ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

DEPARTMENT OF CIVIL ENGINEERING

MSc THESIS ON

Effects of Watershed characteristics on River Flow for the Case of Ribb And Gummara Catchments

BY: EPHREM ALEMU

ADVISOR: Dr. HABTAMU HAILU

OCTOBER, 2011

ADDIS ABABA UNIVERSITY
Addis Ababa Institute of Technology
Department of Civil Engineering

EFFECTS OF WATERSHED CHARACTERISTICS ON RIVER FLOW FOR THE CASE OF RIBB AND GUMMARA, UPPER BLUE NILE

Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree of Master of Science in Civil Engineering
(Hydraulics engineering)
by
Ephrem Alemu

APPROVED BY BOARD OF EXAMINERS

Dr. Habtamu Hailu	----------------------	-------------------------
(Advisor)	Signature	Date
Dr. Daniel F/Silasie		
------------------------	----------------------	------------------------
(External Examiner)	Signature	Date
Dr. Dereje Hailu		
-------------------------	-----------------------	-----------------------
(Internal Examiner)	Signature	Date
Ato Belete		
------------------------	---------------------------	------------------------
(Chairman)	Signature	Date

Table of contents

ABSTRACT

In this study the effect of watershed characteristics on annual outflow contribution of Ribb Catchment is evaluated. The Gummara catchment, which is adjacent to the Ribb catchment and is equivalent in terms of area but a long year annual flow of more than double of Ribb was taken for comparison in the whole process of evaluation. ILWIS model was used for detail evaluation of the physical watershed characteristics (PCC) for both watersheds. The effects of physical catchment characteristics were analysed and characteristics which have high differences (Rainfall and soil) were identified. Distributed physically based hydrological model known as soil and water assessment tool (SWAT) has been applied for evaluation of PCC with significant differences. The model was calibrated and validated over the gauged upper reaches of catchments of Rib and Gummara. The model was calibrated for the period from 1998-2004 and validated for the period from 2005-2007. The performance of the model was evaluated on the basis of performance rating criteria, coefficient of determination, Nash & Sutcliff efficiency, and volumetric error. The overall performance of the two models gives satisfactory result. The physical catchment characteristics which have high differences (Rainfall and Soil) in the two watersheds were evaluated and tested by creating different scenarios in the calibrated and validated models and the result shows soil has a great effect in lower annual flow of Ribb watershed followed by rainfall.

List of Figures

CHAPTER ONE

1. **Introduction**

1.1 Background

Land and water resources degradation are the major problems on Ethiopian highlands. Poor land use practices and improper management systems have significant role in causing high soil erosion rates, sediment transport, loss of agricultural nutrients and most importantly the Loss of water resources both in quantity and quality (Shimelis, 2008). Erosion disturbs the channel substrate and as a result downstream areas may receive excessive sediment loads, leading to poor water quality (Robert, 2002).

A river's flow rate and water quality is dependent on the land-use practices within their entire watershed. Therefore, watershed management is an essential part of maintaining healthy productive rivers. Particularly a better understanding of the hydrological characteristics of different watersheds in the headwaters of the Blue Nile River is of considerable importance given the government special interest towards developing water resources of this river at a larger scale. For instance, Lake Tana in the upper Blue Nile basin is considered as the first growth corridor of the country to ensure agricultural productivity and attain food security so as to reduce the level of poverty and enhance national economic development. Beyond that, the great renaissance dam and the Ribb dam are among the many development attempts on the Blue Nile River.

Lake Tana Sub basin is one of the major basins that significantly contribute the lively hoods of tens of millions of people in the lower Nile river basin. But at the same time, it is one of most affected sub basin in the region as soil erosion, sediment transport and land degradation are great concerns. The land and water resources of the subbasin and its ecosystem are in danger due to the rapid growth of population, deforestation and overgrazing, soil erosion, sediment deposition, storage capacity reduction, drainage and water logging, flooding, pollutant transport, overexploitation of specific fish species. Lake Tana comprises a total area of 15,096 Km^2. The mean annual rainfall of the catchment area is about 1280 mm. The annual mean and actual evapotranspiration of the catchment is estimated to be 773 mm and 392 mm, respectively (Abeyou, 2007).Gilgel Abay, Ribb, Gummara and Megech are the main rivers feeding the lake which contribute more than 93 % of the inflow.

A comparison which is made between area and mean annual runoff from flow data record of 1992-2007 for the major tributaries of Lake Tana showed a higher correlation between area and river runoff except for Ribb river which resulted in lower flow due to watershed characteristics (Abeyou 2007).

In this study therefore the effect of watershed characteristics of Ribb catchment on the flow of Ribb River was evaluated. The Gummara catchment, which is adjacent to the Ribb catchment and equivalent to it in terms of area was taken for comparison in the process of evaluation. To study the effect of physical catchment characteristics on the runoff generation the rainfall runoff modelling (SWAT) and ILWIS were adopted.

1.2 Objectives

1.2.1 General Objective

The main objective of this study is to examine the influence of the characteristics of Ribb catchment on the flow of Ribb River in the upper Blue Nile basin.

1.2.2 The Specific Objectives

- To identify the most sensitive watershed characters that governs the runoff generation.
- To make comparison with the Gummara catchment and forward scientific reason for the less contribution of runoff volume from Ribb catchment, if found less.

1.3 Problem Statement

The Ribb and Gummara catchments which comprise 22 % of the Lake Tana subbasin contribute flow to the Ribb and Gummara rivers which are part of the, major tributaries of Lake Tana. The two rivers feed water to the lake from west direction. The Ribb and Gummara catchments have comparable gauged area of 1283 km^2 and 1302 km^2 respectively while the long-term annual contribution river flow from those two gauged catchments in the same order shows 1230 MCm and 510 MCm (Abeyou, 2007). Previous studies on the regionalization transfer of calibrated model parameters to ungauged catchments based on catchment characteristics (Seibert, 1999; Abeyou, 2007 and Booij,M.J 2005) in the upper Blue Nile have showed catchment area has strong correlation with the amount of runoff generation. As opposed to this claim, however, such association was not observed in Ribb River for the reason not known yet

1.4 Research Question

- What are the dominant watershed characteristics which affect the runoff at Ribb watershed?
- Is there any relationship between catchment area and runoff generation in Ribb catchment?

CHAPTER TWO

2. Literature Review

2.1 Previous Study in the Lake Tana Basin.

Water resource development in Lake Tana basin has been studied at different stages of details by different consultants of various times since 1900's.The most relevant studies carried out are presented as follows:

The study conducted by the United States department of the interior, bureau of reclamation in 1964 is named as study of land and water resource of the Blue Nile and at this time there was no enough available data recorded. This study was conducted at reconnaissance level mainly done to identify considerable potentials for irrigation and hydropower in both Tana and Beles basins. The USBR studies have also propose a regulation dam for Lake Tana at chara chara with the objective to the upper Beles hydropower plant. USBR,(1964).

The Tana Beles study(studio Pelterngeli) were carried out between late 1986 and mid 1990 . The core objective was to develop a plan to resettle up to 1.47 million people from drought affected areas of Ethiopia. In this study the inflow components were estimated from back ward simulation. Evaporation computation was carried out using pitch reading assuming that the pitch reading is directly proportional to Lake Evaporation. Studio Peterngeli, (1990).

The annual water budget of Lake Tana was determined from estimates of rainfall-runoff on the lake, measured outflow and empirically determined evaporation. Simulation of Lake level variation (1960-1992) has been conducted through modelling at a monthly time step. Estimation of evaporation from the Lake was determined using penman formula. S.Kebede *et al*, (2005):

Abeyou has carried out water balance of Lake Tana and in his study a conceptual hydrological model known as HBV has been applied to estimate the water balance components of the Lake. He used regionalization techniques to transfer parameters from gauged catchments to ungauged catchments. Evaporation from the Lake surface was estimated using Penman combination equation. He found the mean annual flow of the Gummara catchment is 1229Mm^3 and Ribb 510 m^3.He also tested the physical catchment characteristics while calculating flow in unguaged catchments. Abeyou, (2008)

Shimeles has tested the performance of SWAT in the northern highlands of Ethiopia for modelling of hydrology and sediment yield. The main objective of his study was to test and examine the influence of topography, land use, soil and climatic conditions on stream flows, sediment yield and soil erosion. He made modelling of four tributaries of Lake Tana and he found SWAT model gives good agreement with observed and simulated flows. Shimeles, (2008).

Water watch, (2006). In a study carried out Water watch remote sensing techniques was applied and made use of satellite imagery as an input. The actual evaporation has been computed using SEBAL (Surface energy balance algorithm for land). SEBAL converts the satellite measured spectral radiances in to surface energy fluxes including evaporation and carried out water balance computation for the year 2001. Water watch, (2006).

Melkamu has carried out Rainfall-runoff modelling applied to estimate total water resources potential of Lake Tana sub basin. He carried out the water balance simulation on monthly time step. Evaporation was estimated by a combination of Mass transfer and Energy budget method. Melkamu, (2005).

Yohanes used WATBAL and SCS model for water resources potential assessment in the Lake Tana basin. The rainfall on the Lake surface was estimated using spatial interpolation of Inverse distance weighted techniques. **.** He found that the mean annual flow of Gummara catchment is 1388.84 MCM**.** Yohanes, (2007).

SMEC, (2007): A rainfall-runoff model was applied using rain run model for the estimation of hydrological processes in the basin and the water balance components of the Lake. Evaporation from the Lake surface was determined by a combination of energy balance and penman formula.

Sirak has used conceptual hydrological model known as SWAT has to estimate the water balance components of the Lake. He used regionalization techniques to transfer parameters from gauged catchments to ungauged catchments. Evaporation from the Lake surface was estimated using Penman combination equation. He found the mean annual flow of the Gummara catchment is 1323Mm^3 and Ribb 510 m^3. Sirak, (2008)

In the Abbay River Basin Integrated Master Plan Study carried out over three years and three phases. Inception, inventory and analysis and, finally, master planning. The Master plan has been conducted for 50 years planning horizon. (BCEOM & Associates, 1998-1999)

2.2. Hydrological Modelling

2.2.1. The Hydrologic Cycle

The continuous movement of all forms of water on the earth is called hydrologic cycle. This includes condensation of vapour pressure in atmosphere that give rise to precipitation. Precipitation partly intercepts by vegetation and partly reaches the surface. Evaporation takes place from intercepted water by vegetation and from the surface storage. Water also flows through streams and reach lakes and reservoirs from where evaporation and seepage to ground water occurs. Precipitation that infiltrate to the soil could also leave by evapotranspiration or reach streams by through flow and partly percolates to ground water. The depletion of water in the surface and sub surface due to evaporation and evapotranspiration causes ground water to move upward directions through the process called capillary rise. Some of it evaporates or moves to streams as base flow or to the ocean and lakes through deeper routes.

Unsaturated flow, macro pore flow and perched flow perform due to the contribution of precipitation. The process of percolation will occur when the unsaturated flow recharges the ground water. Macro pore and perched flow allow passing the water and this water will recharge the ground water flow and cause rise of the water table. Percolation is a process when rainwater reaches ground water and this ground water in to the channel flow which is base flow and evaporation. But, inmost cases most part of the ground water will be as groundwater or it contributes to the groundwater storage. In general evaporation is defined as the aggregation of evaporation from canopy, plant transpiration, evaporation from the soil and free water evaporation. Groundwater is the contribution of catchment runoff and channel flow will contribute to catchment runoff. (Chow *et al.,* 1988).

2.2.2 Hydrological Model

Hydrological model is a mathematical model used to simulate river or stream flow and calculate water quality calculations. These models generally came in to use in the 1960s and 1970s when demand for numerical forecasting of water quality was driven by environmental legislations in the United States and United Kingdom. At about this time computers became more widely accessible and powerful enough to significantly assist in modelling processes. There are numerous hydrological models and they can be grouped by pollutant addressed, complexity of pollutant sources, whether the model is steady state or dynamic, and the time period modelled. Also important in determining the selection of model is whether it is distributed (i.e. capable of predicting multiple points within a river) or lumped. Simple models may only address a single pollutant, whereas a complex model could have multiple runoff and point sources for pollution for more than one chemical, as well as sediment data. It could further divide the channel flow in to strata in which various biotas are modelled in relation to chemical and sediment transport. The ground water component may also be presented in a model (Kim *et al*., 2007).

Models often address individual steps modularly in the simulation process. Typically subroutines for surface runoff include components for a land use type, topography, soil type, vegetation cover, precipitation and land management practice (regular agricultural activities e.g. pesticide or fertilizer application).

The predictions of the model are directly compared with measurements for two purposes. First, most water Resource models include "free parameters," i.e. variables used in the mathematical formulation for which direct measurements do not exist. These can be estimated by adjusting their values until the resulting model prediction agrees with measurements, a process referred to as model "calibration." Second, the model is operated under the same external conditions as encountered during collection of a set of field data, and the model predictions compared to the field measurements, without any adjustment or "fitting" of the model, to evaluate the performance of the model, a process referred to as model "verification." (Ward and Benamen, 1999).

2.2.3. Classification of Hydrological Models

Many different types of hydrological models have been developed. Many of these models share structural similarities because of underlying assumptions, while some of the models are distinctly different. Therefore, these models are classified according to different criteria. Hypothesis traditionally proposed two kind of modelling approaches with their strong points and limitations:

(1). physically based and
(2). Conceptual lumped models

Physically based models consist of formulation in terms of physical laws expressed in the form deterministic conservation equation for mass, momentum and energy. The equations are solved numerically by dispraising the hydrological system in to smaller entities on a square or polygonal mesh. However, accurately modelling of all processes of the hydrologic cycle becomes very complex, demands an eminent insight in hydrological behaviour and is very demanding for input data. Due to these properties it is a time consuming and expensive. An example of such model is SHE (Abbott *et al.*, 1986).

As an alternative to physically based distributed models, conceptual lumped models are often used as robust tools at catchment scale. The model structures of these models are relatively simple and often are based on a series of interconnected reservoirs. Further these models are invaluable instruments for operational water management (eg. Reservoir operation and flood forecasting). The description of the reservoirs behaviour is kept simple in most structures and their response are controlled by parameterization that are rarely described in terms of physical principles such as gravity, pizieometric heads or hydraulic conductivity and can not be measured in the field. They must be estimated using a calibration procedure whereby the model parameters are fined tuned manually or automatically, by means of optimization algorisms, until the natural system output and the model output show an acceptable level of agreement. However, once environmental forcing condition (eg. Land cover pattern) change, the parameters usually need to recalibrated (Reggianti and Rientges, 2005).

Because of the fact that the required input and output data are usually easily available, consequently these models are mostly used in rainfall-runoff modelling. The SWAT rainfall runoff model is an example of a conceptual model (Bergstriom, 1995).

2.2.4. Hydrological Model Selection

Hydrological models are mathematical formulations which determine the runoff signal which leaves a watershed basin from the rainfall signal received by this basin. They provide a means of quantitative prediction of catchment runoff that may be required for efficient management of water resources. Such hydrological models are also used as means of extrapolating from those available measurements in both space and time into the future to assess the likely impact of future hydrological change. Changes in global climate are believed to have significant impacts on local hydrological regimes, such as in stream flows which support aquatic ecosystem, navigation, hydropower, irrigation system, etc. In addition to the possible changes in total volume of flow, there may also be significant changes in frequency and severity of floods and droughts.

Many comprehensive spatially distributed hydrologic models have been developed in the past decade due to advances in hydrologic sciences, Geographical Information System (GIS), and remote sensing. Among the many hydrologic models developed in the past decade, the Soil and Water Assessment Tool (SWAT), developed by Arnold et al. (1993), has been used extensively by researchers. This is because SWAT

(1) Uses readily available inputs for weather, soil, land, and topography,
(2) Allows considerable spatial detail for basin scale modeling, and
(3) It is capable of simulating change in catchment characteristics using different scenarios

Arnold and Allen (1996) compared multiple components of water budget including surface runoff, groundwater flow, groundwater ET, ET in the soil profile, groundwater recharge, and groundwater heights simulated by the SWAT model with measured data for three Illinois watersheds (122-246 km^2). The predicted data compared well with the measured data for each component of the water budget and demonstrated that the interaction among different components of the model was realistic. Most 18 components of the water budget were within 5% of the measured data and nearly all were within 25%.

SWAT is recognized by the U.S. Environmental Protection Agency (EPA) and has been incorporated into the EPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) (Di Luzio et al. 2002a). [BASINS is a multipurpose environmental analysis software system developed by the EPA for performing watershed and water quality studies on various regional and local scales.]. In order to optimally calibrate the model parameters, especially for large-scale modelling, an auto-calibration routine has been added to SWAT (Eckhardt and Arnold, 2001;

Hence, SWAT will be used in this study to simulate evaluation of effects of catchment characteristics on river flow.

2.2.5 SWAT Model

SWAT is a river basin scale, 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 period of time (Neitsch et al., 2005). SWAT model (Arnold et al., 1998; Arnold and Fohrer, 2005) has proven to be an effective tool for assessing water resource and non point source pollution problems for a wide range of scales and environmental conditions across the globe. SWAT can analyse both small and large watersheds by subdividing the area in to homogeneous parts.

a. Hydrologic Water Balance of SWAT

Water balance is the deriving force behind every thing that happens in the watershed. In SWAT simulation of hydrology of the watershed can be separated in to two major divisions. The first division is the land phase of hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings in to the main channel in each sub basin. See Figure 2-2. The second division is the routing phase of hydrological cycle which can be defined as the movement of water, sediments, etc through the channel network of the watershed to the outlet. As far as this research work is concerned the hydrologic cycle mainly focused on only on the movement of water, which is the runoff generation.

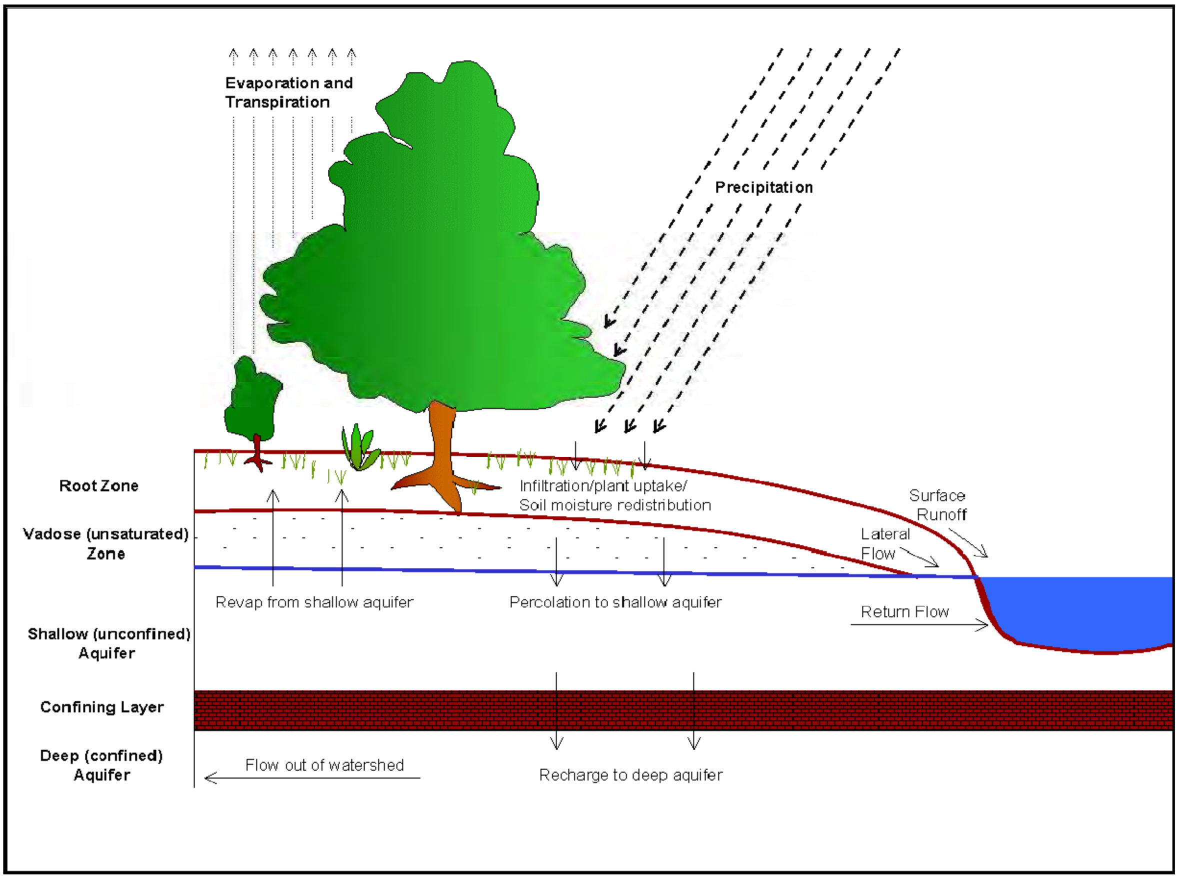


Figure 2-2: Schematic representation of Hydrologic cycle used in SWAT Model.

In the land phase of hydrologic cycles SWAT simulates the hydrological cycle based on the following water balance equation.

$$SW_t = SW_o + [\sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}] \qquad \ldots. \qquad \text{Equation 2-1}$$

Where; SW_t= the final water content (mm H_2O), SW_o= the initial soil water content on day i (mm H_2O), t = time, days, R_{day}= is the amount of precipitation on day i (mm H_2O), Q_{surf} = is the amount of surface runoff on day i (mm H_2O), E_a= is the amount of evapotranspiration on day i (mm H_2O), W_{seep} = is the amount of water entering the vadose zone from the Soil profile on day i (mm H_2O), Q_{gw}= is the amount of ground water flow on day i (mm H_2O).

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

b. **Weather Generator**.

SWAT includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. The occurrence of rain on a given day has a major impact on relative humidity, temperature and solar radiation for the day. The weather generator first independently generates precipitation for the day. Once the total amount of rainfall for the day is generated, the distribution of rainfall within the day is computed if the Green & 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. To Generate the data, weather parameters were developed by using the weather parameter calculator WXPARM (Williams, 1995) and dew point temperature calculator DEW02 (Liersch, 2003).

The daily precipitation generator is a Markov chain-skewed (Nicks, 1974) or Markov chain-exponential model (Williams, 1995). A first-order Markov chain is used to define the day as wet or dry. When a wet day is generated, a skewed distribution or exponential distribution is used to generate the precipitation amount. In this research work a skewed distribution has been used.

Occurrence of Wet or Dry Day.

With the first-order Markov-chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous day. A wet day is defined as a day with 0.1 mm of rain or more Wet-Dry probabilities and monthly statistics value of rainfall, Maximum, Minimum Temperature, Solar radiation, Wind speed and Relative humidity for principal stations.

The weather generator stochastically determines the occurrence of rainfall in a particular day. The probability of a wet day on day i given a wet day on day i – 1, Pi (W/W), and the probability of a wet day on day i given a dry day on day i – 1, Pi (W/D), for each month of the year. From these inputs the remaining transition probabilities can be derived:

$$P_i(D/W) = 1 - P_i(W/W) \text{......} \qquad \text{Equation 2-2}$$

$$P_i(D/D) = 1 - P_i(W/D) \text{.....} \qquad \text{Equation 2-3}$$

Where Pi (D/W) is the probability of a dry day on day i given a wet day on day i – 1 and Pi (D/D) is the probability of a dry day on day i given a dry day on day i – 1.

To define a day as wet or dry, SWAT generates a random number between 0.0 and 1.0. This random number is compared to the appropriate wet-dry probability, Pi (W/W) or Pi (W/D). If the

Random number is equal to or less than the wet-dry probability, the day is defined as wet. If the random number is greater than the wet-dry probability, the day is defined as dry. Skewed probability distribution function has been used for the study area to describe the distribution of rainfall amount.

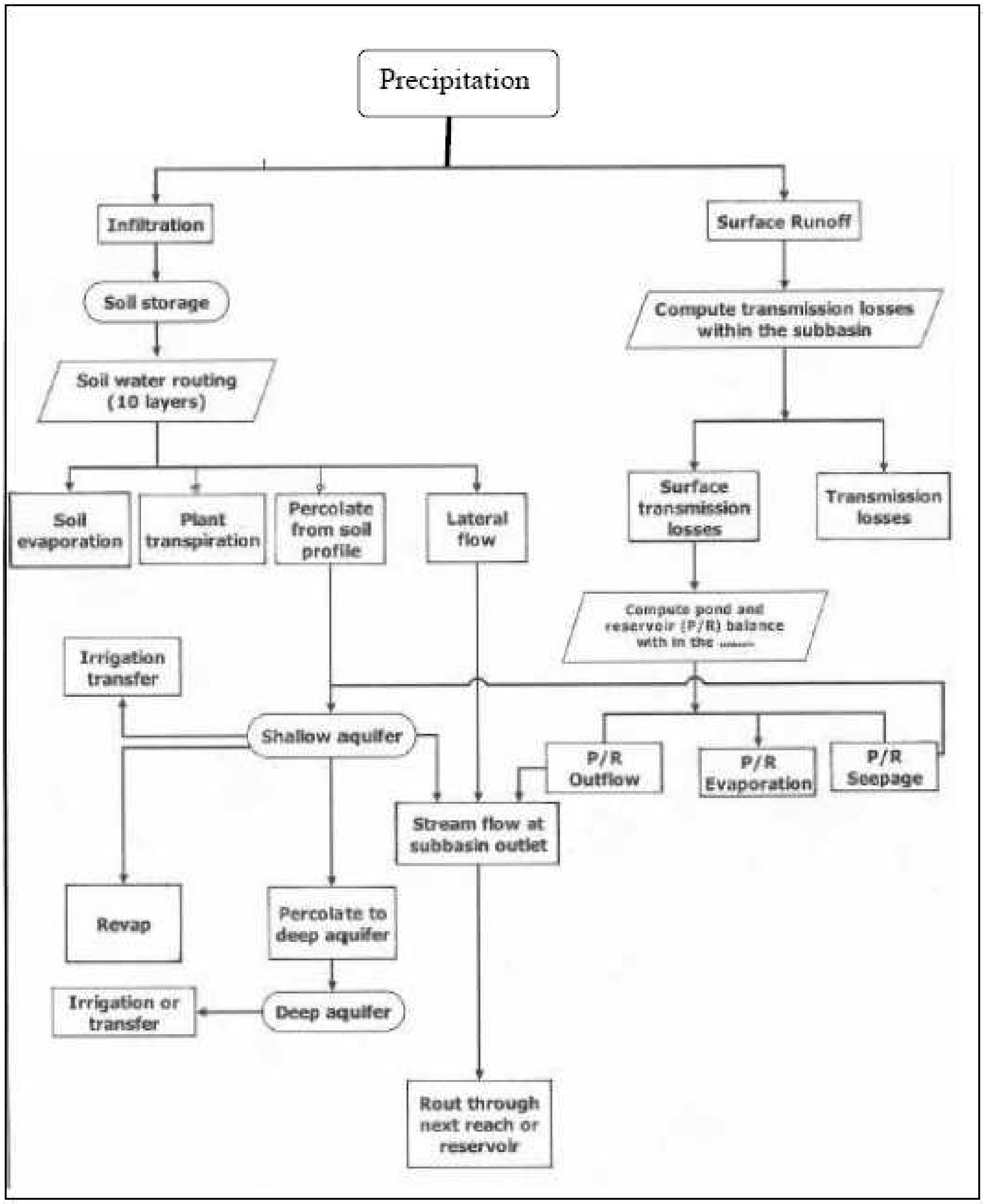


Figure 2-3: Over view of SWAT hydrologic component (Adapted from Arnold *et.al*,. 1998)

c. Surface Runoff

Surface runoff occurs whenever the rate of precipitation exceeds the rate of infiltration. SWAT provides two methods for estimating surface runoff: the SCS curve number procedure (USDA-SCS, 1972) and the Green & Ampt infiltration method (1911).Using daily or sub daily rainfall, SWAT simulates surface runoff volumes and peak runoff rates for each HRU. For these research work SCS curve number method has been used to estimate surface runoff because of the unavailability of sub daily data for Green & Ampt method.

The SCS curve number used (SCS, 1972).

$$Q_{surf} = \frac{(R_d - I_a)^2}{(R_d - I_a + S)} \qquad \text{Equation 2-4}$$

Where; Q_{surf} = is the accumulated runoff or rainfall excess (mmH_2O), R_{day} = is the rainfall depth for the day (mm mmH_2O), I_a = is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), S= is the retention parameter (mm).

The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.49(\frac{1000}{CN} - 10) \qquad \text{Equation 2-5}$$

Where: CN is the curve number for the day.

The initial abstraction, Ia, is commonly approximated as 0.2S and Eq. (4.4) becomes,

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \qquad \text{Equation 2-6}$$

Runoff will only occur when $R_{day} > Ia$.

Dual hydrologic groups are given for certain wet soils that can be adequately drained. The first letter applies to the drained condition, the second to the un drained. Only soils that are rated D in their natural condition are assigned to dual classes.

d. Antecedent Soil Moisture Condition

For the definition of the soil hydrologic groups, the model uses the U.S. Natural Resource Conservation Service (NRCS) classification, which classifies soils into four hydrologic groups (A, B, C, & D) based on infiltration characteristics of the soils. Group A, B, C and D soils have high, moderate, slow, and very low infiltration rates with low, moderate, high, and very high runoff potential, respectively.

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.

Peak Runoff Rate.

The peak surface runoff rate is the maximum volume flow rate passing a particular location during a storm event. SWAT calculates the peak runoff rate with a modified rational method. In rational method it assumed that a rainfall of intensity i begins at time t = 0 and continues indefinitely, the rate of runoff will increase until the time of concentration, $t = t_{conc}$. The modified rational method is mathematically expressed as:

$$q_{peak} = \frac{\alpha_{tc} * Q_{surf} * Area}{3.6 * t_{conc.}} \qquad \text{Equation 2-7}$$

Where: q_{peak} is the peak runoff rate (m^3/s), α_{ct} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm),Area is the sub-basin area (km^2), t_{conc} is the time of concentration (hr), and 3.6 is a conversion factor.

SWAT estimates the value of α using the following equation:

$$\alpha_{tc} = 1 - \exp\left[2 * t_{conc} * \ln\left(1 - \alpha_{0.5}\right)\right] \qquad \text{Equation 2-8}$$

Where: tconc is the time of concentration (hr), and α0.5 is the fraction of daily rain falling in the half-hour highest intensity rainfall.

Time of Concentration.

The time of concentration, t_{conc}, is a time within which the entire sub basin area is discharging at the outlet point. It is calculated by summing up both the overland flow time of the furthest point in the sub basin to reach a stream channel (t_{ov}) and the upstream channel flow time needed to reach the outlet point (t_{ch}):

$$t_{conc} = t_{ov} + t_{ch}$$ Equation 2-9

The overland flow time (t_{ov}) is computed as:

$$t_{ov} = \frac{Lslp}{3600 * V_{ov}}$$ Equation 2-10

Where: L_{slp} is the average sub basin slope length (m), V_{ov} is the overland flow velocity (m/s), and 3600 is a unit conversion factor.

The overland flow velocity for a unit width along the slope is calculated by using the Manning's equation:

$$V_{ov} = \frac{{q_{ov}}^{0.4} * Slp^{0.3}}{n^{0.6}}$$ Equation 2-11

Where: q_{ov} is the average overland flow rate (m3/s), Slp is the average slope of the sub basin (m/m), n is Manning's roughness coefficient of the subbasin. Assuming an average flow rate of 6.35 mm/hr and substituting the equation of V_{ov} into t_{ov},

The simplified equation of the overland flow becomes:

$$t_{ov} = \frac{{L_{slp}}^{0.6} * n^{0.6}}{16 * slp^{0.3}}$$ Equation 2-12

Channel flow time is computed as:

$$t_{ch} \frac{L_c}{3.6 * V_c}$$ Equation 2-13

Where: L_c is the average flow channel length (km), V_c is the average flow velocity (m/s), and 3.6 is a unit conversion factor.

The average flow channel length is calculated as:

$$L_c = \sqrt{L * L_{cen}}$$ Equation 2-14

Where: L is the channel length from the furthest point to the sub basin outlet (km), L_{cen} is the distance along the channel to the sub basin centroid (km).

Assuming L_{cen} = 0.5L, and using the Manning's equation for V_c for a trapezoidal channel with side slope of 2:1 and bottom width to depth ratio of 10:1, channel flow time becomes:

$$t_{ch} = \frac{0.62 * L * n^{0.75}}{Area^{0.125} * Slp_{ch}^{0.375}}$$ Equation 2-15

Where: t_{ch} is the time of concentration for channel flow (hr), L is channel length from the most distant point to the sub basin outlet (km), n is Manning's roughness coefficient for the channel, Area is the sub basin area (km2), and Slp_{ch} is the channel slope (m/m).

Surface Runoff Lag.

In large sub basins with a time of concentration greater than 1 day, only a portion of the surface runoff will reach the main channel on the day it is generated. SWAT incorporates a surface runoff storage feature to lag a part of the surface runoff release to the main channel.

Once surface runoff is calculated, the amount of surface runoff released to the main channel is calculated as:

$$Q_{surf} = (Q'_{surf} + Q_{surf,i-1}) * (1 - Exp[\frac{-surlag}{t_{conc}}])$$ Equation 2-16

Where: $\mathbf{Q_{surf}}$ is amount of surface runoff discharged to main channel in a day (mm), $\mathbf{Q'_{surf}}$ is amount of surface runoff generated in a sub basin in a day (mm), **Qstor**,i-1 is the surface runoff stored or lagged from the previous day (mm), **Surlag** is the surface runoff lag coefficient, and $\mathbf{t_{conc}}$ is the time of concentration for the sub basin (hrs)

Routing Method.

The routing phase is the second division of hydrological cycle which can be defined as the movement of water, sediments, etc through the channel network of the watershed to the outlet. Water is routed through the channel network using the variable storage routing method or the Muskingum River routing method.

The variable storage routing method was developed by Williams (1969) and used in the HYMO (Williams and Hann, 1973) and ROTO (Arnold et al., 1995) model has been used in this research work.

For a given reach segment, storage routing is based on the continuity equation:

$$\Delta V_{stored} = V_{in} - V_{out}$$ Equation 2-17

Where: **V_{in}** is the volume of inflow during the time step (m^3 water), **V_{out}** is the volume of outflow during the time step (m^3 water), and **$\Delta V_{storage}$** is the change in volume of storage during the time step (m^3 water).

This equation can also be detailed as follows:

$$V_{storage,2} - V_{stored,1} = \Delta t * (\frac{q_{in,1} + q_{in,2}}{2}) - \Delta t * (\frac{q_{out,1} + q_{out,2}}{2})$$ Equation 2-18

Where: **Δt** is the length of the time step (s), **q_{in}**, 1 is the inflow rate at the beginning of the time step (m^3/s), **q_{in}**, 2 is the inflow rate at the end of the time step (m^3/s), **q_{out}**, 1 is the outflow rate at the beginning of the time step (m^3/s), **q_{out}**, 2 is the outflow rate at the end of the time step (m^3/s), **Vstorage, 1** is the storage volume at the beginning of the time step (m^3 water), and **Vstorage, 2** is the storage volume at the end of the time step (m^3 water).

Travel time is computed by dividing the volume of water in the channel by the flow rate.

$$TT = \frac{V_{storage}}{q_{out}} = \frac{V_{storage,1}}{q_{out,1}} = \frac{V_{storage,2}}{q_{out,2}}$$ Equation 2-19

Where: **TT** is the travel time (s), $V_{storage}$ is the storage volume (m^3 water), and **q_{out}** is the discharge rate (m^3/s).

e. Potential Evapotranspiration

Potential evapotranspiration (PET) was a concept originally introduced by Thorns Waite (1948) as part of a climate classification scheme. He defined PET is the rate at which evapotranspiration would occur from a large area uniformly covered with growing vegetation that has access to an unlimited supply of soil water and that was not exposed to advection or heat storage effects. Because the evapotranspiration rate is strongly influenced by a number of vegetative surface characteristics, Penman (1956) redefined PET as “the amount of water transpired by a short green crop, completely shading the ground, of uniform height and never short of water”. Penman used grass as his reference crop, but later researchers (Jensen, et al., 1990) have suggested that alfalfa at a height of 30 to 50 cm may be a more appropriate choice.

Numerous methods have been developed to estimate PET. Three of these methods have been incorporated into SWAT: the Penman-Monteith method (Monteith, 1965; Allen, 1986; Allen et al., 1989), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985). The model will also read in daily PET values if the user prefers to apply a different potential evapotranspiration method.

The three PET methods included in SWAT vary in the amount of required inputs. The Penman-Monteith method requires solar radiation, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiation, air temperature and relative humidity. The Hargreaves method requires air temperature only.

Penman-Monteith Method.

The Penman-Monteith equation combines components that account for energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor and aerodynamic and surface resistance terms.

The penman-Monteith equation is:

$$\lambda E = \frac{\Delta.(H_{net} - G) + \rho_{air}.C_p.[e^o{}_z - e_z]/r_a}{\Delta + \gamma.(1 + r_c / r_a)} \qquad \text{Equation 2-20}$$

Where λE is the latent heat flux density (MJ m-2 d-1), E is the depth rate evaporation (mm d-1), Δ is the slope of the saturation vapour pressure-temperature curve, de/dT (kPa °C-1), Hnet is the net radiation (MJ m-2 d-1), G is the heat flux density to the ground (MJ m-2 d-1), ρ_{air} is the air density (kg m-3), cp is the specific heat at constant pressure (MJ kg-1 °C-1), is the saturation vapor pressure of air at height z (kPa), e^o_z e_z is the water vapour pressure of air at height z (kPa), γ is the psychometrics constant (kPa °C-1), r_c is the plant canopy resistance (s m-1), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m-1).

For well-watered plants under neutral atmospheric stability and assuming logarithmic wind profiles, the Penman-Monteith equation may be written (Jensen et al., 1990):

$$\lambda E_t = \frac{\Delta.(H_{net} - G) + \gamma.K_1.(0.622.\lambda.\rho_{air} / P).[e^o{}_z - e_z] / r_a}{\Delta + \gamma.(1 + r_c / r_a)}$$

Equation 2-21

Where λ is the latent heat of vaporization (MJ kg-1), Et is the maximum transpiration rate (mm d-1), K1 is a dimension coefficient needed to ensure the two terms in the numerator have the same units (for uz in m s-1, K_1 = 8.64 x 104), and P is the atmospheric pressure (kPa).

f. Ground Water System.

Groundwater balance in SWAT model is calculated by assuming two layers of aquifers. SWAT partitions groundwater into a shallow, unconfined aquifer and a deep-confined aquifer and it simulates two aquifers in each sub basin. The shallow aquifer is an unconfined aquifer that contributes to flow in the main channel or reach of the sub basin. The deep aquifer is a confined aquifer. Water that enters the deep aquifer is assumed to contribute to stream flow somewhere outside of the watershed (Arnold et al., 1993).

Groundwater flow contribution to total stream flow is simulated by creating shallow aquifer storage (Arnold et al, 1993). Percolate from the bottom of the root zone is recharge to the shallow aquifer. A recession constant, derived from daily stream flow records, is used to lag flow from the aquifer to the stream. Other components of groundwater system include evaporation, pumping withdrawals, and seepage to the deep aquifer.

Shallow Aquifer

The water balance for a shallow aquifer in SWAT is calculated with:

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh}$$

Equation 2-22

where $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm), $aq_{sh,i-1}$ is the amount of water stored in the shallow aquifer on day i-1 (mm), w_{rchrg} is the amount of recharge entering the aquifer on day i (mm), Q_{gw} is the groundwater flow, or base flow, into the main channel on day i (mm), w_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm), wdeep is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm), and $w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping on day i (mm).

Deep aquifer

The water balance for the deep aquifer is:

$$aq_{dp,i} = aq_{dp,i-1} + w_{deep} - w_{pump,dp}$$ Equation 2-23

where aq_{dp}, i is the amount of water stored in the deep aquifer on day i (mm), $aq_{dp,\ i-1}$ is the amount of water stored in the deep aquifer on day i-1 (mm), w_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm), and $w_{pump,dp}$ is the amount of water removed from the deep aquifer by pumping on day i (mm). If the deep aquifer is specified as the source of irrigation water or water removed for use outside the watershed, the model will allow an amount of water up to the total volume of the deep aquifer to be removed on any given day.

CHAPTER THREE

3. Materials and Methods

3.1 Description of The Study Area

3.1.1 General

The Ribb and Gummara catchments are located in the Amhara regional state near Lake Tana, the source of the Blue Nile River. The catchments may be described as a flat to gently slopping plain. The area lies between 11^{o} 30’ North Latitude and 37^{o}30’ East Longitude. It is a vast plain with a majority of the catchment area reaching an elevation of 1800m above mean sea level (MWRE, 1980). They are 19km apart meandering and attaining a slope of 1/5000 towards the Lake Tana shore. The total catchment area of Ribb and Gummara is 2586 km$^{2.}$The source of Ribb River is Guna Mountain. This river is 84 km long and has 34 other small tributaries. The Gummara River starts at an elevation of 3500 m. It has 21 tributaries and the total length of the river is 99.6 km. Figure 3-1 shows the location of Ribb and Gummara catchments in the Lake Tana basin together with rainfall stations.

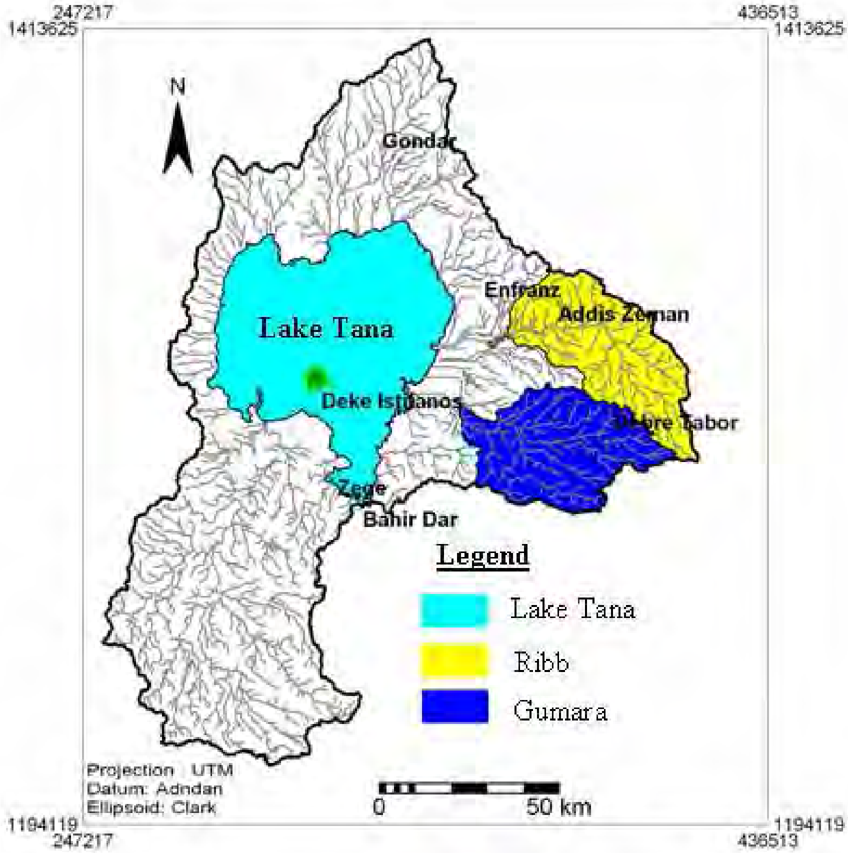


Figure 3-1: Lake Tana Basin and Location of Ribb and Gummara Watershed

3.1.2 Climate of The Study Area

The annual climate may be divided in to two, rainy and dry season. The rainy season may be divided into a minor rainy season in April and May and a major rainy season from June through September. The dry season occurs between October and April. Since there is a meteorology station at the boarder of Ribb and Gummara catchments (Figure 3-2) they record the same rainfall. The long term annual rainfall in the area from (1992-2007) is estimated to be 1494 mm and long-term average maximum and minimum temperature of 19.6 °C and 7.2 °C respectively. The long-term annual rainfall (1992-2007) at Addis Zemen station north of Ribb watershed shows an average of 1082 mm.

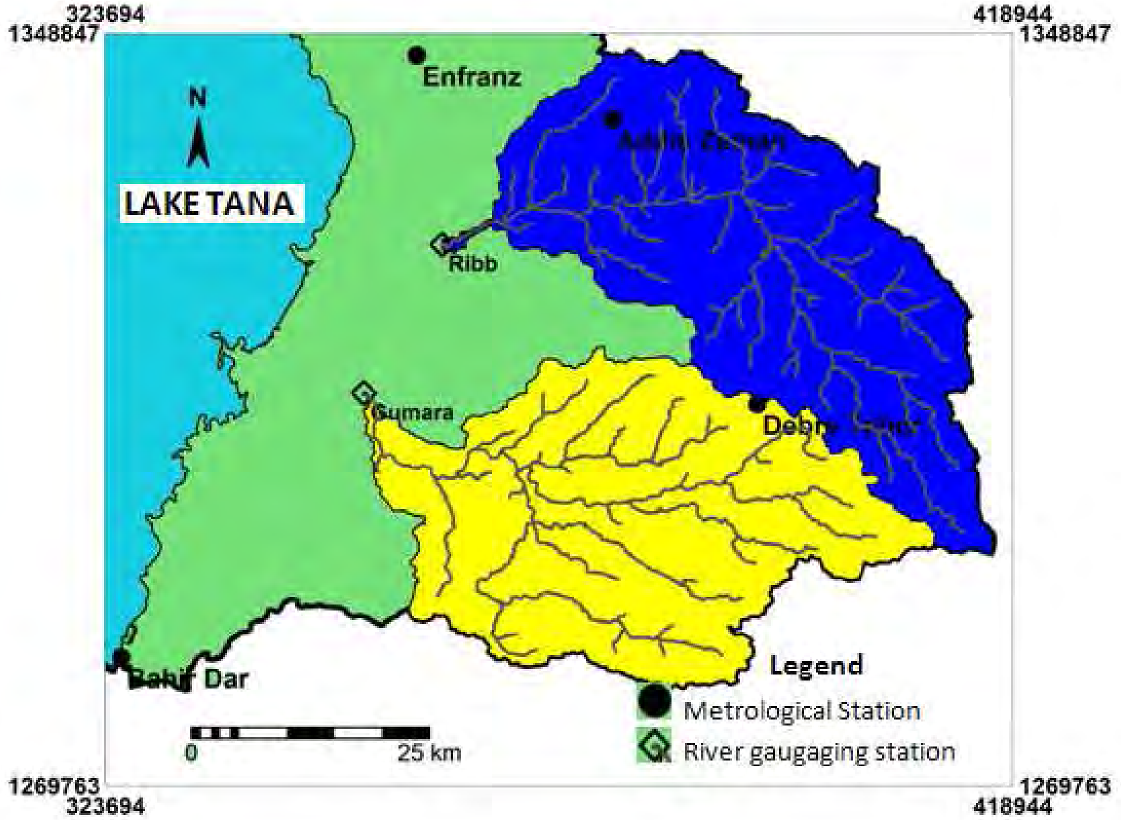


Figure 3-2: Hydrological Setting of the Study Area

3.2 Data Collection and Analysis

For this study, daily river discharge data, metrological data, land use and soil data were collected. The daily river discharge data from the two rivers (Ribb and Gummara) were collected from Ethiopian Ministry of Water Resources and Energy (MWRE), daily metrological data such as rainfall, minimum and maximum temperature, relative humidity, wind speed and daily sunshine hours were collected from Metrological Agency of Ethiopia (EMA). In addition to these a digital elevation model (DEM), Soil map and land use map were collected from MWRE respectively.

3.2.1 Hydrological Data

The stream flow data collected from MWRE has a longer time series data for both Ribb and Gummara rivers. For this study a daily time series data from 1992 to 2007 were used. These data were used to fine hydrological model parameters of SWAT and to see their relation with the watershed characteristics.

Before the data were used they have been checked visually to detect gross errors such as erroneous peak flow, missed recordings and flows of constant rate. These were followed by filling missing data using regression and spatial interpolation methods. From the visual check it was identified that for year 1994, 1996 and 1998 the peak flows of the Ribb River seems trimmed (see Figure 3-3).

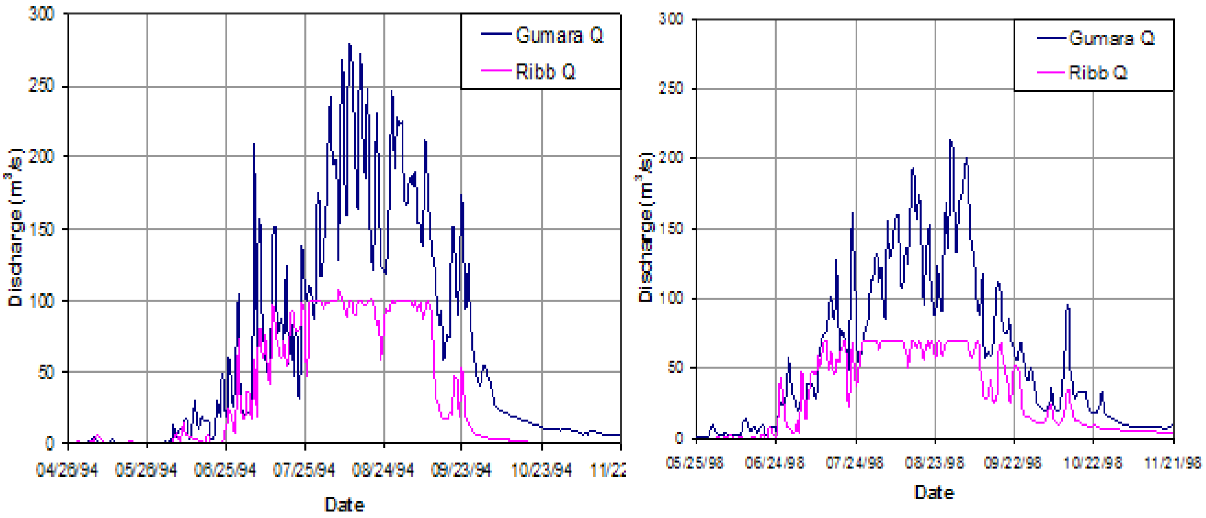
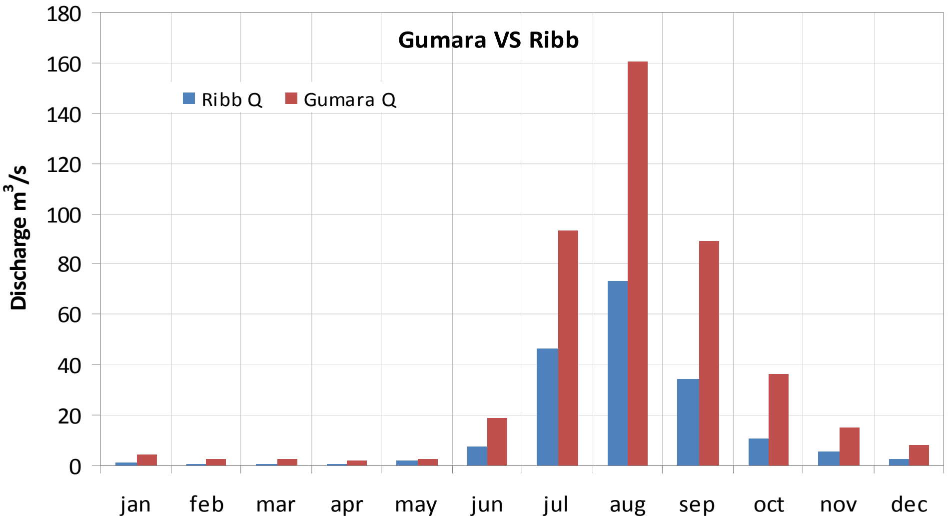


Figure 3-3: Runoff from Gumara and Ribb watersheds with trimmed peak flow of Ribb.

Gummara and Ribb rivers have a similar runoff trend see Figure 3-4 with a high correlation on a long-term monthly basis around 0.98 of R square for the study period. The long-term average monthly discharge of the two rivers is maximum in August and minimum around March and April, the long-term average annual runoff of the two streams shows 1331 Million meter cube (Mcm) and 514Mcm for Gummara and Ribb respectively for the study period.



Month

Figure 3-4: Long-term average monthly discharge of Gummara and Ribb rivers (1992-2007)

3.2.2 Meteorological Data

Ethiopian Meteorological Agency (EMA) classified meteorological stations into four each identified by a code. Code one stations (primary stations) are stations at which observation such as rainfall, relative humidity, maximum and minimum temperature, wind speed and sunshine duration were taken every three hour. For stations categorized under code two (synoptic stations) are those in which observation such as measuring rainfall, relative humidity, maximum and minimum temperature, wind speed and sunshine duration were taken every 24 hours. Stations under code three (ordinary stations) are those only daily rainfall and daily maximum and minimum temperatures are observed. The rest which are categorized under station code four are recording only daily rainfall amount.

There are a total of four metrological stations in and around the study area named as Bahirdar, Debre Tabor, Addis Zemen, and Enfranz station which are owned by EMA (see Figure 3-2).
From the first two stations (Type II) daily metrological data such as precipitation, maximum and minimum temperature, relative humidity, wind speed and daily sunshine hours were collected but from the remaining two stations daily precipitation and maximum and minimum temperature data were collected.

The data collected has been checked visually for outliers and missing values, missed values are filled by simple regression and multiple regressions followed analysis in which accumulated rainfall data is plotted against the average value of all nearby stations.

Rainfall in the study area is highly variable; previous study by Abeyou 2008 has shown that rainfall in Lake Tana Basin has a decreasing pattern to the north direction. For the study area rainfall is maximum at Debre Tabor with annual average rainfall of 1378 mm and a minimum of 896 mm at Infranz from 1992 to 2007. Figure 3-5 shows the long-term average monthly rainfall of the nearby stations.

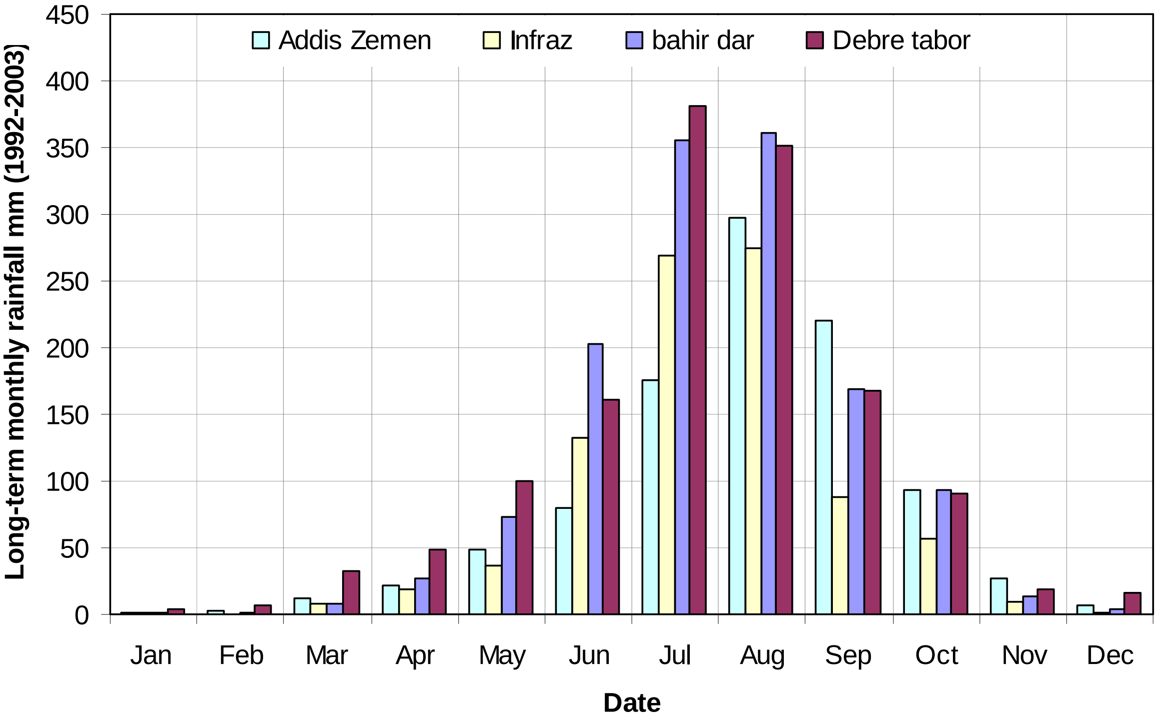


Figure 3-5: Long-term average rainfall of the nearby metrological stations.

3.2.3 Soil and Land Use Data

For this study a soil data of the major soil groups of Gummara and Ribb watershed as per FAO soil group were collected from MWRE GIS department. The major soil groups found in the study area were Fluvisols, Leptosols, Luvisols, Nitosols and Vertisols. And also land use data were collected as land cover map from the MWRE GIS department.

3.3 Methodology

3.3.1 Digital Elevation Model (DEM) Hydro-processing

The purpose DEM hydro-processing is to extract the watershed and to prepare a dataset for further processing. DEM is required as an input for the DEM hydro-processing, in this study a SRTM (shuttle radar topographic mission) of 90 m resolution is used in a tif file format. DEM is a grid in which each cell assigned the average elevation on the area represented by the cell. For this study ILWIS open source software is used to process the SRTM DEM. The DEM hydro-processing tool of ILWIS is able to extract the drainage network and the catchments based on outlet location and stream order, the module has the following procedures:

Fill sink: used to clean up single or multiple depressions artificially from the DEM
Flow direction: determines into which neighbouring pixel any water in a central pixel will flow naturally.
Flow accumulation: performs a cumulative count of the number of pixels that naturally drain into outlets.
Drainage network extraction: extracts a basic drainage network (Boolean raster map) based on a user defined threshold number.
Drainage network ordering: examines all drainage lines in the drainage network map, finds the nodes where two or more streams meet, and assigns a unique ID to each stream in between these nodes, as well as to the streams that only have a single node.
Catchment extraction: constructs catchments; a catchment will be calculated for each stream found in the output map of the Drainage network ordering operation.
***Catchment merge**:* is able to merge adjacent catchments, as found by the Catchment extraction operation.

In this study watersheds area were extracted based on the outlet location collected at coordinates $11^0$51’27.97” N, $37^0$37’51.21” E and $11^0$59’56.35”N, $37^0$42’21.69”E for Gummara and Ribb watersheds respectively. The extracted watershed shape file for Gummara and Ribb watershed were used to evaluate the physical catchment characteristics (PCCs) for evaluation of the Ribb and Gummara watersheds.

3.3.2 Evaluation of Physical Catchment Characteristics (PCC).

A watershed is defined by all points enclosed within an area from which rain falling at these points will contribute water to the outlet. Generally runoff in the watershed is affected by the physical catchment characteristics (PCC) which can be grouped in to five major classes, those are: Climate characteristic, Geography and physiography, Geology, Soil and Land use and cover condition. In this study to evaluate the lesser annual river flow of Ribb watershed major classes of PCC are extracted and evaluated for Ribb and Gummara watersheds.

3.3.2.1 Climate Characteristics

Climate characteristics include precipitation, temperature, wind, relative humidity and other metrological elements for a given region over a long period of time. For this study climate index (Abebe and Foerch, 2006), often denoted as humidity/aridity index was used , it is the ratio of mean annual long-term precipitation to the mean annual long-term potential evapotranspiration. **Potential evaporation** is calculated by Penman-Monteith equation, which is widely used as the standard method in hydrologic engineering applications to estimate potential evapotranspiration estimation.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad \text{[Equation 3-1]}$$

Where

ETo : Reference evapotranspiration [mm day-1],
Rn : Net radiation at the crop surface [MJ m-2 day-1],
G : Soil heat flux density [MJ m-2 day-1],
T : Mean daily air temperature at 2 m height [°C],
U2 : Wind speed at 2 m height [m s-1],
es : Saturation vapour pressure [kPa],
ea : Actual vapour pressure [kPa],
es - ea : Saturation vapour pressure deficit [kPa],
Δ : Slope of vapour pressure curve [kPa °C-1],
γ : Psychrometric constant [kPa °C-1].

Net radiation (Rn) is the balance of the shortwave and long wave radiation streams, such as

$$R_n = R_{SW} \downarrow - R_{SW} \uparrow + R_{LW} \downarrow - R_{LW} \uparrow \qquad \text{[Equation 3-2]}$$

R_{SW} and R_{LW} are the shortwave and long wave components and the arrows denote the direction of the flux, generally expressed in units of Watts per square meter (Wm-2). Thus, the Rn is the difference between total upward and downward radiation fluxes and is a measure of the energy available at the ground surface.

Net shortwave radiation is the difference between incoming and outgoing shortwave radiation expressed as:

$$R_{ns} = R_{sw}\downarrow - R_{sw}\uparrow = (1-\alpha)R_s \qquad \text{[Equation 3-3]}$$

The amount of radiation reaching a horizontal plane is known as the solar radiation, Rs. If the solar radiation, Rs, is not measured, it can be calculated as:

$$R_S = \left(a_S + b_s \frac{n}{N}\right)R_a \qquad \text{[Equation 3-4]}$$

Where

Rs : Solar radiation (MJ/m^2 day)
n : Actual duration of sunshine (hour)
N : Maximum possible duration of sunshine or daylight hours (hour)
n/N : Relative sunshine duration (-)
Ra : Extraterrestrial radiation (MJ/m^2 day)
a_s, b_s : Regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n=0)
$a_s + b_s$: Fraction of extraterrestrial radiation reaching the earth on clear sky days (n= N)

In and around the study area there were two metrological stations Bahir Dar and Debre Tabor will all required input parameters to estimate reference evapotranspiration by Penman-Monteith, the weights of those stations is estimated by Thiessen polygon method based on the Thiessen weights, the long-term annual reference evaporation.

To estimate the areal rainfall of Gummara and Ribb a Thiessen polygon map of rainfall station were made. Based on the weights the long-term annual rainfall data’s the results were calculated.

3.3.2.2 Geography and Physiography:

Geography and physiographic characteristics includes size and shape, elevation, slope and aspect characteristics.

Catchment Area: is an important watershed characteristics for hydrological modelling, the amount of water reaching the river from its catchment depends on the size of the area. Catchment area reflects the volume of water that can be generated from rainfall.

In this study catchment area of the two catchments were calculated through DEM-Hydroprocess of ILWS using GPS coordinates of outlet location the watersheds.

Longest flow path length

The length of longest flow path is usually used in computing the response time at the outlet of a watershed, which is a measure time of concentration which is defined as the length of time it takes for water to travel from hydrologically most remote point in the basin to the outlet, and time of concentration defined as the time required for all parts of a basin to contribute to the runoff at the outlet simultaneously.

In this study through DEM-Hydro processing the length of longest flow path for the two catchments were calculated and the profile of longest flow path was constructed.

Basin Shape: Basin shape is not usually used directly in hydrologic modelling; however, parameters that reflect basin shape are used occasionally and have a conceptual basis. Watersheds have an infinite variety of shapes, and the shape supposedly reflects the way that runoff will accumulate at the outlet.

A circular watershed would result in runoff from various parts of the watershed reaching the outlet at the same time. An elliptical watershed having the outlet at one end of the major axis and having the same area as the circular watershed would cause the runoff to be spread out over time, thus producing a smaller flood peak than that of the circular watershed (http://cnx.org/content/m14421/latest/). A number of watershed parameters have been developed to reflect basin shape. For this study circular index were estimated for both Watersheds.

Circularity Ratio (CR): is the ratio of the area of a drainage basin to the area of a circle having the same perimeter as a drainage basin. To estimate this ratio, the area and perimeter of a drainage basin were measured. The ratio is equal to unity when the basin shape is perfect circle, decreases to 0.785 when the basin is square, and continues to decrease to the extent to which the basin becomes elongated

$$CR = \frac{A_b}{A_c} = \frac{4\pi A}{P^2}$$

Where Ab is area of basin, Ac area of circle whose circumference is equal to basin perimeter and P drainage basin parameter.

Slope: is one of the factors which influence surface runoff velocity. Where higher slope result in higher velocity of flow, therefore the water will travel quickly to reach the river outlet. For this study SRTM DEM of 90 m resolution is processed to estimate slope of the watershed pixel by pixel then the average slope and slope class based on FAO major slope classes are done.

Average slope: is estimated by ILWIS software using filters pixel by pixel, average slope of Gummara and Ribb watershed were estimated pixel by pixel.

3.3.2.3 Geology

Geology includes drainage feature (pattern, density, etc.) parent rock (igneous, sedimentary, and metamorphic).

Drainage density: is calculated by dividing the total stream length for the basin by the catchment area. A high drainage density reflects a highly dissected drainage basin with a relatively rapid hydrologic response to rainfall events, while a low drainage density means a poorly drained basin with a slow hydrologic response. In this study drainage network was extracted by DEM Hydro-processing module of ILWIS.

3.3.2.4 Soil

Soil data is required as input for hydrological modelling which influences runoff generation, generally runoff occurs when rainfall intensity exceeds the infiltration capacity of the soil which is a measure of the ability of the soil to absorb and transmit rain water. Runoff is limited on soils with a high infiltration capacity. For this study a soil map of the major soil groups of Gumara and Ribb watershed as per FAO soil group is collected from MWRE GIS department. The detail soil properties of the study area were arranged for ready made data for modelling.

3.3.2.5 Land use and cover condition

Land use and cover condition can affect the hydrological balance of the watershed by changing magnitude and pattern of runoff, peak flow and ground water levels. It is well known that deforestation causes changes in soil properties and infiltration rates, which ultimately affects the soil erosion processes and hydrological cycle of the catchment. In this study a land cover map was collected from MWRE GIS department.

3.3.3 Summary of The Physical Catchment Characteristics (PCC).

The physical catchment characteristics (PCC) for the Ribb and Gummara watersheds discussed above were summarized and their effect were analysed and classified in to Low, Medium and High Differences based on basic PCC differences and those characteristics which have significantly deviated from mean were evaluated through the watershed model using different scenarios and presented in chapter four of result and discussion section.

3.3.4 Hydrological Modelling

Many comprehensive spatially distributed hydrologic models have been developed in the past decade due to advances in hydrologic sciences, Geographical Information System (GIS), and remote sensing. Among the many hydrologic models developed in the past decade, the Soil and Water Assessment Tool (SWAT), developed by Arnold et al. (1993), has been used extensively by researchers. This is because, SWAT uses readily available inputs for weather, soil, land, and topography, allows considerable spatial detail for basin scale modeling, and it is capable of simulating change in catchment characteristics. Besides SWAT was checked in the highlands of Ethiopia and gave satisfactory results (Shimeles, 2008 and Sirak, 2008). SWAT model was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields. However, this study concentrated on the hydrological aspect of the watershed. The description of the model, model inputs and model setup are discussed in detail in the following sections.

3.3.4.1 SWAT Model

SWAT is a river basin scale, 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 period of time (Neitsch et al., 2005). SWAT model (Arnold et al., 1998; Arnold and Fohrer, 2005) has proven to be an effective tool for assessing water resource and non point source pollution problems for a wide range of scales and environmental conditions across the globe. SWAT can analyse both small and large watersheds by subdividing the area in to homogeneous parts.

3.3.4.2 Hydrologic Water Balance of SWAT

Water balance is the deriving force behind every thing that happens in the watershed. In SWAT simulation of hydrology of the watershed can be separated in to two major divisions. The first division is the land phase of hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings in to the main channel in each sub basin. The second division is the routing phase of hydrological cycle which can be defined as the movement of water, sediments, etc through the channel network of the watershed to the outlet. As far as this research work is concerned the hydrologic cycle mainly focused on only on the movement of water, which is the runoff generation.

In the land phase of hydrologic cycles SWAT simulates the hydrological cycle based on the following water balance equation.

$$SW_t = SW_o + [\sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}] \qquad \text{Equation 3-5}$$

Where; SW_t= the final water content (mm H_2O), SW_o= the initial soil water content on day i (mm H_2O), t = time, days, R_{day}= is the amount of precipitation on day i (mm H_2O), Q_{surf} = is the amount of surface runoff on day i (mm H_2O), E_a= is the amount of evapotranspiration on day i (mm H_2O), W_{seep} = is the amount of water entering the vadose zone from the Soil profile on day i (mm H_2O), Q_{gw}= is the amount of ground water flow on day i (mm H_2O).

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.

3.3.4.3 SWAT Model Inputs

a. Digital Elevations Model

Topography is defined by a Digital Elevation Model (DEM), which describes the elevation of any point in a given area at a specific spatial resolution as a digital file. In this study DEM which is 90 by 90 meter resolution was collected from the federal Ministry of Water Resources and

Energy (MWRE). The digital elevation model (DEM) data was used to delineate the sub-watersheds in the Arc SWAT interface A 90 m by 90 m resolution DEM was used in the catchments delineation. Digital elevation model is one of the essential inputs required by SWAT to delineate the watershed in to a number of sub watershed or sub basins.

DEM was used to analyze the drainage pattern of the land surface terrain, sub basin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length and width were derived from the DEM.

b. Soil Data

SWAT model requires different soil textural and physio-chemical properties, soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. These data were collected from Ministry of Water Resources and Energy (MWRE). The soil map was produced in 1996-1998 during Abay river master plan study by BCEOM with a map scale of 1: 250,000.

c. Land use/Land cover

Land use is one of the most important factors that affect runoff, Evapotranspiration and surface erosion in a watershed. The land use map of the study area was obtained from MoWRE Meta data section, which was used during Abay river master plan study by BCEOM in 1996-1998. The land use / Land cover map scale used during the master plan study were 1:250,000. Land cover/ Plant growth is one of the data base used in SWAT. The model already has predefined SWAT four letter codes for each land cover classification in such away that the land use/Land cover classification used in the study area were assigned in SWAT database.

Land use classification as per BCEOM (1999).

A - Agriculture: These are the areas identified as dominantly cultivated on the land cover map. Although animals play an important role in these areas, they are considered as secondary to cultivation. The key economic activity in these areas is cultivation, especially for grains, and these areas include sources of major surplus producing regions of the country. Crops include both large (Maize) and small (Wheat, Teff) grains.

AP-Agro pastoral: these areas are those defined as moderately cultivated on the land cover map, except as defined in the next unit. Only part of the area is cultivated; grazing activities are at least as important as cultivation.

AS-Agro-Sylvicultural: These are moderately cultivated areas mixed with significant forest, plantation or wood land, or forest/ wood land areas with extensive cultivation. Most of such areas will also be grazed. The units have been called Agro-Sylvicultural because of the importance of trees.

P-Pastoral: These are the grass land areas, generally above 1500m altitude. Pastoral areas are particularly difficult to define. Almost all areas are pastured to some degree. Most cultivated land is pastured after harvest; wood lands, bush lands and shrub lands are all grazed; animals may be found in high forest areas, even where relatively dense, seasonal wet lands are grazed during the dry season.

SP-Sylivo-Pastoral: These are the wood land, bush land and shrub land areas generally above 1500m these areas provide both grazing and wood resources.

S- Sylivicultural: These areas are essentially confined to the intact forest areas, plantations and high land wood lands. The term sylvicultural has been optimistically applied to all forest lands.

d. Weather Data

SWAT requires daily metrological data that could either be read from a measured data set or be generated a weather generator model. In this study, the weather variables used for driving the hydrological balance are daily precipitation, minimum and maximum air temperature, wind speed and solar radiation. Before preparation of the weather data metrological stations in the study area were selected based on Thissen polygon method. The meteorological stations within and around the study area, were Bahirdar, Addis Zemen, Debretabor stations. These data were obtained from Ethiopian Metrological Agency (EMA). In the SWAT model weather is carried out for two near by stations of type II namely Bahirdar and Debretabor and precipitation and temperatures data of the Addis Zemen station (Type III) is also included.

In this study, the weather data used was considered for a period of 1992-2009. Missing weather data are left as it was in name. dbf format and a negative (-99.0) inserted for missing data. This value tells SWAT to generate weather data for that missed data day. Daily values for weather are generated from average monthly values. The model generates a set of weather data for each sub basin. The method used for weather generator has been mentioned in literature review section.The same weather generator technique has been applied for filling in maximum, minimum temperature, wind speed, relative humidity and solar radiation.

3.3.4.4 SWAT Model Setup

The model setup involves five steps: (a) data preparation, (b) Sub basin discretization, (c), HRU definition, (d) parameter sensitivity analysis, (e) calibration and model performance.

a. Data Preparation and subbasin discretization

The required spatial data sets were projected to the same projection called Adindan UTM Zone 37, which is the transverse Mercator projection parameter for Ethiopia, using Arc GIS 9.3. The DEM was used to delineate the watershed and to analyse the drainage patterns of the land surface terrain. The land use / Land cover special data were decalcified in to SWAT land cover/plant types. A user lookup table was created that identified the SWAT code for different categories of Land cover/Land use on the map as per the required format. The soil map is linked with the soil data base which is a soil data base designed to hold data for soils not included in the U.S. The watershed and sub watershed delineation was done using DEM data. The watershed delineation process include five major steps, DEM setup, stream delineation, outlet and inlet definition, watershed outlet selection and definition and calculation of sub basin parameters. For the stream definitions the threshold based stream definition option was used to define the minimum size of the sub basins. The ArcSWAT interface allows the user to fix the number of subbasins by deciding the initial threshold area. The threshold area defines the minimum drainage area required to form the origin of a stream. Subdividing the sub watershed in to areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrological conditions for different land covers, soil and slopes. The land use, soil and slope data sets were imported overlaid and linked with the SWAT databases.

b. HRU definition

To define the hydraulic response unit (HRU) both single and multiple HRU definition options were tested. For multiple HRU definition four scenarios were tested for their efficiency in predicting stream flow in the study catchments. These were 20% - 10% - 20%, 10% - 20% -10% , 10% - 10% - 20%, and 20% - 20% - 10%. Each scenario was arranged in order of land use area and slope class percentage over soil area. Land uses that cover a percentage of the subbasin area less than the threshold level were eliminated. After the elimination processes the area of the land use is reallocated so that 100% of the land area in the subbasins was included in the simulation**.**

c. Sensitivity Analysis.

Sensitivity analysis is a simple technique for assessing the effect of uncertainty on the system performance. It is also a measure of the effect of change of one parameter on another. The sensitivity analysis was undertaken by using a built-in tool in SWAT2005 that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) design method of Morris (1991). The OAT design appeared to be a very useful method for SWAT modelling as it is able to analyze sensitivity on high number of parameters. The LH-OAT sensitivity analysis method combines thus the robustness of the Latin Hypercube sampling that ensures that the full range of all parameters has been sampled with the precision of an OAT designs assuring that the changes in the output in each model run can be unambiguously attributed to the input changed in such a simulation leading to a robust and efficient sensitivity analysis method.

Therefore sensitivity analysis as an instrument for the assessment of the input parameters with respect to their impact on model output is useful not only for model development, but also for model validation and reduction of uncertainty (Hamby, 1994 cited in Lenhart *et al.* 2002)

Table 3:1 Sensitivity classes as per Lenhart *et al.* (2002)

Class	Index	Sensitivity
I	0.00<=/ I / <0.05	Small to negligible
II	0.05<= / I /<0.2	Medium
III	0.2<= / I /<1	High
IV	/ I />= 1	Very high

At the same time Sensitivity analysis of parameters of the models were done manually by dividing model parameters space in to equal intervals and simulating the model with number of intervals times for each of the parameter by changing one parameter at a time.

d. Calibration and Validation of Model.

Physically based semi distributed model SWAT generally have a large number of parameters which are not directly measurable and must therefore be estimated through model calibration, i.e. by fitting the simulated outputs of the model to the observed outputs of the watershed by adjusting the model parameters. A measure of the fit between the simulated and observed outputs is called calibration. The goal of calibration is to find those values for the model parameters that minimize (Maximize) the specified calibration criterion.

As per (Refsgaard and Storm, 1996) three types of calibration procedures can be differentiated:

1. Trial-and-error, manual parameter adjustment;
2. Automatic, numerical parameter optimization;
3. A combination of (1) and (2).

For this study the measured stream flow data of Gumara at Bahirdar and Rib at Addis Zemen were manually calibrated from a period of 1998-2003 and the result is presented in chapter five of this report.

SWAT developers Santhi et.al, (2001) assumed an acceptable calibration for hydrology at $r^2 > 0.6$ and $E_{NS} > 0.5$ these values were also considered in this study as adequate statistical values for acceptable calibration.

Table 3:2 most common parameters used in SWAT model for runoff generation.

S.No.	**Parameters**
1	Base flow alpha factor [days]; ALPHA_BF
2	Threshold water depth in the shallow aquifer for flow [mm]; GWQMN
3	Groundwater "revap" coefficient ;GW_REVAP
4	Threshold water depth in the shallow aquifer for "revap" [mm]; REVAPMN
5	Soil evaporation compensation factor ; ESCO
6	Average slope steepness [m/m]SLOPE
7	Average slope length [m];SLSUBBSN
8	Temperature lapse rate [°C/km];TLAPS
9	Channel effective hydraulic conductivity [mm/hr]; CH_K2
10	Initial SCS CN II value;CN2

11	Available water capacity [mm WATER/mm soil]; SOL_AWC
12	Surface runoff lag time [days]; surlag
13	Groundwater delay [days];GW_DELAY
14	Deep aquifer percolation fraction ; rchrg_dp
15	Maximum canopy storage [mm]; canmx
16	Saturated hydraulic conductivity [mm/hr]; sol_k
17	Soil depth [mm]; sol_z
18	Moist soil albedo ; sol_alb
19	Plant uptake compensation factor ;epco
20	Manning's n value for main channel ;ch_n
21	Maximum potential leaf area index ;blai
22	Biological mixing efficiency ;BIOMIX

e. Model Validation

Model validation is the process of testing model performance of the calibrated model parameter set against an independent set of measured data. For this research work validation period was taken as 3 years beginning Jan. 1st, 2004 – Dec. 31, 2007.

f. Model Performance

The performance of a model must be evaluated on the extent of its accuracy, consistency and adaptability (Goswami et al., 2005). A forecast efficiency criterion is therefore necessary to judge the performance of the model. Assessing performance of a hydrologic model (Krause et al., 2005) requires subjective and/or objective estimates of the closeness of the simulated behaviour of the model to observations.

In this study the model simulation has been evaluated using efficiency criteria such as coefficient of determination, R^2 [Nash and Sutcliff (E_{NS}), 1970] & percent difference. The r^2 coefficient and E_{NS} simulation efficiency measure how well trends in the measured data are reproduced by the simulated results over a specified time period and for a specified time step. The range of values for r^2 is 1.0 (best) to 0.0

The r^2 coefficient for n time steps is calculated as:

$$r^2 = \frac{\left[\sum_{i=1}^{n}(q_{si}-\overline{q}_s)(q_{oi}-\overline{q}_o)\right]^2}{\sum_{i=1}^{n}(q_{si}-\overline{q}_s)^2\sum_{i=1}^{n}(q_{oi}-\overline{q}_o)^2} \qquad \text{Equation 3-1}$$

Where:

q_{si} is the simulated value, q_{oi} is the measured values, $\overline{q}_s$ is the average simulated value, $\overline{q}_o$ is the average measured value

The E_{NS} simulation efficiency for n time steps was calculated as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(q_{oi}-q_{si})^2}{\sum_{i=1}^{n}(q_{oi}-\overline{q}_o)^2} \qquad \text{Equation 3-2}$$

Where: q_{si} is the simulated value q_{oi} is the measured value

The statistical index of modelling efficiency (E_{NS}) values range from 1.0(best) to negative infinity.

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

$$D = 100 \cdot \left[\frac{\left(\sum_{i=1}^{n} q_{oi} - \sum_{i=1}^{n} q_{si}\right)}{\sum_{i=1}^{n} q_{oi}}\right] \qquad \text{Equation 3-3}$$

Where: $\boldsymbol{q_{si}}$ is the simulated value, $\boldsymbol{q_{oi}}$ is the measured value

A value close to 0% is best for D. A negative value indicates model over estimation and a positive value indicate model under estimation.

Table 3:3 General Performance ratings for recommended statistics for a monthly time step. (D. N Moriasi, et al. 2007)

Performance rating	For stream Flow		
	R^2	NSE	% D
Very good	RSR>=0.7	0.75<NSE<=1	D <=±10
Good	0.6<RSR<=0.7	0.65<NSE<=0.75	±10 <=D < ±15
Satisfactory	0.5<RSR<=0.6	0.5<NSE<=0.65	±15<=D<± 25
Unsatisfactory	0.0<=RSR<=0.5	NSE<=0.5	D >= ± 25

CHAPTER 4

4. Results and Discussion

4.1 Physical Catchment Characteristics

Generally runoff in the watershed is affected by the physical catchment characteristics (PCC) which can be grouped in to five major classes, those are: Climate characteristic, Geography and physiography, Geology, Soil and Land use and cover condition. Using different sources the five major classes of PCC are extracted for Gummara and Ribb watersheds.

4.1.1Climate Characteristics:

In and around the study area there are two metrological stations, Bahirdar and Debre Tabor were all required input parameters to estimate reference evapotranspiration by Penman-Monteith, the weights of those stations is estimated by Thiessen polygon method and it shows the Debre tabor station has a higher weight for both rivers see Figure 4-1 and Table 4-1 below.

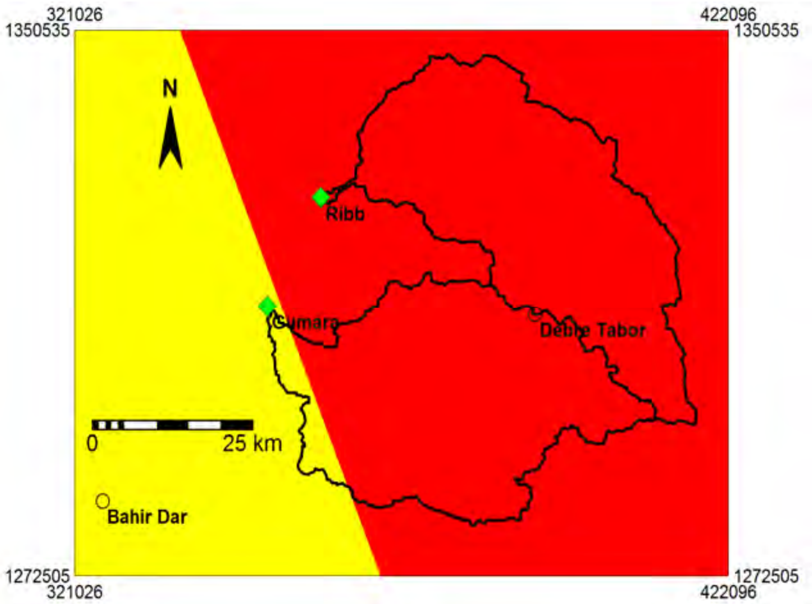


Figure 4-1: Weights of the station for reference Evaporation on Rib and Gummara Watershed

Table 4:1 Reference Evaporation weight of the nearby station on Ribb and Gumara Watershed

Gumara Watershed	
Station Name	**Weight**
Debre Tabor	0.92
Bahirdar	0.08
Ribb Watershed	
Station Name	**Weight**
Debre Tabor	1

Based on the Thiessen weights the long-term annual reference evaporation from 1992-2007 of the two watersheds is 1234mm/year and 1225mm/year for Gumara and Ribb respectively, the result of reference evaporation shows a comparable result.

To estimate the areal rainfall of Gumara and Ribb a Thiessen polygon map of rainfall station is made see Figure 4-2, for Gumara; Debre Tabor station will influence more than 90% of the study area and for Ribb Debre Tabor station will influence 55% of the watershed see Table 4-2.

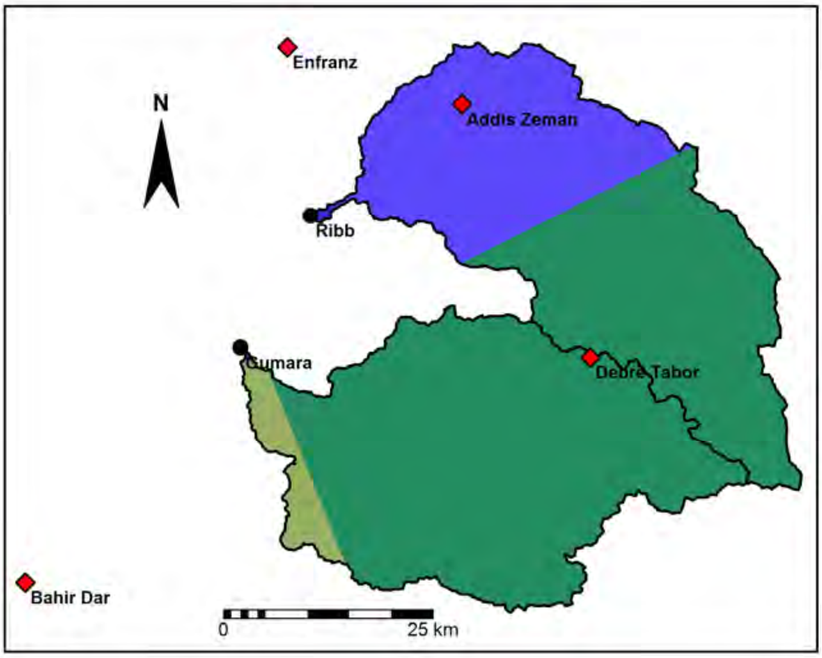


Figure 4-2: Thiessen polygon map of Rainfall station for Gumara and Ribb Watershed

Based on the weights the long-term annual rainfall for Gumara and Ribb is 1373mm/year and 1202mm/year respectively, the result shows an average rainfall difference of 171mm/year from 1992-2003.

Table 4:2 Weights of Rainfall stations for Gummara and Ribb watershed

Gummara Watershed	**Ribb Watershed**

Station Name	**Weight**	**Station Name**	**Weight**
Debre Tabor	0.930	Debre Tabor	0.550
Bahirdar	0.069	Addis Zemen	0.448
Infranz	0.001	Infanz	0.002

The result of the climate index for Gumara and Ribb is 1373/1234 (≈1.11) and 1202/1225 (≈0.98). This shows Gumara is wetter than Ribb Watershed this will help Gumara River to generate more runoff than Ribb watershed but the annual average discharge difference is by far the largest.

4.1.2 Geography and Physiography

Through DEM-Hydroprocess of ILWS using GPS coordinates of outlet location the catchment area of Gumara and Ribb is extracted the result shows 1284 km^2 and 1302 km^2, whereas the annual runoff of Gumara with smaller area is larger than Ribb discharge.

a. Longest flow path length

Through DEM-Hydroprocessing the length of longest flow path for Gumara and Ribb is 84 km and 99.6 km respectively see Figure 4-3, this shows that Gumara watershed has relatively faster response time than Ribb River.

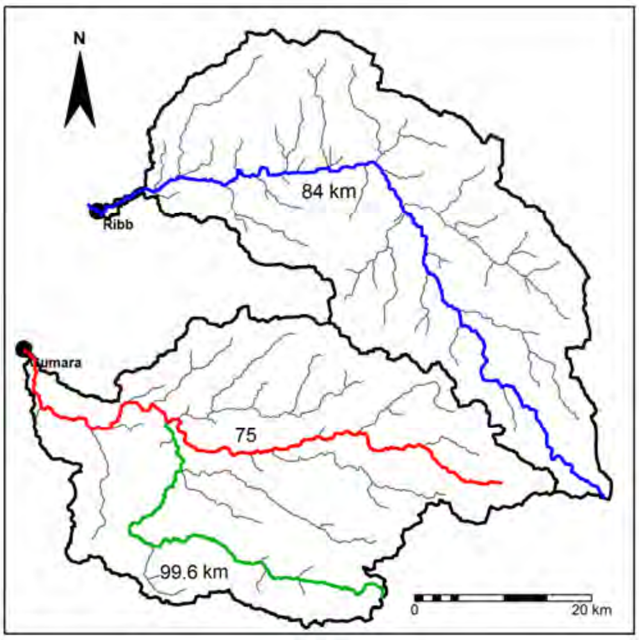


Figure 4-3: Longest flow path of Gumara and Ribb Rivers

The profile of longest flow path was constructed using a digital elevation model, as shown in Figure 4-4. The x-axis represents the distance along a stream from the most remote area of the watershed and y-axis elevation amsl.

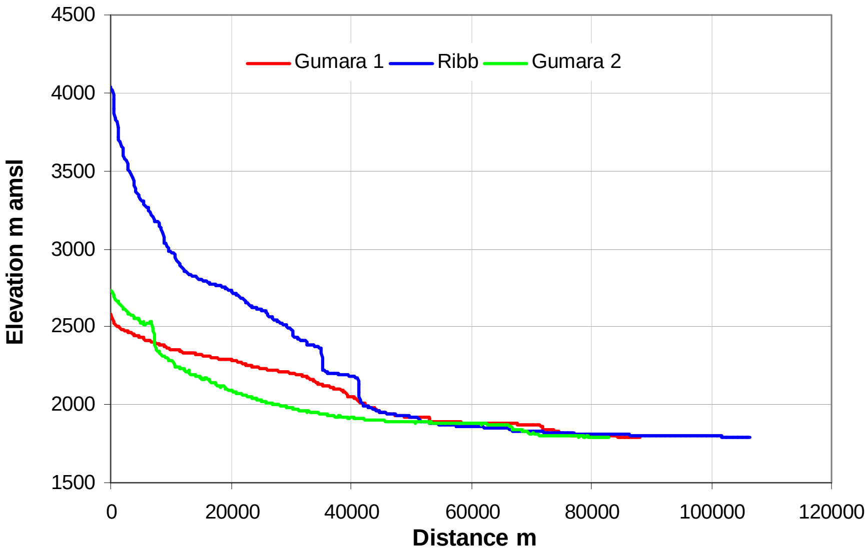


Figure 4-4: longest flow path profile of Gumara and Ribb watershed

Basin Shape:

A number of watershed parameters have been developed to reflect basin shape. For this study circular index is estimated for both Watersheds.

b. Circularity Ratio (CR):

To estimate circularity ratio, the area and perimeter of a drainage basin were measured. The ratio is equal to unity when the basin shape is perfect circle, decreases to 0.785 when the basin is square, and continues to decrease to the extent to which the basin becomes elongated.

$$CR = \frac{A_b}{A_c} = \frac{4\pi A}{P^2}$$

Where A_b, area of basin, A_c area of circle whose circumference is equal to basin perimeter and P drainage basin parameter. The result of circularity ratio is shown in Table 5-3.

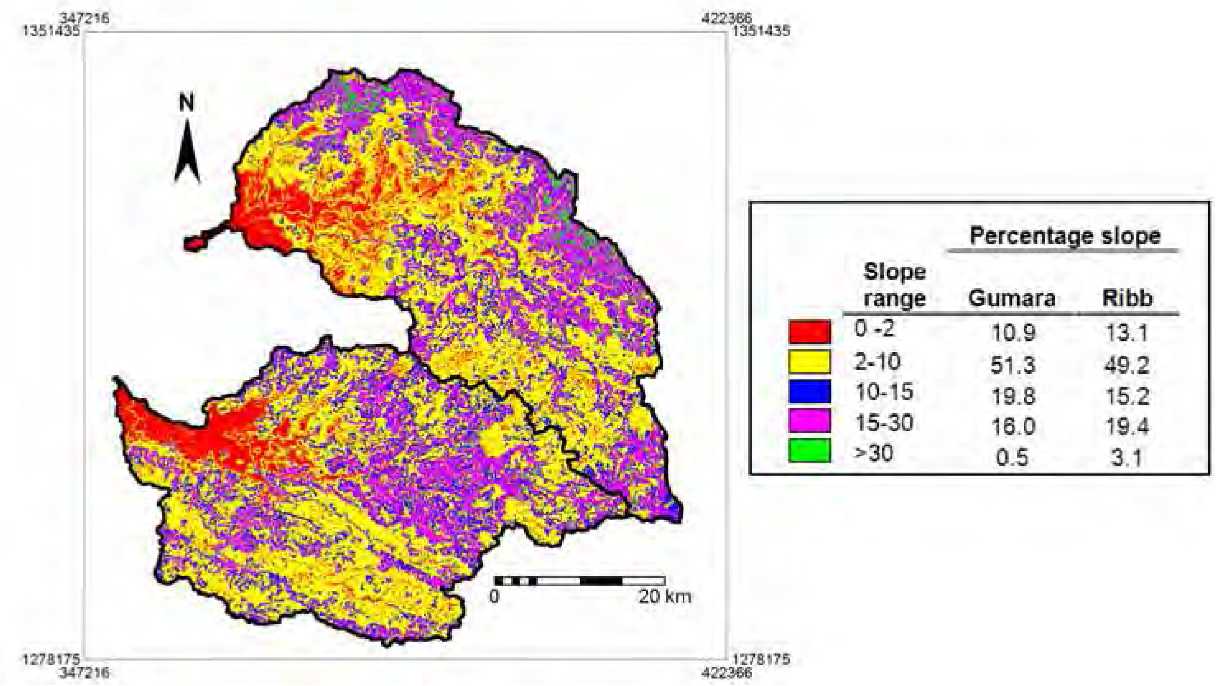
Table 4:3 Basin shape, circularity ratio of Gumara and Ribb watersheds

Watershed	**Area (A_b) km2**	**Perimeter (P) km**	**Circularity Ration (CR)**
Gumara	1284	214	0.352
Ribb	1302	224	0.326

Gummara is relatively more circular than Ribb watershed, this indicates that precipitation in Gumara watershed has a relatively shorter distance to travel to reach a stream and to leave the watershed at its mouth.

c. Slope

For this study SRTM DEM of 90 m resolution is processed to estimate slope of the watershed pixel by pixel then the average slope and slope class based on FAO major slope classes are done. **Average slope**: is estimated by ILWIS software using filters pixel by pixel, average slope of Gummara and Ribb watershed estimated pixel by pixel shows 17.88^{O} and 21.55^{O} respectively. The slope sliced based on FAO slope classes namely 0 to 2 degrees slope, 2 to 10, 10 to 15, 15 to 30 and more than 30 FAO (2001) see Figue 4-5.



	Slope range	Percentage slope	
		Gumara	Ribb
🟥	0 -2	10.9	13.1
🟨	2-10	51.3	49.2
🟦	10-15	19.8	15.2
🟪	15-30	16.0	19.4
🟩	>30	0.5	3.1

Figure 4-5: Slope sliced by FAO soil class for Gummara and Ribb Watersheds.

The result of slope classification shows that around 62 % of the study area for Gummara and Ribb is covered by 0 to 10 degree slope and for both Rivers the dominant slope range is from 2 to 10 degree.

4.1.3 Geology

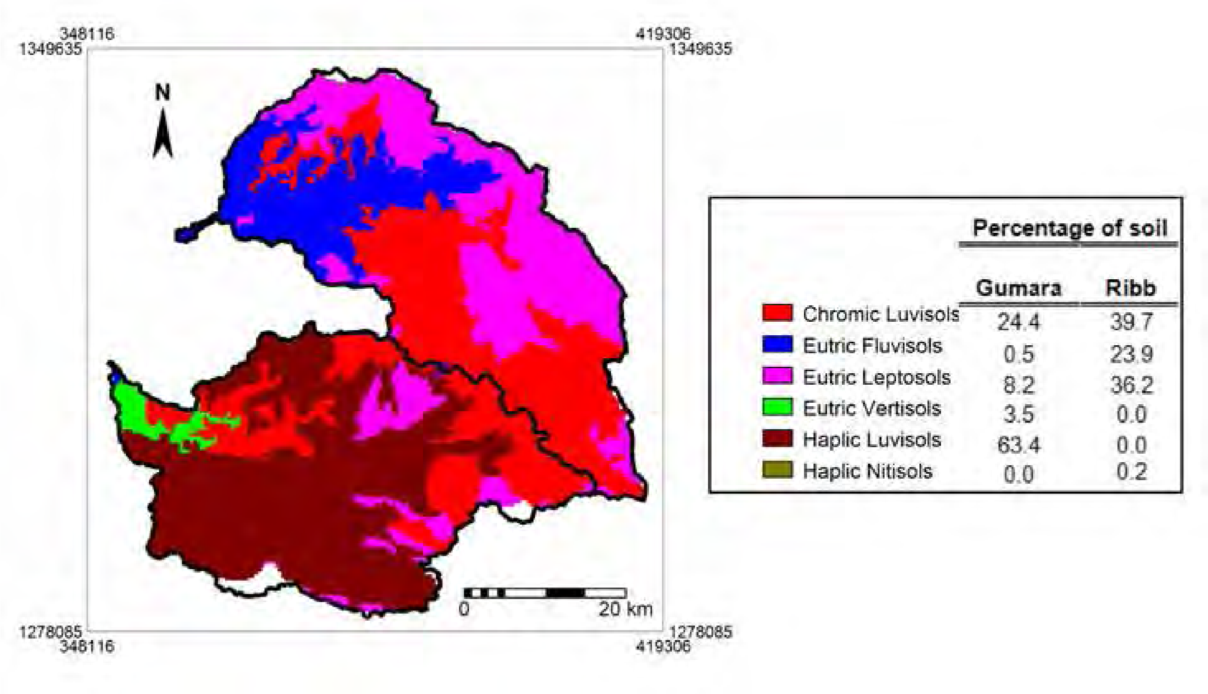
Geology includes drainage feature (pattern, density, etc.) parent rock (igneous, sedimentary, and metamorphic).

Drainage density: is calculated by dividing the total stream length for the basin by the catchment area. A high drainage density reflects a highly dissected drainage basin with a relatively rapid hydrologic response to rainfall events, while a low drainage density means a poorly drained basin with a slow hydrologic response.

The drainage network is extracted by DEM Hydro-processing processing module of ILWIS, the result shows 284 m/km2 and 301 m/km2 for Gumara and Ribb respectively.

4.1.4 Soil

Soil data is required as input for hydrological modelling which influences runoff generation, generally runoff occurs when rainfall intensity exceeds the infiltration capacity of the soil which is a measure o the ability of the soil to absorb and transmit rain water. Runoff is limited on soils with a high infiltration capacity. For this study a soil map of the major soil groups of Gummara and Ribb watershed as per FAO soil group is collected from EMWR GIS department. See Figure 4-6. Detail description of different soil groups in the study area are described below.



	Percentage of soil	
	Gumara	**Ribb**
🟥 Chromic Luvisols	24.4	39.7
🟦 Eutric Fluvisols	0.5	23.9
🟪 Eutric Leptosols	8.2	36.2
🟩 Eutric Vertisols	3.5	0.0
🟫 Haplic Luvisols	63.4	0.0
🟫 Haplic Nitisols	0.0	0.2

Figure 4-6: Major FAO soil group map of Gummara and Ribb watershed

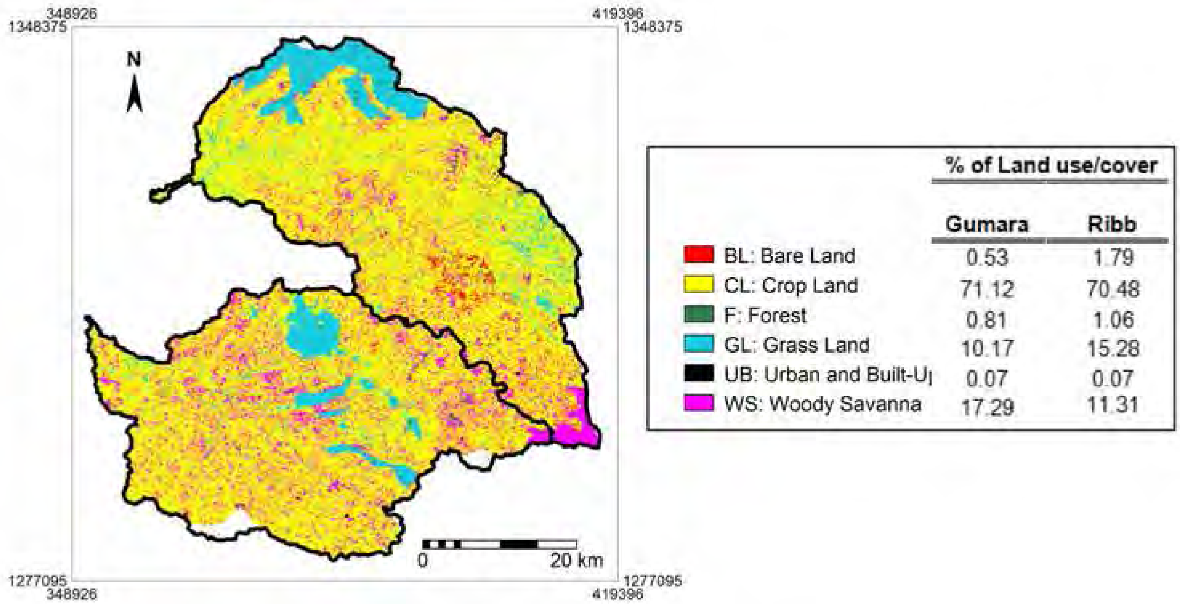
Fluvisols are found typically on level topography that is flooded periodically by surface waters or rising groundwater, as in river floodplains and deltas and in coastal lowlands. Fluvisols are, by definition, flooded by rivers. Fluvisols are young soils where sedimentary structures are clearly recognizable in the soil profile. **Leptosols** are very shallow soils over continuous rock and soils that are extremely gravely and/or stony. Leptosols are azonal soils and particularly common in mountainous regions. **Luvisols** are soils that have a higher clay content in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration) leading to an argic subsoil horizon. **Nitisols** are deep, well-drained, red, tropical soils with diffuse horizon

boundaries and a subsurface horizon with more than 30 percent clay and moderate to strong angular blocky structure elements that easily fall apart into characteristic shiny, polyhedric

(nutty) elements. **Vertisols** are churning, heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out, which happens in most years. All the above descriptions of the FAO soil groups are from (FAO, 2006).
Gumara and Ribb watersheds are dominated by different groups of soil, the major dominant soil groups for Gumara watershed are Haplic Luvisols (63.4%) and Chromic Luvisols (24.4%) which are characterzed by higher clay content and Ribb watershed is dominated by Chromic Luvisols (39.7%) and Eutric Leptosols (36.2%) see Figure 5-6, Ribb watershed is partly dominated by Leptosols characterised by extreme gravelly and/or stony subsoil's.

4.1.5 Land Use and Cover Condition

In this study a land cover map was collected from EMWR GIS department. Figure 4-7 shows the land cover map of Gummara and Ribb Watersheds.



	% of Land use/cover	
	Gumara	Ribb
🟥 BL: Bare Land	0.53	1.79
🟨 CL: Crop Land	71.12	70.48
🟩 F: Forest	0.81	1.06
🟦 GL: Grass Land	10.17	15.28
⬛ UB: Urban and Built-U	0.07	0.07
🟪 WS: Woody Savanna	17.29	11.31

Figure 4-7: Major land use groups of Gumara and Ribb Watersheds

Crop land is the major land use group for both watersheds 71.12% and 70.48% respectively for Gummara and Ribb watersheds, the second dominant land use group for Gummara is Woody Savanna 17.29% and Grass land 15.28% for Ribb watershed.

4.2 Summary of The Physical Catchment Characterstics

The physical catchment characteristics discussed in the previous subtopic demonstrates a similarities and differences between watershed characteristics of Gummara and Ribb watershed, Table 5-4 summarises the similarities and differences of those watershed characteristics in a relative terms as high, moderate and low difference. The PCCs which make lesser flow for annual contribution of Ribb watershed were identified and tested in SWAT model based on their effect on the possible runoff volume generation.

Table 4:4: Summary of physical catchment characteristics for Gumara and Ribb watersheds

PCC		**Gumara**	**Ribb**	**Flow in favour**
Climate characteristic	Annual rainfall (mm/year)	1373	1202	Gummara
	Annual Evaporation (mm/year)	1234	1225	
	Climate index	1.11	0.98	Gummara
Geography and physiography	Catchment area (km^2)	1284	1382	Ribb
	Longest flow path length (km)	99.60	84.00	Ribb
	Circularity ratio	0.35	0.26	Gummara
	Average slope (degree)	17.88	21.55	Ribb
Geology Soil	Drainage density (m/km^2)	284	301	Ribb
	% of Chromic Luvisols	24.40	39.70	Ribb
	% of Eutric Fluvisols	0.50	23.90	Gummara
	% of Eutric Leptosols	8.20	36.20	Gummara
	% of Eutric Vertisols	3.50	0.00	---
	% of Haplic Luvisols	63.40	0.00	---
	% of Haplic Nitisols	0.00	0.20	---
Land use and cover	% of Bare Land	0.53	1.79	Ribb
	% of Crop Land	71.12	70.48	--
	% of Forest	0.81	1.06	Ribb
	% of Grass Land	10.17	15.28	---
	% of Urban and Build up	0.07	0.07	---
	% of Woody savannah	17.29	11.31	---

Catchments characteristics which have high differences in the two watersheds were evaluated through the **SWAT model** using different assumptions /scenarios/ and their results presented in section 4.4.

4.3 Hydrological Modelling of Ribb and Gumara watersheds

4.3.1Swat Spatial Mdelling Inputs of Ribb watershed

Rib watershed has a catchment area of 1398 Km2 and its elevation ranging from 1800-4108 m. +MSL.

Table 4:5 Land use classification of Rib catchment used in SWAT

No.	Land use	SWAT Land use Class	Area (Km^2)	% of Total Area
1	Agriculture	AGRL	886.	63.4
2	Pasture	PAST	11.8	8.7
3	Agro- Pastoral	AGRC	360.68	25.8
4	Forest Ever green	FRSE	29.5	2.1
5	Urban	URLD	1	0.07
Total			1398	100

Table 4-6 Soil type of Rib catchment as per FAO-UNESCO soil classification system.

No.	Soil Type	Soil classes defined in SWAT	Area (Km^2)	% of Total Area
1	Eutric Leptosol	Eutric Le	478.1	34.2
2	Halpic Nitisol	Haplic Ni	4.2	0.3
3	Chromic Luvisol	Chromc L	494.9	35.4
4	Eutric Fluvisol	Eutric Fl	420.0	30.04
5	Urban	URBAN LAN	0.8	0.06
Total			1398	100

Table 4-7 Major slope of Ribb catchments delineation

No.	Slope category (%)	Area (Km^2)	% of Total Area
1	0 – 10	501.2561	35.86
2	10-20	365.7374	26.16
3	> 20	531.0066	37.98
Total		1398	100

4.3.2 Swat spatiall Mdelling spatial Inputs of Gumara watershed

Gumara watershed has a catchment area of 1280 Km2 and its elevation ranging from 1791-3712 m. +MSL.

Table 4:8 Land use classification of Gummara catchment used in SWAT

No.	Land use	SWAT Land use Class	Area (Km^2)	% of Total Area
1	Agriculture	AGRL	821	64.1

2	Pasture	PAST	55	4.2
3	Agro- Pastoral	AGRC	402	31.4
4	Urban	URLD	2	0.06
Total			1280	100

Table 4:9 Soil type of Gummara catchment as per FAO-UNESCO soil classification system.

No.	Soil Type	Soil classes defined in SWAT	Area (Km^2)	% of Total Area
1	Eutric Leptosol	Eutric Le	113	8.8
2	Halpic Luvisols	Haplic Lu	811	63.3
3	Chromic Luvisol	Chromc L	311	24.4
4	Eutric Fluvisol	Eutric Fl	43	3.4
5	Urban	URBAN LAN	4	0.1
Total			1280	100

Table 4:10 Major slope of the catchment delineation

No.	Slope category (%)	Area (Km^2)	% of Total Area
1	0 – 10	438	34.22
2	10-20	406	31.75
3	> 20	436	34.03
Total		1280	

4.3.3 Model parameter Sensitivity analysis

In rainfall – runoff modelling it is often not possible to find unique best parameter set, different parameter sets may be give similar good results during calibration. In order to reduce uncertainty and to define the optimum parameter set it is essential analysis on model parameters. Sensitivity analysis has been carried out for 27 parameters. But only few sensitive parameters were considered and the parameters with their mean relative sensitivity value at the outlet after calibration for the study area watersheds were selected. Sensitivity analysis of parameters of the models were done manually by dividing model parameters space in to equal intervals and simulating the model with number of intervals times for each of the parameter by changing one parameter at a time.

Table 4-11: Results of sensitivity analysis for Ribb watershed.

No	Parameters	Description of the parameters	Sensitivity rank
1	Sol_Awc	Available water capacity [mm WATER/mm soil]	1
2	ALPHA_BF	Base flow alpha factor [days]	3
3	CN2	Initial SCS CN II value	2
4	Gwqmn	Threshold water depth in the shallow aquifer for flow [mm]	4
5	ESCO	Soil evaporation compensation factor	5
6	Sol_Z	Soil depth [mm]	6
7	Sol_Z	Soil depth [mm]	7
8	Revapmn	Threshold water depth in the shallow aquifer for "revap" [mm]	8
9	Canmx	Maximum canopy storage [mm]	9
10	Gw_Revapmn	Groundwater "revap" coefficient	10

Table 4-12: Results of sensitivity analysis for Gummara watershed.

No	Parameters	Description of the parameters	Sensitivity rank
1	CN2	Initial SCS CN II value	1
2	ALPHA_BF	Base flow alpha factor [days]	2
3	Gwqmn	Threshold water depth in the shallow aquifer for flow [mm]	3
4	ESCO	Soil evaporation compensation factor	4
5	Sol_Z	Soil depth [mm]	5
6	Sol_Awc	Available water capacity [mm WATER/mm soil]	6
7	Sol_Z	Soil depth [mm]	7
8	Revapmn	Threshold water depth in the shallow aquifer for "revap" [mm]	8
9	Canmx	Maximum canopy storage [mm]	9
10	Gw_Revapmn	Groundwater "revap" coefficient	10

4.3.4 Model calibration

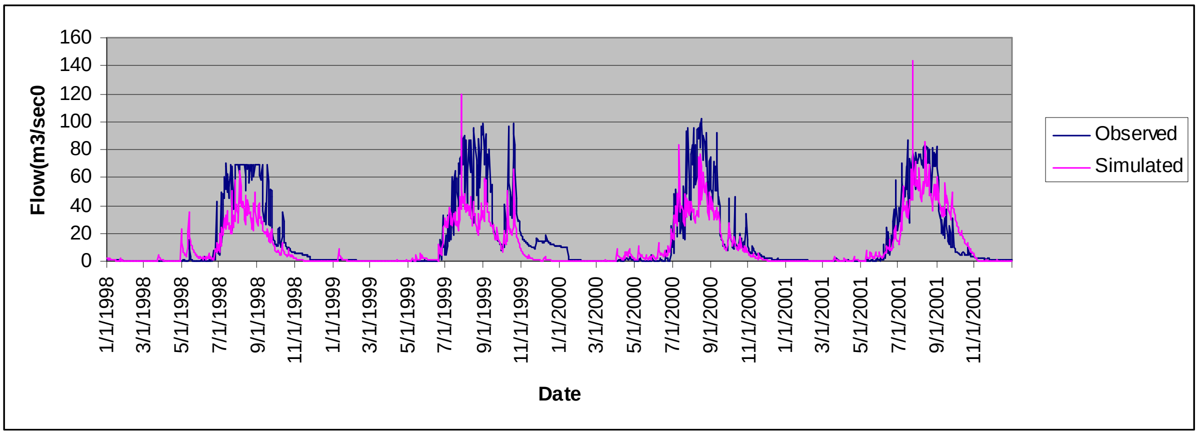
All models ranging from lumped to complex distributed physically based needs to be calibrated, since it is difficult to estimate parameter values through field measurement. The SWAT model is calibrated against the observed daily discharge and the best fit parameter sets are selected.

After setting up of the model, the default simulations of stream flow, using the default parameter values were done for the study area catchments for the calibration period (1998 – 2004). The default simulation outputs were compared with the observed stream flow data of the two catchments. The most sensitive parameter considered for manual calibration were Available soil water (AWC), soil hydraulic conductivity (sol-k), soil evaporation compensation factor, initial SCS curve number II value, base flow alpha factor(days), threshold depth of water in the shallow aquifer for “revap” to occur (mm water/ mm soil), ground water “revap’’ coefficient, channel effective hydraulic conductivity (mm/hr and threshold depth of water in the shallow aquifer for return flow to occur (mm).

The comparison between the observed and simulated flow discharge values for nine years of simulations indicated that there is a Very good agreement between observed and simulated flows for Ribb catchment lower value of relative volume error, good value of coefficient of correlation(R2) and Nash Sutcliff coefficient (NSE) and good agreement for Gumara watershed. The results of the performance indicating parameter are stated below.

Table 4:13 Stream flow calibration results for Gumara and Ribb catchments.

Objective function	Rivers	
	Gumara	Ribb
R^2	0.68	0.73
Relative Volume error (%D)	0.5	0.08
NSE	0.67	0.72



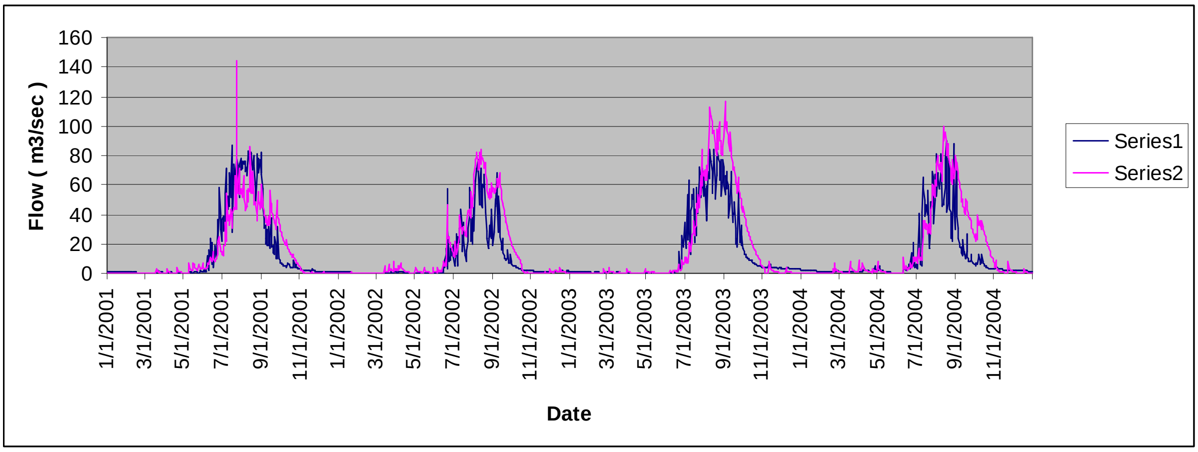
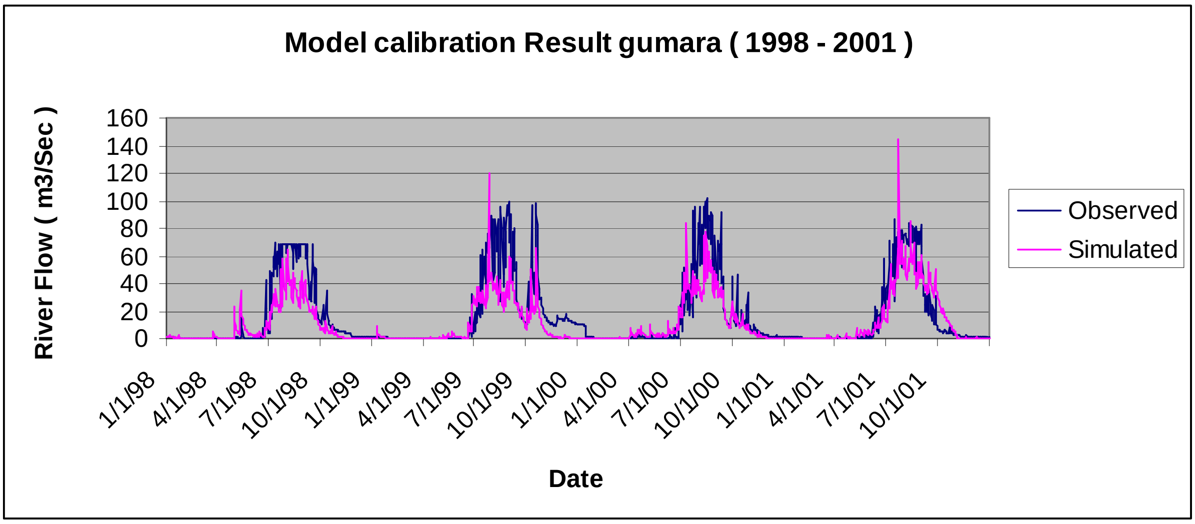


Figure 4-8: Ribb calibrated flow from (1998 – 2004)



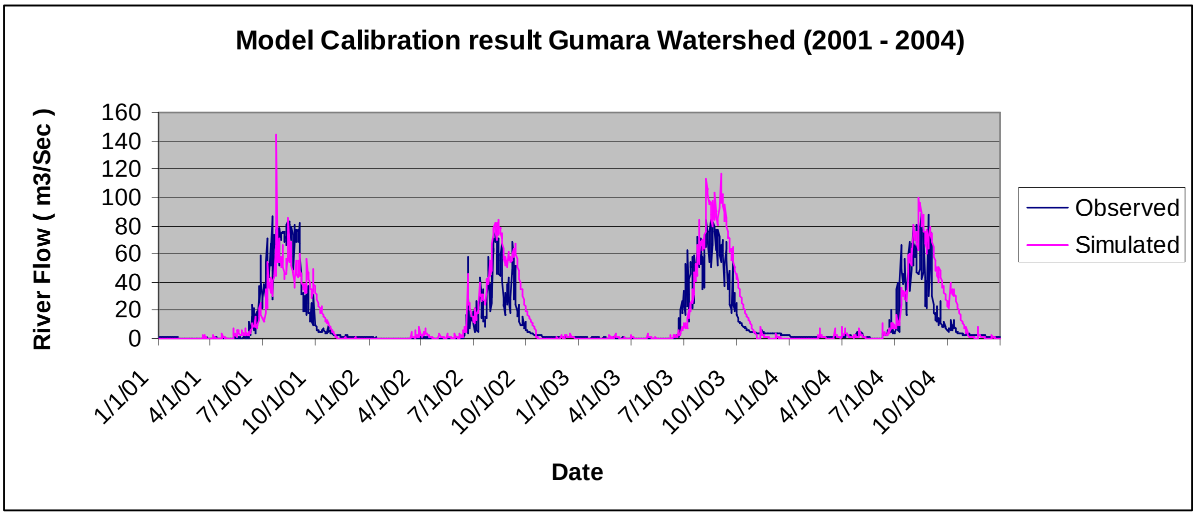


Figure 4-9: Gummara calibrated flow from (1998 – 2004)

4.3.5 Model Validation

To validate the model, model parameters have to be tested against another independent set of stress conditions; in this study validation data of 2004 to 2007 is selected. If the calibrated model parameter sets fail on the validation period the model is regarded unreliable and so not used. The model must be recalibrated with a new set of model parameters followed by model validation until it satisfies calibration targets in terms of objective function values. Model validation was done for catchment satisfies objective function values of calibration period and the result is shown below (Table 5-12).

Table 5:14 Stream flow validated flow results for Gummara and Ribb catchments.

Objective function	Rivers	
	Gumara	Ribb
R^2	0.69	0.76
Relative Volume error	-11.5	-7.9
NSE	0.7	0.75

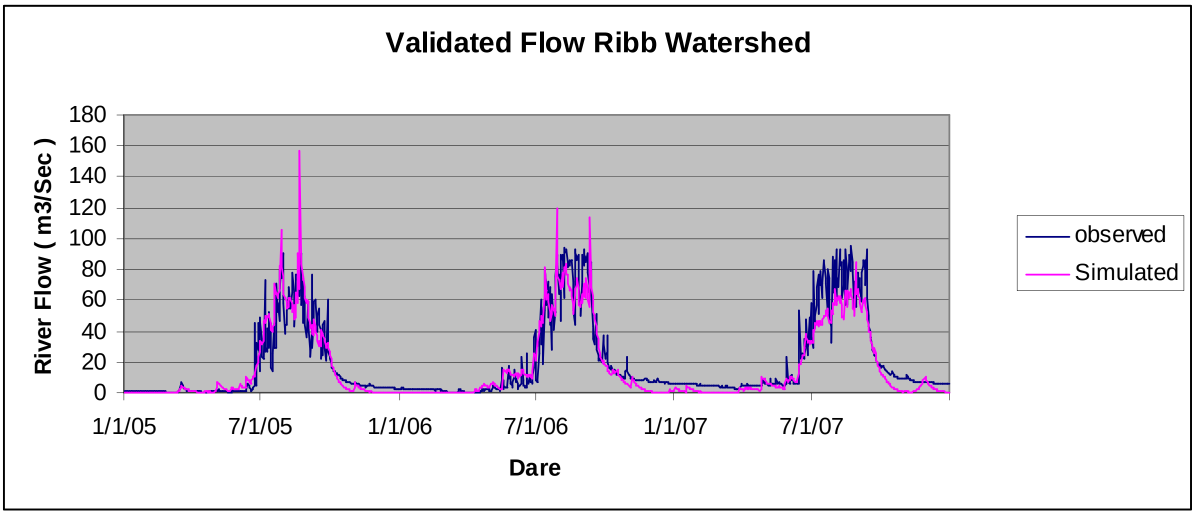


Figure 4-10: Ribb Validated flow from (2005 – 2007)

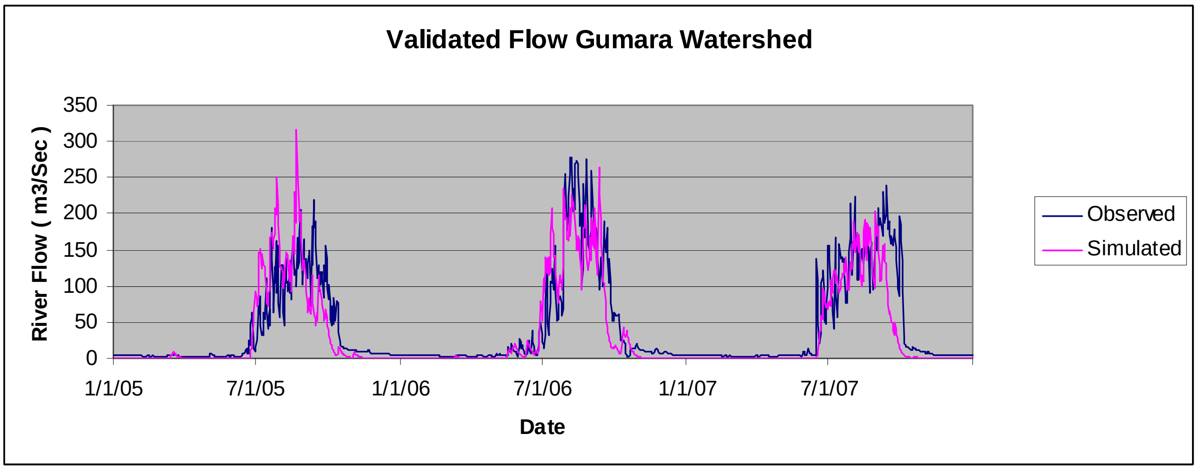


Figure 4-11: Gummara Validated flow from (2005 – 2007).

4.4 Evaluation of Physical Catchment Characteristics With SWAT Model.

As stated and discussed in section 4.2 above the physical catchment characteristics which have significant high differences (Rainfall and Soil) in the two watersheds were evaluated by different scenarios in the SWAT model using calibrated and validated flow parameters.

4.4.1 Evaluation of Difference in Rainfall

Here the effect of rainfall variation in the two catchments result shown in summary section of 4.2 shows that Ribb receives less rainfall than Gummara. The lesser amount of rainfall from Ribb watershed is captured through rainfall gauging station in Addis Zemen north of Lake Tana subbasin. In section 4.2.1 Gummara watershed uses 93% Debre tabor station and Ribb uses 55% from Debre tabor and 45% from Addis Zemen . The following different scenarios were used for rainfall effect evaluation.

Scenario I (Assumption that Ribb receives same rainfall as Gummara)

In this Scenario to see the effect of lesser rainfall received by Ribb an assumption is made Ribb to receive equivalent amount of rainfall with Gummara. In the above sections it is described that Gummara received almost the entire watershed from Debre Tabor station. In this scenario Debretabor station assumed to cover the whole watershed of Ribb and Gummara. This is done by removing the rainfall data of Addis Zemen from SWAT model and re-run the calibrated and validated watershed parameters in the model of Ribb watershed. The results shown in Fig.4-12

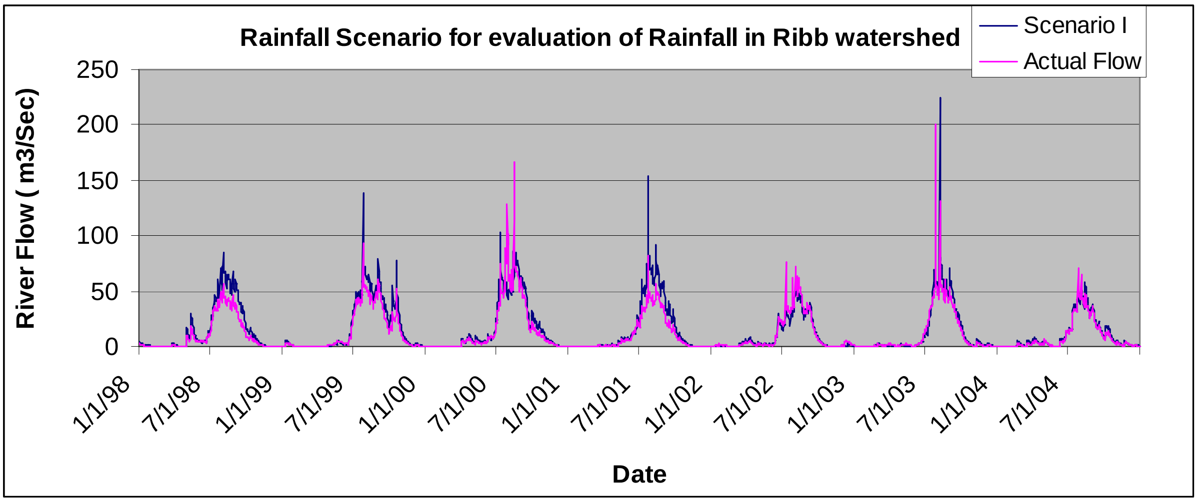


Figure 4-12: Rainfall Scenario I for evaluation of lesser rainfall captured in Ribb

When the calibrated and validated model rerun(with scenario I assumption) with fixed model parameters the long run annual flow by volume increases by 23% which shows lesser rainfall amount received at Ribb has a greater effect alone.

Scenario II (Assumption that Ribb receives the whole rainfall from Addis Zemen Station.)

In the above section the theison polygon analysis result shows Ribb watershed uses 45% from Addis Zemen station and the rest from Deberetabor station. In this Scenario to see the further effect of lesser rainfall received from Addis Zemen station the whole Ribb watershed assumed to receive from Addis Zemen station. This is done by removing the rainfall data of Debretabor from SWAT model and re-run the calibrated and validated watershed parameters in the model of Ribb watershed. The result is shown in Figure below.

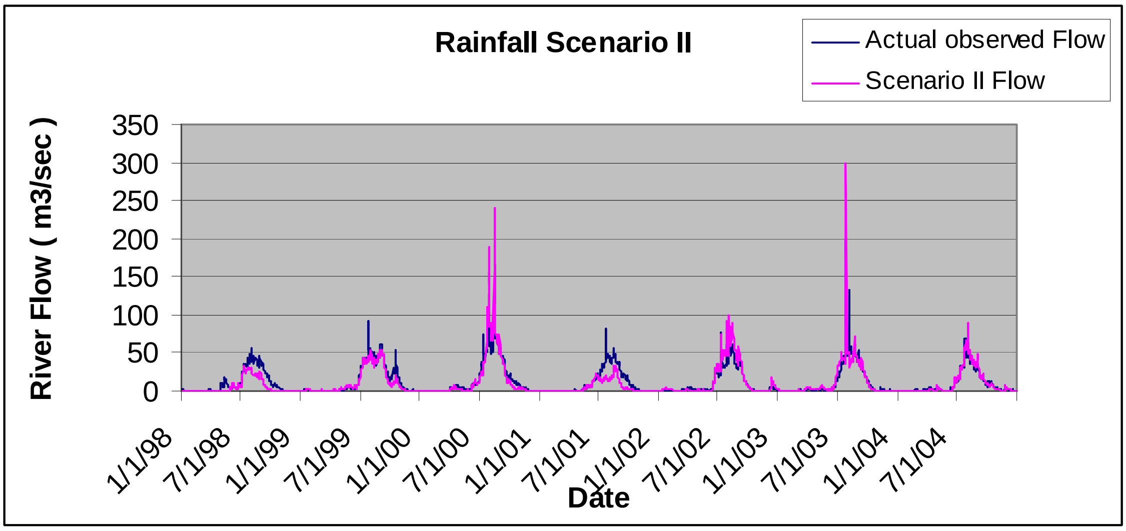


Figure 4-13: Rainfall Scenario II for evaluation of lesser rainfall captured in Ribb

When the calibrated and validated model rerun (with scenario II assumptions) with fixed model parameters the long run annual flow by volume Decreases by 17% which shows still lesser rainfall amount received at Ribb has a greater effect by itself alone.

Scenario III (Assumption that Gumara watershed receives the whole rainfall from Addis Zemen Station.)

In the above section the theison polygon analysis result shows the whole Gumara watershed almost uses from Debretabor station which records higher rainfall than Ribb. In this Scenario to see the further effect of lesser rainfall received from Addis Zemen station the whole Gummara watershed assumed to receive rainfall of Addis Zemen station. This is done by Substituting recorded rainfall data's of Debre Tabor with Addis Zemen SWAT model and re-run the calibrated and validated watershed parameters in the model of Ribb watershed. The result is shown in Figure below.

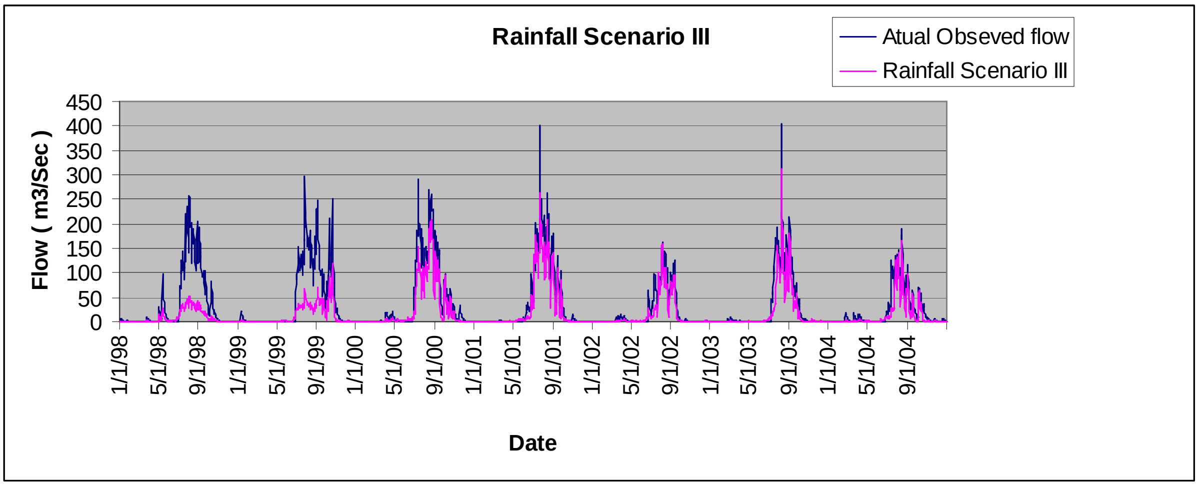


Figure 4-14: Rainfall Scenario III for evaluation of lesser rainfall captured in Ribb

When the calibrated and validated model rerun (with scenario III assumptions) with fixed model parameters the long run annual flow by volume Decreases by 81% which shows by far very great effect on Gummara watershed than Ribb but still with the annual amount Gummara leads.

4.4.2 Evaluation of Differences in Soil

As stated and discussed in section in the summary section, there is a significant variation of soil groups in the two catchments. The major dominant soil groups for Gumara watershed are Haplic Luvisols (63.4%) and Chromic Luvisols (24.4%) which are characterized by higher clay content and Ribb watershed is dominated by Chromic Luvisols (39.7%) and Eutric Leptosols (36.2%). Ribb watershed is partly dominated by Leptosols characterised by extreme gravelly and/or stony subsoil's. Here the effect of the soil characteristics of Ribb watershed is evaluated with the following different scenarios.

Soil Scenario I (Assumption Ribb has same soil groups as Gumara)

In this scenario to evaluate the effect of soil in Ribb watershed an assumption is made what will happen with Ribb watershed if its soil type is substituted with Gumara. These is done by changing equivalent soil area characteristics of Gumara with Ribb soil groups and rerun the Ribb models with the actual calibrated and validated model parameters. The results is shown in Figure below.

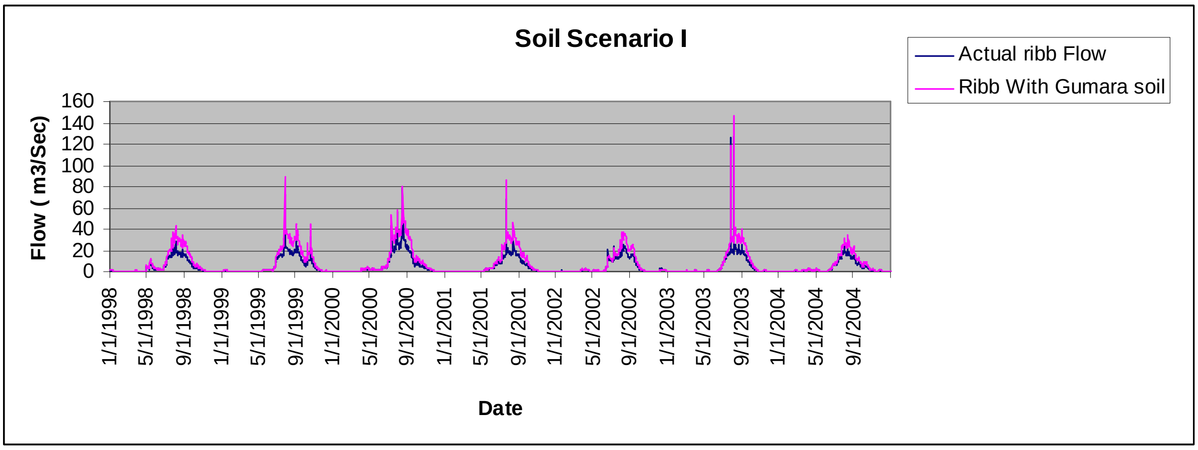


Figure 4-14: Soil Scenario I for evaluation of lesser rainfall captured in Ribb

When the calibrated and validated model rerun (with soil scenario I assumptions) with fixed model parameters the long run annual flow by volume of Ribb increases by 43% which shows by far very great effect on Gumar watershed than Ribb but still with the annual amount Gumara leads.

CHAPTER FIVE

5.Conclusion and Recommendation

In Lake Tana Watershed two adjunct watersheds (Ribb and Gummara) with a comparable area has indicated a significant runoff difference, in this research the effect of watershed characteristics was studied by identifying 10 watershed characteristics for Gummara and Ribb. After classifying characteristics with high, moderate and low difference. The effect of those characteristics was captured through hydrological modelling using SWAT model after model calibration and model validation respectively. Based on the research result the following conclusion and recommendation are made.

5.1 Conclusion

- The rainfall in the study are increases towards south direction, this has affected the climate index which is defined as rainfall divided by evaporation which is greater than 1 for Gummara and less than 1 for rib. This was propagate on the runoff generation at Ribb basin.
- The effect of difference in Rainfall for Ribb and Gummara is evaluated in three scenarios using the calibrated and validated SWAT model of the two watersheds and the lesser annual rainfall received at Ribb alone has an over all mean decrease in a long year annual mean flow 37 %.
- The effect of difference in soil types for Ribb and Gummara is evaluated in scenario using the calibrated and validated SWAT model of the two watersheds and the result shows soil types of Ribb watershed made an over all decrease in a long year annual mean flow 45 %.
- Even though the long year annual flow of Gummara is more than twice higher Ribb in the calibrated and validated model testing of PCCs and only half of it is addressed in the above scenarios.

5.2 Recommendation

Based on the results obtained, the following is recommended:

- The gauging stations of the two catchments are located at the middle of the floodplains, especially the Ribb watershed is affected by a flood passes outside the station and accumulation of sand in the stream. Therefore it is better to locate the station away from the flood plain in the downstream or else revising and updating the conveyance profile of the existing station every time.

- There are a lot of sand collection sites “erosion”, are observed in Ribb watershed and from the watershed modelling it is clearly shown these effect associated with upstream sub basins. Therefore a mitigation measure should be applied in these sub watersheds, especially there is on going irrigation project in the upstream of Ribb watershed where a clear sedimentation is shown on the stated mitigation should be done to protect the dam.

- The flow gauging stations in the two watersheds is manual and some of the readings show inconsistency which might be associated with carelessness in reading and due to an ongoing large scale irrigation project in the two watersheds the gauging stations has to be changed with automatic stations.

- From the watershed characteristics the effect of soil has a great impact in the study area therefore a soil data with a high resolution which can enhance the result has to be prepared.

- From the watershed characteristics the effect of Rainfall has a significant effect. Areal rainfall estimated by Thiessen polygon method was used for this study. Therefore in order to improve the results well either additional stations shall be established or augmented from already available satellite estimated rainfall.

6.References:

Abebe, A. and G. Foerch (2006). Catchment characteristics as predictors of base flow index (BFI) In Wabi Shebele River Basin, East Africa, Tropentag Bonn, University of Siegen, Germany.

Abeyou W. W. (2007). Hydrological balance of Lake Tana Upper Blue Nile Basin Ethiopia.M.Sc Thesis. ITC, The Netherlands.

Abbot, M.B. , Bathurst, 1986. An introduction to European hydrology system – System hydrologique European "SHE", 1: history and philosophy of a physically based, distributed modelling system.

Allen, R.G. (1986). A Penman for all seasons. J. Irrig. and Drain Engng., ASCE, 12(4): 348-368

Arnold, J. G., and P. M. Allen. (1996). Estimating hydrologic budgets for three Illinois watersheds. J. Hydrol. 176(1-4): 57-77.

Arnold, J. G., and N. Fohrer. (2005). SWAT 2000: Current capabilities and research opportunities in applied watershed modeling. *Hydrol. Process.* 19(3): 563-572.

Arnold, J.G., Sirinivasan, R., Muttiah, R.S, Williams, J.R. (1998).Large area hydrologic modelling and assessment, Part 1: Model development. Journal of the American water resources association, 34(1).

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen, (1999): Continental scale simulation of the hydrologic balance. J. Am. Water Resource Association 35(5), 1037-1051

BCEOM & Associates (1999): Abbay Basin Integrated Master Plan Studies, Volume VI Part 2- Large Dams and Hydropower, Part 3 Dams and Reservoirs.

Bergsrtom, S. 1995. The HBV model. In: V.P. Singh (Ed.) Computer models of watershed hydrology. Water Resources publications, Highlands Ranch, CO.

Beven,K.,1989. Changing ideas in hydrology – The case of physically based model. Journal of hydrology 105.

Booij, M. J. (2005). Impact of climate change on river flooding assessed with different spatial model resolutions. Journal of Hydrology 303 (1-4): 176-198.

Chow, V.T. (1988). Applied Hydrology, McGraw HILL INTERNATIONAL EDITIONS. New York.

Di Luzio, M. Di, R. Srinivasan, J.G. Arnold, S.L. Neitsch, (2002). ArcView Interface for SWAT2000 (AVSWAT2000), User's Guide, Grassland Soil and Water Research Laboratory, Blackland Research Center, Texas Agricultural Experiment Station, Texas Water Resources Institute, Texas Water Resources Institute, College Station, Texas TWRI

FAO 2001 Preparation of Land Cover Database of Bulgaria through Remote Sensing and GIS, Vershion 6. Bulgaria, Europe.

FAO, 2006 Food and Agriculture Organization of the United Nations: World reference base for soil resources 2006. A framework for international classification, correlation and communication. 2nd edition. World Soil Resources Reports No. 103. FAO, Rome.

Goswami, M., K.M. O'connor, K.P. Bhattarai And A.Y. Shamseldin (2005), Assessing the performance of eight real-time updating models and procedures for the Brosna River, Hydrology and the Earth System Sciences. 9 (4): 394-411

Jensen, M.E., R.D. Burman, and R.G. Allen (ed). (1990). Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70, ASCE, N.Y. 332 pp.

Kim, U. *et al.* , 2008 – Application of parameter estimation and regionalization methodologies to ungauged basins of upper Blue Nile River basin.

Krause P. And F. Base (2006), Sensitivity and uncertainty analysis of the Hydrological model J2000, Geophysical Research Abstracts, Vol. 8, 02510.

Lenhart, T., K. Eckhardt, N. Fohrer, H.-G. Frede, (2002). Comparison of two different approaches of sensitivity analysis, Physics and Chemistry of the Earth 27 (2002), Elsevier Science Ltd., 645–654pp

Liersch S., August (2003). Dew02 Users' Manual, Berlin, 5pp.

Melkamu Amare, (2005). Reservoir operation and establishment of reservoir rule for Lake Tana. Addis Ababa University, MSC. Thesis.

Nancy D. Gordon., Thomas A. McMahon, Brian L. Finlayson and Rory J. Nathan (2004). Stream Hydrology an introductory of Ecologist. Second edition. Wiley, England.

Neitsch S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams (2005). Soil and Water Assessment Tool

(SWAT) Theoretical Documentation, Version 2005, Grassland Soil and Water Research Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural experiment Station.

Nicks, A.D. (1974). Stochastic generation of the occurrence, pattern and location maximum amount of daily rainfall. p. 154-171. In Proc. Symp.Statistical Hydrology, Tucson, AZ. Aug.-Sept. 1971. USDA Misc. Publ. 1275. U.S. Gov. Print. Office, Washington, DC

Penman, H.L. (1956). Evaporation: An introductory survey. Netherlands Journal Agricultural Science 4:7-29.

Priestley, C.H.B. and R.J. Taylor. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather. Rev. 100:81-92.

Refsgaard, J.C. and Storm, B., (1996), Construction, calibration and validation of hydrological models, Distributed Hydrological Modelling (eds. M.B.Abbott and J.C. Refsgaard), Kluwer Academic Publishers, 41-54.

Reggianti P. Rientges, T.H.M., 2005 Flux parameterization in the presentation elementary watershed approach

Robert L. F. (2002). Handbook of water sensitive planning and design. Lewis publishers

Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, and L. Hauck. (2001). “Validation of the SWAT Model on a Large River Basin with Point and Non point Sources.” *J. Am. WaterResoucer.* Assoc. 37(5): 1169-88.

S. Kebede – Water balance of Lake Tana and its sensitivity fluctuation in rainfall, Blue Nile, Ethiopia.

Seibert. J. (1999). Regionalization of parameters for a conceptual rainfall-runoff model. Agricultural and Forest Meteorology 98-99: 279-293.

Sirak,(2008) Watershed modelling of Lake Tana Basin using SWAT

Srinivasan, R., and J. G. Arnold. (1994). Integration of a basin-scale water quality model with GIS. *Water Resour. Bull.* (30)3: 453-462.

Srinivasan, R., T. S. Ramanarayanan, J. G. Arnold, and S. T. Bednarz. (1998). Large-area hydrologic modeling and assessment: Part II. Model application. *J.* American Water Resour. Assoc. 34(1): 91-101.

Sharpley, A.N. and J.R. Williams, eds. (1990). EPIC-Erosion Productivity Impact Calculator, 1. Model documentation. U.S. Department of Agriculture, Agricultural Research Service, Tech. Bull. 1768.

Studio Pietrangeli, (1990). Tana Beles Project studies document.

Shimelis G. (2008). Hydrological and sediment yield modeling in Lake Tana basin, Blue Nile Ethiopia. M.Sc paper, KTH-hydraulic engineering research group.

SMEC I.P (2007) Hydrological study of the Tana Beles sub-basins part –I

Thornthwaite, C.W., (1948). An approach toward a rational classification of climate. Geographical Review 38:55-94

USBR (1964). Land and water resource of the Blue Nile basin

Water Watch (2006), Remote sensing studies of Tana-Beles sub-basins, Wageningen, The Netherlands

Ward, G., and J. Benaman, (1999): Models for TMDL application in Texas water courses: screening and model review. Report to Texas Natural Resource Conservation Commission, Center for Research in Water Resources, University of Texas at Austin

Williams, J.R. (1995). Chapter 25: The EPIC model. p. 909-1000. In V.P. Singh (ed). Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch Co.

Williams,J.R. and R.W.Hann. (1973). HYMO, problem oriented language for hydrologic modeling-user manual USDA, ARS-5-9.

Yohanse, (2007). Remote sensing based assessment of water resource Potential for Lake Tana basin. Addis Ababa University. MSc Thesis.

List of Abbreviations

AVSWAT – The Arc View Integrated SWAT Hydrological Model
BCEOM-Le Bureau, central d’Etudes Pourles Equipments d’outre-Mer.
DEM – Digital Elevation Model
DEW02 – Dew Point Temperature Calculator
ET- Evapotranspiration
EMA – Ethiopian Meteorological Agency, Ethiopia
FAO – Food and Agricultural Organization of the United Nations
GIS – Geographic Information System
HRU – Hydrologic Response Unit
+MSL – above mean sea level
MCM-Million Cubic Meter
MoWRE – Ministry of Water Resources & Energy, Ethiopia
NSE- Nash Sutcliff Efficiency
PET – Potential Evapotranspiration
SCS – Soil Conservation System
SRTM-Shuttle Radar Topographic Mission
SWAT – The Soil and Water Assessment Tool
UNESCO-United Nation Educational Scientific and Cultural Organization
UTM-Universal Transverse Mercator
WGEN – Weather Generator
XPARM – Weather Parameter Calculation

Appendices

Appendix-A: Location of Meteorological station in the study area.

Station Name	X-Co-ordinate	Y-Co-ordinate	Elevation	Station code
Addiszemen	377034	1339957	1550	
Bahirdar	331001	1282667	1770	
Debretabor	394353	1313350	2690	
Enfraz	356388	1346686	1500	
Georgia	315083	1354659	1830	
Wereta	356249	1317931	1865	

Appendix-B Summary of Meteorological data collected from NMA

Station name	Daily meteorological data collected						
	P	T	RH	n	WS	From	TO
Addiszemen	x	x	-	-	-	1997 1997	2008 2008
Bahirdar	x	x	x	x	x	1985 1985 1996 1982 1996	2008 2008 2008 2008 2008
Debretabor	x	x	x	x	x	1980 1985 1996 1996 1996	2008 2008 2008 2008 2008
Enfranz	x	x	-	-	-	1997 1997	2008 2008
Gonder	x	x	x	x	x	1985 1985 1996 1996 1996	2008 2008 2008 2008 2008

Appendix-C: Location of List of Hydrological Station in The study area

RIVER	SITE	LAT.	LON.	AREA Km2
Gilgel Abay	Near Merawi	$11^{0}22^{1}$N	$37^{0}02^{1}$E	1656.2
Koga	At Merawi	$11^{0}22^{1}$N	$37^{0}02^{1}$E	299.8
Ribb	Near Addis Zemen	$12^{0}00^{1}$N	$37^{0}43^{1}$E	1302.6
Gumara	Near Bahir Dar	$11^{0}50^{1}$N	$37^{0}38^{1}$E	1283.4
Megech	Near Azezo	$12^{0}29^{1}$N	$37^{0}27^{1}$E	513.5

Appendix-D: Summary of collected Hydrological data in Lake Tana Basin.

River Name	Data collected		Year	Missing Discharge Data (Number of days)											
	From	To		Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gumara @ Bahirdar	1991	2007	1999												20
			2000	31	29	7									
			2006								7	1			
Rib @ Addiszemen	1991	2007	1966					31	30	31					

Appendix E: Conveyance of Ribb River near the gauging station after over flooding the embankment

Appendix-F :Weather generator (WGEN) parameters used by the SWAT Model

Legend of the parameters used in the weather generation		
	Symbol	Description
A	TMPMX	Average or mean daily maximum air temperature for month (ºC).
B	TMPMN	Average or mean daily minimum air temperature for month (ºC).
C	TMPSTDMX	Standard deviation for daily maximum air temperature in month (ºC).
D	TMPSTDMN	Standard deviation for daily minimum air temperature in month (ºC).
E	PCPMM	Average or mean total monthly precipitation (mm H2O).
F	PCPSTD	Standard deviation for daily precipitation in month (mm H2O/day).
G	PCPSKW	Skew coefficient for daily precipitation in month.
H	PR_W1	Probability of a wet day following a dry day in the month.
I	PR_W2	Probability of a wet day following a wet day in the month.
J	PCPD	Average number of days of precipitation in month.
K	SOLARAV	Average daily solar radiation for month (MJ/m2/day).
L	DEWPT	Average daily dew point temperature in month (ºC).
M	WNDAV	Average daily wind speed in month (m/s).

TMPMX (mon): Average or mean daily maximum air temperature for month (ºC).
Calculated based on following formula:

$$\mu mx_{mon} = \frac{\sum_{d=1}^{N} T_{mx,mon}}{N}$$

Where μmax_{mon} is the mean daily maximum temperature for the month (^{0}C), Tmx,mon is the daily maximum temperature on record *d* in month *mon* (^{0}C), and *N* is the total number of daily maximum temperature records for month *mon*.

TMPMN(mon): Average or mean daily minimum air temperature for month (ºC).
Calculated based on following formula:

$$\mu mn_{mon} = \frac{\sum_{d=1}^{N} T_{mn,mon}}{N}$$

Where μmn_{mon} is the mean daily minimum temperature for the month (^{0}C), $T_{mn,mon}$ is the daily minimum temperature on record *d* in month *mon* (^{0}C), and *N* is the total number of daily minimum temperature records for month *mon*.

TMPSTDMX(mon): Standard deviation for daily maximum air temperature in month (ºC)
Calculated based on following formula:

$$\sigma mx_{mon} = \sqrt{\frac{\sum_{d=1}^{N} (T_{mx,mon} - \mu mx_{mon})^2}{N-1}}$$

Where σmx_{mon} is the standard deviation for daily maximum temperature in month *mon* (ºC), $T_{mx,mon}$ is the daily maximum temperature on record *d* in month *mon* (^{0}C), $\mu_{mx, mon}$ is the average daily maximum temperature for the month (^{0}C), and *N* is the total number of daily maximum temperature records for month *mon*.

TMPSTDMN(mon): Standard deviation for daily minimum air temperature in month (ºC).

Calculated based on following formula:

$$\sigma mn_{mon} = \sqrt{\frac{\sum_{d=1}^{N} (T_{mn,mon} - \mu mn_{mon})^2}{N-1}}$$

Where σmn_{mon} is the standard deviation for daily minimum temperature in month *mon* (ºC), *Tmn,mon* is the daily minimum temperature on record *d* in month *mon* (^{0}C), $\mu mnmon$ is the average daily minimum temperature for the month ^{0}C), and *N* is the total number of daily minimum temperature records for month *mon*.

PCPMM(mon): Average or mean total monthly precipitation (mm H2O).
Calculated based on following formula:

$$\overline{R}_{mon} = \frac{\sum_{d=1}^{N} R_{day,mon}}{yrs}$$

where $\overline{R}_{mon}$ is the mean monthly precipitation (mm H2O), $R_{day,mon}$ is the daily precipitations for record *d* in month *mon* (mm H2O), *N* is the total number of records in month *mon* used to calculate the average, and *yrs* is the number of years of daily precipitation records used in calculation.

PCPSTD(mon): Standard deviation for daily precipitation in month (mm H2O/day).
Calculated based on following formula:

$$\sigma_{mon} = \sqrt{\frac{\sum_{d=1}^{N} (R_{day,mon} - \overline{R}_{mon})^2}{N-1}}$$

Where σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H2O), $\overline{R}_{mon}$ is the mean monthly precipitation (mm H2O), $R_{day,mon}$ is the daily precipiation for record *d* in month *mon* (mm H2O), *N* is the total number of records in month *mon* used to calculate the average, and *yrs* is the number of years of daily precipitation records used in calculation.

PCPSKW(mon): Skew coefficient for daily precipitation in month.

Calculated based on following formula:

$$g_{mon} = \frac{N \cdot \sum_{d=1}^{N} (R_{day,mon} - \overline{R}_{mon})^3}{(N-1) \cdot (N-2) \cdot (\sigma_{mon})^3}$$

Where g_{mon} is the skew coefficient for precipitation in the month, *N* is the total number of daily precipitation records for month *mon*, $R_{day,mon}$ is the amount of precipitation for record *d* in month *mon* (mm H2O), $\overline{R}_{mon}$ is the average precipitation for the month (mm H2O), and σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm H2O).

PR_W(1,mon) : Probability of a wet day following a dry day in the month.

Calculated based on following formula:

$$P_i(W/D) = \frac{days_{W/D,i}}{days_{dry,i}}$$

Where *Pi(W/D)* is the probability of a wet day following a dry day in month *i*, $days_{W/D,i}$ is the number of times a wet day followed a dry day in month *i* for the entire period of record, and $days_{dry,i}$ is the number of dry days in month *i* during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation.

PR_W(2,mon) : Probability of a wet day following a wet day in the month.
Calculated based on following formula:

$$P_i(W/W) = \frac{days_{W/W,i}}{days_{wet,i}}$$

Where *Pi(W/W)* is the probability of a wet day following a wet day in month *i*, $days_{W/W,i}$ *i* is the number of times a wet day followed a wet day in month *i* for the entire period of record, and $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0 mm precipitation.

PCPD(mon): Average number of days of precipitation in month.
Calculated based on following formula:

$$\bar{d}_{wet,i} = \frac{days_{wet,i}}{yrs}$$

Where $\bar{d}_{wet,i}$, is the average number of days of precipitation in month *i*, $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record, and *yrs* is the number of years of record.

SOLARAV(mon): Average daily solar radiation for month (MJ/m2/day).
Calculated based on following formula:

$$\mu rad_{mon} = \frac{\sum_{d=1}^{N} H_{day,mon}}{N}$$

	LAT	LONG	ELEV	Rain-	AM1	AM2	AM3	AM4	AM5	AM6	AM7	AM8	AM9

Where μrad_{mon} is the mean daily solar radiation for the month (MJ/m^2/day), $H_{day,mon}$ is the total solar radiation reaching the earth's surface for day *d* in month *mon* (MJ/m^2/day), and *N* is the total number of daily solar radiation records for month *mon*.

DEWPT(mon): Average daily dew point temperature in month (ºC).
Calculated based on following formula:

$$\mu dew_{mon} = \frac{\sum_{d=1}^{N} T_{dew,mon}}{N}$$

Where μdew_{mon} is the mean daily dew point temperature for the month (ºC), $Tdew,mon$ is the dew point temperature for day *d* in month *mon* (ºC), and *N* is the total number of daily dew point records for month *mon*.

WNDAV(mon): Average daily wind speed in month (m/s).
Calculated based on following formula:

$$\mu wnd_{mon} = \frac{\sum_{d=1}^{N} \mu_{wnd,mon}}{N}$$

Where μwnd_{mon} is the mean daily wind speed for the month (m/s), $\mu_{wnd,mon}$ is the average wind speed for day *d* in month *mon* (m/s), and *N* is the total number of daily wind speed records for month *mon*.

The numbers M1 to M12 in the following tables represent the months from January to December and the alphabets A – M , indicate the description of weather generator parameters presented in appendix- Appendix E

STATION				yrs									
Bahirdar	11.6	37.45	1770	22	26.77	28.41	29.39	29.95	29.30	27.05	24.36	24.39	25.63
Debretabor	11.88	38.03	2690	21	21.60	23.88	23.81	22.83	22.93	21.88	18.44	18.95	19.20
STATION	AM11	AM12	BM1	BM2	BM3	BM4	BM5	BM6	BM7	BM8	BM9	BM10	BM11
Bahirdar	26.76	26.74	9.11	10.98	13.28	15.27	15.48	14.88	14.49	14.36	13.78	13.73	11.82
Debretabor	14.05	5.83	1.13	1.26	1.53	2.02	2.34	2.24	1.73	1.48	1.33	1.36	1.10
STATION	CM1	CM2	CM3	CM4	CM5	CM6	CM7	CM8	CM9	CM10	CM11	CM12	DM1
Bahirdar	1.55	1.81	1.74	1.99	1.92	1.69	1.50	1.43	1.28	1.18	1.05	1.16	2.18
Debretabor	1.29	1.35	1.48	1.54	1.37	1.30	1.35	1.19	1.08	1.32	1.34	1.27	20.15
STATION	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10	DM11	DM12	EM1	EM2	EM3
Bahirdar	2.70	2.45	1.83	1.25	1.03	1.06	1.13	1.53	2.11	2.29	2.52	3.29	20.45
Debretabor	37.36	58.35	99.78	181.35	394.34	372.59	195.24	96.68	35.38	42.45	3.21	1.58	3.55
STATION	EM6	EM7	EM8	EM9	EM10	EM11	EM12	EM13	FM1	FM2	FM3	FM4	FM5
Bahirdar	75.29	204.67	420.88	378.74	192.26	94.93	13.51	3.11	0.62	1.09	3.11	3.70	6.65
Debretabor	7.48	8.99	11.24	11.07	8.60	7.77	3.oo61	4.03	11.77	5.13	6.39	3.71	4.25
STATION	FM7	FM8	FM9	FM10	FM11	FM12	GM1	GM2	GM3	GM4	GM5	GM6	GM7
Bahirdar	16.18	15.04	10.00	7.13	2.33	0.79	9.10	14.38	13.29	5.78	5.05	2.70	2.33
Debretabor	1.57	1.71	2.33	7.09	3.77	9.29	11.77	5.13	6.39	3.71	4.25	4.56	1.57
STATION	GM9	GM10	GM11	G12	HM1	HM2	HM3	HM4	HM5	HM6	HM7	HM8	HM9
Bahirdar	2.77	3.29	7.16	9.79	0.01	0.03	0.08	0.10	0.20	0.48	0.81	0.83	0.58
Debretabor	2.33	7.09	3.77	9.29	0.04	0.05	0.11	0.16	0.23	0.59	0.93	0.76	0.52
STATION	HM11	HM12	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10	IM11
Bahirdar	0.04	0.05	0.03	0.39	0.59	0.60	0.63	0.76	0.92	0.90	0.78	0.58	0.33
Debretabor	0.01	0.05	0.67	0.64	0.60	0.68	0.66	0.80	0.94	0.93	0.80	0.79	0.72
STATION	JM1	JM2	JM3	JM4	JM5	JM6	JM7	JM8	JM9	JM10	JM11	JM12	KM1
Bahirdar	0.81	1.13	5.31	6.19	11.56	20.81	29.38	28.38	22.94	11.50	2.63	1.1	21.14
Debretabor	3.87	3.67	7.33	10.67	13.33	23.13	30.00	29.33	23.00	15.33	7.00	8.20	18
STATION	KM3	KM4	KM5	KM6	KM7	KM8	KM9	KM10	KM11	KM12	LM1	LM2	LM3
Bahirdar	21.62	21.38	21.28	20.64	20.09	20.09	20.71	20.83	20.93	20.71	9.88	9.24	9.94
Debretabor	20	20	20	10	15	10	18	16	14	18	4.10	4.69	6.09
STATION	LM5	LM6	LM7	LM8	LM9	LM10	LM11	LM12	MM1	MM2	MM3	MM4	MM5
Bahirdar	12.77	15.24	15.55	15.87	15.34	13.93	11.87	10.32	0.46	0.53	0.63	0.70	0.65
Debretabor	9.17	11.28	11.28	11.18	9'28	1.71	0.39	12.27	MM3	1.24	1.18	1.21	1.5
STATION	MM7	MM8	MM9	MM10	MM11	M12							

Bahirdar	0.59	0.60	0.60	0.60	0.51	0.46							
Debretabor	1.15	1.26	1.13	0.78	0.84	1.04							

List of tables