

3.10. Data Sources, Analysis and Gap-Filling

To assess surface water potential, secondary data such as daily rainfall, maximum and minimum temperature, relative humidity, wind speed, sunshine hours, stream flow and soil were collected from responsible agencies such as Ethiopian National Meteorological Service Agencies, Ethiopian Water Resource, Irrigation and Energy Minister and from other sources. Missing daily rainfall, maximum and minimum temperature data were filled by using direct coefficient and regression methods respectively. Using meteorological and hydrological stations located in the nearby stations, provided that the stations are located in a hydrologically homogenous region, missing rainfall and temperature data were filled.

The most important and basic data with their sources are listed below.

1. Meteorological Data

- Daily rainfall, Temperature (maximum and minimum), humidity, wind speed and sunshine hours were collected from Ethiopian National Meteorological Service Agencies (NMSA).

2. Hydrological and GIS Data

- Stream flow and other necessary data were collected from the Hydrology Department of Ethiopian Water Resource; Irrigation and Energy Minister and topographic map of the study area were collected from GIS and Remote Sensing Department of Ethiopian Water Resource, Irrigation and Energy Minister.

3.10.1. Analysis of Meteorological Data

3.10.1.1. Analysis of Rainfall Data, Selection of Stations and Gap Filling

Generally, there is a scarcity of meteorological data in the study area. Rainfall data was collected from Ethiopian National Meteorological Service Agency for a total of 76 stations. The collected data are available for different periods at different stations ranging from 1971-2013. The longest continuous record period is 44 years (1971-2013) at Gondar airport station and the smallest continuous record period is 2 years at Gobgob station in 2012 and 2013. The longest record period with break is 44 years (1971-2013) at Gondar, Mekele, Shire Endessilasse, Maksegnit and Enticho stations. The smallest record period with break is 4 years at Sekota station. Among 76 rainfall gauging stations, 34 representative rainfall gauging stations with percentage of missing data $\leq 50\%$ have been selected and the remaining stations were not selected due to short period of record data, long break without data and recently installed instruments with only one and two year recorded data. Almost for all stations in the basin, the data from 1989-1993 is not available and it is difficult to get the nearby stations to fill this gap for the above mentioned period. Due to unavailability of data from 1989-1993 and by analyzing percentage of missing data and the number of stations to be used, assessment of surface water potential in the basin has been estimated for 20 years (i.e. 1994-2013). Among 34 stations, 30 stations have been selected as representative stations and the others were used to fill missing data and only 20 stations were selected by the SWAT model.

Most of the selected stations are within the basin and some of them, which were selected for the gap filling, are outside of the basin with the same climatic zone as the Tekeze River Basin. The selected gauging stations have no fully record data, some stations have less number of years of record that needs to be extended and other stations have missing data that need to be filled.

Direct coefficients were obtained for selected representative stations by selecting nearby stations with similar daily average rainfall for the same data available period. By using these coefficients, missing daily rainfall data was filled and extended. In order to select the representative rainfall gauging stations, the percentage of missing data and the number of stations were analyzed and the final comparisons are summarized below.

Table 6: Percentage of missing data and number of stations

Proposed years	Number of	Percentage of missing data	Number of rainfall recording stations
25(1989-2013)		≤50%	29
		≤40%	23
		≤30%	18
		≤20%	14
		≤10%	9
		≤5%	4
		≤0%	4
20(1994-2013)		≤50%	34
		≤40%	29
		≤30%	26
		≤20%	21
		≤10%	16
		≤5%	12
		≤0%	7
15(1999-2013)		≤50%	43
		≤40%	38
		≤30%	33
		≤20%	29
		≤10%	17
		≤5%	4
		≤0%	4

3.10.1.2. Consistency of Rainfall Recording Stations

If the conditions relevant to the recording of a rain gauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station.

The double mass curve analysis is a consistency check used to detect whether the data at a site have been subjected to a significant change in magnitude due to external factors such as tempering with the instrument, change in the recording conditions or shift in the observation practices.

If the data are consistent, the plot will be a straight line. On the other hand, inconsistent data will exhibit a change in slope or break at the point where the inconsistency occurred. Double mass curve analysis was carried out for 34 rainfall stations in the basin. The curves show that all stations are consistent according to the criteria set above.

After the missing periods (year, month and day) have been identified, the direct coefficient has been obtained by estimating average monthly rainfall, average number of rainy days and average daily rainfall per rainy days for each selected stations and the missing data have been filled using these coefficients. After identifying stations with approximately equal average daily rainfall per rainy days, direct coefficients were obtained for all stations.

Sample direct coefficient estimation: a direct coefficient between Lalibela and Ibnat stations for overall average daily rainfall is obtained as follow:

Average daily rainfall of Lalibela station/ Average daily rainfall of Ibnat station= $5.39/7.57=0.712$ and the same procedure was applied for all stations.

Sample details of average monthly rainfall, average number of rainy days, average daily values per rainy day and direct coefficients are given in table 7 and direct coefficients for all stations are presented in table 8.

Table 7: Sample daily rainfall details for Lalibela and Ibnat Stations

Station name	1998-2005	Average Monthly Rainfall	Average number of rainy days	Average daily rainfall per rainy days
	Month			
Lalibela	January	8.825	2.5	3.53
	February	12.45	2.5	4.98
	March	38.20	7	5.36
	April	29.24	6	4.99
	May	15.71	3	4.66
	June	46.03	8	5.66
	July	280.78	28	10.03
	August	273.55	25	10.78
	September	44.59	11	3.92
	October	16.91	4	4.23
	November	6.25	2	4.17
	December	3.88	2	2.38
Total		776.415	101	64.69
Average daily rainfall per rainy days/month				$64.69/12=5.39$
Average daily rainfall for Lalibela / Average daily rainfall for Ibnat				$5.39/7.57=0.712$
Ibnat	January	5.89	1	5.89
	February	8.83	1	8.83
	March	17.00	5	3.68
	April	12.49	3	4.54
	May	36.03	5	7.21
	June	136.21	13	10.59
	July	313.55	26	12.12
	August	270.56	23	11.96
	September	91.36	12	7.69
	October	43.66	5	8.26
	November	10.64	1	8.28
	December	1.82	1	1.82
Total		948.04	96	90.87
Average daily rainfall per rainy days/month				$90.87/12=7.57$

Table 8: Direct coefficients for rainfall data gap filling

S. No	Station Name	Name of the station used to fill the gap	Direct coefficient	Remark	S. No	Station Name	Name of the station used to fill the gap	Direct coefficient	Remark
1	Humera	Aykel	0.76	Filled	18	Kulmesk	Lalibela	0.99	Filled
		Adiremets	0.68	Filled			Korem	0.74	Filled
2	Lalibela	Ibnat	0.712	Filled	19	Tikil dengay	Gondar	1.46	Filled
3	Metema	Aykel	0.987	Filled	20	Adiremets	Shire Endasilasse	3.03	Filled
4	Adwa	Abi-adi	0.628	Filled			Ashere	2.5	Filled
5	Mekele	Abi-adi	0.591	Filled	21	Ashere	Aykel	1.04	Filled
6	Shire – Endasilas	Abi-adi	0.676	Filled			Adiremets	0.4	Filled
7	Adidaro	Shire Endasilasse -	1.526	Filled	22	Chenek	Ambagiorgies	0.76	Filled
		Abi-adi	1.047	Filled	23	Mekane Birhane	Ambagiorgies	0.76	Filled
8	Adigudom	Mekele	1.34	Filled			Chenek	1.01	Filled
9	Ambagiorgies	Gondar	1.07	Filled	24	Edagaselus	Abi-Adi	0.75	Filled
10	Aseged	Shire Endasilasse -	1.19	Filled			Adwa	1.14	Filled
11	Dengolet	Samre	0.92	Filled	25	Senkata	Wukiro	0.94	Filled
12	Samre	Dengolet	1.09	Filled			Adigrat	1.06	Filled
13	Selehlehe	Shire Endasilasse -	1.42	Filled	26	Estaysh	Kulmesk	1.41	Filled
14	Wukiro	Atsebi	0.93	Filled			Korem	1.04	Filled
15	Atsebi	Wukiro	1.07	Filled	27	Ibnat	Debre tabor	0.97	Filled
16	Asketema	Lalibela	1.33	Filled	28	Adishehu	Maichew	0.99	Filled
17	Aykel	-----	-----		29	Endabaguna	Shire Endasilasse	1.21	Filled
					30	Abi-Adi	Mekele	1.694	filled

In order to check the method that has been used for filling missing data, a station with a full recorded data (i.e. Aykel) was selected and the data was filled by considering as a missing data and the result showed missing data filling method is somewhat acceptable.

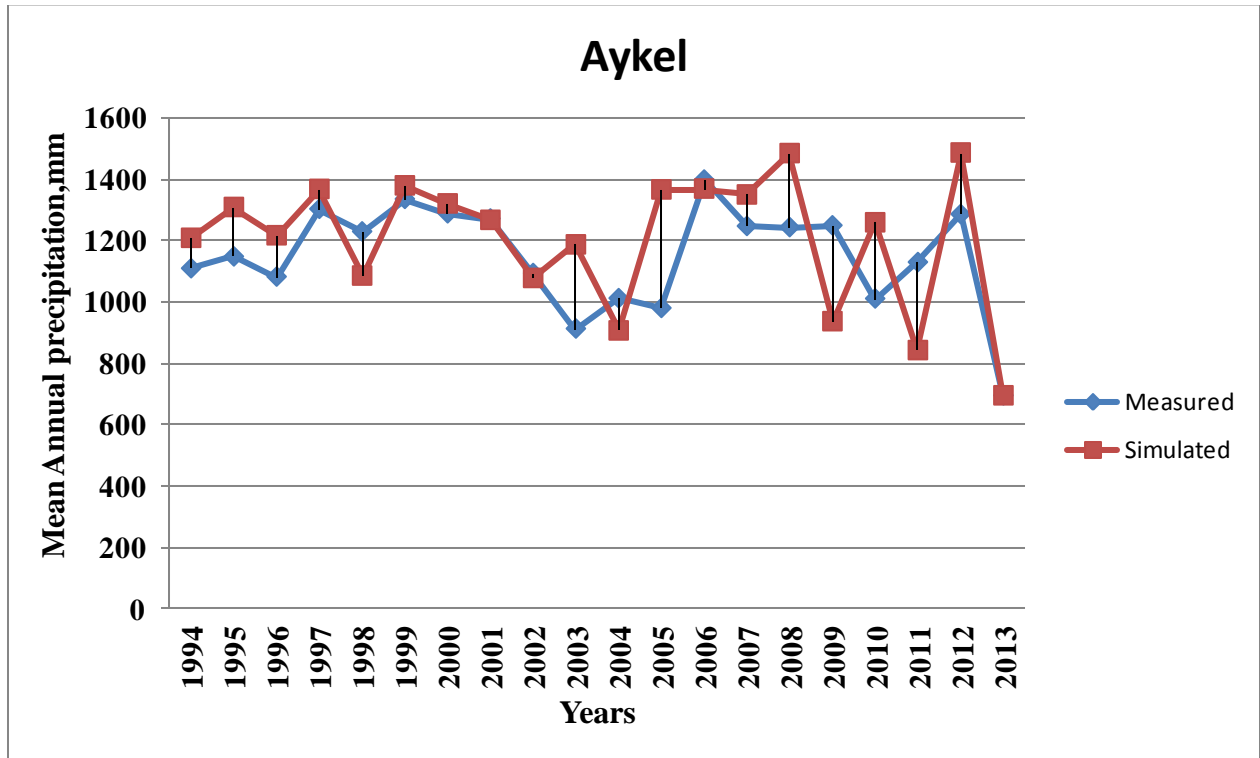


Figure: 11. Simulated verses observed rainfall at Aykel station

3.11. Rainfall Trend Analysis

After plotting a time series, one must be sure that there is no correlation between the order in which the data have been collected and the increase or decrease in magnitude of those data. Trend analysis of rainfall data series for 1994-2013 has been done using Spearman's Rank Correlation method. According to Spearman's Rank Correlation method, the time series has no trend if: $t [v, 2.5\%] < t_t < t [v, 97.5\%]$. Where v is degrees of freedom and t is the probability of rejecting the null hypothesis given that it is true. During test for absence of trend, this condition was unsatisfied and the presence of downward trend is detected.

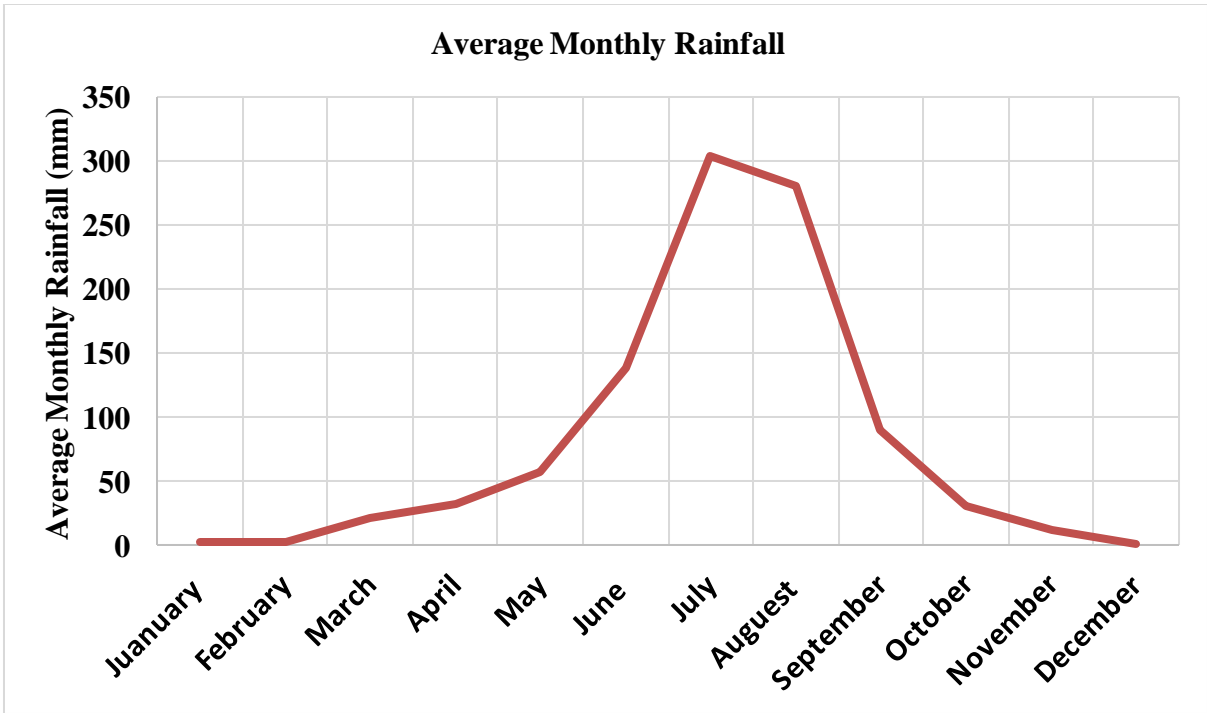


Figure: 12. Average monthly rainfall (i.e. 1994-2013) in the basin

As the result shows, there is a downward trend in rainfall amount in the basin from 1994-2013 and this downward trend also mentioned in the Tekeze River Basin Integrated Development Master Plan study.

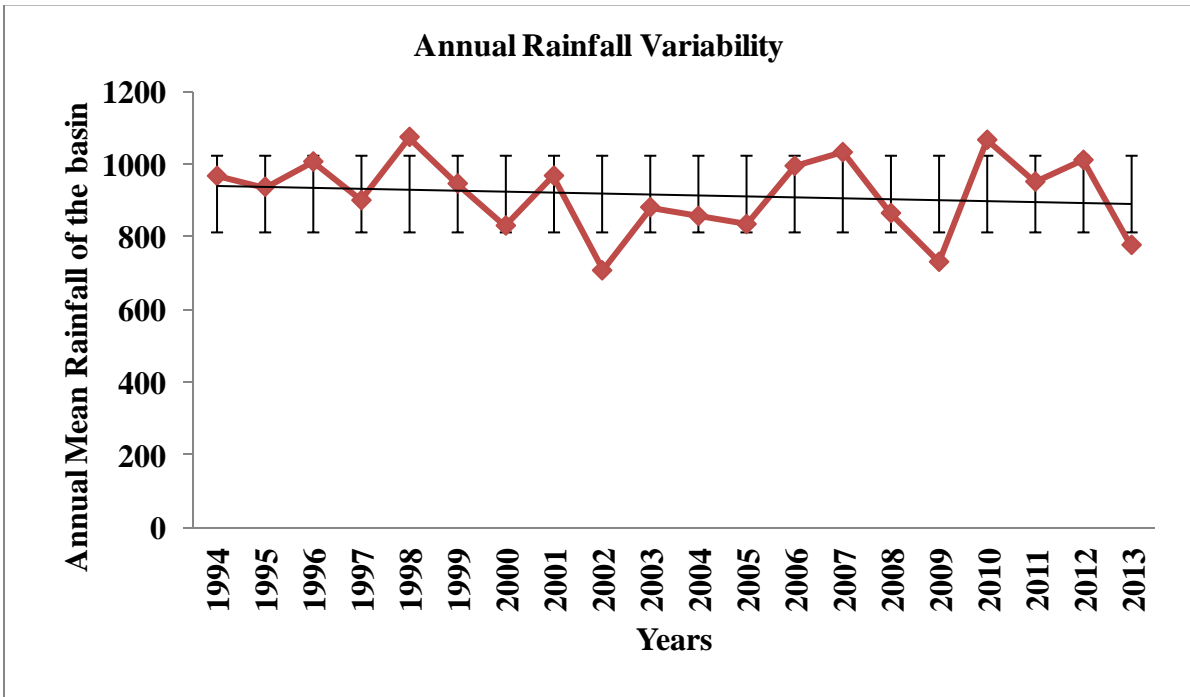


Figure: 13. Annual rainfall trend in the basin

3.12. Temperature Data Analysis, Selection of Stations and Gap Filling

By applying the same procedure, which has been done for rainfall data gap filling, 13 representative meteorological stations were selected. Even though the most nearest stations and the missing periods have been identified, the missed data were not filled using these nearest stations because of the missing data period is the same for all stations. Average daily maximum and minimum temperature values for consecutive available recorded period for each station were calculated and the stations with almost similar average daily maximum and minimum temperature values were selected and linear regression equations for both maximum and minimum temperatures were developed. The missing maximum and minimum temperature values for the selected representative stations were filled by selecting stations with the best correlation value (R^2) and the regression equations are summarized below. Figure 14 and 15 indicate both maximum and minimum temperatures are increasing from 1994 to 2013 in the basin.

Table 9: Regression equations to fill missed temperature data

S. no.	Station name	Regression equation for daily maximum temperature	Regression equation for daily minimum temperature	Remark
1	Humera	$= 0.7539x(\text{Metema}) + 10.607$ $R^2 = 0.8615$ $\text{Humera (y)} = 1.22x(\text{Adwa}) + 3.409$ $R^2 = 0.8083$	$y = 1.022x (\text{Metema}) + 0.0075$ $R^2 = 0.795$ $\text{Humera (y)} = 0.9608x (\text{Adwa}) + 7.8$ $R^2 = 0.6534$	Filled
2	Adwa	$\text{Adwa(Y)} = 0.8998x(\text{Lalibela}) + 5.803$ $R^2 = 0.88$	$\text{Adwa(Y)} = 1.5617x(\text{shire}) - 9.3134$ $R^2 = 0.9263$	Filled
3	Adiremets	$\text{Adiremets (y)} = 0.4876x(\text{Ambagiorgies}) + 4.2826$ $R^2 = 0.6794$	$\text{Adiremets(y)} = 0.67x(\text{Ambagiorgies}) + 7.7712$ $R^2 = 0.7888$	Filled
4	Aykel	$y = 1.0177x(\text{Gondar}) - 4.2771$ $R^2 = 0.9581$	$Y = 1.0248x(\text{Lalibela}) + 0.1885$ $R^2 = 0.7653$	Filled
5	Lalibela	$y = 0.8498x(\text{Aykel}) + 4.4142$ $R^2 = 0.8138$	$y = 1.0248x(\text{Aykel}) + 0.1885$ $R^2 = 0.7653$	Filled
6	Metema	$y = 0.9144x(\text{May-Tsebri}) + 6.2361$ $R^2 = 0.886$ $y = 1.1427x(\text{Humera}) - 7.2012$ $R^2 = 0.8615$	$y = 0.7779x(\text{Humera}) + 4.0204$ $R^2 = 0.795$	Filled
7	Gondar	$\text{Gondar (y)} = 0.8992x(\text{Aykel}) + 5.83$ $R^2 = 0.9755$	$\text{Gondar(y)} = 0.9595x(\text{Ambagiorgies}) + 5.8497$ $R^2 = 0.8$	Filled
8	Mekele	$\text{Mekele(Y)} = 1.0239x(\text{wukiro}) - 4.76$ $R^2 = 0.8229$	$\text{Mekele(Y)} = 0.5561x(\text{Adwa}) + 4.7792$ $R^2 = 0.9392$	Filled
9	Shire - Endassilase	$y = 0.884x (\text{Gondar}) + 3.0052$ $R^2 = 0.8505$	$y = 1.0725x(\text{Gondar}) - 0.8009$ $R^2 = 0.8272$	Filled
10	Abi-Adi	$y = 0.8461x(\text{Adwa}) + 5.6886$ $R^2 = 0.9138$	$y = 0.8703x(\text{Gondar}) + 0.8027$ $R^2 = 0.7385$	Filled
11	Ambagiorgies	$\text{Ambagiorgies (y)} = 0.4403x(\text{Aykel}) + 8.4977$ $R^2 = 0.6577$	$\text{Ambagiorgies(y)} = 0.8657x(\text{Gondar}) - 3.6571$ $R^2 = 0.8307$	Filled
12	Wukiro	$\text{Wukiro (y)} = 0.8037x(\text{Mekele}) + 8.75$ $R^2 = 0.8229$	$\text{Wukiro (y)} = 0.887x (\text{Maichew}) + 1.33$ $R^2 = 0.9365$	Filled
13	May -Tsebri	$y = 0.9689x(\text{Metema}) - 2.391$ $R^2 = 0.886$	$y = 0.6289x(\text{Humera}) + 5.527$ $R^2 = 0.7802$	Filled

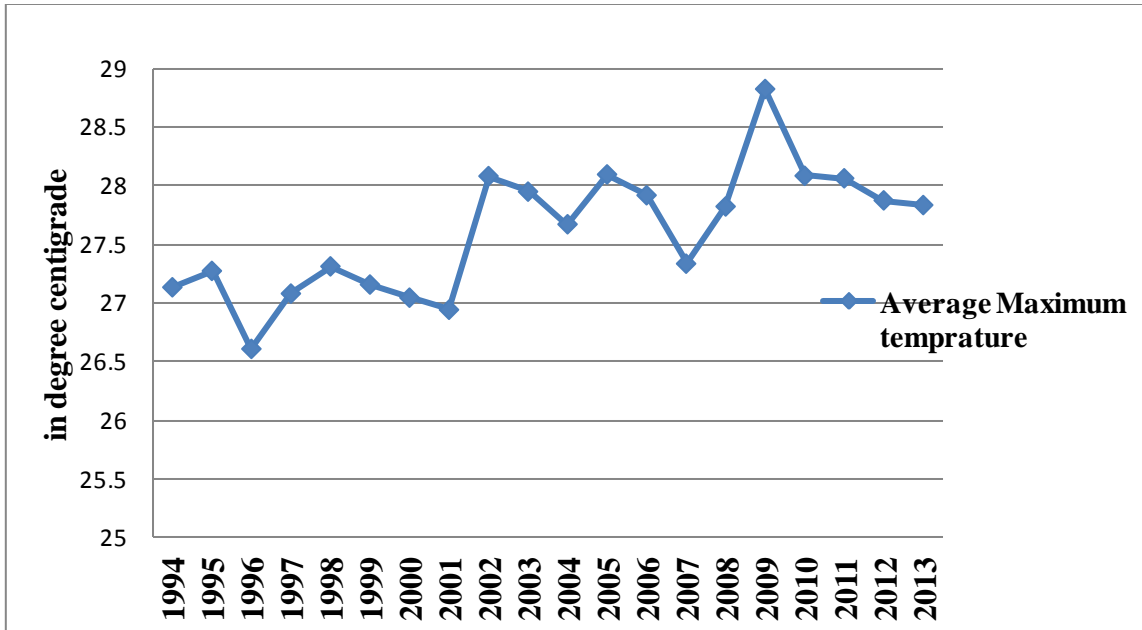


Figure: 14. Average annual maximum temperature variability (1994-2013) in the basin

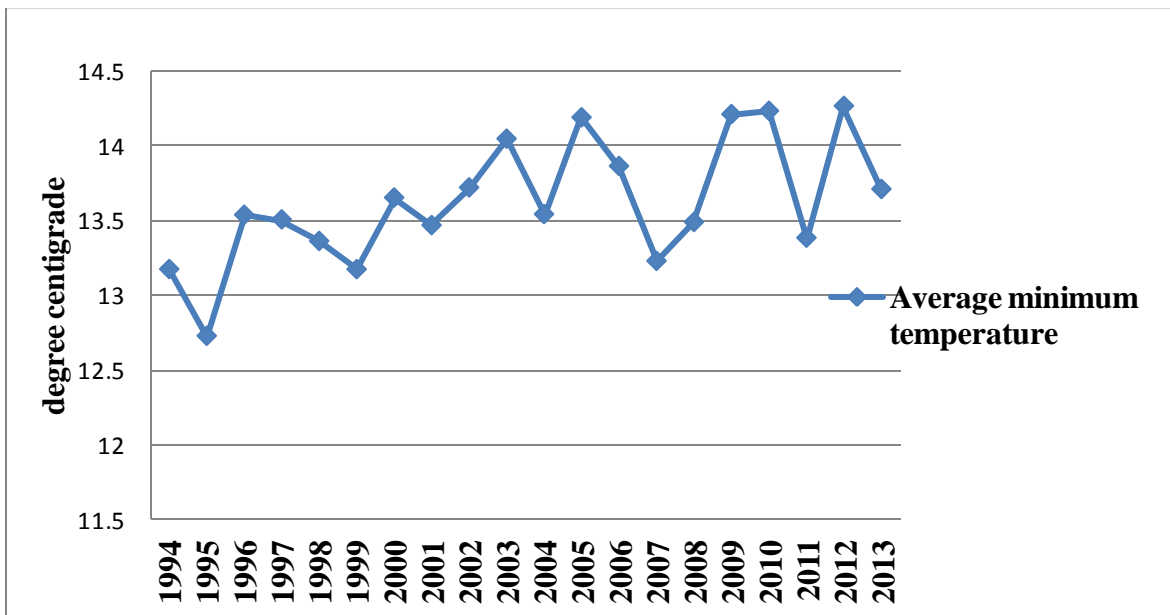


Figure: 15. Average annual minimum temperature variability (1994-2013) in the basin

3.12.1. Wind Speed, Sunshine Hours and Relative Humidity Data Analysis

For wind speed, sunshine hours and relative humidity, the recorded available data are for short period of time and it is impossible to fill and extend the missing data. For SWAT model, recorded data of precipitation and temperature was used and for wind speed, sunshine

hours and relative humidity, necessary monthly parameters for the weather generator were calculated using dew point and PCPstat for Gondar, Metema and Lalibela stations and the results are available in appendix table 18.

Data for wind speed, sunshine hours and relative humidity, which have been collected from Ethiopian National Meteorological Service Agency, are summarized in the table below.

3.12.2. Relative Humidity

Table 10: Relative humidity data

S. No	Station Name	Length of recording years	Number of years with recorded data	periods of years without recorded data	Number of years of missing data	Percentage of missing
1	Hummera	(1975-2000)	9	<ul style="list-style-type: none"> • 1976 - 1980 • 1989 - 2000 	17	54.5%
2	Lalibala	(1992-2005)	14	-----	0	0%
3	Metema	(1987-2007)	15	<ul style="list-style-type: none"> • 1989 - 1993 • 1996 	6	28.6%
4	Debark	(1993-2007)	15	-----	0	0%
5	Debre Tabor	(1988-2008)	18	<ul style="list-style-type: none"> • 1990 - 1991 	3	14.3%
6	Gondar	(1970-2004)	31	<ul style="list-style-type: none"> • 1998 - 2001 • 2004 	4	11.4%
7	Aykel	(1988-2008)	18	<ul style="list-style-type: none"> • 1991 • 1994 • 2008 	3	14.3%

3.12.3. Sun shine hours

Table 11: Sunshine hour data

S. No.	Station Name	Length of recording years	S. No.	Station Name	Length of recording years	S. No.
1	Lalibala	(2010-2013)	2	• 2001,2013	2	50%
2	Adwa	(2011-2013)	2	• 2012	1	33.33%
3	Debark	(2011-2013)	2	• 2013	1	33.33%
4	Debre Tabor	(2011-2013)	3	• -----	0	0%
5	Gondar	(1986-2013)	14	• 1999 • 2001-2002 • 2004-2012	14	50%

3.12.4. Wind speed

Table 12: Wind speed data

S. No.	Station Name	Length of recording years	Number of years with recorded data	periods of years without recorded data	Number of years of missing data	Percentage of missing
1	Lalibala	(1989-2005)	7	• 1990-1996	10	58.8%
2	Metema	(1987-2005)	12	• 1990-1996	7	36.8%
3	Adwa	(1992-2006)	11	• 1995,2001	4	26.7%
4	Debark	(1992-2005)	13	---	1	7.1%
5	Debre Tabor	(1988-2005)	15	• 1999	3	16.67%
6	Gondar	(1981-1998)	5	• 1995-1997	13	72.22%
7	Shire endassilasse	(1992-2013)	12	• 1996 • 2005-2012	10	45.5%

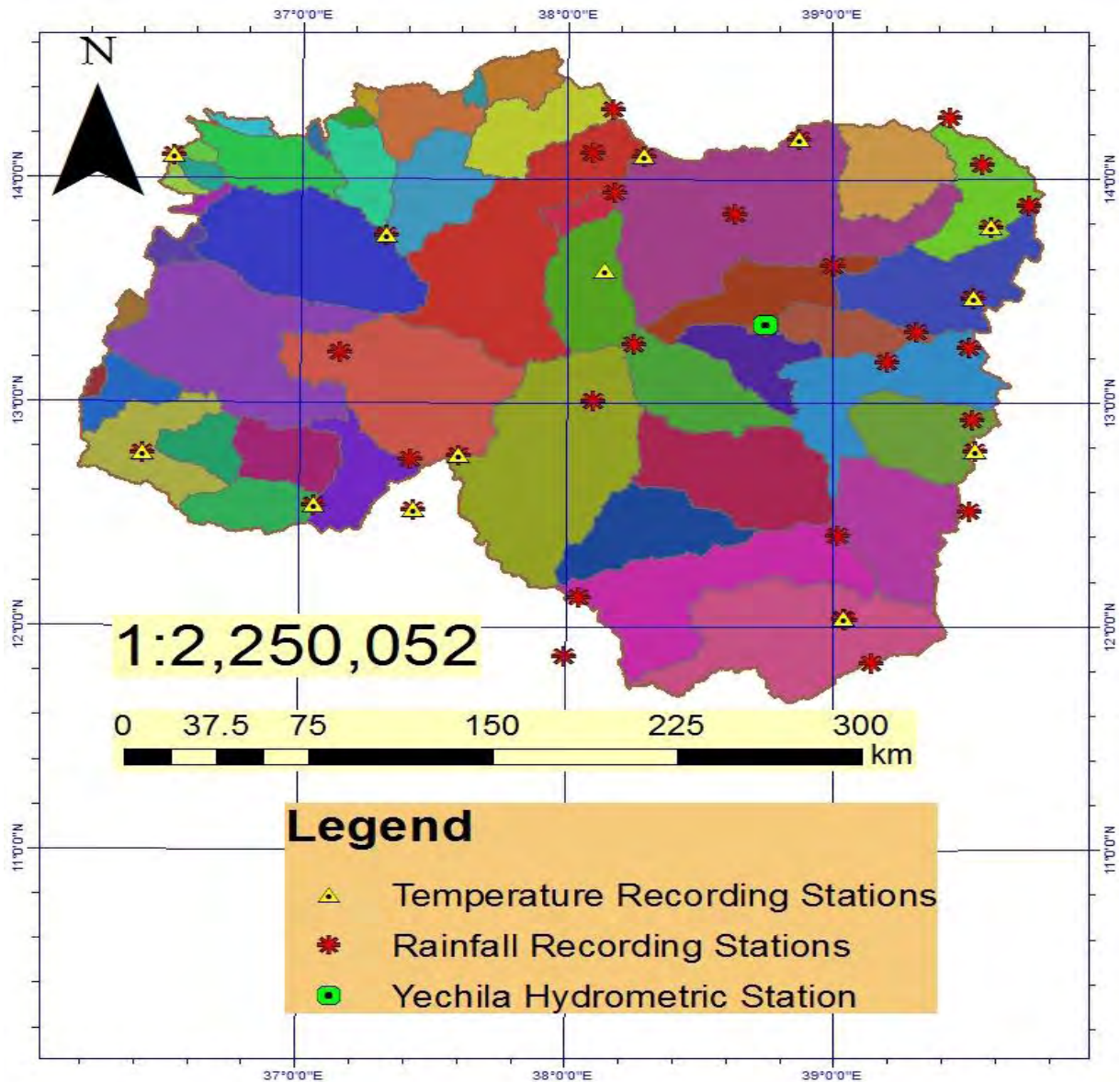


Figure: 16. Locations of selected meteorological and hydrometric stations

3.13. Analysis of Daily Flow Data

The existing flow data obtained from the Hydrology Department of Ethiopian Water Resource, Irrigation and Energy Ministry is measurements taken at different hydrometric stations. Among all stations, Tekeze near Yechila has 8 years of data and used for calibration and validation of the SWAT model. The model was calibrated and validated for the available flow data from 1995-2002. Even though 12 hydrometric stations at different locations have been collected, only Yechila station has a good flow data and it was used for model

calibration and validation from 1997-1999 and 2000-2002 respectively and the first two years (i.e.1995-1996) were used for model warm up or initialization. The location of Yechila station is obtained in figure 16. Table 13 shows daily flow data of all gauging stations in the basin.

Table 13: Daily flow data at different stations

S. No.	Location of gauging station	periods of available daily runoff data	Catchment area (km ²)	periods of years without recorded data	Period of data availability with break	Selected period for calibration and validation
1	Tekeze @yechila	1994-2002	28,152	(2)1994 and 2003	1994	1995-2002=8
2	Suluh nr. hawsien	1994-1999	399	1994-1999	-----	1994-1999=6
3	Metere Nr.Aaynalem	1994-2001	69	1994-1998 2000-2001	1999	1994-1998=5
4	Lake ashenge near korem	1994-2000	129	1994-1995 1998-2000	1996-1997	1998-2000=3
5	Gheba@Adikumsi	1999-2003	4,342	1999-2003	-----	1999-2003=5
6	Worie near maikental	1998-1999	1,770	1998-1999	----	1998-1999=2
7	Genfel at wukiro	1998-2002	481	1998-2002	-----	1998-2002=5
8	Ayehida near axum	1998-2006	No data	1999-2004	----	1999-2004=6
9	Atsela near adishihu	1994-1999	81	1994-1999	-----	1994-1999=6
10	Zarema@zarema	1994-1999	3,259	1994-1999	-----	1994-1999=6
11	Agula near agula	1995-2002	No data	1995-1997 1999-2002	1998 2000	1995-1997=3
12	Tekeze Nr. embamadre	1995-2001	45,694	1995-2001	----	1995-2001=7

CHAPTER FOUR

4. Results and Discussions

4.1. Sensitivity Analysis, Model Calibration and Validation

4.1.1. Sensitivity Analysis

Sensitivity analysis was performed on 14 SWAT parameters and the most sensitive parameters were identified using Global sensitivity analysis method in SWAT-CUP SUFI2. Parameter sensitivities were determined by calculating the following multiple regression system, which regresses the Latin hypercube generated parameters against the objective function values (in file goal.sf2):

$$g = \alpha \sum_{i=1}^m \beta_i b_i \text{-----} -6.1$$

A *t*-test is then used to identify the relative significance of each parameter *b_i*. The sensitivities given above are estimates of the average changes in the objective function resulting from changes in each parameter, while all other parameters are changing. This gives relative sensitivities based on linear approximations and information about the sensitivity of the objective function to model parameters. T-stat provides a measure of sensitivity (larger in absolute values are more sensitive) p-values determined the significance of the sensitivity.

A value close to zero has more significance.

Based on the Global sensitivity analysis, CN2, ESCO, SOL_K, SOL_AWC, SOL_Z, ALPHA_BF, GW_DELAY, GWQMN, GW_REVAP, REVAPMN, BIOMIX, EPCO, SOL_ZMX and SOL_ALB) were found the most sensitive parameters. The most sensitive parameters are listed starting from the lowest sensitive parameter to the highest parameter.

Table 14: Most sensitive parameters

Parameter Name	t-Stat	P-Value	Parameter Name	t-Stat	P-Value
14:R__REVAPMN.gw	-0.0022	0.998	7:R__ALPHA_BF.gw	-1.352	0.234
13:R__SOL_K (1).sol	0.1289	0.902	6:R__GW_REVAP.gw	1.622	0.166
12:R__SOL_ZMX.sol	0.2467	0.815	5:R__SOL_Z (1).sol	1.651	0.159
11:R__GW_DELAY.gw	-0.9725	0.376	4:R__ESCO.bsn	-1.685	0.153
10:R__SOL_ALB (1).sol	-1.0087	0.359	3:R__EPCO.bsn	1.777	0.136
9:R__BIOMIX.mgt	1.0473	0.343	2:R__CN2.mgt	1.871	0.120
8:R__GWQMN.gw	-1.1129	0.316	1:R__SOL_AWC (1).sol	3.271	0.022

4.2. Model Calibration and Validation

Model calibration and validation were done using SUFI2 with the objective function of R^2 and the numbers of simulations were more than 700 and the results are presented below.

4.2.1. Model calibration

Calibration for stream flow was first done for average monthly time step using SWAT-CUP. After the model was calibrated for average monthly conditions, the calibration was also done on daily time step. Initial simulation was first made using default parameter values assigned by the model and the values between observed and simulated stream flow at the outlet of sub basin number 28 was below the accepted range. The model was run for a period of five years from January 1, 1995 to December 31, 1999. The first two years (1995 to 1996) were used for stabilization of model runs (warm up period). The calibration was therefore performed for a period of three years (January 1, 1996 to December 31, 1999) on monthly and daily bases. After a number of simulations, the monthly calibration results for R^2 and NS were 0.82 and

0.81 respectively which are beyond the acceptable ranges (fig 17). R^2 and NS values on daily time step were found to be 0.54 and 0.53 respectively.

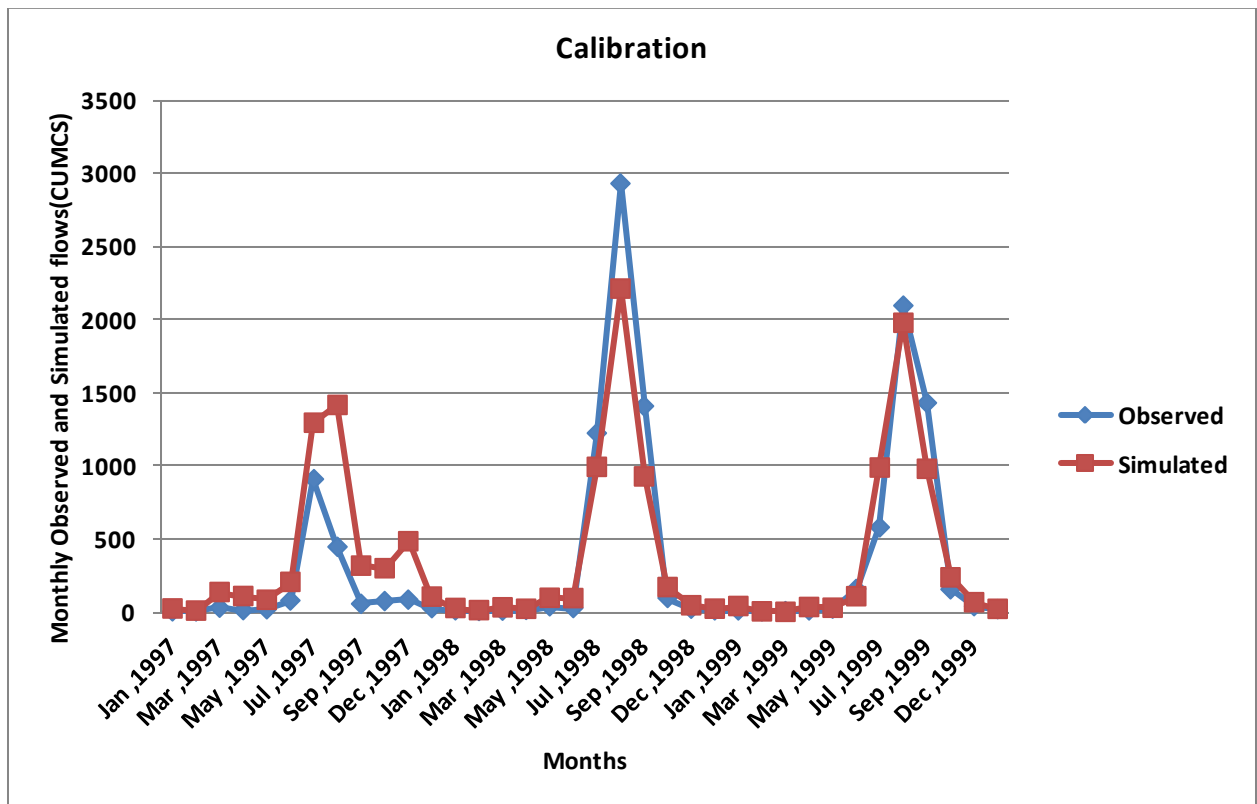


Figure: 17. Monthly flow plot for calibration period

The result shows that, SWAT can be used for the assessment of surface water flow at the monthly time step of the basin. The daily stream flow calibration result was found to be unsatisfactory which was failed to meet especially the requirement of $r^2 > 0.6$.

4.2.2. Model validation

For model validation, the model was run for a period of three years from January 1, 2000 to December 31, 2002. During validation, statistical model efficiency criteria were fulfilled the requirement of $R^2 > 0.6$ and $NS > 0.5$ which was recommended by SWAT developer in (Santhi *et al.*, 2001). The model validation results on monthly time step shows a good relationship between measured and simulated results (fig18) and the results of R^2 and NS values were 0.7 and 0.63 respectively. However, unsatisfactory performance of SWAT model

in daily validation was obtained which was failed to meet statistical model efficiency criteria with r^2 and NS values of 0.47, 0.41 respectively.

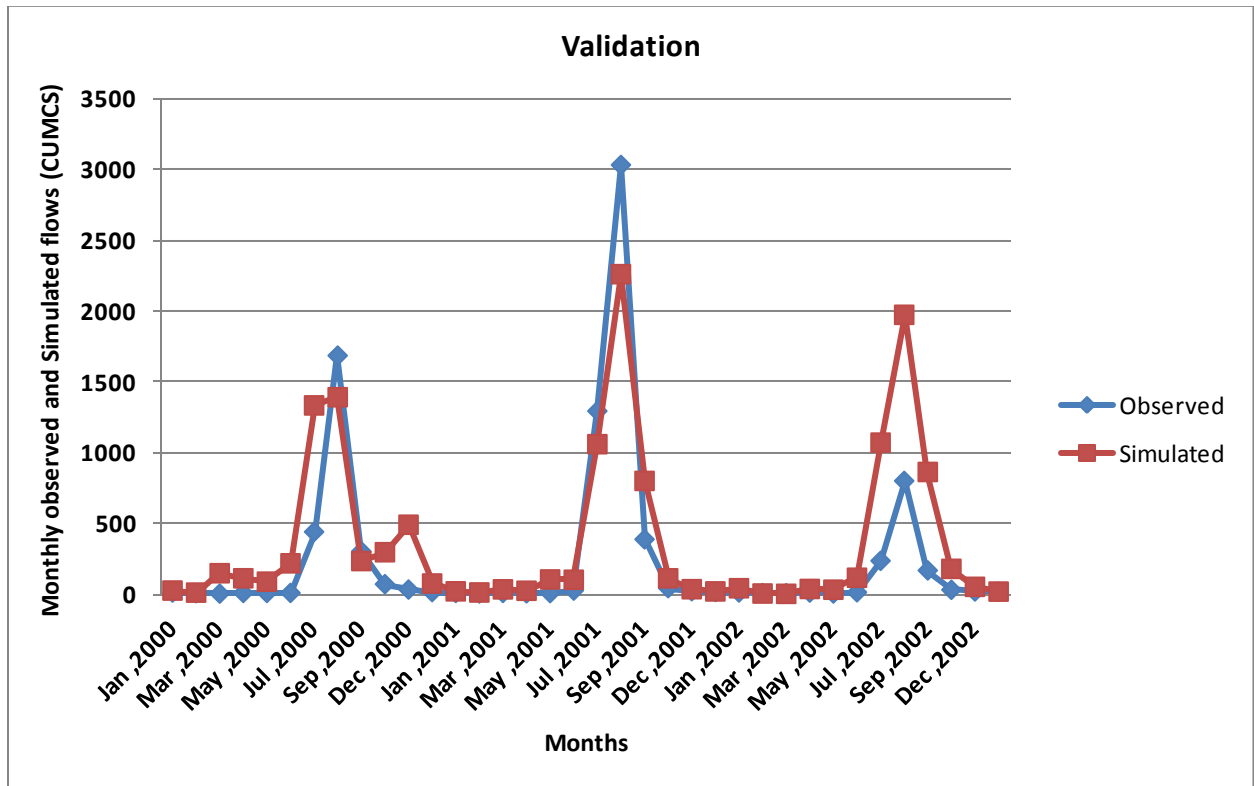


Figure: 18. Monthly flow plot for validation period

Table 15: Summary of model performance for calibration and validation period

Subbasin number	Parameters	Simulation period	Coefficient of Determination [R^2]		
			Daily	Monthly	
28 (Yechila Gauging station)	Calibrated	1997-1999	0.54	0.82>0.6	
	Validated	2000-2002	0.47	0.70>0.6	
				Nash-Sutcliffe Coefficient [NS]	
				Daily	Monthly
	Calibrated	1997-1999	0.53	0.81>0.5	
	Validated	2000-2002	0.41	0.63>0.5	

4.3. Results on Surface Water Availability

According to the result obtained from SWAT model, the basin receives a mean annual rainfall of 976.4 mm which is 80.9BM³. The mean annual actual evapotranspiration is 9.5BM³ or 11.8% of the mean annual rainfall of the basin. The mean annual surface runoff that leaves from the basin is 7.8BM³ which corresponds to 93.97 mm. Out of the mean annual rainfall of 80.9BM³; the remaining 40.1BM³ is lost due to percolation for the recharging of the aquifer and 23.5BM³ is lateral flow or subsurface flow.

Out of the mean annual surface runoff of the basin, 96.07 % of the runoff is generated from May to September and the rest 3.93 % of the surface runoff is generated from October to April. 63.33 % the mean annual surface runoff of the basin is produced from the heavy rainy months (i.e. July and August). Average monthly rainfall and the corresponding surface runoff of the basin are shown in figure 20.

Table 16: Monthly runoff of the basin estimated by SWAT model

MON	AVE MONTHLY BASIN VALUES							
	RAIN (MM)	SNOW FALL (MM)	SURF Q (MM)	LAT Q (MM)	WATER YIELD (MM)	ET (MM)	SED YIELD (T/HA)	PET (MM)
1	3.29	0.00	0.03	1.19	8.35	1.09	0.01	61.39
2	3.26	0.00	0.02	1.10	3.27	1.23	0.00	101.61
3	21.73	0.00	0.56	7.06	10.08	5.48	0.16	144.00
4	32.77	0.00	0.66	9.69	15.46	8.40	0.21	120.87
5	56.84	0.00	4.01	14.24	27.91	10.28	1.14	86.08
6	137.87	0.00	12.72	36.11	70.21	14.60	2.98	54.48
7	303.22	0.00	36.85	93.53	187.38	19.36	9.08	38.62
8	280.32	0.00	29.36	84.84	217.83	27.59	5.72	65.34
9	90.54	0.00	7.25	22.08	139.61	16.52	1.19	90.56
10	31.16	0.00	1.79	8.83	90.76	6.60	0.45	95.33
11	12.84	0.00	0.62	4.73	49.15	2.71	0.19	63.72
12	1.87	0.00	0.01	0.62	22.10	0.84	0.00	44.04

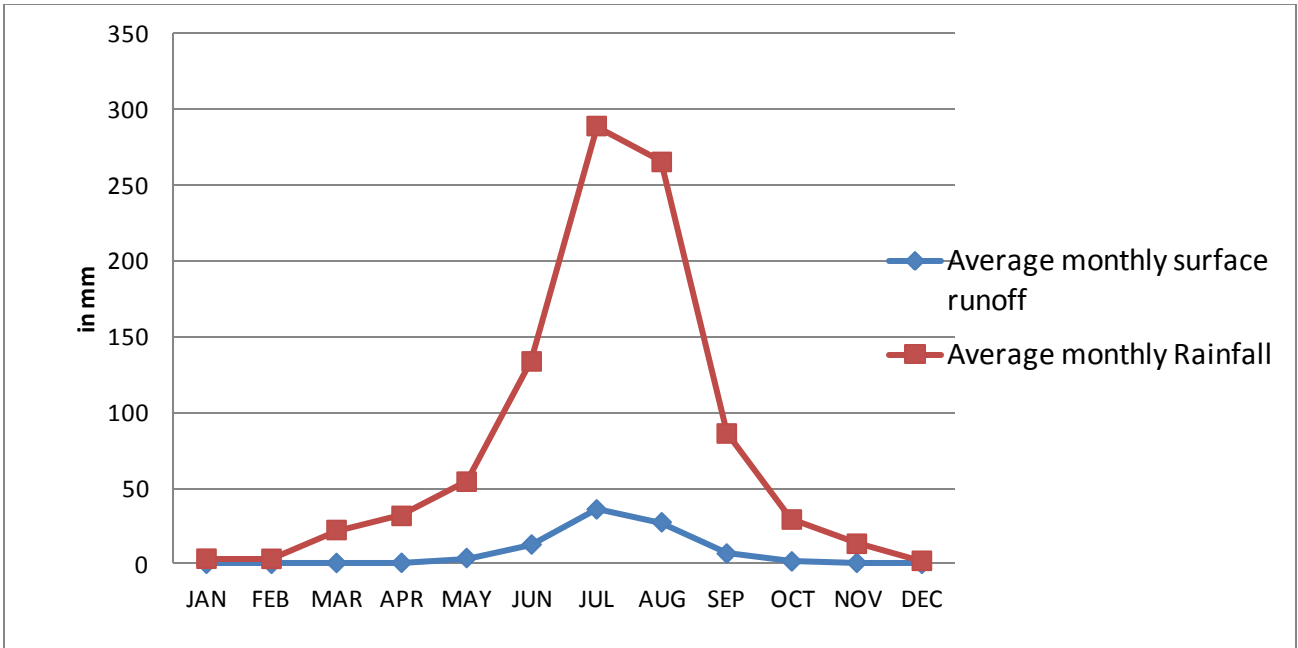


Figure: 19. Average monthly rainfall verses surface runoff

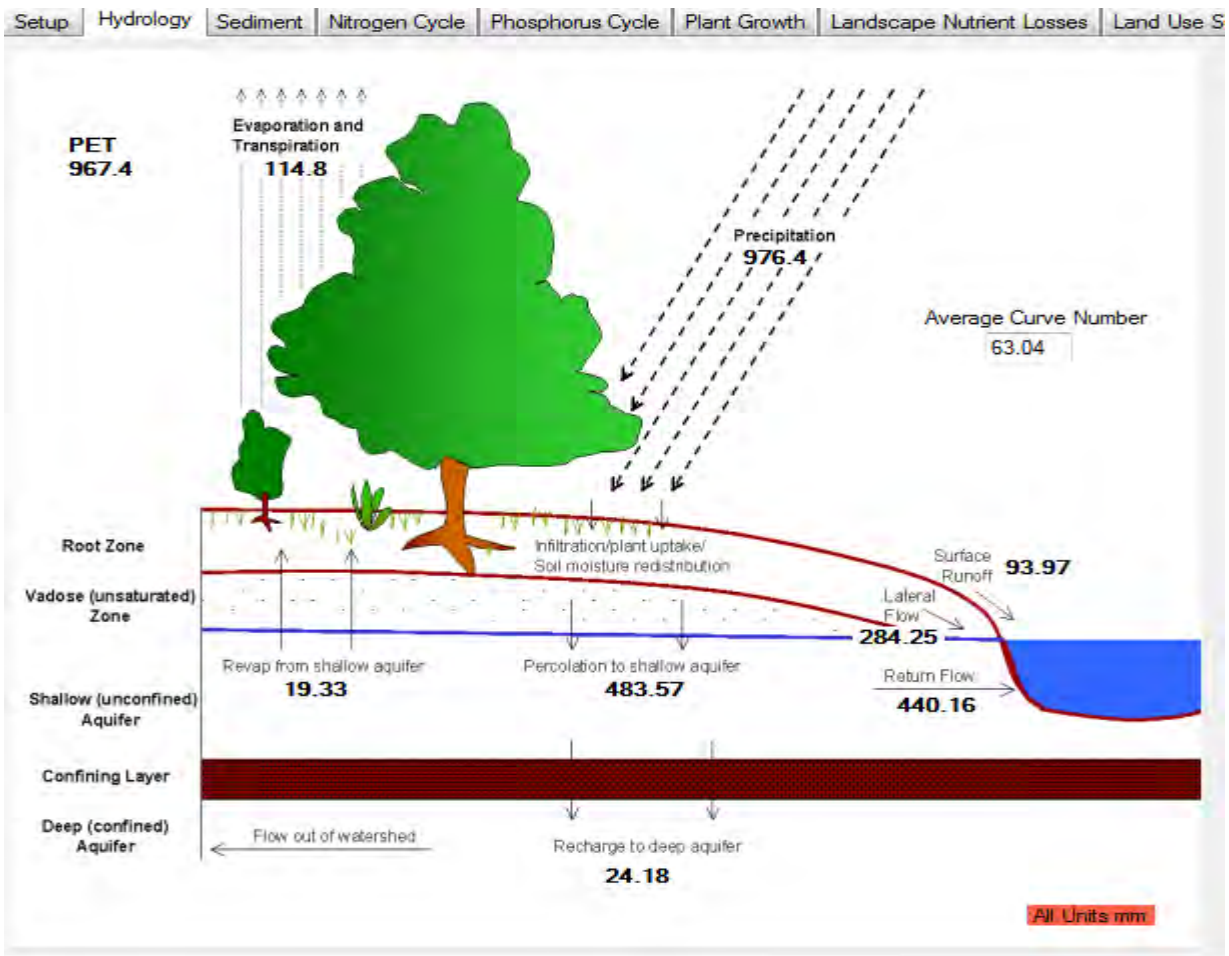


Figure: 20. General SWAT model result

4.3.1. Comparison of Result with Previous Studies in the Study Area

The knowledge of Surface water availability in the Tekeze river basin is very scanty, despite the fact that measuring started 28 years ago. Often, however, not enough flow measurements were taken or measurements did not cover a large enough part of the flow range to make rating curves (Tekeze River Basin Integrated Development Master Plan Project).

The first estimates of flows in the Tekeze river basin were made by ELC (1971), based on Atbara flows, measured at its mouth. The results are listed below, in units of 10^9m^3 .

Ethiopian catchment: Goung River =0.8

Angereb River=1.6

Tekeze River=8

Sudanese catchment: Atbara and Setit=1.2

Total= 11.6

This indicates that the basin discharge is $10.4 \times 10^9 \text{m}^3$. The total of $11.6 \times 10^9 \text{m}^3$ corresponds fairly well with the 1912-1973 average $11.9 \times 10^9 \text{m}^3$ from the series at the mouth of Atbara quoted by Shahin (1985) and the average $12.4 \times 10^9 \text{m}^3$, quoted by TAMS (1973).

The following table summarizes surface water resources of the basin as calculated by WAPCOS (EVDSA, 1990), based on the Tekeze Embamadre 1968-1976 series and the runoff factor approach supplemented with a rainfall-runoff model, master plan for different length of periods, based on the Tekeze Embamadre flows and rainfall data and this research based on different gauging stations by using SWAT model.

Table 17: Surface water resources in the Tekeze, Angereb and Goung river basins

Sub basin	Area (km ²)	Preci. WAPC OS(m m)	Preci. Master plan (mm)	MAR WAPCOS (Bm ³) (1968-1976)	MAR Master plan(Bm ³) (1900-1960)	MAR Master plan (Bm ³) (1961-1990)	MAR Master plan(Bm ³) (1900-1990)	MAR Thesis Research (Bm ³)
Tekeze	63,375	616	799	5.800	7.203	5.875	6.765	-----
Angereb	13,326	730	1006	1.180	1.773	1.454	1.668	-----
Goung	6,694	930	849	0.660	1.051	0.862	0.989	-----
Total	83,395			7.640	10.027	8.191	9.422	7.8

4.3.2. Possible Reasons for Variations of Results

Table 17 indicates that there is a difference in estimates of surface water between this research and the other two studies. This can be due to:

- ✚ The length of period taken in to consideration for the estimation of surface water potential
- ✚ Methods of estimation
- ✚ The variation of rainfall and evaporation amount(the Tekeze River basin Master plan shows that, there is a decrease in rainfall amount and this trend also proved in this research)
- ✚ Constructions of different small, medium and large scale projects in the basin and the increment of surface water storage in the reservoirs (for example: in the Tekeze hydropower dam reservoir, the mean annual storage of water is 0.02BM³)
- ✚ Considered area of the basin (i.e. 83,395km² for the two studies and 82,824.094 km² for this research). The basin area has different values for different studies. For example according to Ethiopian Ministry of Water Resources, 2010, the area of the basin is estimated to be 82,350 km². The specified threshold area range by the SWAT

model was 28,444-5,688,745 ha. To increase the number of sub-basins for a more detailed analysis of the hydrologic processes, about one third (1/3) of the minimum suggested threshold area (i.e. 9,000ha) is suggested by the Arc SWAT interface manual. But, to delineate the whole watershed area of the basin, the threshold area was set to be 200ha. Hence, for the delineation of the watershed, threshold area of 200ha with the area of 82,824.09 km² was taken for this study.

4.4. Results on Water Demand

The overall results generated by the model in the form of overall inflows, outflows from the rivers and the un-met demands for the five demand sites for the basin are shown in fig 21. The outflows from areas include the water that comes out of the demand sites when their needs are fulfilled.

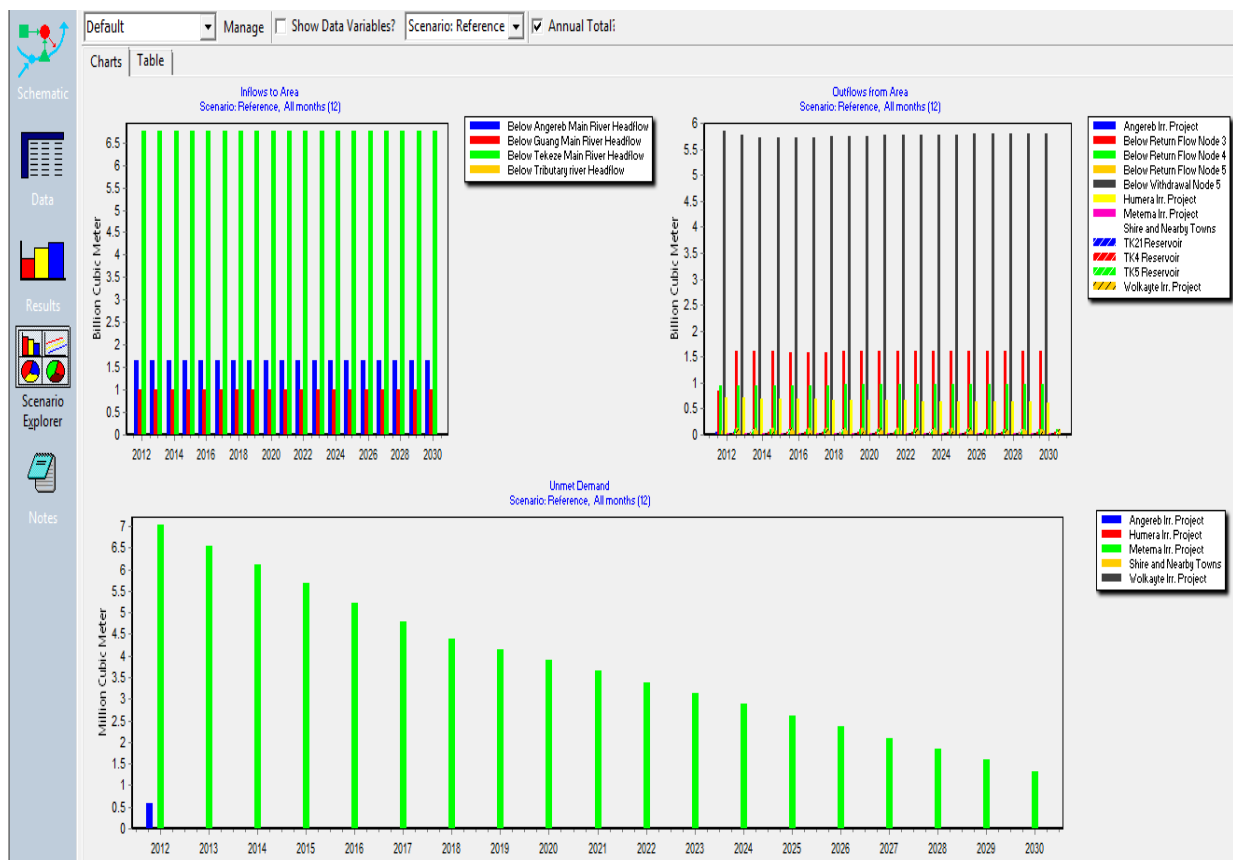


Figure: 21. Results Generated by the WEAP Model from 2012-2030

4.4.1. Water Supply Requirement

The supply requirements are generated for five demand sites that include domestic water demands for Shire town and its 11 nearby towns and irrigation water demands for Metema, Angereb, Humera, and Wolkayte irrigation projects.

WEAP model has generated the water requirement for five demand sites from 2012-2030. The model result shows that water requirements for Shire town and its nearby towns increases from (3.37-7.18) Million cubic meters from 2012 to 2030. The domestic water demand for Shire and its nearby towns is increasing due to increasing population, whereas the demand for Metema, Angereb, Humera, and Wolkayte irrigation projects decreases 49.2-23.1, 57.6-43.9, 792-693 and 155-124 Million cubic meters from 2012 to 2030 respectively, due to the improvement of efficient agriculture. The annual water supply requirement for domestic and agricultural activities is 95.9MM³ and 18.304 BM³ respectively.

Table 18: Annual average water demands (supply requirement) (not including loss, reuse and DSM) (in Mm³)

Year	Angereb Irrigation Project	Humera Irrigation Project	Metema Irrigation Project	Shire and Nearby Towns	Wolkayte Irrigation Project	Sum
2012	57.6	792	49.3	3.37	155	1060
2013	59.8	785	47.8	3.51	152	1050
2014	62	778	46.2	3.66	149	1040
2015	64.2	771	44.7	3.82	146	1030
2016	66.3	764	43.2	3.98	143	1020
2017	68.5	756	41.6	4.16	141	1010
2018	65.8	750	40.2	4.33	138	999
2019	63.1	744	38.8	4.52	136	987
2020	60.3	738	37.5	4.71	134	974
2021	57.6	731	36.1	4.92	132	962
2022	54.8	725	34.7	5.13	130	949
2023	53.5	721	33.2	5.35	129	942
2024	52.1	717	31.8	5.58	128	935
2025	50.7	713	30.3	5.82	128	928
2026	49.4	709	28.9	6.07	127	921
2027	48	705	27.5	6.33	126	913
2028	46.6	701	26	6.6	126	906
2029	45.2	697	24.6	6.89	125	899
2030	43.9	693	23.1	7.18	124	892
Sum	1070	14000	685	95.9	2570	18400

Table 19: Monthly average water demand (not including losses, reuse and DSM) (in Mm³)

Month	Angereb Irrigation Project	Humera Irrigation Project	Metema Irrigation Project	Shire and Nearby Towns	Wolkayte Irrigation Project	Sum
January	6.08	57.1	3.88	0.429	27.7	95.2
February	9.66	103	6.44	0.387	19.7	139
March	6.52	69.9	4.17	0.429	24.4	105
April	4.58	47	2.93	0.415	13.9	68.8
May	7.20	89.3	4.54	0.429	9.96	111
June	2.34	53.7	1.46	0.415	7.36	64.7
July	0.00	23.3	0.00	0.429	0.00	23.7
August	0.00	40	0.00	0.429	0.00	40.4
September	4.10	73.1	2.63	0.415	1.92	82.1
October	6.85	78.6	4.32	0.429	4.45	94.7
November	5.09	58.8	3.22	0.415	4.28	71.8
December	3.87	43.3	2.49	0.429	2.17	71.8
Sum	56.3	73.6	36.1	5.05	135.0	969

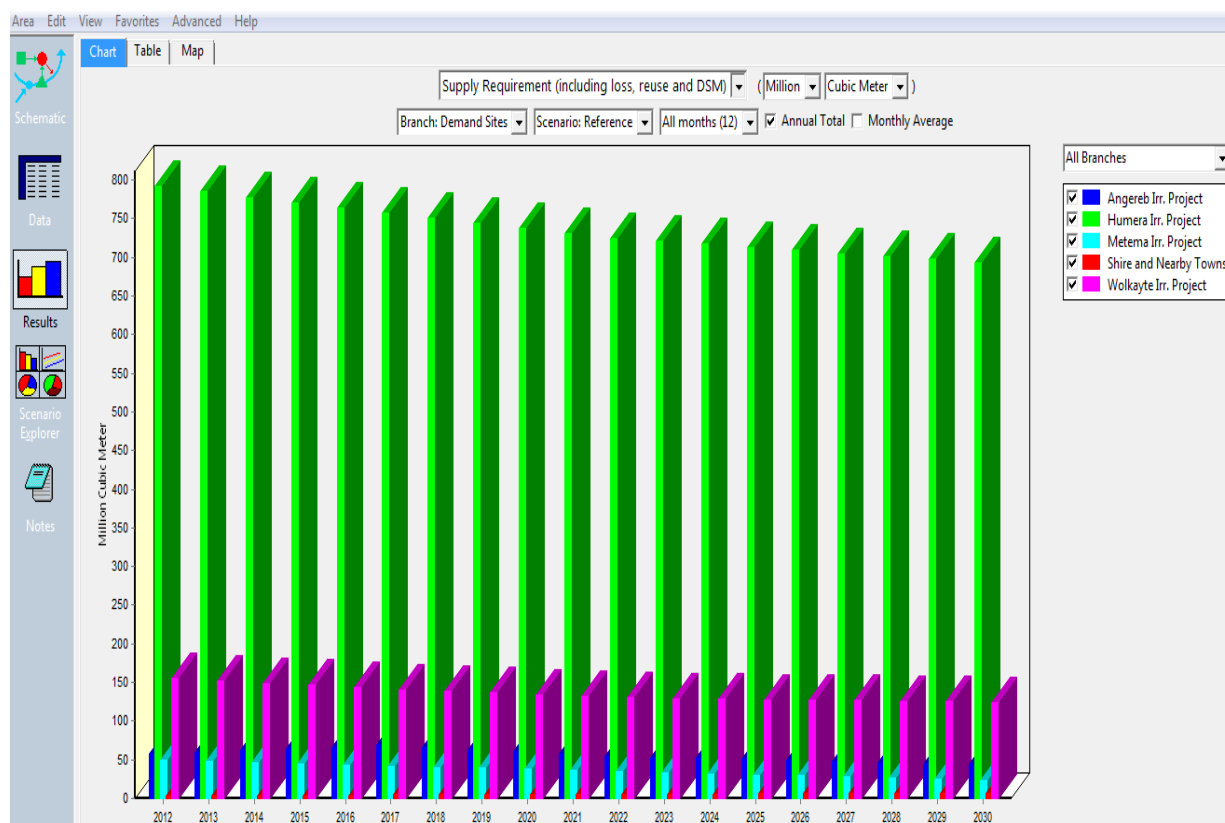


Figure 22. Annual water Supply Requirements in million cubic meters

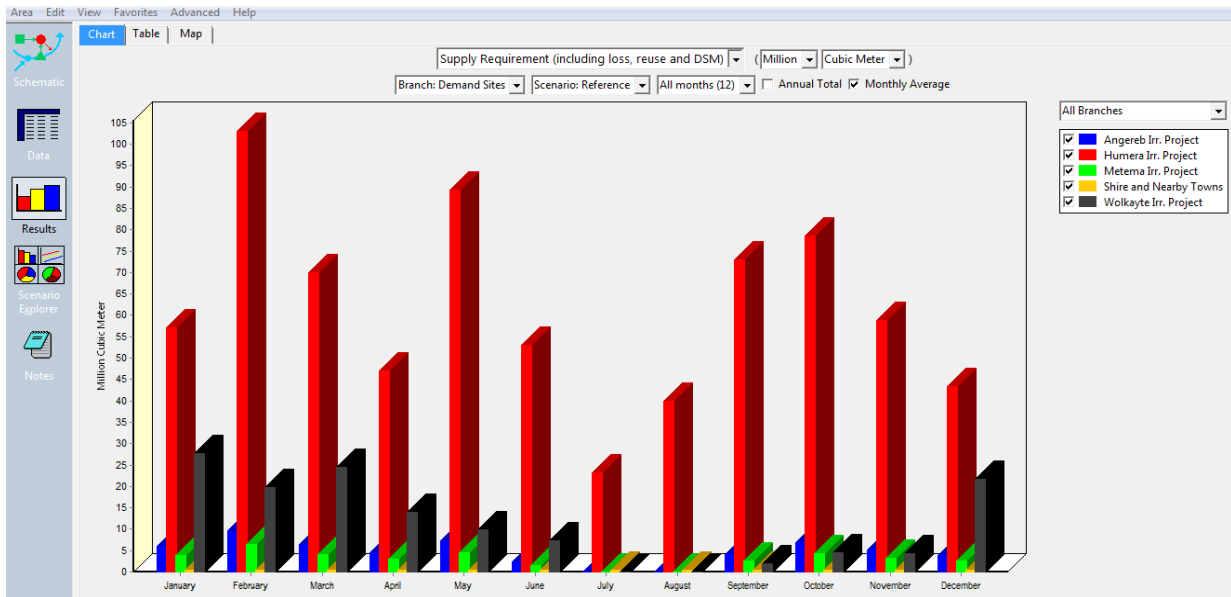


Figure: 23. Monthly water Supply Requirements in million cubic meters

4.4.2. Supply Delivered

Based on the availability of water, the model result indicates supply delivered to the demand sites is varying for different demand sites. The supply delivered for most demand sites is 100% and in some years there is little shortage of supply for the demand sites. Supply delivered to the demand sites is shown in figure 24.

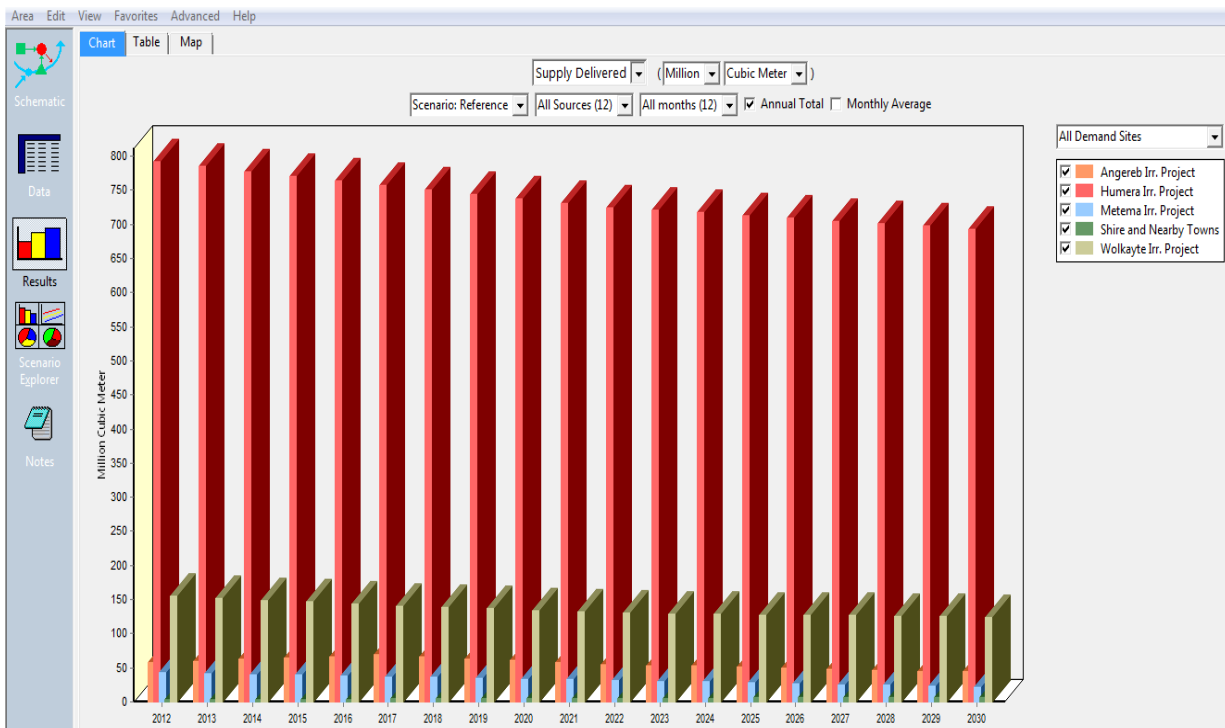


Figure: 24: Annual Water Supply delivered to the demand sites (million cubic meters)

4.4.3. Unmet Water Demands

Unmet demand is the supply requirement that is not met the demand. In other words unmet demand is the differences between supplies require and supply delivered at particular demand site and time duration. In this study the quantity of unmet demand for Metema irrigation project is observed and in the reference scenario analysis among the total water requirement of 18.4Bm³, the unmet demand observed is 73.3M m³ for the years 2012 to 2030

Table 20: Monthly average unmet demand (in Mm³) at different demand sites

Month	Angereb Irrigation Project	Humera Irrigation Project	Metema Irrigation Project	Shire and Nearby Towns	Wolkayte Irrigation Project	Sum
January	0.00	0.00	0.182	0.00	0.00	0.182
February	0.308	0.00	3.64	0.00	0.00	3.67
March	0.00	0.00	0.00	0.00	0.00	0.00
April	0.00	0.00	0.00	0.00	0.00	0.00
May	0.00	0.00	0.0273	0.00	0.00	0.0273
June	0.00	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00
Sep	0.00	0.00	0.00	0.00	0.00	0.00
October	0.00	0.00	0.00	0.00	0.00	0.00
Nove	0.00	0.00	0.00	0.00	0.00	0.00
Dece	0.00	0.00	0.00	0.00	0.00	0.00
Sum	0.308	0.00	3.83	0.00	0.00	3.86

Table 21: Annual average unmet demands (in Mm³) at different demand sites

Year	Angereb Irrigation Project	Humera Irrigation Project	Metema Irrigation Project	Shire and Nearby Towns	Wolkayte Irrigation Project	Sum
2012	0.585	0.00	7.04	0.00	0.00	7.62
2013	0.00	0.00	6.55	0.00	0.00	6.55
2014	0.00	0.00	6.11	0.00	0.00	6.11
2015	0.00	0.00	5.67	0.00	0.00	5.67
2016	0.00	0.00	5.23	0.00	0.00	5.23
2017	0.00	0.00	4.79	0.00	0.00	4.79
2018	0.00	0.00	4.40	0.00	0.00	4.40
2019	0.00	0.00	4.13	0.00	0.00	4.13
2020	0.00	0.00	3.89	0.00	0.00	3.89
2021	0.00	0.00	3.64	0.00	0.00	3.64
2022	0.00	0.00	3.39	0.00	0.00	3.39
2023	0.00	0.00	3.13	0.00	0.00	3.13
2024	0.00	0.00	2.88	0.00	0.00	2.88
2025	0.00	0.00	2.62	0.00	0.00	2.62
2026	0.00	0.00	2.36	0.00	0.00	2.36
2027	0.00	0.00	2.10	0.00	0.00	2.10
2028	0.00	0.00	1.84	0.00	0.00	1.84
2029	0.00	0.00	1.59	0.00	0.00	1.59
2030	0.00	0.00	1.33	0.00	0.00	1.33
Sum	0.585	0.00	72.70	0.00	0.00	73.30

4.4.4. Demand Site Coverage

Demand site coverage is the percent of each demand site's requirement (adjusting for demand site losses, reuse and demand-side management savings) that is met, from 0% (no water delivered) to 100% (delivery of full requirement). The coverage report gives a quick assessment of how well demands are being met. According to the model result, except for Humera and Angereb irrigation projects the percentage of demand coverage is 100% for all months and the result is given in table 22.

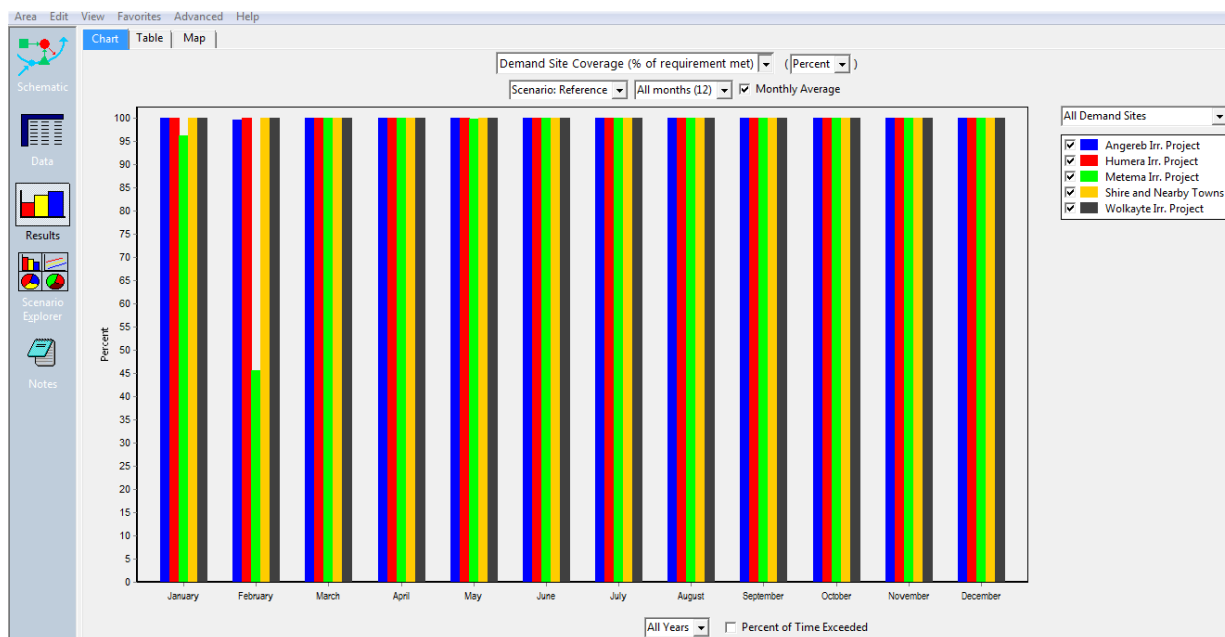


Figure: 25. Average monthly demand site coverage

Table 22: Percentage of demand coverage for each demand sites (in %)

Demand site	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Angereb Irr. Project	100	100	96.4	100	100	100	100	96.4	100	100	100	100
Humera Irr. Project	99.7	100	45.7	100	100	99.7	100	45.7	100	100	99.7	100
Metema Irr. Project	100	100	100	100	100	100	100	100	100	100	100	100
Shire & Nearby Towns	100	100	100	100	100	100	100	100	100	100	100	100
Wolkayte Irr. Project	100	100	100	100	100	100	100	100	100	100	100	100

4.4.5. Hydropower Water Demand

In the basin, one existing hydropower (TK5) is currently available with installed capacity of 300MW and further five mini and medium hydropower projects were identified during the master plan study. Among these planned hydropower projects, two of them were selected based on their hydropower production (medium hydropower) and data availability for the estimation of hydropower water demand. Table 23 shows the average monthly water demand for TK21, TK4 and TK5

Table 23: Average monthly water demand for TK21, TK4 and TK5 in Mm³

Month	TK21 Reservoir	TK4 Reservoir	TK5 Reservoir	Sum
January	82.9	761	612	1460
February	86.3	783	639	1510
March	89.8	803	666	1560
April	94	833	706	1630
May	98.4	877	752	1730
June	103	925	800	1830
July	106	963	857	1920
August	78.3	810	725	1610
September	70.7	697	587	1360
October	70.7	672	561	1300
November	72.2	691	575	1340
December	74.6	719	593	1390
Sum	1030	9540	8070	18600

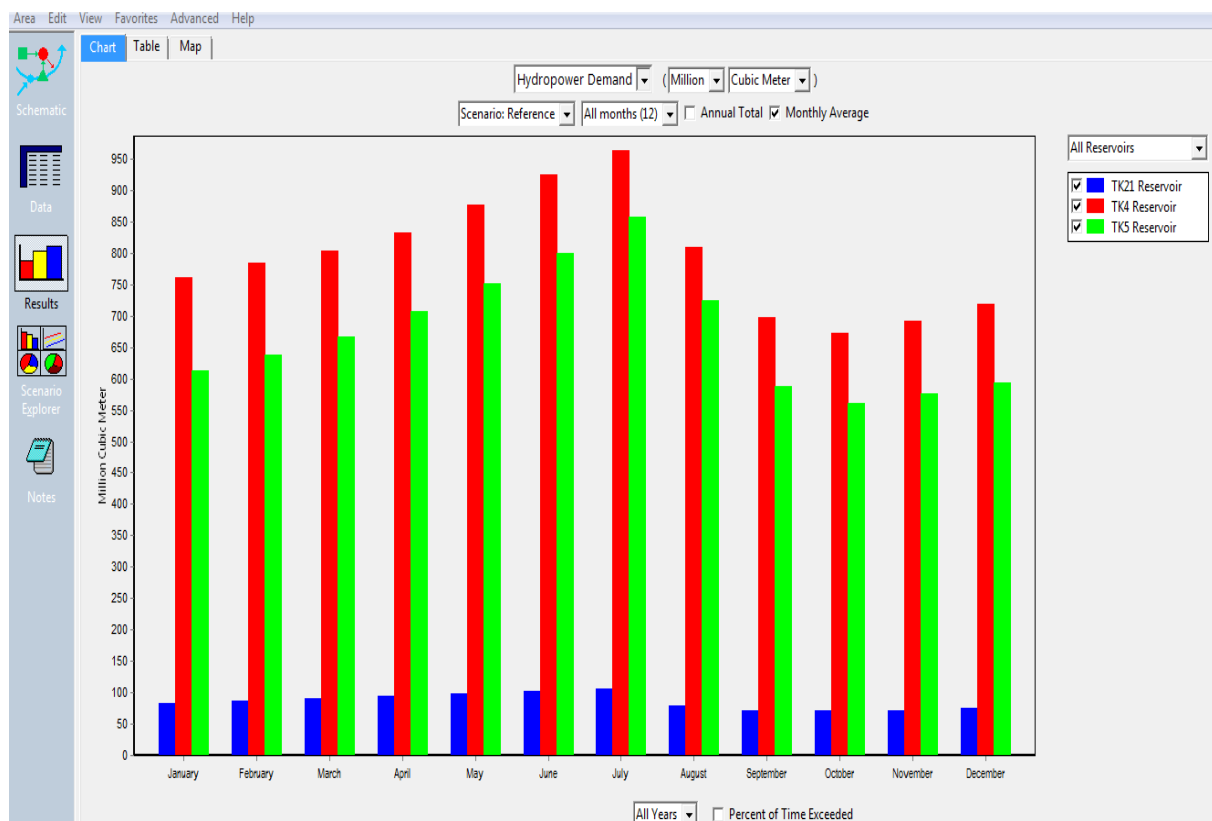


Figure: 26. Average monthly hydropower water demand

CHAPTER FIVE

5. Conclusion and Recommendation

5.1. Conclusions

Performance of the SWAT model for the basin was evaluated using standard calibration and validation statistics. A good agreement between measured and simulated monthly stream flow at Yechila gauging station was evaluated by correlation coefficient ($R^2 = 0.82$) and Nash-Sutcliffe model efficiency ($ENS = 0.81$) for calibration period and $R^2 = 0.7$ and $ENS = 0.63$ for validation periods.

The SWAT model sensitivity in predicting stream flow was done as a function of size of the threshold area (TA) and the result shows surface runoff is not significantly affected by varying the size of TA. This is because the surface runoff is directly related to the CN, and CN is not affected significantly by the size of the sub watersheds. In HRU definition, the number of HRUs in the watershed decreases with increasing threshold values. (Example for 10% of LU, 5% of soil and 10% slope the number of HRU was=622 and 20%LU, 10% of soil and 20% slope the number of HRU=281). During estimation of surface runoff, the model was run by changing one factor and by considering the remaining as constant and the result shows: surface runoff quantity is highly affected by land use type, soil type and rainfall amount in the basin.

Monthly time step model performance evaluation coefficients shows that, the model can be considered reasonably satisfactory and the SWAT model is capable of predicting stream flow for the basin. When surface water resources result is compared with previous studies, it is decreased by 4.9% from the master plan study result (1961-1990) and it is greater than only by 2.6% from WAPCOS (1968-1976) result.

For estimation of water demands part, the main consumption in the river basin from large scale project is the agricultural demand, followed by domestic demand.

The model results showed that, for the reference scenario from year 2012 to 2030 are 18.4Bm³, 18.3267Bm³ and 73.3 Mm³ for water demand, supply delivered and unmet demands respectively for domestic and irrigation water demands. The annual average water demand, supply delivered and unmet demand are 969Mm³, 965.14Mm³, and 3.86 Mm³ respectively for the proposed large scale projects.

Generally, from the assessment of surface water potential result (i.e. average annual of 7.8BM³) which shows that the inflow is greater than the outflow and by comparing the average annual water demand (i.e.969Mm³); the basin has sufficient surface water potential that can be used for the selected planned and ongoing large scale projects for the coming 15 years and also the surface water potential is enough for additional large scale projects.

5.2. Recommendations

SWAT needs reliable input data and sufficient time for obtaining improved model parameters and best estimated results that can be fit with the observed data. Further efforts are required to conduct the best estimated results of surface water using SWAT model in the basin.

Since only stream flow at Yechila gauging station was calibrated and validated, the model could be calibrated and validated for further gauging stations especially at the outlet of the whole watershed and for other outputs, such as sediment yield and ground water when data on sediment load and ground water is available.

From the model results, it is found that the streams can cover 98.1% of water demands for all selected demand sites; therefore, reservoirs at various places along these streams are required for additional large scale projects, so as to store the water for meeting the demands of water during the winter months mainly from October to February.

6. REFERENCE

1. Abyou, 2014, Regional Training Course on Integrated Flood Management (IFM) Lake Tana Flood Zone Mapping Using GIS Regional Training Course in Integrated Flood Management
2. Allen RG, Pereira L S, Raes D and Smith M. Crop evapotranspiration, Guidelines for computing crop water requirements. 1998 - FAO Irrigation and Drainage Paper 56, FAO, Rome.
3. Arnold et al, 1996; Arabi et al., 2007; Schuol et al., 2008; Setegn et al., 2010)The influence of parameter distribution uncertainty on hydrological and sediment modeling: a case study of SWAT model applied to the Daning watershed of the Three Gorges Reservoir Region, China
4. Arora, K.R (2001), Irrigation, Water Power Resources Engineering, Standard Publishers Distribution.
5. Awulachew et al., 2007, Nile River basin water, agriculture, governance and livelihoods
6. Belete et al, 2013, GIS-based hydrological zones and soil geo-database of Ethiopia
7. Ben Asher et al, 1988, Effects of rainfall intensity, underlying surface and slope gradient on soil infiltration under simulated rainfall experiments
8. Chow Ven Te, D.R Maidment, and L.W Mays (1988). Applied Hydrology. McGraw hill, New York.
9. Cunderlik (2003), Hydrologic Models for Inverse Climate Change Impact Modeling
10. Dilnesaw,2006,Modeling of Hydrology and Soil Erosion of Upper Awash River Basin
11. Dooren Boss J. and Freitals F., 1984, Guidelines for predicting crop water requirement, FAO irrigation and drainage paper 24 and 56
12. Dzurik,1996, water resources development planning
13. Fetter, C.W. (1988): Applied Hydrogeology, Prentice Hall Inc., New Jersey.
14. Gleik, 1996, the changing water paradigm: a look at twenty-first century water resources development
15. Global Water Partnership, 2000, Global Water Partnership Technical Advisory Committee, Background Paper no.4.
16. Gray T.; Matthew C. (2004). Use of SLC-Off Landsat Image Data for Monitoring
17. ICID,2000,international commission on irrigation and drainage report

18. IDCOF (2002). Food Security, Sustainable Agriculture and Trade. A report prepared for the Christian Relief and Development Association (CRDA). Addis Ababa
19. IWMI, 2006, Water scarcity: Fact or fiction? Frank R. Rijsberman *International Water Management Institute, P.O. Box 2075, Colombo, Sri Lanka
20. J. E. Nash and J. V. Sutcliffe, "River Flow Forecasting through Conceptual Models, Part I—A Discussion of Principles," *Journal of Hydrology*, Vol. 10, No. 3, 1970, pp. 282-290.
21. K. C. Abbaspour, "SWAT-CUP4: SWAT Calibration and Uncertainty Programs—A User Manual," Swiss Federal Institute of Aquatic Science and Technology, Eawag, 2011.
22. K. C. Abbaspour, J. Yang, I. Maximov, R. Siber, K. Bogner, J. Mieleitner, J. Zobrist and R. Srinivasan, "Spatially-Distributed Modelling of Hydrology and Water Quality in the Prealpine/Alpine Thur Watershed Using SWAT," *Journal of Hydrology*, Vol. 333, No. 2-4, 2007, pp. 413- 430.
23. K. Subramanian, "Engineering Hydrology," 3rd Edition, McGraw-Hill, New York, 2008.
24. Ministry of Water Resources. 2001. Initial national communication of Ethiopia to the United Nations Framework Convention on Climate Change (UNFCCC). A report submitted to the conference of parties of the UNFCCC under the GEF support Climate Change Enabling Activities Project of Ethiopia. Ethiopia, Addis Ababa.
25. Molle, 2006, Dealing with Closed Basins: The Case of the Lower Jordan River Basin
26. Mulugeta Azeze, (2009). development of synthetic unit hydrographs for watersheds in the upper awash and upper tekeze basins
27. Murthy VVN. Land and Water Management Engineering, Kalyani Publishers, Ludhiana, 2001; pp.213
28. Nata Tadesse (2006). "Surface Waters Potential of the Hantebet Basin, Tigray, Northern Ethiopia")
29. Nature and features of Ethiopian river basins master plan study, Ethiopian Ministry of Water Resource, 2010.
30. NEDECO, 1998. Tekeze River Basin Integrated Development Master Plan Project, Vol 5 & 6. Ministry of water resources, Addis Ababa.
31. Neitsch et al, 2005, soil and water assessment tool model: current developments and applications

32. Paw et al, 2002, Climate change impacts on water demand and salinity in California's irrigated agriculture
33. S. L. Neitsch, J. G. Arnold, J. R. Kiniry and J. R. Williams, "Soil and Water Assessment Tools Theoretical Documentation," Texas Water Resources Institute Technical Report No. 406, Texas A and M University System, Grassland, Soil and Water Research Laboratory, Texas, 2011, Blackland Research Center, Texas, 2005.
34. Seleshi et al, 2010, water resources and irrigation development in Ethiopia
35. Sieber, J., Huber-Lee, A., & Raskin, P. (2002), WEAP: Water Evaluation And Planning System User Guide (WEAP 21), Stockholm Environmental Institute—Boston, and Tellus Institute, User Guide for WEAP 21, Boston, MA
36. Silveira et al, 2000, Arsenic immobilization in soils amended with drinking-water treatment residuals
37. Soil conservation department. (1985). National engineering handbook. Section 4, Hydrology. Washington, DC.
38. Stockholm Environment Institute, SEI. (2001), WEAP: Water Evaluation and Planning system—user guide, Boston, USA
39. Tekeze Master Plan Project, "Tekeze River Basin Integrated Development Master Plan Project," Ministry of Water Resource (MoWR), the Federal Democratic Republic of Ethiopia, 1998.
40. UNESCO, 2006, Executive summary on Water, a shared responsibility, The United Nations World Water Development Report 2 (WWDR) 2)
41. V. T. Chow, D. R. Maidment and L. W. Mays, "Applied Hydrology," McGraw-Hill, New York, 1988.
42. Verosmarty *et al.* 2000; UN, 2006, first super-high-resolution model projection that the ancient "fertile crescent" will disappear in this century
43. Wang Xiao – Jun et al, 2009, Water resources management strategy for adaptation to droughts in China
44. Yang et al, 2007, a process-based analysis of green and blue water scarcity, productivity, trade
45. Yang, H., and Zehnder, A.J.B, (2007), A water resources threshold and its implication for food security, Environmental Science and Technology.
46. Yibeltal Ayenew, (2008). Rainfall-Runoff Modeling for Sustainable Water Resources Management: The Case of Gumara Watershed, Ethiopia
47. Yohannes, (2007). Remote Sensing based assessment of water resources in lake Tana

7. APPENDIXES

Appendix Table 1: Average daily dew point temperature for period (1994 - 1999) for Gondar station

Month	Tmp_Max	Tmp_Min	Hmd	Dewpt
Jan	28.09	12.71	51.02	10.70
Feb	29.09	10.98	43.25	8.49
Mar	29.66	13.61	45.53	9.89
Apr	29.54	15.83	45.25	10.68
May	27.27	15.71	62.85	14.09
Jun	25.13	14.62	71.59	14.65
Jul	22.63	13.01	79.60	14.74
Aug	23.36	13.12	82.02	15.72
Sep	25.81	11.77	68.99	14.03
Oct	27.04	10.66	58.24	11.41
Nov	27.28	10.67	56.79	11.29
Dec	27.61	8.18	54.27	10.48

Appendix Table 2: Average daily dew point temperature for period (1994 - 1999) for Lalibela station

Month	Tmp_Max	Tmp_Min	Hmd	Dewpt
Jan	25.74	12.97	52.93	10.09
Feb	27.28	13.79	42.33	7.90
Mar	27.14	14.32	43.74	8.18
Apr	26.79	14.62	48.82	9.68
May	26.20	14.58	49.53	9.59
Jun	25.24	14.05	56.39	10.67
Jul	19.41	11.85	82.78	12.91
Aug	19.62	11.90	86.90	13.90
Sep	22.94	12.99	71.62	13.10
Oct	24.41	12.54	57.13	10.36
Nov	24.99	12.28	53.18	9.56
Dec	25.14	12.40	46.48	7.55

Appendix Table 3: Monthly average MAXSTD, MINSTD, WNDV and SOLARAV for Lalibela, Metema and Gondar stations

STATION	MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Lalibela	MAXSTD	0.54	0.52	0.91	0.96	1.02	1.47	0.90	0.63	0.68	0.55	0.62	0.45
	MINSTD	0.53	0.64	0.57	0.72	0.75	0.84	0.45	0.45	0.55	0.44	0.58	0.51
	WNDV	1.32	1.47	1.52	1.58	1.80	1.51	0.96	0.89	1.04	1.24	1.15	1.19
	SOLARAV	5.97	15.09	18.78	14.64	6.54	1.42	3.96	11.13	14.59	15.39	9.27	1.60
Metema	MAXSTD	1.42	1.47	2.12	1.36	1.36	0.94	0.82	0.65	1.14	1.45	1.59	1.12
	MINSTD	1.55	2.74	2.20	2.21	1.91	2.47	2.31	1.48	1.52	1.67	1.26	1.29
	WNDV	1.16	1.23	1.35	1.62	1.61	1.46	1.09	0.93	0.83	0.85	1.08	1.12
	SOLARAV	6.07	15.33	21.31	15.57	7.08	1.32	3.42	11.12	17.71	16.34	8.84	1.47
Gondar	MAXSTD	0.60	0.77	0.73	1.16	1.41	0.93	0.91	0.63	0.72	1.27	0.61	0.52
	MINSTD	2.27	2.69	2.94	2.84	2.62	1.69	2.41	2.23	2.12	2.40	2.49	3.13
	WNDV	1.71	1.90	2.00	1.94	1.94	1.89	1.54	1.34	1.42	1.51	1.54	1.60
	SOLARAV	5.69	14.14	19.04	13.93	6.72	1.29	3.26	10.54	16.73	15.05	8.74	1.47

Appendix Table 4: Average daily dew point temperature for period (1998 - 2002) for Metema station

Month	Tmp_Ma	Tmp_Min	Hmd	Dewpt
Jan	36.49	14.81	56.89	17.81
Feb	38.82	17.80	50.54	17.71
Mar	39.61	20.44	37.47	14.67
Apr	40.57	23.66	43.40	18.26
May	39.25	23.06	51.31	19.87
Jun	34.55	21.03	63.15	20.34
Jul	30.18	20.29	73.65	20.51
Aug	29.83	19.81	83.88	22.26
Sep	31.48	19.17	81.25	22.59
Oct	33.58	19.34	75.89	22.88
Nov	36.30	16.14	63.82	20.53
Dec	36.16	15.14	50.11	16.04

Appendix Table 5: Statistical analysis of daily precipitation data (1994 - 2012)

Input Filename = Gondar.txt

Number of Years = 19

Number of Leap Years = 5

Number of Records = 7299

Number of No Data values = 0

Month	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	4.13	1.2127	11.9061	0.0227	0.2353	0.89
Feb.	4.05	1.0384	9.1787	0.0290	0.1500	1.05
Mar.	14.01	2.5151	11.8641	0.0774	0.305	3.11
Apr.	33.87	3.5308	5.1507	0.1368	0.459	6.53
May.	95.39	7.3936	4.5304	0.2600	0.577	12.58
Jun.	199.66	10.9352	3.2506	0.5519	0.71	20.37
Jul.	344.29	11.6723	1.7004	0.9091	0.89	28.68
Aug.	286.97	10.2171	1.8557	0.7176	0.84	26.53
Sep.	103.55	6.8109	3.3124	0.3591	0.547	14.32
Oct.	78.79	7.6683	4.8037	0.2076	0.458	8.95
Nov.	17.52	2.8171	8.1055	0.0605	0.413	3.05
Dec.	6.92	1.8577	13.3125	0.0283	0.304	1.21

Appendix Table 6: Statistical analysis of daily precipitation data (1994 - 2012)

Input Filename = La libel.txt

Number of Years =19

Number of Leap Years =5

Number of Records = 7299

Number of NoData values = 0

Month PCP_MM PCPSTD PCPSKW PR_W1 PR_W2 PCPD

Jan.	9.43	1.7826	9.4932	0.0552	0.347	2.42
Feb.	9.21	1.6865	7.7175	0.0592	0.3191	2.47
Mar.	44.59	4.6396	6.2496	0.1406	0.580	8.16
Apr.	37.42	3.4564	4.5776	0.1415	0.532	7.32
May.	25.03	3.3585	7.4261	0.0970	0.393	4.95
Jun.	70.51	5.5827	4.0159	0.2016	0.6162	10.42
Jul.	297.31	10.5628	2.1987	0.7213	0.886	27.79
Aug.	251.15	9.3434	2.2501	0.6122	0.839	25.84
Sep.	41.48	3.4604	4.3479	0.1878	0.5573	10.11
Oct.	18.47	3.2790	10.6846	0.0660	0.500	3.89
Nov.	16.47	3.1151	9.1008	0.0501	0.4314	2.68
Dec.	4.54	0.8492	8.0208	0.0359	0.3750	1.68

Appendix Table 7: Statistical analysis of daily precipitation data (1994 - 2012)

Input Filename = Metema.txt

Number of Years =19

Number of Leap Years =5

Number of Records =7299

Number of NoData values = 0

Month	PCP_MM	PCPSTD	PCPSKW	PR_W1	PR_W2	PCPD
Jan.	0.00	0.0000	0.000	0.00	0.0	0.00
Feb.	0.90	0.5182	17.1232	0.0056	0.0000	0.16
Mar.	10.07	2.6670	10.7034	0.0123	0.6500	1.05
Apr.	23.55	4.0134	7.4202	0.0660	0.3818	2.89
May.	77.25	5.6903	3.1047	0.2034	0.530	9.53
Jun.	198.89	11.3923	2.5750	0.5875	0.542	17.37
Jul.	249.45	11.9842	2.1312	0.6131	0.729	22.16
Aug.	249.41	12.0066	2.3463	0.6642	0.767	23.95
Sep.	184.73	11.0906	2.8859	0.4779	0.585	16.89
Oct.	32.83	4.7547	6.5271	0.1074	0.2907	4.53
Nov.	7.56	2.2797	15.4997	0.0181	0.3529	0.89
Dec.	0.01	0.0082	24.2694	0.0017	0.0000	0.00

Where:-

TMPMX: Average or mean daily maximum air temperature for month (°C).

TMPMN: Average or mean daily minimum air temperature for month (°C).

TMPSTDMX: Standard deviation for daily maximum air temperature in month (°C).

TMPSTDMN: Standard deviation for daily minimum air temperature in month (°C).

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 hour rainfall in entire period of record for month (mm H₂O).

SOLARAV: Average daily solar radiation for month (MJ/m²/day).

DEWPT: Average daily dew point temperature in month (°C).

WNDVAV: Average daily wind speed in month (m/s).

Appendix Table 8: Mean monthly surface runoff (mm) at Yechila gauging station

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1995	2.1	2.1	19.7	47.7	26.7	25.6	16.6	21.0	19.8	18.0	24.0	21.4
1996	15.2	11.3	13.3	36.6	60.4	28.2	496.5	523.3	361.5	32.6	26.8	4.6
1997	4.3	3.9	29.1	12.2	18.4	78.4	908.8	445.4	55.8	74.5	84.3	25.9
1998	11.5	6.9	8.8	14.1	38.8	26.7	1223.7	3432.1	1408.6	95.7	22.2	11.0
1999	10.7	4.2	5.6	10.6	22.9	157.4	579.2	2096.4	1430.7	155.0	39.7	19.0
2000	10.1	5.1	2.4	7.1	6.9	7.3	438.7	1683.9	301.1	69.3	31.2	13.3
2001	6.9	3.4	7.1	4.5	5.8	23.5	1292.1	3030.7	385.7	41.2	19.4	14.2
2002	10.3	6.0	5.4	9.9	3.2	11.6	234.0	798.7	166.0	29.1	17.6	14.9

Appendix Table 9: Mean monthly surface runoff (mm) at Embamadre gauging station

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1995	0.4	0.7	49	133	34.8	43.98	566.3	1078	394	85.7	31	26.130
1996	20	20.9	94	79.3	101	202	511.4	1044	372	123	69	55.430
1997	27	15.9	54	31.1	64.8	149.4	480	577	163	197	114	43.780
1998	16	6.34	7.6	27.3	81.1	87.31	890.8	942.5	1002	292	161	81.076
1999	80	49.7	50	47.3	45.4	99.53	663.6	1305	817	320	157	87.830
2000	8.7	21.1	17	8.4	8.12	19.1	334.4	984.7	314	102	31	15.543

Appendix Table 10: Data for hydropower water demand estimation (TK5)

- Inflow data for the reservoir =(Mm³/month)
- Storage capacity =9,293Mm³
- Volume elevation curve,

Elevation	Storage (Mm ³)	Elevation	Storage (Mm ³)
1000	69	1080	2707
1020	245	1100	4354
1040	678	1120	6499
1060	1474	1140	9293

- Initial storage =4603.8MM³
- Net evaporation from the reservoir =1300mm

Evaporation data used in the reservoir and hydropower operations (mm/month)

Month	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Evaporation	150	158	165	168	185	114	-82	-110	87	185	141	138

- Top of conservation =6,499Mm³
- Top of buffer =5,293Mm³
- Top of inactive =680Mm³
- Maximum turbine flow =220m³/s
- Tail water elevation =970m
- Plant factor =60%

- Generating efficiency= 75%
- 1joule=1 watt*1second
- $E=1065\text{GWh}/\text{yr}=1065*3600\text{GWs}/\text{yr}=1065*3600\text{GJ}/\text{yr}=1065*3600/12=1065*3600/12\text{GJ}/\text{month}=319,500\text{GJ}/\text{month}$

Appendix Table 11: Data for hydropower water demand estimation (TK4)

- Storage capacity =3,802Mm³
- Volume elevation curve=

Elevation	Storage (Mm ³)	Elevation	Storage (Mm ³)
1160	0	1240	1541.6
1200	377.6	1280	3802.4

- Initial storage =1017.8MM³
- Net evaporation from the reservoir =mm

Evaporation data used in the reservoir and hydropower operations (mm/month)

Month	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Evaporation	118	117	139	153	131	62	-125	-202	108	135	111	104

- Top of conservation =3,519.8Mm³
- Top of buffer =2,942Mm³
- Top of inactive =1017.8Mm³
- Maximum turbine flow =140m³/s
- Tail water elevation =1,160m
- Plant factor =60%
- Generating efficiency= 75%
- $E=808\text{GWh}/\text{yr}=808*3600\text{GWs}/\text{yr}=808*3600\text{GJ}/\text{yr}=808*3600/12=808*3600/12\text{GJ}/\text{month}=242,400\text{GJ}/\text{month}$

Appendix Table 12: Data for hydropower water demand estimation (TK21)

- Storage capacity =1,118Mm³
- Volume elevation curve=

Elevation	Storage (Mm ³)	Elevation	Storage (Mm ³)
740	0	800	1150.23
760	123.96	820	2225.57
780	485.03		

- Initial storage =178.12MM³
- Net evaporation from the reservoir =mm

Evaporation data used in the reservoir and hydropower operations (mm/month)

Month	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Evaporation	114	107	126	104	47	-38	-222	-200	-14	60	85	101

- Top of conservation =1,100Mm³
- Top of buffer =950Mm³
- Top of inactive =125Mm³
- Maximum turbine flow =29.54m³/s
- Tail water elevation =740m
- Plant factor =60%
- Generating efficiency= 75%
- $E=71\text{GWh/yr}=71*3600\text{GWh/yr}=71*3600\text{GJ/yr}=71*3600/12=71*3600/12\text{GJ/month}=21,300\text{GJ/month}$

Source: Tekeze River Basin Integrated Development Master Plan, 1998

Appendix Table 13: Monthly crop water requirement, irrigation area and annual water use rate data for irrigation demand sites

		Monthly Water Requirement							
Demand sites		Humera (15,761ha) Annual water use rate =50,250m ³ /ha		Angereb (6,535ha) Annual water use rate =10,498.6m ³ /ha		Metema(11,561 ha Annual water use rate =4,264m ³ /ha		Welkayte (27,039ha) Annual water use rate =5,726.2m ³ /ha	
S No.	Month	In MM ³	In %	In	In %	In MM ³	In %	In MM ³	In %
1	January	61.4	7.75	23.9	10.71	5.3	10.75	31.7	20.47
2	February	110.8	13.99	40	17.92	8.8	17.85	22.5	14.53
3	March	75.2	9.49	25.6	11.47	5.7	11.56	27.9	18.02
4	April	50.5	6.38	18	8.06	4	8.11	15.9	10.27
5	May	96	12.12	28.3	12.68	6.2	12.58	11.4	7.36
6	June	57.1	7.21	9.2	4.12	2	4.06	8.43	5.44
7	July	25	3.16	0	0.00	0	0.00	0	0.00
8	August	43	5.43	0	0	0	0	0	0
9	September	78.6	9.92	16.1	7.21	3.6	7.30	2.2	1.42
10	October	84.6	10.68	26.9	12.05	5.9	11.97	5.1	3.29
11	November	63.2	7.98	20	8.96	4.4	8.92	4.9	3.16
12	December	46.6	5.88	15.2	6.81	3.4	6.90	24.8	16.02
Total		792	100	223.2	100	49.3	100	154.83	100

Source: Ministry of Water resource

Appendix Table 14: Soil parameters in SWAT database for each soil layers in the basin

FID	Shape *	SYMBOL	SOIL_TYPE	Area_(sqkm)	MUID	SNAM	NLAYERS	HYDGRP	SOL_ZMX	L	SOL_CRK
0	Polygon	VRe	Eutric Vertisols	9301.3	ET056	EUVERTISOLS	1	D	1000	0.5	0.5
1	Polygon	LPe	Eutric Leptosols	17147.2	ET031	EULEPTOSOLS	1	A	300	0.5	0.5
2	Polygon	LPq	Lithic Leptosols	25015.1	ET033	LTLEPTOSOLS	1	A	100	0.5	0.5
3	Polygon	CMc	Calcaric Cambisols	152.3	ET015	CLCAMBISOLS	1	A	1000	0.5	0.5
4	Polygon	LPu	Umbric Leptosols	4.1	ET034	UMLEPTOSOLS	1	B	300	0.5	0.5
5	Polygon	CMe	Eutric Cambisols	3507.5	ET017	EUCAMBISOLS	1	D	1000	0.5	0.5
6	Polygon	LVh	Haplic Luvisols	15494.3	ET036	HPLUVISOLS	1	B	1000	0.5	0.5
7	Polygon	ARh	Haplic Arenosols	1.1	ET008	HPARENOSOLS	1	A	1000	0.5	0.5
8	Polygon	LVx	Chromic Luvisols	1475.0	ET038	CHLUVISOLS	1	B	1000	0.5	0.5
9	Polygon	ALh	Haplic Alisols	7.9	ET002	HPALISOLS	1	B	1000	0.5	0.5
10	Polygon	CLh	Haplic Calcisols	0.8	ET011	HPCALCISOLS	1	A	1000	0.5	0.5
11	Polygon	CMd	Dystric Cambisols	1.4	ET016	DYCAMBISOLS	1	A	1000	0.5	0.5
12	Polygon	LXh	Haplic Lixisols	1111.1	ET039	HPLIXISOLS	1	C	1000	0.5	0.5
13	Polygon	RGc	Calcaric Regosols	75.1	ET047	CLREGOSOLS	1	B	1000	0.5	0.5
14	Polygon	CMx	Chromic Cambisols	1749.8	ET019	CHCAMBISOLS	1	D	1000	0.5	0.5
15	Polygon	CMv	Vertic Cambisols	2025.4	ET018	VTCAMBISOLS	1	D	1000	0.5	0.5
16	Polygon	LPk	Rendzic Leptosols	48.2	ET032	RNLEPTOSOLS	1	A	300	0.5	0.5
17	Polygon	NTu	Humic Nitisols	2884.2	ET044	HUNITISOLS	1	B	1000	0.5	0.5
18	Polygon	LPd	Dystric Leptosols	3239.9	ET030	DYLEPTOSOLS	1	A	300	0.5	0.5
19	Polygon	CLp	Petric Calcisols	111.4	ET013	PTCALCISOLS	1	A	1000	0.5	0.5

Continued,

TEXTURE_1	SOL_Z1	SOL_BDI	SOL_AWC1_1	SOL_K1	SOL_CBN1	CLAY1_1	SILT1_1	SAND1_1	ROCK1_1	SOL_ALB1	USLE_K1	S_ECE	Tex Code	Object ID
Clay	100	1.22	12	3.6E-04	1.0	56	25	19	4	0.23	0.1	0.1	6	25
Sandy loam	30	1.61	15	1.8E+02	0.6	8	16	76	2	0.23	0.1	0	2	23
Sandy loam	10	1.59	50	1.80E+0	1.4	9	18	73	2	0.23	0.1	0	2	23
Sandy loam	100	1.55	15	1.80E+0	0.3	12	12	76	5	0.23	0.1	0.4	2	21
loam	30	1.43	15	1.80E+0	2.4	20	31	49	6	0.23	0.1	0	3	23
Clay	100	1.25	50	3.60E-04	1.1	48	29	23	1	0.23	0.1	0.1	6	21
loam	100	1.4	15	1.80E+0	0.7	22	37	41	4	0.20	0.1	0.1	3	23
Sand	100	1.71	10	3.60E+0	0.4	5	5	90	4	0.37	0.1	0.1	1	21
loam	100	1.4	15	1.80E+0	0.8	24	28	48	1	0.20	0.1	0.1	3	24
loam	100	1.39	10	1.80E+0	1.1	23	37	40	8	0.23	0.1	0.1	3	20
lomy sand	100	1.6	10	3.60E+0	0.4	9	10	81	1	0.23	0.1	0.2	2	21
Sandy loam	100	1.58	15	1.80E+0	0.7	10	15	75	1	0.23	0.1	0.1	2	21
Sandy clay	100	1.43	10	1.80E+0	0.6	23	16	61	5	0.23	0.1	0.1	4	24
loam	100	1.41	50	1.80E+0	0.7	21	35	44	1	0.35	0.1	0.3	3	24
Clay	100	1.24	15	3.60E-04	1.4	50	29	21	2	0.23	0.1	0.1	6	22
Clay	100	1.23	15	3.60E-04	0.9	51	29	20	2	0.23	0.1	0.1	6	22
Sandy loam	30	1.61	50	1.80E+0	1.9	8	16	76	2	0.21	0.1	0	2	23
loam	100	1.39	15	1.80E+0	2.2	24	31	45	9	0.23	0.1	0.1	3	24
Sandy loam	30	1.58	15	1.80E+0	0.6	10	14	76	2	0.23	0.1	0	2	23
lomy sand	100	1.61	10	3.60E+0	0.4	9	8	83	2	0.23	0.1	0.1	2	21

Appendix Table 15: Average monthly rainfall (1994-2013) at different gauging stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Humera	0.3	0.3	37.1	15.6	46.4	154.0	225.5	245.2	116.2	29.1	5.4	0.8
la libela	9.3	7.9	42.8	38.4	24.9	61.7	284.9	258.9	50.9	17.3	36.7	4.5
Mekele	2.0	2.1	13.8	25.1	24.5	48.4	175.5	236.7	39.0	6.3	4.5	0.7
Abi_Adi	1.6	2.1	17.8	31.7	53.7	107.4	286.5	414.7	107.1	27.9	6.2	0.5
Aseged	1.7	1.1	7.4	13.9	51.3	118.4	294.7	307.1	151.1	35.6	10.1	0.4
Samre	1.1	2.3	22.9	27.3	25.1	67.2	235.7	274.7	49.1	6.4	3.8	2.3
Asketema	10.4	11.7	48.6	49.4	30.7	58.8	427.2	368.5	54.4	23.5	27.0	4.8
Mekane berhan	1.5	3.0	14.3	41.1	55.4	108.0	273.4	236.9	62.6	29.6	16.3	3.8
Adiremets	2.4	1.0	12.8	23.1	83.0	215.2	425.3	424.4	198.7	45.8	10.5	0.5
Ashere	0.1	0.8	31.0	20.0	63.5	183.3	230.9	210.8	110.1	38.1	6.6	3.4
Metema	0.0	0.4	10.1	14.4	67.4	190.8	240.5	256.1	185.3	39.5	7.4	0.0
Aykel	2.1	1.6	11.8	31.3	99.0	199.6	287.9	265.9	146.6	80.2	19.4	4.6
Endabaguna	2.4	1.6	9.2	16.6	52.1	147.8	292.5	321.0	200.5	33.5	6.3	2.0
Senkata	0.7	3.7	33.8	40.4	28.9	48.7	192.9	177.9	23.1	5.3	8.1	2.2
Adishehu	7.2	3.1	18.4	29.8	25.7	36.2	169.2	213.3	41.9	14.4	16.8	6.4
Endagaselus	1.2	1.4	15.1	24.7	40.5	100.2	252.2	269.8	103.1	14.1	5.9	1.9
Chenek	0.7	2.5	14.8	36.7	62.6	129.5	268.6	230.4	65.2	31.1	19.4	2.7
Adidaro	2.3	0.0	15.6	25.9	49.8	134.3	283.5	319.1	150.3	42.4	9.9	0.9

Source: Ethiopian National Meteorological Service Agency

Appendix Table 16: Average monthly maximum and minimum temperature (1994-2013) at different gauging stations

Station	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Humera	Max Temp	37.4	38.7	39.5	41.3	39.8	37.4	33.6	32.6	34.2	36.7	37.7	37.3
	Min Temp	15.6	16.7	19.9	23.3	23.4	20.9	20.9	20.4	19.5	19.0	17.7	15.8
Adwa	Max Temp	28.2	30.0	30.2	30.5	30.4	28.4	24.1	23.6	26.2	27.9	27.7	27.8
	Min Temp	7.9	9.8	12.0	14.2	15.5	14.4	14.2	13.9	12.2	10.8	9.6	7.7
Adiremets	Max Temp	22.0	23.1	23.3	25.0	24.2	21.9	20.1	20.1	20.7	21.0	20.7	20.8
	Min Temp	11.9	13.2	13.5	14.7	15.0	13.8	13.4	13.2	13.0	12.5	12.0	11.7
Aykel	Max Temp	24.9	26.8	27.4	27.5	25.5	22.3	19.9	20.0	21.6	22.5	24.1	24.4
	Min Temp	12.8	14.6	15.4	15.2	15.4	13.5	12.1	12.3	12.7	12.7	13.0	12.3
Lalibela	Max Temp	25.8	27.4	27.2	26.8	26.7	25.0	20.2	20.0	22.7	24.6	25.0	25.1
	Min Temp	13.1	14.0	14.4	14.6	15.0	14.2	12.3	11.8	12.8	12.7	12.6	12.7
Metema	Max Temp	36.4	38.4	39.1	40.2	38.7	34.6	30.7	30.0	31.7	34.4	36.2	36.1
	Min Temp	15.3	17.1	19.9	22.5	22.2	19.9	20.2	19.5	18.8	18.4	16.7	15.3
Gondar	Max Temp	28.3	30.0	30.4	30.5	29.0	25.7	23.4	23.5	25.4	26.5	27.6	27.8
	Min Temp	10.2	12.0	13.0	13.4	14.6	13.8	12.3	12.2	12.0	11.3	11.4	9.6
Mekele	Max Temp	23.3	24.5	25.3	26.0	27.1	26.9	23.6	22.5	23.9	23.5	22.7	22.4
	Min Temp	9.2	10.4	11.7	13.2	13.7	13.4	13.1	12.8	11.8	10.9	10.2	9.4
Shire	Max Temp	27.8	29.6	30.2	30.7	30.0	27.0	24.0	23.6	25.6	27.1	27.4	27.4
	Min Temp	11.2	12.6	14.4	14.9	16.3	15.1	13.9	14.4	13.9	12.5	12.2	10.3
Abi_Adi	Max Temp	29.3	29.5	31.3	32.2	31.9	30.3	26.9	26.6	28.6	29.6	29.0	28.8
	Min Temp	11.8	12.3	13.4	13.6	14.2	13.8	12.4	12.7	13.0	13.3	12.3	11.3
Ambagiorgis	Max Temp	19.4	20.3	21.2	21.3	20.6	19.0	17.2	17.3	18.4	18.3	18.4	18.6
	Min Temp	6.9	8.2	8.9	9.6	9.8	9.3	8.7	8.6	8.6	7.8	6.7	6.0
Wukiro	Max Temp	27.5	28.6	29.1	29.6	30.3	30.4	27.1	26.6	27.8	26.9	26.4	26.7
	Min Temp	7.9	8.9	11.2	12.8	13.0	12.8	12.8	12.7	11.5	10.1	9.0	7.4
May_Tsebri	Max Temp	32.8	33.8	35.1	36.3	34.5	31.5	27.1	26.6	27.2	31.2	32.1	32.3
	Min Temp	15.1	16.5	18.5	20.4	20.5	19.0	18.3	17.9	16.5	17.2	16.4	15.3

Source: Ethiopian National Meteorological Service Agency

Appendix Table 17: Monthly parameters for user weather generator of Lalibela, Mtema and Gondar stations

Object id	1	2	3
STATION	Lalibela	Metema	Gondar
WLATITUDE	12.04	12.77	12.52
WLONGITUDE	39.04	36.41	37.43
WELEV	2487	790	1973
RAIN_YRS	10	10	10
TMPMX1	25.74	36.49	28.09
TMPMX2	27.28	38.8	29.09
TMPMX3	27.14	39.61	29.66
TMPMX4	26.79	40.57	29.54
TMPMX5	26.2	39.25	27.27
TMPMX6	25.24	34.55	25.13
TMPMX7	19.41	30.18	22.63
TMPMX8	19.62	29.83	23.63
TMPMX9	22.94	31.48	25.81
TMPMX10	24.41	33.58	27.04
TMPMX11	24.99	36.3	27.28
TMPMX12	25.14	36.16	27.61
TMPMN1	12.97	14.81	12.71
TMPMN2	13.79	17.8	10.98
TMPMN3	14.32	20.44	13.61
TMPMN4	14.62	23.66	15.83
TMPMN5	14.58	23.06	15.71
TMPMN6	14.05	21.03	14.62
TMPMN7	11.85	20.29	13.01
TMPMN8	11.9	19.81	13.12
TMPMN9	12.99	19.17	11.77
TMPMN10	12.54	19.34	10.66
TMPMN11	12.28	16.14	10.67
TMPMN12	12.4	15.14	8.18
TMPS TDMX1	0.5	1.4	0.6
TMPS TDMX2	0.5	1.5	0.8
TMPS TDMX3	0.9	2.1	0.7
TMPS TDMX4	1	1.4	1.2
TMPS TDMX5	1	1.4	1.4

Station	Lalibela	Metema	Gondar
TMPS TDMX11	0.6	1.6	0.6
TMPS TDMX12	0.5	1.1	0.5
TMPS TDMN1	0.5	1.5	2.3
TMPS TDMN2	0.6	2.7	2.7
TMPS TDMN3	0.6	2.2	2.9
TMPS TDMN4	0.7	2.2	2.8
TMPS TDMN5	0.8	1.9	2.6
TMPS TDMN6	0.8	2.5	1.7
TMPS TDMN7	0.5	2.3	2.4
TMPS TDMN8	0.5	1.5	2.2
TMPS TDMN9	0.6	1.5	2.1
TMPS TDMN10	0.4	1.7	2.4
TMPS TDMN11	0.6	1.3	2.5
TMPS TDMN12	0.5	1.3	3.1
PCPMM1	9.43	0	4.13
PCPMM2	9.21	0.9	4.05
PCPMM3	44.59	10.07	14.01
PCPMM4	37.42	23.55	33.87
PCPMM5	25.03	77.25	95.39
PCPMM6	70.51	198.89	199.66
PCPMM7	297.31	249.45	344.29
PCPMM8	251.15	249.41	286.97
PCPMM9	41.48	184.73	103.55
PCPMM10	18.47	32.83	78.79
PCPMM11	16.47	7.56	17.52
PCPMM12	4.54	0.01	6.92
PCPSTD1	1.78	0	1.2
PCPSTD2	1.69	0.52	1.04
PCPSTD3	4.64	2.67	2.5
PCPSTD4	3.46	4.02	3.5
PCPSTD5	3.36	5.69	7.39
PCPSTD6	5.59	11.39	10.94
PCPSTD7	10.56	11.98	11.67
PCPSTD8	9.34	11.99	10.22

TMPSTDMX6	1.5	0.9	0.9
TMPSTDMX7	0.9	0.8	0.9
TMPSTDMX8	0.6	0.7	0.6
TMPSTDMX9	0.7	1.1	0.7
TMPSTDMX10	0.6	1.5	1.3

PCPSTD9	3.46	11.09	6.81
PCPSTD10	3.27	4.75	7.67
PCPSTD11	3.11	2.27	2.82
PCPSTD12	0.85	0.0082	1.86
PCPSKW1	9.49	10	11.9
PCPSKW2	7.72	17.12	9.2

Continued,

PCPSKW3	6.25	10.7	11.86
PCPSKW4	4.58	7.4	5.15
PCPSKW5	7.43	3.1	4.53
PCPSKW6	4.02	2.57	3.25
PCPSKW7	2.2	2.11	1.7
PCPSKW8	2.25	2.34	1.86
PCPSKW9	4.35	2.89	3.35
PCPSKW10	10.68	6.53	4.8
PCPSKW11	9.1	15.5	8.1
PCPSKW12	8.02	24.27	13.31
PR_W1_1	0.06	0	0.03
PR_W1_2	0.06	0.0056	0.03
PR_W1_3	0.14	0.0123	0.077
PR_W1_4	0.14	0.066	0.14
PR_W1_5	0.09	0.2034	0.26
PR_W1_6	0.201	0.587	0.552
PR_W1_7	0.72	0.612	0.91
PR_W1_8	0.61	0.66	0.72
PR_W1_9	0.18	0.48	0.36
PR_W1_10	0.07	0.1	0.21
PR_W1_11	0.05	0.018	0.06
PR_W1_12	0.04	0.0017	0.0283
PR_W2_1	0.35	0	0.24
PR_W2_2	0.32	0	0.15
PR_W2_3	0.58	0.65	0.31
PR_W2_4	0.53	0.38	0.46
PR_W2_5	0.39	0.53	0.58
PR_W2_6	0.62	0.54	0.71
PR_W2_7	0.88	0.73	0.89
PR_W2_8	0.84	0.78	0.84

RAINHHMX1	1	1	2
RAINHHMX2	1	1	1
RAINHHMX3	3	2	2
RAINHHMX4	3	2	1.5
RAINHHMX5	4	3	4
RAINHHMX6	45	50	57
RAINHHMX7	274	214	240
RAINHHMX8	210	194	173
RAINHHMX9	214	247	154
RAINHHMX10	78	86	98
RAINHHMX11	12	17	18
RAINHHMX12	3	2	4
SOLARAV1	185.2	188	176.5
SOLARAV2	440.9	446.9	412.7
SOLARAV3	582.2	660.6	590.3
SOLARAV4	435	461.3	412.8
SOLARAV5	202.7	219.4	208.4
SOLARAV6	37.6	33.9	33.4
SOLARAV7	122.8	106	100.9
SOLARAV8	345.1	344.6	326.9
SOLARAV9	441.1	538.6	507.9
SOLARAV10	477.1	506.8	466.4
SOLARAV11	272.1	257.8	255.9
SOLARAV12	49.1	45.6	45.5
DEWPT1	10.09	17.81	10.7
DEWPT2	7.9	17.71	8.49
DEWPT3	8.18	14.67	9.89
DEWPT4	9.68	18.26	10.68
DEWPT5	9.68	19.87	14.09
DEWPT6	9.59	20.34	14.65

PR_W2_9	0.56	0.58	0.55
PR_W2_10	0.5	0.29	0.49
PR_W2_11	0.43	0.352	0.413
PR_W2_12	0.37	0	0.304
PCPD1	2.42	0	0.89
PCPD2	2.47	0.16	1.05
PCPD3	8.16	1.05	3.11
PCPD4	7.32	2.89	6.53
PCPD5	8.16	9.53	12.58
PCPD6	7.32	17.37	20.37
PCPD7	4.95	22.16	28.68
PCPD8	10.42	23.95	26.53
PCPD9	27.79	16.89	14.32
PCPD10	25.84	4.53	8.92
PCPD11	10.11	0.89	3.05
PCPD12	3.89	0.05	3.21

DEWPT7	10.67	20.51	14.74
DEWPT8	12.91	22.26	15.72
DEWPT9	13.9	22.59	14.03
DEWPT10	13.1	22.88	11.41
DEWPT11	10.36	20.53	11.29
DEWPT12	9.56	16.04	10.48
WNDV1	1.3	1.2	1.7
WNDV2	1.5	1.2	1.9
WNDV3	1.5	1.4	2
WNDV4	1.6	1.6	1.9
WNDV5	1.8	1.6	1.9
WNDV6	1.5	1.5	1.9
WNDV7	1	1.1	1.5
WNDV8	0.9	0.9	1.3
WNDV9	1	0.8	1.4
WNDV10	1.2	0.9	1.5
WNDV11	1.2	1.1	1.5
WNDV12	1.2	1.1	1.6

Appendix Table 18: One-sided 10 percent significance outlier test K_N values for a normal distribution (Interagency Advisory Committee on Water Data, 1982, after Grubbs and Beck, 1972).

Sample size	K_N value	Sample size	K_N value	Sample size	K_N value	Sample size	K_N value
10	2.036	45	2.727	80	2.940	115	3.064
11	2.088	46	2.736	81	2.945	116	3.067
12	2.134	47	2.744	82	2.949	117	3.070
13	2.175	48	2.753	83	2.953	118	3.073
14	2.213	49	2.760	84	2.957	119	3.075
15	2.247	50	2.768	85	2.961	120	3.078
16	2.279	51	2.775	86	2.966	121	3.081
17	2.309	52	2.783	87	2.970	122	3.083
18	2.335	53	2.790	88	2.973	123	3.086
19	2.361	54	2.798	89	2.977	124	3.089
20	2.385	55	2.804	90	2.981	125	3.092
21	2.408	56	2.811	91	2.984	126	3.095
22	2.429	57	2.818	92	2.989	127	3.097
23	2.448	58	2.824	93	2.993	128	3.100
24	2.467	59	2.831	94	2.996	129	3.102
25	2.486	60	2.837	95	3.000	130	3.104
26	2.502	61	2.842	96	3.003	131	3.107
27	2.519	62	2.849	97	3.006	132	3.109
28	2.534	63	2.854	98	3.011	133	3.112
29	2.549	64	2.860	99	3.014	134	3.114
30	2.563	65	2.866	100	3.017	135	3.116
31	2.577	66	2.871	101	3.021	136	3.119
32	2.591	67	2.877	102	3.024	137	3.122
33	2.604	68	2.883	103	3.027	138	3.124
34	2.616	69	2.888	104	3.030	139	3.126
35	2.628	70	2.893	105	3.033	140	3.129
36	2.639	71	2.897	106	3.037	141	3.131
37	2.650	72	2.903	107	3.040	142	3.133
38	2.661	73	2.908	108	3.043	143	3.135
39	2.671	74	2.912	109	3.046	144	3.138
40	2.682	75	2.917	110	3.049	145	3.140
41	2.692	76	2.922	111	3.052	146	3.142
42	2.700	77	2.927	112	3.055	147	3.144
43	2.710	78	2.931	113	3.058	148	3.146
44	2.719	79	2.935	114	3.061	149	3.148

Appendix Table 19: Mean monthly flows (Mm^3) at dam sites

Dam site	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Embama dre	10.18	7.34	12.75	10.68	14.57	52.82	613.98	1025.16	368.14	49.00	22.11	14.18
Humera	13.17	9.33	16.50	13.77	18.85	68.34	679.25	1134.15	481.98	63.40	28.61	18.35
Metema	1.61	2.15	2.38	1.68	2.30	8.32	105.47	177.70	58.01	7.72	3.48	2.24
Abderafi	2.18	1.84	1.90	2.67	3.66	13.26	181.95	303.81	92.46	12.31	5.55	3.56
TK4	4.95	3.57	6.21	5.18	7.09	25.71	334.77	558.98	179.22	23.85	10.76	6.91
TK5	7.01	5.05	8.78	7.32	10.03	36.36	464.93	776.29	253.43	33.73	15.22	9.76
TK21	1.00	0.72	1.25	1.05	1.43	5.20	84.66	141.35	36.26	4.83	2.18	1.40

Appendix Table 20: Consistency plots of each gauging stations

