ArbaMinch University School of Graduate studies
Department of Hydrology and Water Resources Management

Watershed Modelling of Lake Tana Basin Using SWAT

Sirak Tekleab Gebrekristos

September, 2008

Watershed Modeling of Lake Tana basin Using SWAT

By
Sirak Tekleab Gebrekristos

A Thesis submitted to School of Graduate studies, ArbaMinch University in partial fulfilment requirements for the degree of masters of Science in Hydrology and Water Resources Management.

September, 2008

CERTIFICATION

I, the undersigned, certify that I read and hereby recommend for the acceptance by the ArbaMinch University a dissertation entitled: Watershed Modeling of Lake Tana basin using SWAT, part of Blue Nile basin, Ethiopia in partial fulfilment of a degree of Masters of Science in Hydrology and Water Resources Management

Dr. Semu Ayalew Moges
Supervisor

DECLARATION AND COPY RIGHT

I, Sirak Tekleab Gebrekristos, declare that this thesis is my own original and it has not presented and will not be presented to any other University for the similar or any other degree award.

Signature ________________________

ACKNOWLEDGEMENT

First of all I would like to thank my holy father God, for his care and endless love during my stay at ArbaMinch University for the whole study period.

I would like to express my deepest gratitude to my supervisor Dr. Semu Ayalew Moges, for his valuable advice, encouragement and critical comment during the research period. His contribution was really appreciable. Even with far distance & a lot of work he was engaged, his immediate reply through internet was great. He devoted his time from the beginning of the research title to the completion of the thesis work. With out him this research would not have been possible.

I would like to extend my sincere gratitude to Nile Basin Initiative (NBI), Applied Training Program (ATP), for granting the scholar ship during the whole study period. I am also grateful to my Employer Hawassa University, Technology Faculty for giving me leave of absence for study duration.

I would like to thank MoWR, Hydrology department and NMA for their help by providing Hydrological & Meteorological datas to conduct this research work.

My special thanks also goes to Ato Kassa Tadelle, who initiated and taught SWAT model from the beginning and provided all the necessary data information from abroad. I am also deeply appreciating Ato Lijalem Zeray, Ato Shimelis Gebreye for their help during the research work.

I am extremely grateful to my fiance Meseret Hailu, for her love and care during the whole study period. I am also highly indebted to my special friends, Girma Yimer, Fikere Enku, Tessema Birhanu, Tewedros Meless, Tewedros Zeyinu, and Tizitaw Tefera. I extend my sincere gratitude to my friend Ato Andualem Wube for his help during the whole study period.

I would like to thank Miss. Hiwot Kebede, Mrs. Tsehay Kebede, and Ato Habtewold, my brother Dawit and Eshetu for their encouragement through out the study period.

I thank all of my course mate, for all challenges, knowledge sharing and happy time we spent together at Arbaminch University.

Last but not least, I would like to thank my family, especially my father, Tekleab and my mother Azalech, for their continuous support and encouragement that Contribute great to my life.

Abstract

The main purpose of this study was mainly to accurately estimate the inflow components of Lake Tana from both gauged and un-gauged catchments for water balance modeling. Distributed physically based hydrological model known as soil and water assessment tool (SWAT) has been applied.

The model was calibrated and validated over the gauged upper reaches of major catchments of Gilgel Abay, Koga, Gumera, Rib and Megech. The model was calibrated for the period from 1996-2001 and validated for the period from 2002-2004. The performance of the model was evaluated on the basis of performance rating criteria, coefficient of determination, Nash & Sutcliff efficiency, and percent deviation. The overall performance of the model appears satisfactory. The R^2 for all catchments vary between 0.69 to 0.89 during calibration and 0.81 to 0.86 during validation. The hydrograph fit between the estimated and observed is also adequately represented except the underestimated, which stands out for Gilgel Abay, Gumera and Megech catchments for the year 2003. The year 2003 has been underestimated due to many missed rainfall data of the surrounding stations.

The Curve Number (CN) has been found the most sensitive parameters in all the catchments indicating the importance of this parameter during modeling and fine tuning. However, the level of sensitivity of this parameter differs from catchment to catchment.

The calibrated parameters were transferred to un-gauged catchments to estimate the ungauged flow contribution based on similarity of the hydrologic response unit (HRUs). The model output indicates that, the annual inflow volume estimated to be 3909 MCM contributed from gauged catchment and about 2431 MCM contributed from ungauged catchment.

TABLE OF CONTENT

List of Acronyms

AVSWAT – The ArcView Integrated SWAT Hydrological Model
BCEOM-Le Bureau, central d'Etudes Pourles Equipments d'outre-Mer.
BCM-Billion Cubic Meter
DEM – Digital Elevation Model
DEW02 – Dew Point Temperature Calculator
ET- Evapotranspiration
FAO – Food and Agricultural Organization of the United Nations
GIS – Geographic Information System
HBV-Hydraologiska Byrans Vattenbalansavde
HEC-HMS-Hydraulic Engineering Center, Hydrologic Modeling System
HRU – Hydrologic Response Unit
JICA-Japan International Co-operation Agency
KW-Kinematic Wave
LGAC-Lower Gilgel Abay catchment
LGC-Lower Gumera catchment
LMC-Lower Megech catchment
LRC-Lower Rib catchment
LTB-Lake Tana Basin
+MSL – above mean sea level
MCM-Million Cubic Meter
MoWR – Ministry of Water Resources, Ethiopia
NMA – National Meteorological Agency, Ethiopia
NSE- Nash Sutcliff Efficiency
PET – Potential Evapotranspiration
SCS – Soil Conservation System
SEBAL-Surface Energy Balance Algorithm for Land
SRTM-Shuttle Radar Topographic Mission
SWAT – The Soil and Water Assessment Tool
UNESCO-United Nation Educational Scientific and Cultural Organization
USBR- United States Bureau of Reclamation
UTM-Universal Transverse Mercater
WGEN – Weather Generator
XPARM – Weather Parameter Calculator

List of Figures

List of Tables

CHAPTER ONE

1. Introduction

1.1 Back Ground

The increased demand of water for agriculture, industries, domestic, and power generation in Lake Tana sub-basin requires proper planning and management of water resources in the basin. The basin has more than 40 rivers inflow in to Lake Tana and about 93% of the inflow is coming from the four major rivers Gilgel Abbay, Gumera, Rib and Megech (Kebede et al. 2005). Since, only major rivers in the upper part of the basin have hydrometric station, the water resource potential in the basin in general and the Lake water balance components in particular have not been determined accurately.

A number of studies have been conducted in the basin which is referred and explained in the literature review section of this document. From these past studies it can be seen that significant variation in determining the hydrological variables have been detected in assessing the water resource potential of the basin. Hence, assessment of water resource potential and understanding the hydrological processes in the basin has become important to manage and to make optimal use of water resource development alternatives.

Moreover, based on the studies conducted so far a number of water resource development projects have been identified. Since, most of the projects intended for the purpose of irrigation and water supply, it is essential to take in to account the Lake ecosystem not affected by using the water in the upper catchments for consumptive use.

Thus, from operational water resources management point of view, hydrological models are developed to guide the formulation of water resource management strategies by understanding spatial and temporal distribution of water resources (Dingman, 2002; Liden and Harlin, 2000). Hence, the same is applied in Lake Tana basin.

The purpose of this research is therefore applying a physically based semi distributed model i.e. Soil and water assessment tool (SWAT), to understand the hydrology of the basin and to know the water resource potential as a whole from gauged and un-gauged catchments.

1.2 Statement of the problem

In the past few decades several project studies and research activities have been conducted on Upper Blue Nile Basin by different international consultants and academia. Nevertheless, the inflow components of the water balance to the Lake varies significantly from one study to another study. The inflow value varies from 4.18 BCM to 12.05 BCM obtained was mainly due to many rivers in Lake Tana basin is not gauged and as a result it has been difficult to estimate accurately the runoff generated from ungauged catchments. This big uncertainty and variation on the inflow has resulted in uncertainty in the water balance components. As a consequence water management studies over the Lake remain illusive.

Since, previous hydrological studies in Lake Tana basin were hampered by lack of properly distributed spatial inputs such as topography, soil properties and land use, this study mainly focuses on accurately estimating the inflow with the view of establishing accurate water management policies by modeling the hydrology of the basin using soil and water assessment tool, which will help to understand the hydrological process and to achieve proper planning, designing and managing of water resources.

1.3 Objective of the study

The main objective of this study is hydrological modeling of the water balance components of the Lake Tana sub-basin using semi distributed physically based watershed model known as Soil and Water Assessment tools (SWAT).

Specific objective:

1. Developing the spatial and temporal database appropriate the SWAT modeling environment and setting up of the model for each catchments of Lake Tana.
2. Calibration and validation of the SWAT model for gauged catchments and derivation of parameters for ungauged part of the Lake Tana sub-basin to accurately estimate the inflow in to the Lake.
3. Simulation of the Lake Water balance with out development projects.

CHAPTER TWO

2. Study Area

2.1 General

Lake Tana Basin is part of the Blue Nile basin, which lies in a natural drainage basin of about 15114 Km^2 as per this research work using SWAT delineation. Among which about 20.41% is covered by the Lake Tana. Of more than 40 rivers feeding the lake, Gilgel-Abay, Rib, Gumera and Megech contribute more than 93% of the inflow. The only surface outflow is the Blue Nile, which comprises 7% of the Blue Nile flow at the Ethio-Sudanese border (Shahin, 1988; Conway, 2000). All of these rivers rise in the highland surrounding the basin.

2.2 Location

Lake Tana basin is found in north west part of Ethiopia in Amhara administrative region covering eight Woredas (smaller administrative units) .Dembia and Gondar Zuria in the northern part of the sub-basin; Libo Kemkem, Fogera, Farta and Dera in the eastern part of the basin, Achefer and Alefa-Bechigne on the western part and with Bahirdar Zuria on the southern part of the basin. Geographically it extends between 10.95^0N to 12.78^oN latitude and from 36.89^oE to 38.25^oE longitude.

2.3 Topography

Topography is generally uniform and quite well adapted to irrigation development surrounding Lake Tana. The elevation ranges between 1784 m to 4079 m +MSL, which is extracted from DEM (90*90m) resolution. The mean elevation of the basin is found to be 2241 m +MSL. The sub basin is generally characterized by a large flat to very gently sloping plain bordering the lake on the North and East and an extensive area of gently rolling to hilly uplands on the South.

2.4 Climate

Like most of the central highlands, the elevated position of the Lake Tana area makes for a temperate, subtropical, and equable climate despite its proximity to the equator (approximately 12^0 North Latitude) There are two seasons rainy and dry. The rainy season has two periods, the little rains, during April and May, and the big rains, which last from mid- June to mid-September. The rainfall distribution in the basin is found to be a mono-modal pattern i.e. one peak value observed during rainy season especially in July, and August. Considering the rainfall stations in the basin for a period of 1997-2006 the mean annual rainfall amount ranges between 813 mm in Yifag and 2328 mm in Enjibara. Similarly the mean annual minimum and maximum temperature ranges between 9.3 ^oC in Dangla and 29.6 ^oC in Gorgora respectively.

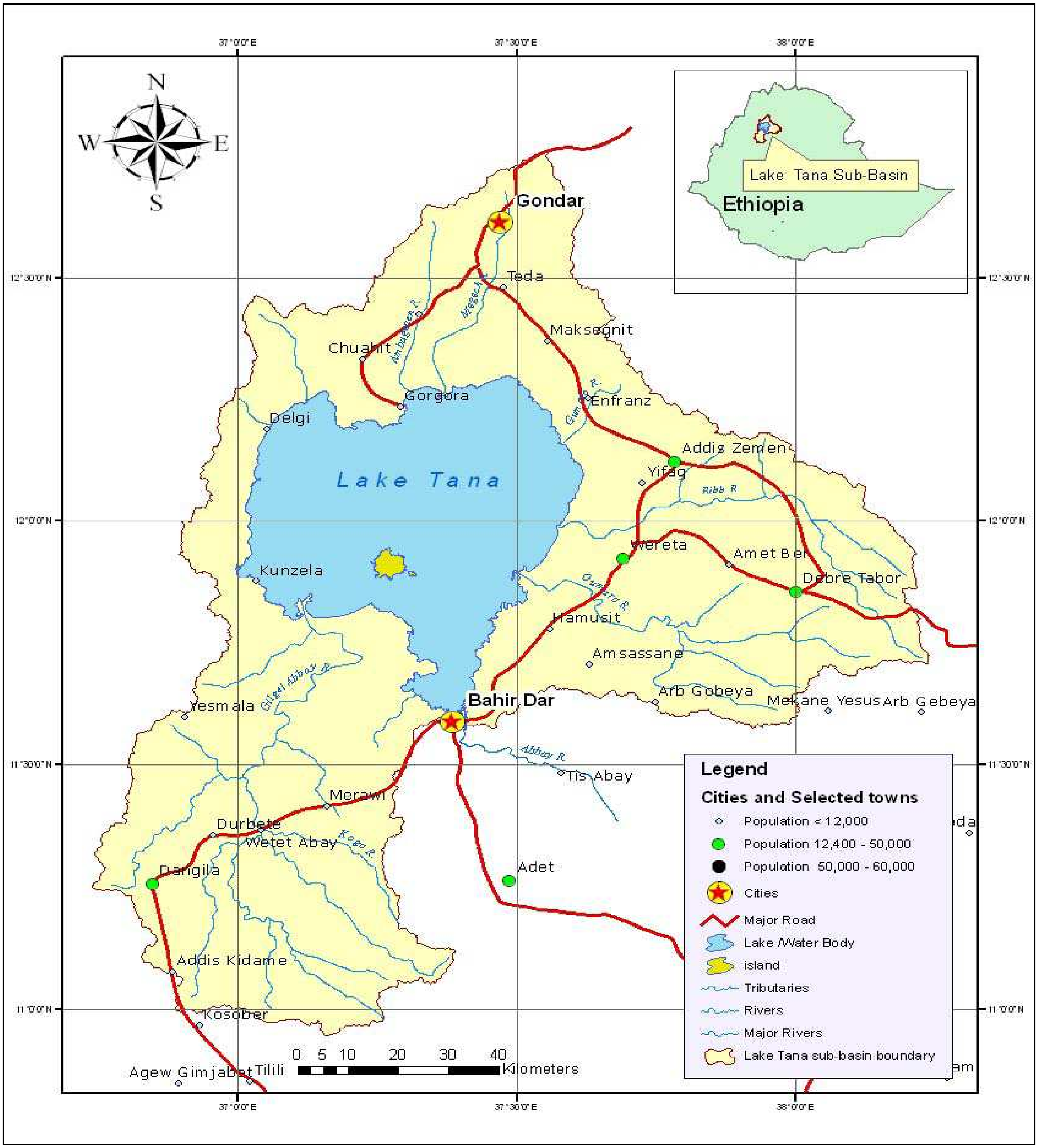


Fig 2.1 Location Map of Lake Tana Basin (Source; Yohanse, 2007)

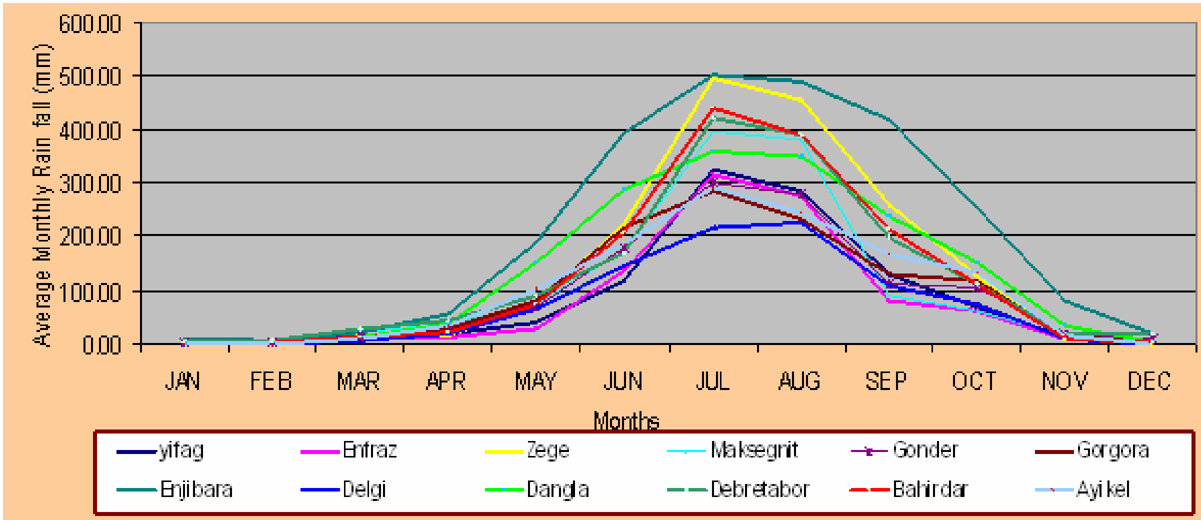


Fig 2.2 Average Monthly rainfall distribution in the study area (1997-2006)

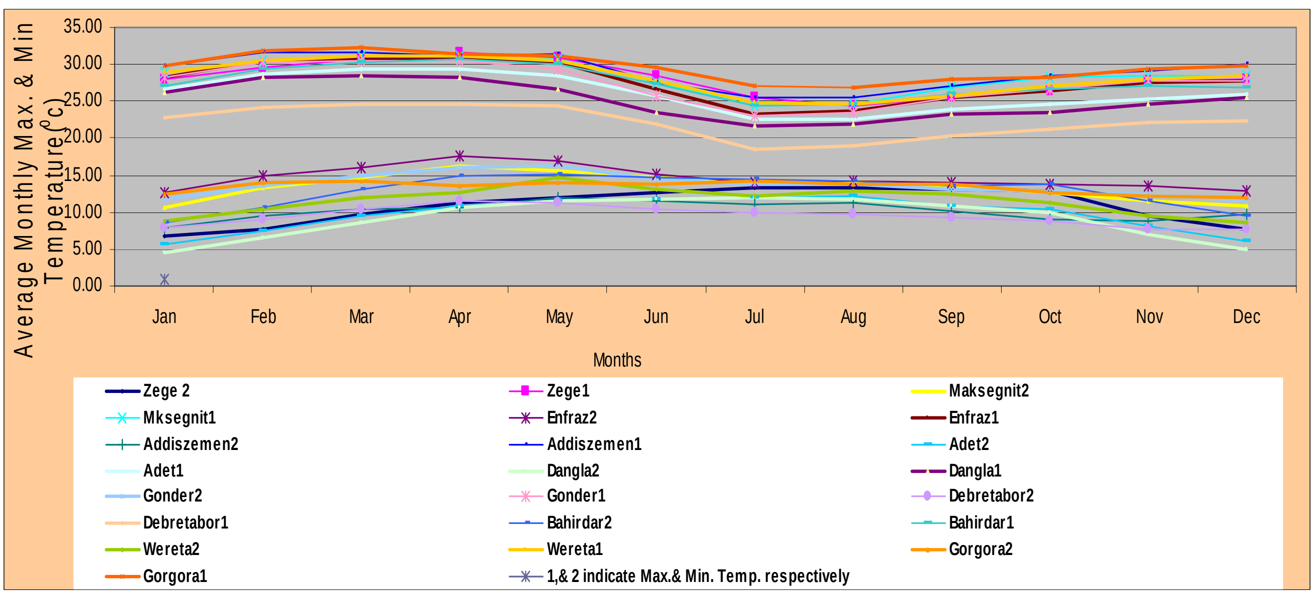


Fig 2.3 Average Monthly Minimum and Maximum Temperature for the study area (1997-2006)

2.5 Land use

Land use of study area was classified based on Abay river master plan study conducted by BCEOM, in 1996-1999, about 51.37 % of the watershed area was covered by Agriculture, 21.94 % Agro-pastoral, 20.41 % by Lake Tana, 0.39 % Agro-slyvicultural, 0.13 % wetland, 5.47 % Pastoral, 0.15 % slyvicultural, 0.03 % sylvo-pastoral and 0.11 % Urban.

Detailed description of the land use classification has been found in Data availability and analysis section of this thesis document.

2.6 Soil

The soil classification for the study area is also adopted from Abay river master plan study in 1996-1999 conducted by BCEOM. Based on the classification Halpic luvisol which covers about 20.69 % of the watershed area is considered to be the major dominant soil in the study area. For use in SWAT database, FAO, UNESCO Soil classification system has been used and the detail of soil classification is presented in data availability and analysis section of this document.

Table 2.1 Major gauged rivers and areal coverage in the study area

River Name	UTM (used in SWAT)		Location of gauged station	SWAT Delineated Area(Km^2)	Area (Km^2) obtained from MoWR
	X- Coordinate	Y-Coordinate			
Arno-Garno	350365	1351163	Infraz	104.69	94
Gemero	341406	1369576	-	163.21	174
Gilgel Abay	285390	1258020	Merawi	1657.93	1664
Gumera	350626	1310671	Bahirdar	1376.67	1394
Koga	285565	1257123	Merawi	271.63	244
Megech	331557	1381143	Azezo	484.05	462
Rib	359783	1325758	Addiszemen	1592.17	1592
Total				5650.35	5624

Based on this areal distribution, about 5650.35 Km^2 (46.97 %) of the LTB is gauged and 6378.89 Km2 (53.03 %) is un-gauged.

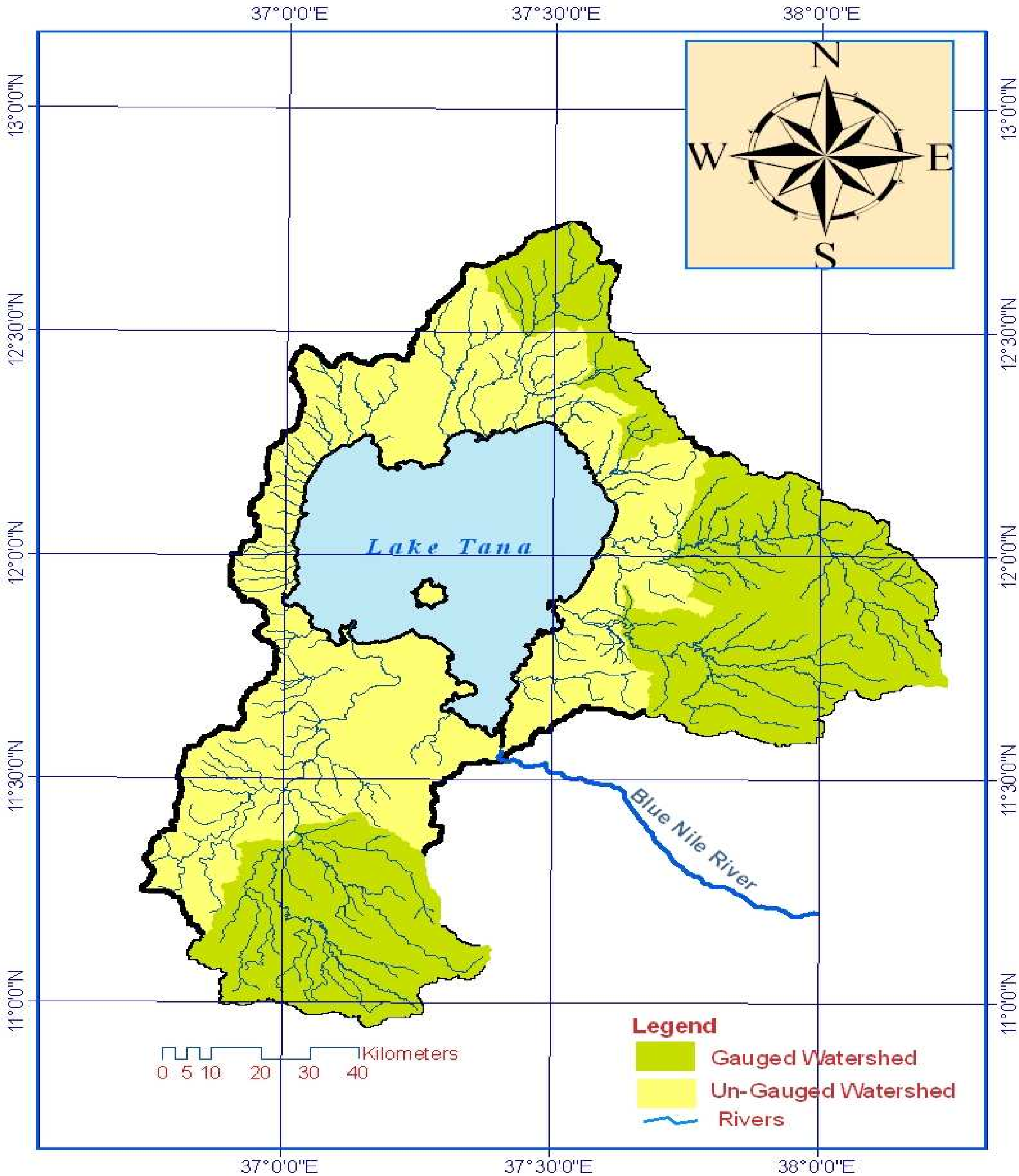


Fig 2.4 Gauged and un-gauged watershed in Lake Tana basin.

CHAPTER THREE

3. Literature review

3.1 Previous work in the study area.

Various study works have been conducted in Lake Tana basin to estimate the water balance terms and total water resource potential. Different researchers with different approaches have come up with the following results.

Table 3.1 Comparison of Lake Inflow by different study works in Lake Tana basin.

Investigator	Study works	Inflow to Lake Tana (BCM)
Studio Pietrangeli,(1990)	Tana-Beles project studies	9.380
Humphrey & associates,(1996)	Tis Abbay II Hydropower Studies	9.53
Melkamu Amre, (2005)	Reservoir operation & establishment of operation rule for Lake Tana	12.05
Water watch,(2005)	Remote Sensing Studies of Tana-Beles Sub Basins	11.56
Yohanse Daniel, (2007)	Water Resource Potential Assessment using RS	7.68
S. Kebede, et al, (2005)	Water Balance of Lake Tana & its sensitivity to fluctuation to rainfall.	4.18
SMEC, (2007)	Hydrological study of Tana-Beles sub-basin	4.93
Abeyou ,(2008)	Hydrological Water balance of Lake Tana	6.69
Abayeh , (2005)	Assessment of cause of Lake Tana water level change & its impact on Tiss Abay Hydropower production.	6.7

Table 3.2 Previously done Water Balance components by different researchers over Lake Tana.

Investigator	Precipitation (mm/yr)	In flow (mm/yr)	Out flow (mm/yr)	Evaporation (mm/yr)	Data analysis period
S.Kebede et.al., (2005)	1451	1162	1113	1478	1960-1992
SMEC, (2007)	1254	1627	1225	1675	1960-1995
Yohanse, (2007)	1262	2528	1648	1695	1998-2003
Water watch, (2005)	1541	1616	1499	1588	For 2001
Melkamu, (2005)	1678	3963	3735	1655	1973-2003
Abeyu, (2008)	1200	2160	1520	1690	1995-2000
Abayneh , (2005)	1238	2200	1265	1965	1990-2003

Studio Peterngeli, (1990): 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. According to this study the mean annual evaporation is estimated to be 190.3 m^3/sec (6000 MCM) per annum.

S.Kebede et. al, (2005): 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 modeling at a monthly time step. Estimation of evaporation from the Lake was determined using penman formula.

Water watch, (2005): This study was carried out by remote sensing techniques 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.

Abayneh, (2005): In this study he tried to estimate the inflow in to the Lake using EXCEL spread sheet model. Thee evaporation from the Lake surface was computed using Penman formula.

Melkamu, (2005): Rainfall-runoff modeling was 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.

Yohanes, (2007): He used WATBAL and SCS model for water resources potential assessment in the basin. The rainfall on the Lake surface was estimated using spatial interpolation of Inverse distance weighted techniques. The evaporation from the Lake surface also determined by aerodynamic method.

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.

Abeyou, (2008): 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.

3.2 Water Resources Development.

As for utilize of water for Lake Tana basin, Water works Design and enterprise studied water resources development projects based on BECOM, 1999, Integrated master plan studies of Abay River basin.

Table 3.3 Water Resource development projects in LTB

S.No	Development project	Reservoir volume (MCM)	Surface Area At Normal pool level (Km^2)	Irrigable area (Ha)	X-coordinate	Y-Coordinate
1	Gilgel Abay Dam-B	224	10.9	11508	282814	1267540
2	Jema-Dam	86	4.6	7786	370151	1299989
3	Koga-Dam	76	16	6000	390697	1331241
4	Gumera Dam-A	306	10	12920	333391	1384998
5	Rib Dam	234	9	15270	303095	1238215
6	Megech-Dam	181.85	7.8	7311	292701	1255320

Table 3.4 Irrigation water demand (mm) for Dam projects in LTB

S.No.	Project Name	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
1	Gilgel Abay-Dam-B	148	187	144	41	0	0	0	0	0	0	86	151
2	Jema-Dam	142	180	138	37	0	0	0	0	0	0	84	147
3	Koga-Dam	99	183	258	149	0	0	0	0	0	90	111	24
4	Gumera Dam-A	252	307	264	132	33	0	207	36	86	161	28	259
5	Rib Dam	290	138	155	197	60	0	0	0	0	53	78	17
6	Megech-Dam	143	164	170	66	0	0	0	0	0	0	91	157

(Source: Water works Design and supervision, Design of Dams in Lake Tana Sub-Basin Gilgel Abbay, Megech, Ribb, Gumera and Jemma Project Hydrological Study Final Report June, 2007)

(Acres International Limited Canada, March, 1995 Feasibility study of Birr and Koga irrigation project)

3.3 Hydrological Model

3.3.1 Definition of Modelling:

A model in its broadest sense is a simplified depiction of a natural entity that in some way exhibits its important features while eliminating or suppressing matters of irrelevant detail. In science and engineering, an essential attribute of a model is that it be quantitative, that is, that it yields a numerical value for a feature of the natural entity, as a surrogate for a measurement. A quantitative model can be used to explore cause-and-effect relations and to determine values of physical variables that are too costly or difficult to measure directly. Models have long been used in water resources management to guide decision making and improve understanding of the system.

It is essential that a model used in water-resources management be sufficiently accurate for its intended purpose. Because a model is a simplified depiction of the natural system, its accuracy is subject to question until proven.

The acceptability of a model can only be determined by a confrontation with observation. Therefore, the existence of a model does not obviate the need for data from the watercourse, but in fact imposes additional needs and requirements on the data base.

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, G., Benamen, 1999)

3.3.2 Classification of Hydrologic Simulation Models

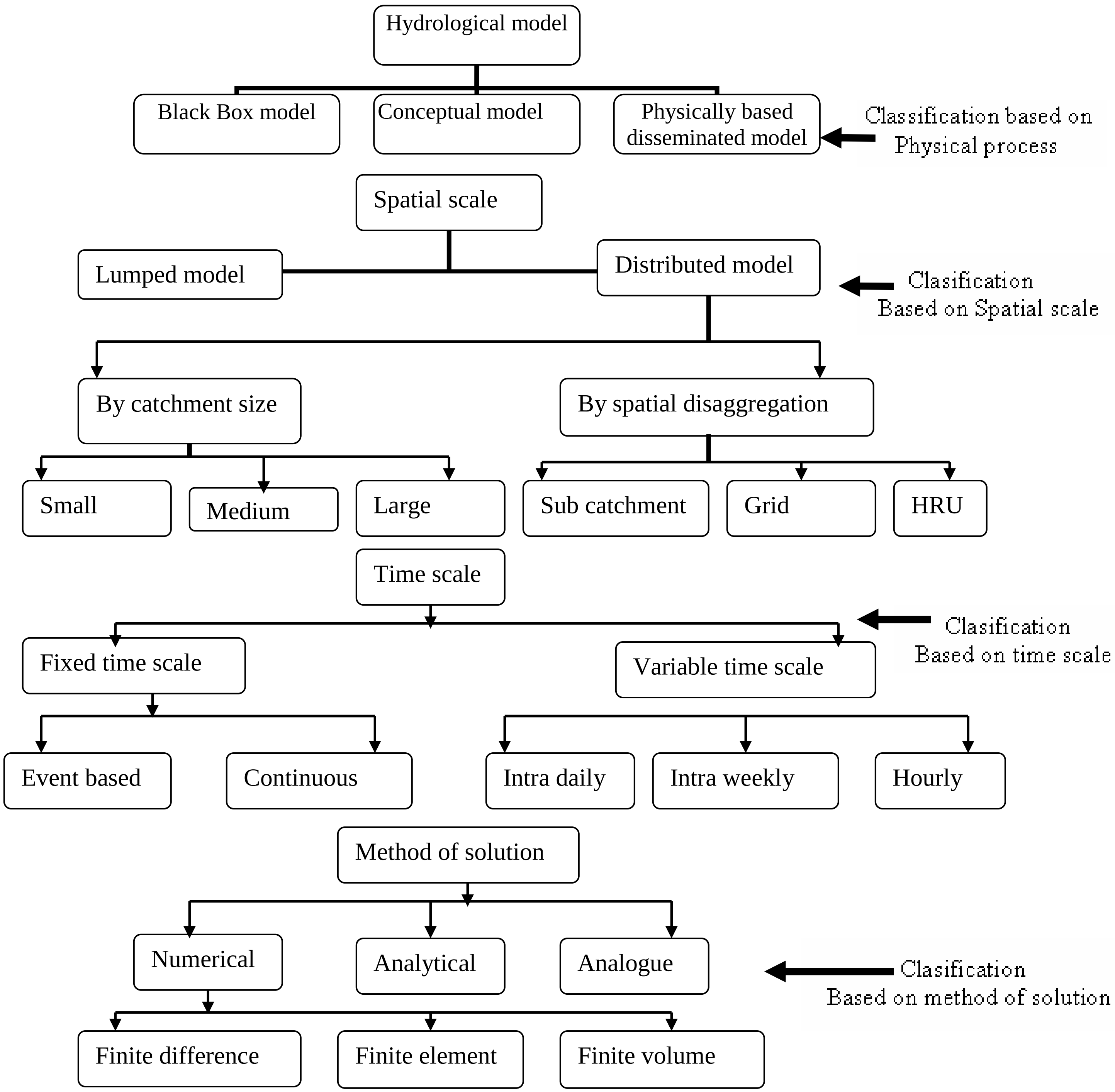


Figure 3.1 Simplified flow chart of hydrological model classification (Source: Semu, 2007)

CHAPTER FOUR

4. Methodology

4.1 SWAT Model

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

4.1.1 Sub watershed Discretization and Determination of HRUs.

The sub watershed discretization divides the watershed into sub basins based on topographic features of the watershed. This technique preserves the natural flow paths, boundaries, and channels required for realistic routing of water, sediment and chemicals. All of the GIS interfaces developed for SWAT use the sub watershed discretization to divide a watershed.

The number of sub basins chosen to model the watershed depends on the size of the watershed, the spatial detail of available input data and the amount of detail required to meet the goals of the project. When subdividing the watershed, keep in mind that topographic attributes (slope, slope length, channel length, channel width, etc.) are calculated or summarized at the sub basin level. The sub basin delineation should be detailed enough to capture significant topographic variability within the watershed.

Once the sub basin delineation has been completed, the user has the option of modeling a single soil land use management scheme for each sub basin or partitioning the sub basins into multiple hydrologic response units (HRUs). HRUs are used in most SWAT runs since they simplify a run by lumping all similar soil and land use areas into a single response unit. It is often not practical to simulate individual field. (Neitsch et. al, 2005), Soil and Water Assessment Tool input /output file documentation, version 2005.

4.2 Hydrologic Water Balance.

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.

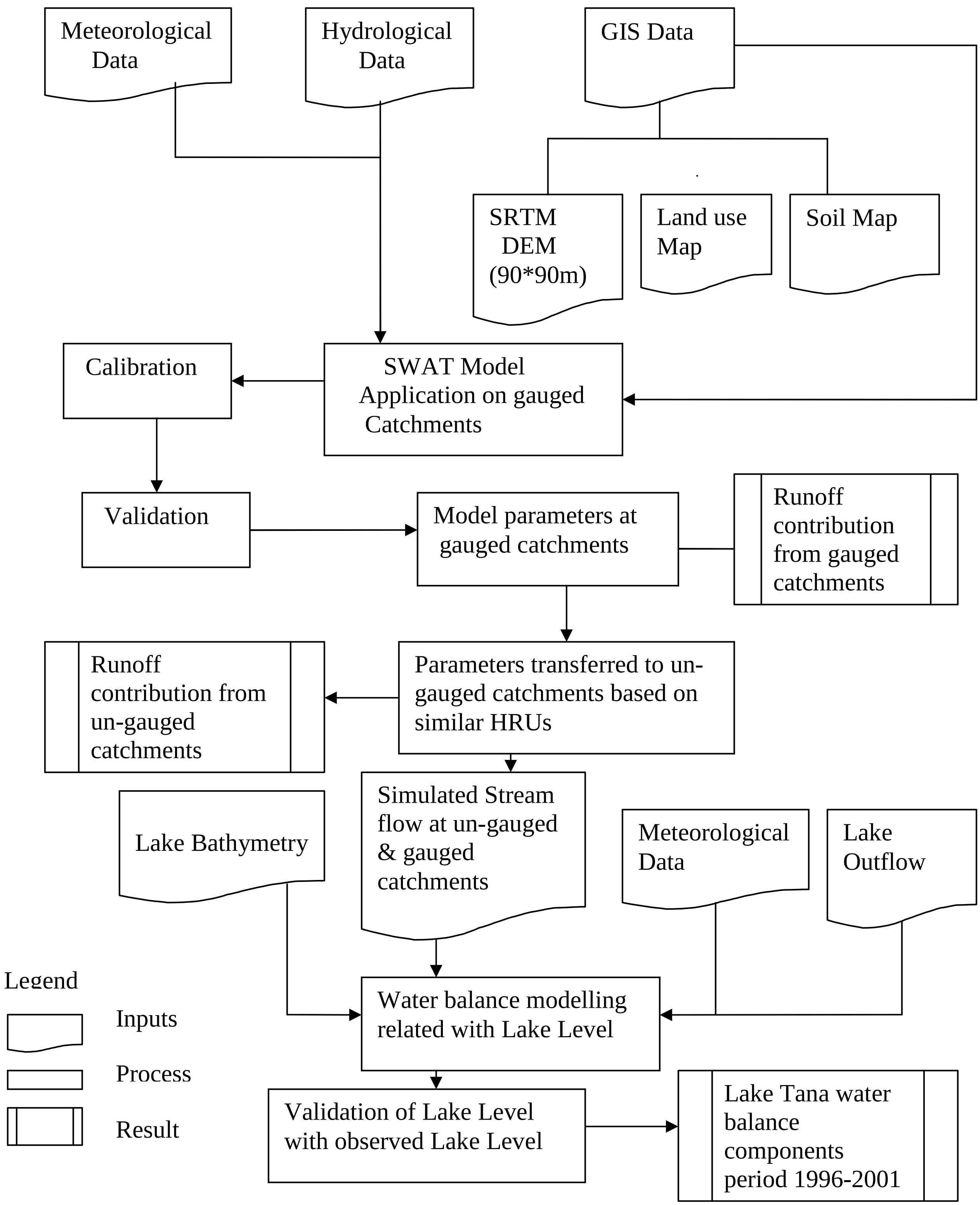


Figure 4.1 Simplified flow chart of the Methodology adopted in the research

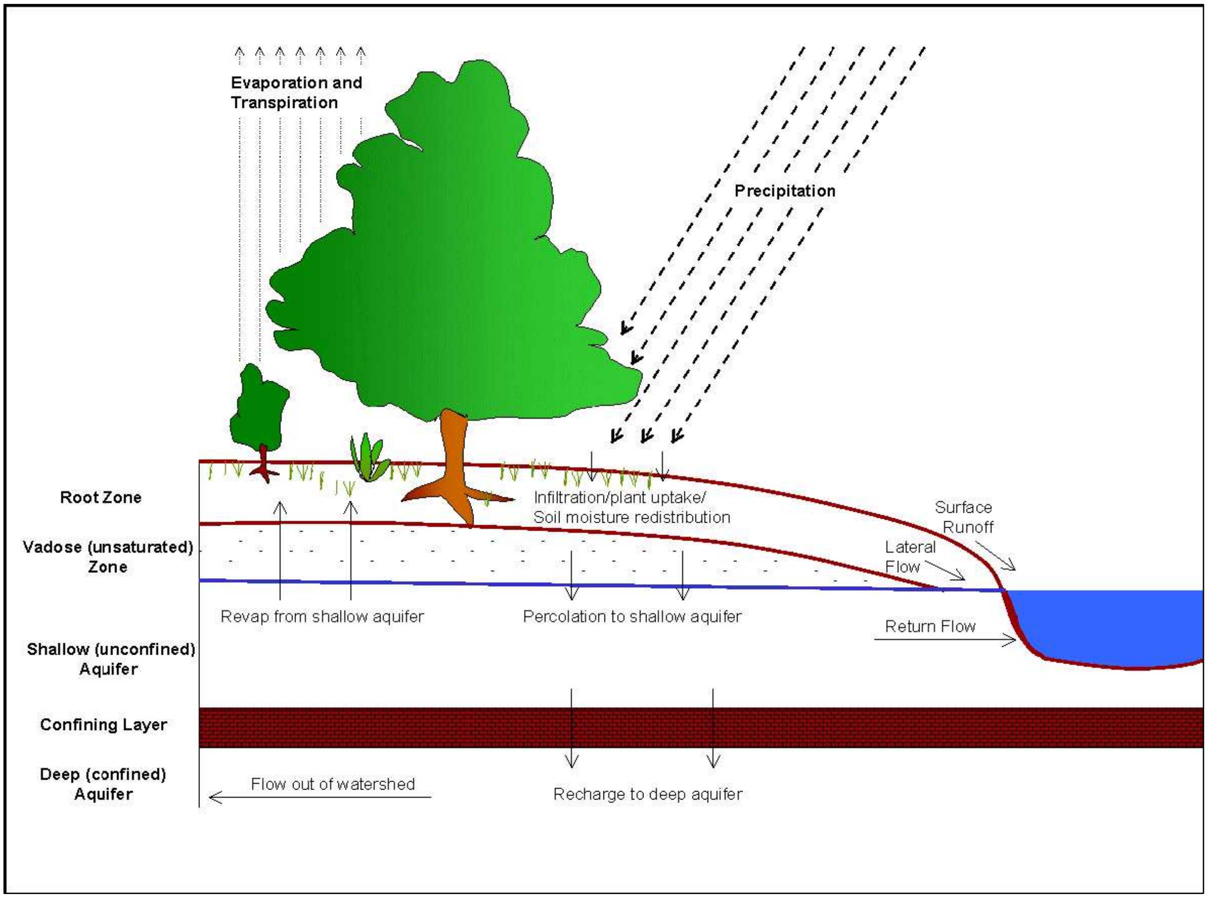


Figure 4.2 Schematic representation of Hydrologic cycle used in SWAT Model.

The hydrologic cycle simulated by SWAT is based on the following water balance equation.

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

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 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.

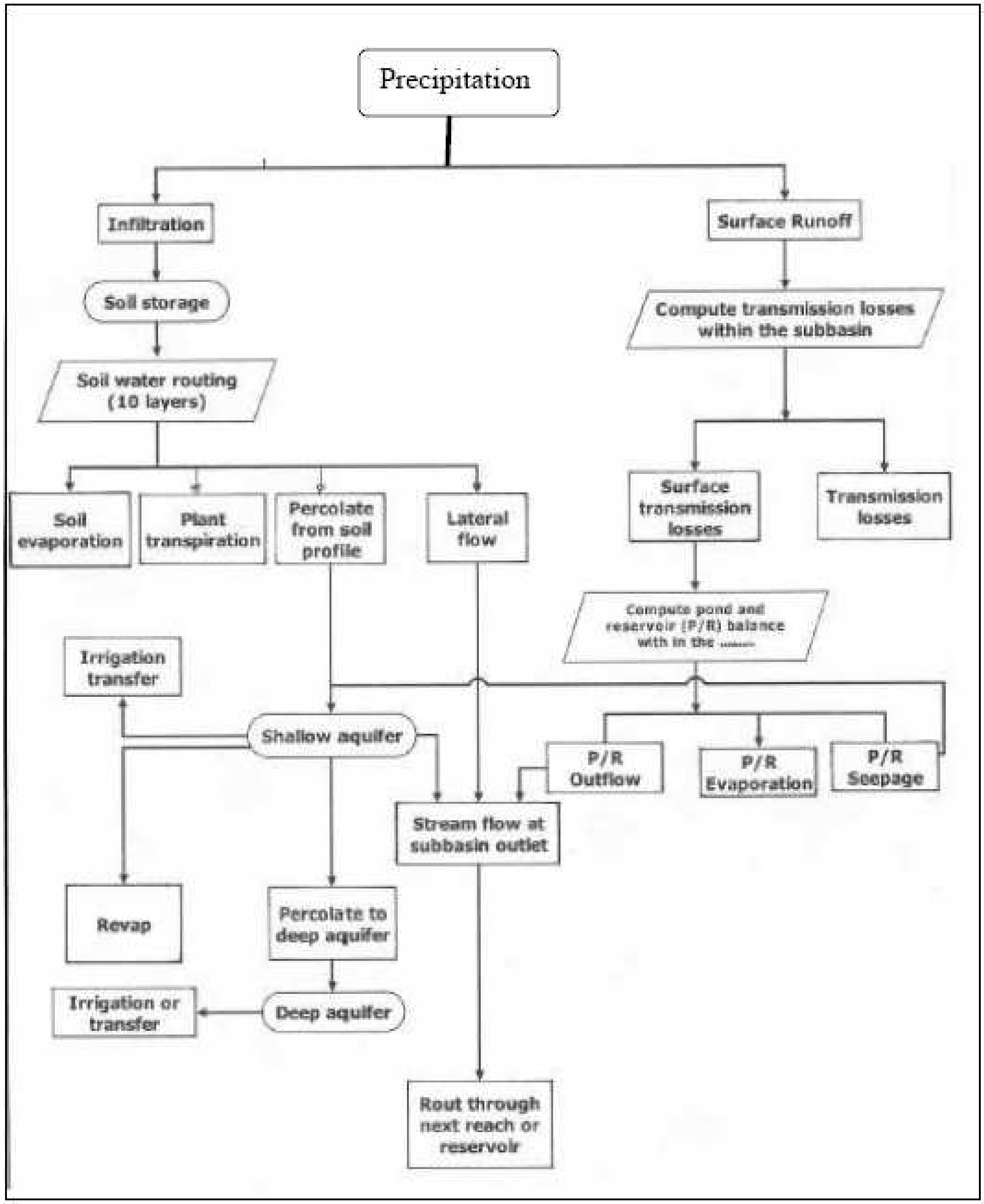


Figure 4.3 Over view of SWAT hydrologic component (Adapted from Arnold et.al, 1998)

4.3 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), which were downloaded from SWAT website (http://www.brc.tamus.edu/swat/soft_links.html).

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. See appendix-B

4.3.1 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 in the study area have been computed based on the formula presented in Appendix-B

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:

$P_i(D/W) = 1 - P_i(W/W)$ ------------ Eq. (4.2)

$P_i(D/D) = 1 - P_i(W/D)$ ------------- Eq. (4.3)

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.

4.4 Surface Runoff.

Surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. SWAT provides two methods for estimating surface runoff: the SCS curve number procedure (SCS, 1972) and the Green & Ampt infiltration method (1911). For these research work SCS curve number method has been used.

The SCS curve number used (SCS, 1972)

$$Q_{surf} = \frac{(R_d - I_a)^2}{(R_d - I_a + S)}$$ ---------------------Eq (4.4)

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:

$$S = 25.49(\frac{1000}{CN} - 10) \text{----------------Eq. (4.5)}$$

Where: CN is the curve number for the day.

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

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \text{--------------Eq. (4.6)}$$

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

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.

4.4.1 Peak Runoff Rate.

The peak discharge or 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:

$$q_{peak} = \frac{\alpha_{tc} * Q_{surf} * Area}{3.6 * t_{conc.}} \text{--------------------------------Eq. (4.7)}$$

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 (km²),

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:

$$\alpha_{tc} = 1 - \exp[2 * t_{conc} * \ln(1 - \alpha_{0.5})] \text{ --------------------Eq. (4.8)}$$

Where: t_{conc} is the time of concentration (hr), and
$\alpha_{0.5}$ is the fraction of daily rain falling in the half-hour highest intensity rainfall.

4.4.2 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}):

$$t_{conc} = t_{ov} + t_{ch} \text{ --Eq. (4.9)}$$

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

$$t_{ov} = \frac{Lslp}{3600 * V_{ov}} \text{ ---Eq. (4.10)}$$

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:

$$V_{ov} = \frac{q_{ov}^{0.4} * Slp^{0.3}}{n^{0.6}} \text{ --Eq. (4.11)}$$

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 sub basin.
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:

$$t_{ov} = \frac{L_{slp}^{\ \ 0.6} * n^{0.6}}{16 * slp^{0.3}}$$ --Eq. (4.12)

Channel flow time is computed as:

$$t_{ch} \frac{L_c}{3.6 * V_c}$$ --Eq. (4.13)

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:

$$L_c = \sqrt{L * L_{cen}}$$ --Eq. (4.14)

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:

$$t_{ch} = \frac{0.62 * L * n^{0.75}}{Area^{0.125} * Slp_{ch}^{\ \ 0.375}}$$ ---Eq. (4.15)

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).

4.4.3 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:

$$Q_{surf} = (Q'_{surf} + Q_{surf,i-1}) * (1 - Exp[\frac{-surlag}{t_{conc}}])$$ ----------------------------------Eq. (4.16)

Where: Q_{surf} is amount of surface runoff discharged to main channel in a day (mm),

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

t_{conc} is the time of concentration for the sub basin (hrs)

4.4.4 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:

$$\Delta V_{stored} = V_{in} - V_{out} \quad \text{---Eq. (4.17)}$$

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:

$$V_{storage,2} - V_{stored,1} = \Delta t * (\frac{q_{in,1} + q_{in,2}}{2}) - \Delta t * (\frac{q_{out,1} + q_{out,2}}{2}) \quad \text{---------------------Eq. (4.18)}$$

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.

$$TT = \frac{V_{storage}}{q_{out}} = \frac{V_{storage,1}}{q_{out,1}} = \frac{V_{storage,2}}{q_{out,2}}$$ --Eq. (4.19)

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)

4.5 Potential Evapotranspiration.

Potential evapotranspiration (PET) was a concept originally introduced by Thornthwaite (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.

4.5.1 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:

$$\lambda E = \frac{\Delta.(H_{net} - G) + \rho_{air}.C_p.[e^o{}_z - e_z]/r_a}{\Delta + \gamma.(1 + r_c / r_a)}$$ --------------------------------Eq. (4.20)

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 vapor 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 vapor pressure of air at height z (kPa), γ is the psychrometric 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):

$$\lambda E_t = \frac{\Delta.(H_{net} - G) + \gamma.K_1.(0.622.\lambda.\rho_{air} / P).[e^o{}_z - e_z]/r_a}{\Delta + \gamma.(1 + r_c / r_a)}$$ ------------------Eq. (4.21)

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).

4.6 Groundwater 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.

4.6.1 Shallow Aquifer.

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

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh} \qquad \text{-------------------------Eq. (4.22)}$$

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).

4.6.2 Deep aquifer.

The water balance for the deep aquifer is:

$$aq_{dp,i} = aq_{dp,i-1} + w_{deep} - w_{pump,dp} \qquad \text{---Eq. (4.23)}$$

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.

4.7 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 modeling 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 4.1 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

Using the built in tool in SWAT model sensitivity analysis has been performed for all major gauged stream flow in the basin and the result is found in modeling section of this report.

4.8 Calibration and Validation of Model.

4.8.1 Calibration.

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 research work the measured stream flow data of Gilgel Abay River at Merawi Koga at Mrawi, Gumara at Bahirdar, Rib at Addiszemen and Megech at Azezo were manually calibrated from a period of 1996-2001 and the result is presented in chapter six of this report.

Automatic calibration method also embedded in SWAT 2005 could automatically calibrate the model. However, since the default parameters gave a good performance, only manual calibration has been adopted in this research work.

SWAT developers in 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. Both observed and simulated stream flow should be separated into base flow and surface flow. Surface runoff should be calibrated until average measured and simulated surface runoff within $\pm$15% and the model performance statistics should be D<±25%, r^2 >0.6 and E_{NS} > 0.5 for monthly simulation period.

Table 4.2 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

4.8.2 Validation

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, 2002 – Dec. 31, 2004.

4.8.3 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 behavior of the model to observations.

The model simulation has been evaluated using efficiency criteria such as coefficient of determination, R^2 [Nash and Sutcliff (E_{NS}), 1970], percent difference D, & root mean square error standard deviation ratio (RSR)

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:

$$r^2 = \frac{\left[\sum_{i=1}^{n}(q_{si}-\bar{q}_s)(q_{oi}-\bar{q}_o)\right]^2}{\sum_{i=1}^{n}(q_{si}-\bar{q}_s)^2\sum_{i=1}^{n}(q_{oi}-\bar{q}_o)^2} \quad \text{------------------------------Eq. (4.26)}$$

Where:

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

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

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(q_{oi}-q_{si})^2}{\sum_{i=1}^{n}(q_{oi}-\bar{q}_o)^2} \quad \text{--Eq. (4.27)}$$

Where:

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

The statistical index of modeling 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:

$$D = 100 \cdot \left[\frac{\left(\sum_{i=1}^{n} q_{oi} - \sum_{i=1}^{n} q_{si} \right)}{\sum_{i=1}^{n} q_{oi}} \right] \text{---------------------------------------Eq. (4.28)}$$

Where:

q_{si} is the simulated value

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.

RMSE Observation standard deviation ratio (RSR) also another performance rating can be described as follows:

RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by Legates and (McCabe 1999, Cited in D.N Moriasi, 2007). RSR is calculated as the ratio of the RMSE and standard deviation of measured data, as shown in equation Eq. (4.29)

$$RSR = \frac{[\sum_{i=1}^{n} (Q_{obs} - Q_{sim})^2]^{1/2}}{[\sum_{i=1}^{n} (Q_{obs} - \overline{Q}_{obs})^2]^{1/2}} \text{-----------------------------------Eq. (4.29)}$$

Where: Q_{obs} is the observed flow.

Q_{sim} is the simulated flow.

$\overline{Q}_{obs}$ is mean observed flow.

RSR incorporates the benefits of error index statistics and includes a scaling / normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero

RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR, the lower the RMSE, and the better the model simulation performance.

Note: $NSE = 1 - (RSR)^2$

Table 4.3 General Performance ratings for recommended statistics for a monthly time step. (D. N Moriasi, et al. 2007)

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

CHAPTER FIVE

5. Data Availability and Analysis

5.1 AVSWAT Model input

5.1.1 Hydro meteorological and Hydrological data.

Hydrological model SWAT largely depends on hydro meteorological data such as precipitation, temperature, relative humidity, wind speed and solar radiation and hydrological data such as river discharge. To obtain reliable model output, the quality of input data should be checked for consistency.

The climatic variable required by SWAT consists of daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. The model allows values for daily precipitation, maximum/ minimum air temperatures, solar radiation, wind speed and relative humidity to be input from records of observed data or generated during the simulation.

Hydrometeoological datas were collected from National Meteorological Agency (NMA). Datas like daily precipitation, daily maximum and minimum temperature were collected in a soft copy format and other weather information like wind speed, sunshine hours and relative humidity were collected in a hard copy format which later encoded to soft copy format. The summary of meteorological data is presented in appendix-C.

5.1.2 Filling in missing weather data

The ability of SWAT to reproduce observed stream hydrographs is greatly improved by the use of measured precipitation data. For this research work the weather information used was considered for a period of 1985-2006. 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 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 methodology section.

The same weather generator technique has been applied for filling in maximum, minimum temperature, wind speed, relative humidity and solar radiation.

To check the quality of the data cross correlation between stations has been done and from the result the coefficient varies between 0.65 Enfraz with Gorgora and 0.94 Dangla with Enjibara. As it can be seen from appendix-C1 monthly correlation coefficient is sufficient to indicate strong spatial and temporal correlation among the stations and as a result all the stations have been used for simulation purpose.

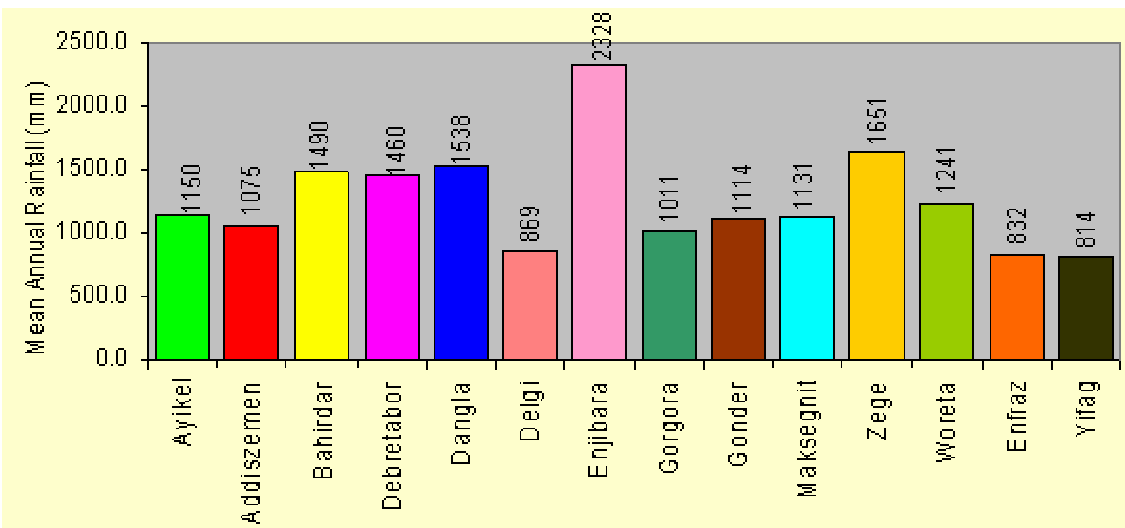


Figure 5.1 Mean Annual Rainfall from a period of 1997-2006 in Lake Tana Basin.

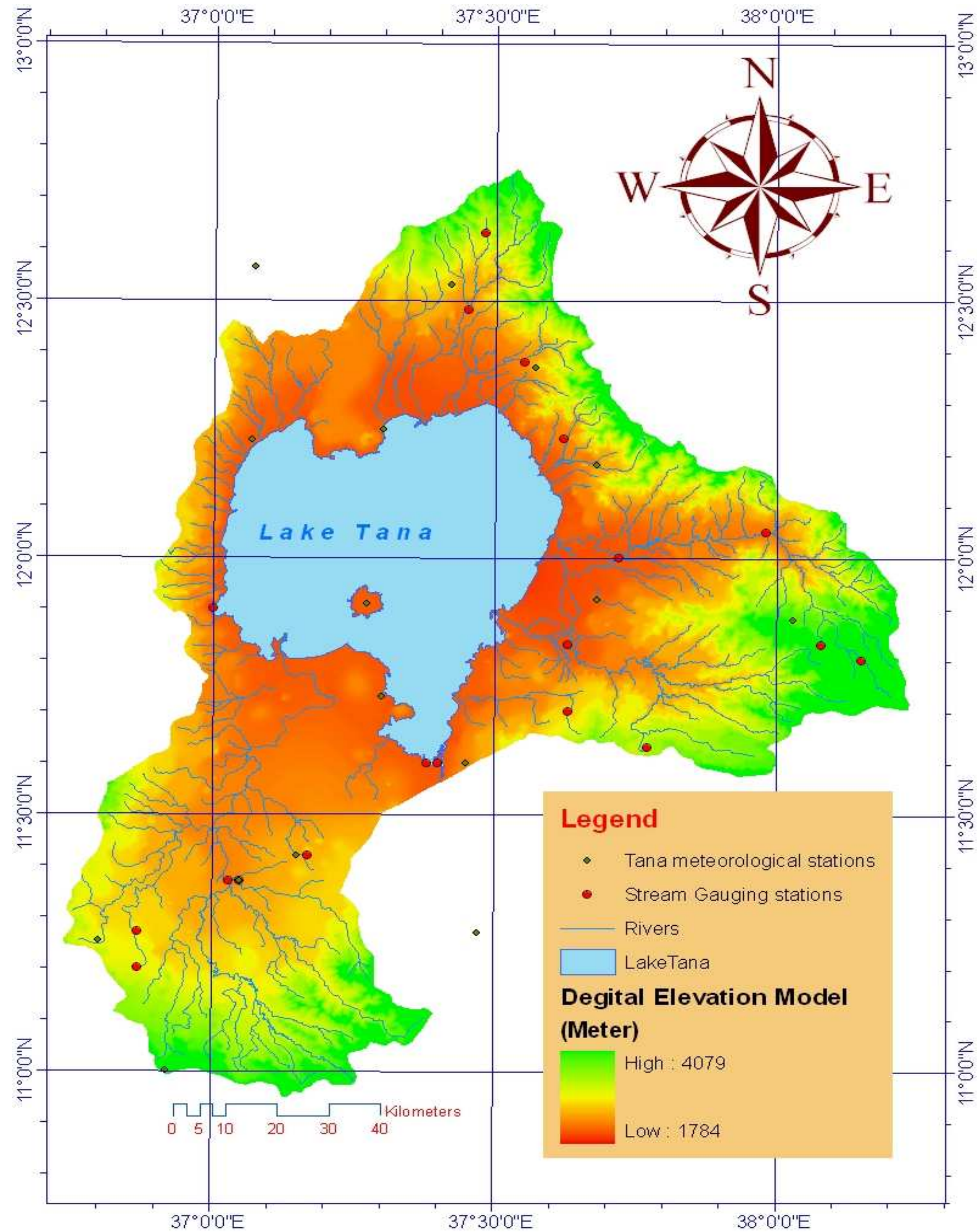


Figure 5.2 Spatial distribution of Meteorological & gauging station used in Lake Tana Basin.

5.2 Hydrological Data

Daily stream flow data with in Lake Tana Basin were collected from Ministry of Water Resources (MoWR). The data collected has missing discharge data that can be summarized in the following table. Even though, long record of time series data are available, concurrent data set for all the stations from a period of 1996-2001 has been used for model calibration and from 2002-2004 used for model validation. The summary of hydrological data is found in appendix-C2

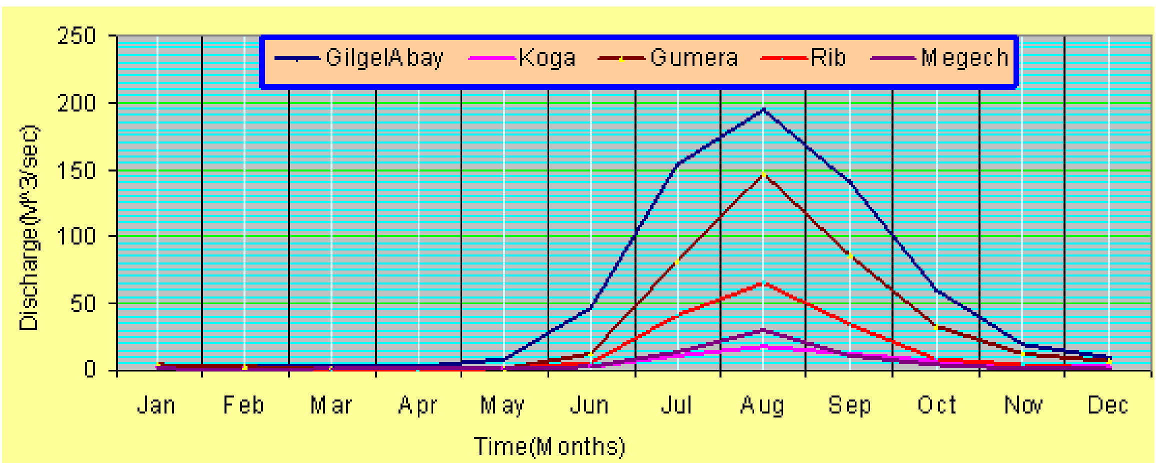


Figure 5.3 Long term Monthly average discharge from a period of 1980 – 2006

Regression analysis has been used to fill in missing time series of stream flow data of rib and Gumera stations. The regression equation is shown in table 5.1 and the stations having R^2 of 0.74.

All the rest gauging stations have complete data for calibration and validation period 1996-2001 and 2002-2004 respectively.

Table 5.1 Monthly regression equation for Rib and Gumera gauging station

	Rib	Gumera
Rib	-	Y=0.3203X+2.1373
Gumera	$Y1=2.3099X_1+3.7835$	-

Where Y=Gumera and X= Rib, Y_1=Rib and X_1=Gumera

5.3 Spatial input Data

5.3.1 Digital Elevation Model (DEM)

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. 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 is used to analyze the drainage pattern of the watershed, slope, stream length, width of channel with in the watershed. The digital elevation model used in this study was obtained from the NASA Shuttle Radar Topographic Mission (SRTM) with a resolution of 90m*90m. The raw DEM was processed & projected using ARCGIS 9.0 & Arc Map 9.1 version software package. Detail of Transverse Mercator Projection (UTM) used in Lake Tana Basin is found in appendix-C3.

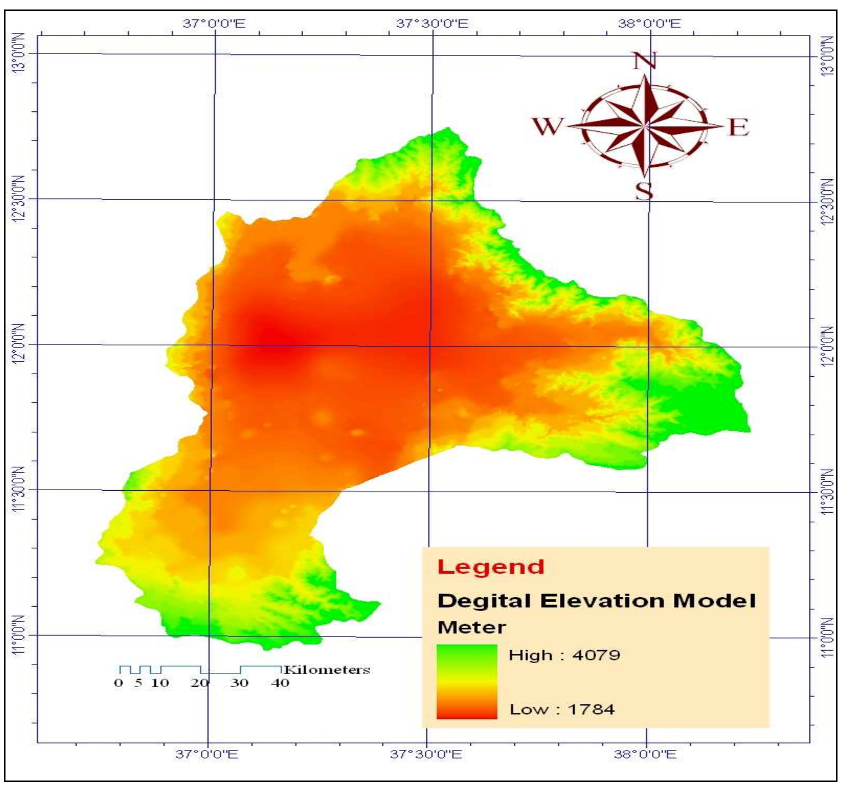


Figure 5.4 Digital Elevation Model (Meter, +MSL) for Lake Tana Basin.

5.3.2 Land use / Land cover Data

Land use / Land cover are the second spatial input data required by SWAT model. Land use/ Land cover data were collected from MoWR 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.

Table 5.2 Land use classification of Lake Tana Basin based on SWAT

Land use as per BECOM	Land use SWAT	SWAT Code	Area (ha)	% watershed Area
Agriculture	Agriculture Generic	AGRL	776406.18	51.37
Agro-Pastoral	Agriculture close grown	AGRC	331601.16	21.94
Agro-Sylvicultural	Forest deciduous	FRSD	5894.46	0.39
Marsh	Wetland	WETL	1964.82	0.13
Pastoral	Pasture	PAST	82673.58	5.47
Sylvicultural	Forest evergreen	FRSE	2267.1	0.15
Sylivo-Pastoral	Range Brush	RNGB	453.42	0.03
Urban	Urban	URLD	1662.54	0.11
Water	Water	WATR	308476.74	20.41
Total			1511400	100

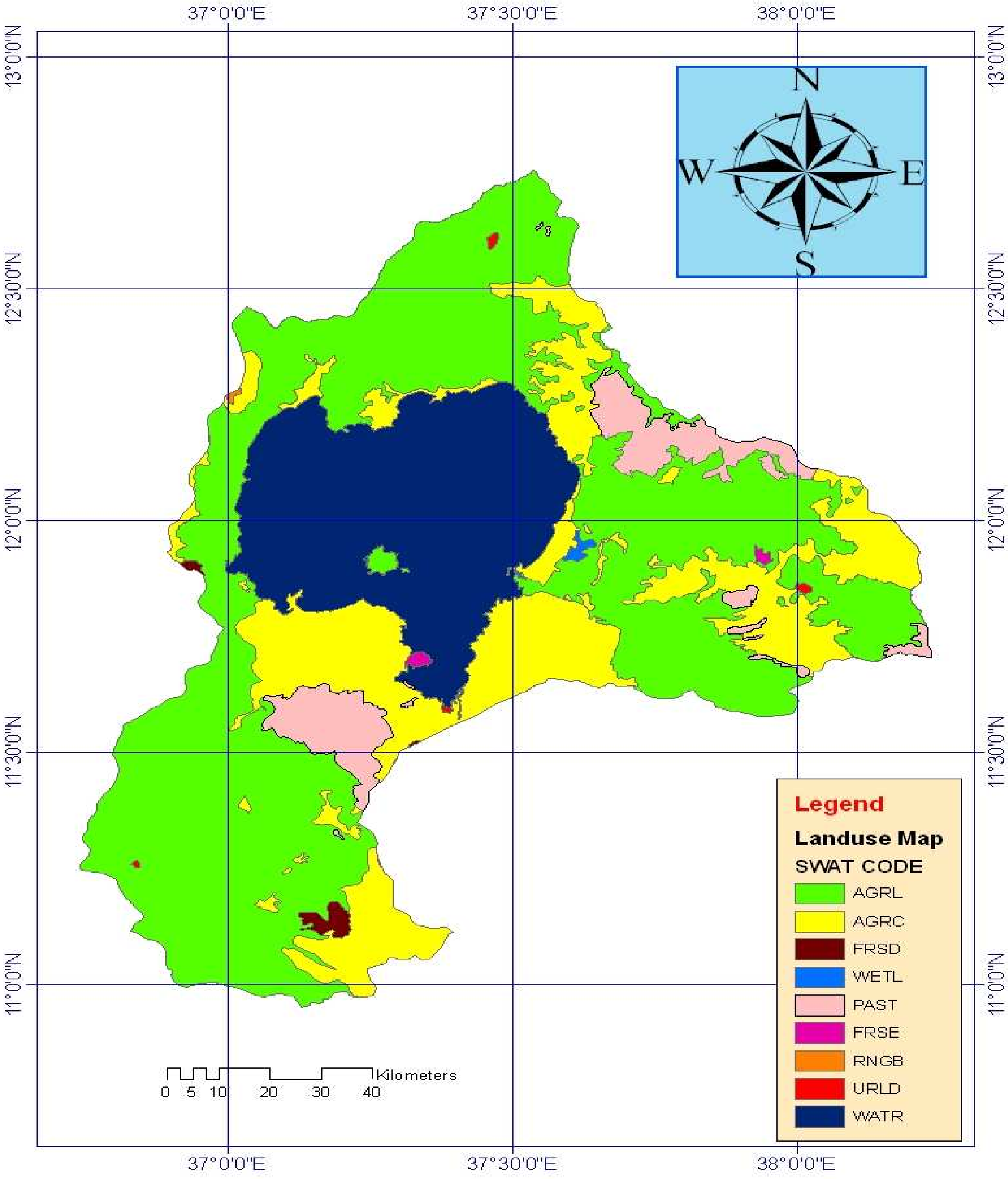


Figure 5.5 Land use map of Lake Tana Basin classified based on SWAT Land use /Land cover data base.

5.3.3 Soil Data

Soil data are another spatial input required by SWAT. The information regarding soil physical and chemical properties were gathered from Ministry of Water Resources (MoWR). The soil map was produced in 1996-1998 during Abay river master plan study by BCEOM with a map scale of 1: 250,000. The soil parameters required by SWAT model used in this research after calibration is found in Appendix-C

Table 5.3 Major Soil types of the Lake Tana Basin (FAO-UNESCO Soil Classification Systems)

Soil Type	Symbol	Area [ha]	% Watershed Area
Chromic Luvisol	LVx	238498.92	15.78
Eutric Cambisol	CMe	302.28	0.02
Eutric Fluvisol	FLe	149024.04	9.86
Eutric Leptosol	LPe	184088.52	12.18
Eutric Rgesol	RGe	4080.78	0.27
Eutric Vertisol	VRe	178798.62	11.83
Haplic Alisol	ALh	71489.22	4.73
Halpic Luvisols	LVh	312557.52	20.68
Halpic Nitisols	NTh	18892.5	1.25
Lithic Leptosol	LPq	43679.46	2.89
URBAN	URLD	1511.40	0.10
Water	WATR	308476.74	20.41
Total		1,511,400	100

Table 5.4 Major Soil group, texture and respective hydrologic Soil group in LTB

Major Soil group	Soil texture	Drainage condition	Hydrological Soil group
Eutric Cambisol	Silty Clay	Moderately deep to well drained	B
Eutric Regosol	Sandy Loam to Loam	Excessively drained	A
Halpic Nitisols	Silty Clay to Clay	Well drained	B
Lithic Leptosol	Loam to Clay Loam	Moderately deep to deep	D
Haplic Alisol	Clay	Favorable drainage	C
Eutric Fluvisol	Silty Clay	Moderately well drained	B
Eutric Vertisol	Clay	Imperfectly to poorly drained	D
Eutric Leptosol	Clam Loam to Clay	Moderately deep to deep	C
Chromic Luvisol	Clay	Moderately well to well drained	B
Halpic Luvisols	Clay to Silty Clay	Well drained	B

(Source; Yohanse, 2007)

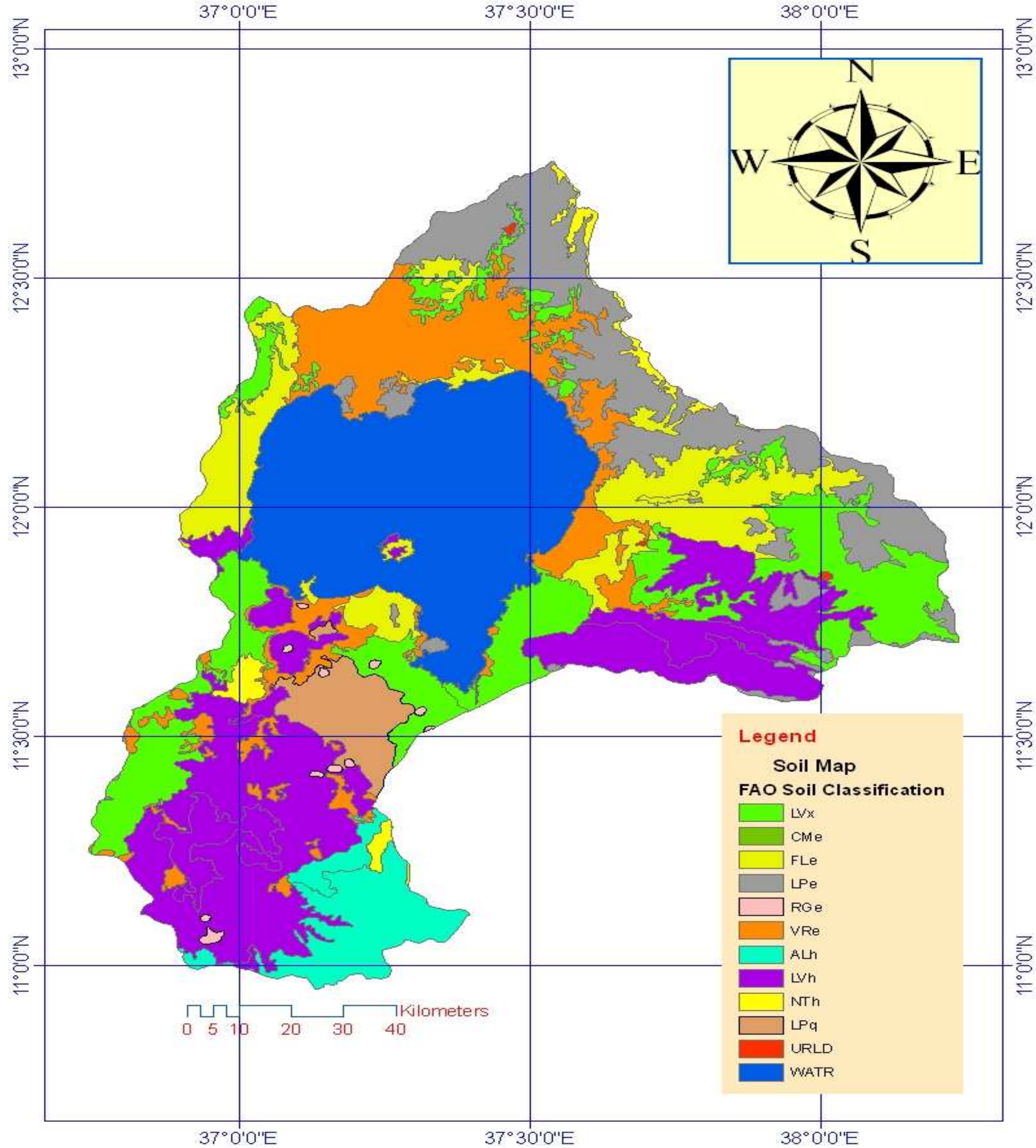


Figure 5.6 Soil Map of Lake Tana Basin based on FAO UNESCO Soil Classification System.

CHAPTER SIX

6. Estimation of Total Inflow to Lake Tana

6.1 Calibration and verification of gauged catchments

Hydrological modeling plays an important role in planning and management of water resources. In Lake Tana basin, most of the rivers which are flowing in to the lake are not gauged and the water yield from un-gauged part of the basin has not quantified properly. In order to quantify the runoff contribution from each un-gauged catchments, and to study hydrological processes in LTB, SWAT hydrological model has been applied. As it was indicated in the description of study area only 46.97 % of the total area is gauged and 53.03 % is not gauged and hence, the estimation of runoff from this huge percentage area of un-gauged part is very crucial for current and future Water resources development projects. The gauged station with their location is presented here below in table (6.1)

Table 6.1 Major gauged rivers in LTB

River Name	Location	Catchment Area (Km^2) Based on SWAT Delineation
Arno-Garno	Infraz	104
Gemero	-	163
Gilgel Abay	Merawi	1657
Gumera	Bahirdar	1376
Koga	Merawi	271
Megech	Azezo	484
Rib	Addiszemen	1592

Due to lack of reliable stream flow time series data for Arno-Gano, Gemero and other rivers, only Gilgel Abay, Koga, Gumera, Rib and Megech rivers have been considered for modeling.

6.1.1 Modeling Gilgel Abay Watershed.

Gilgel Abay River is one of the biggest river in the basin which empties the flow in to Lake Tana. It has a catchment area of 1657 Km^2 and its elevation ranging from 1885-3524 m. +MSL In order to model this gauged river using SWAT, the spatial input which is shown in fig 6.1 have been used. For modeling purpose a watershed is partitioned in to a number of sub watersheds. In the delineation process the watershed is partitioned in to twenty five sub watershed and by taking a thresh hold value of 20% for land use and 10 % for soil, 43 HRU's have been derived from the overlay analysis. According to (Luzio *et al.* 2002) user manual, the threshold levels set for multiple HRUs is a function of the project goal and the amount of detail desired by the modeler. For most applications, the default settings for land use threshold (20 %) and soil threshold (10 %) are adequate and applied in this research work.

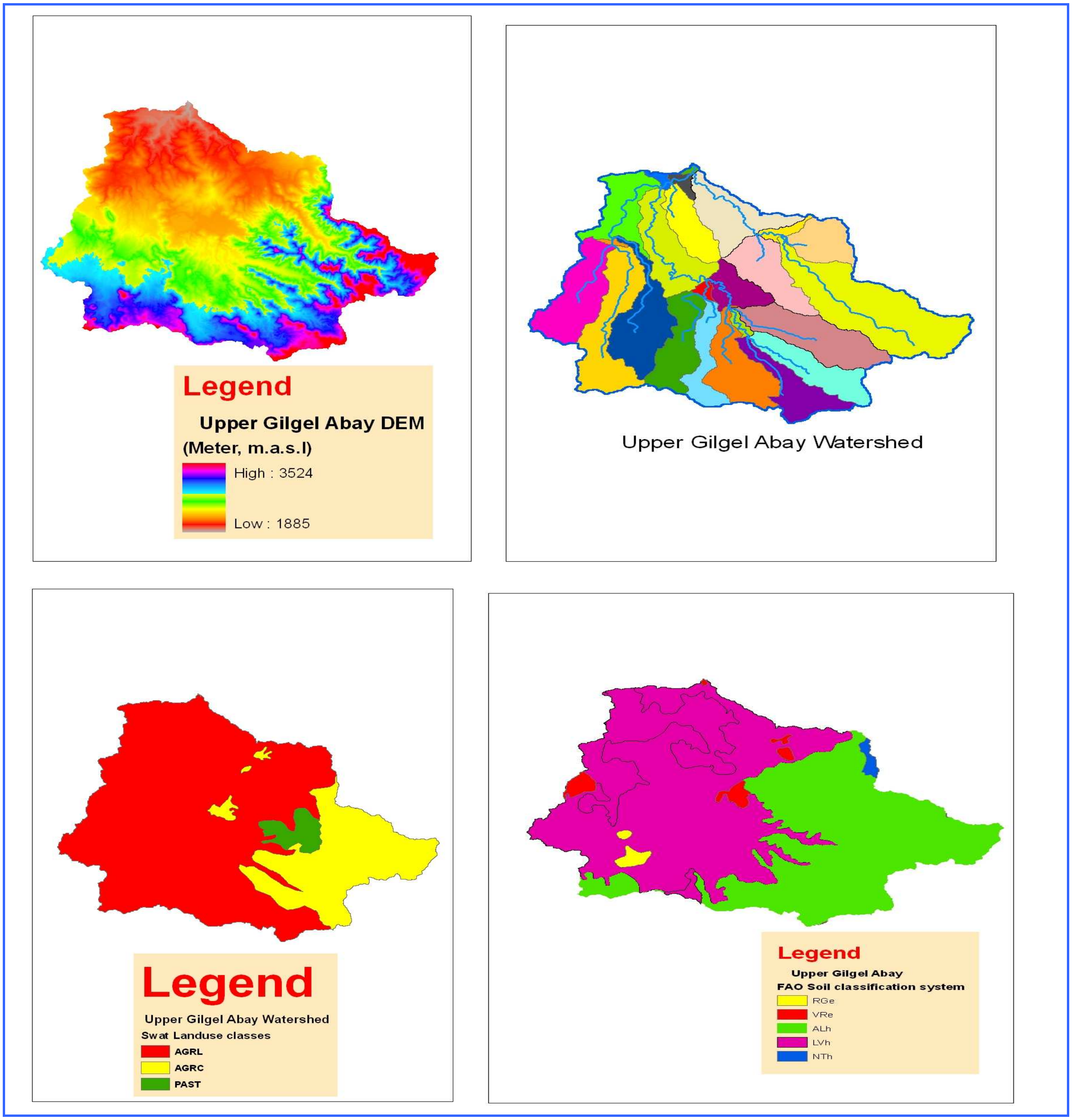


Fig 6.1 Spatial input data of Upper Gilgel Abay Watershed used in SWAT Model.

Table 6.2 Land use classification of upper Gilgel Abay catchment used in SWAT

No.	Land use	SWAT Land use Class	Area (Km^2)	% of Total Area
1	Agriculture	AGRL	1222	73.75
2	Agro- Pastoral	AGRC	383	23.11
3	Pastoral	PAST	52	3.14
Total			1657	100

Table 6.3 Soil type of upper Gilgel Abay catchment as per FAO-UNESCO soil classification system

No.	Soil Type	Soil Classes defined In SWAT	Area (Km^2)	% of Total Area
1	Halpic luvisols	LVh	944	56.97
2	Halpic Alisols	ALh	668	40.31
3	Eutric vertisols	VRe	22	1.33
4	HalpicLuvisols	NTh	9	0.54
5	Eutric Rigosols	RGe	14	0.84
Total			1657	100

From the above illustrated figure and table we can see that from land use classes, extensively cultivated Agriculture is the dominant land use in the catchment and Halpic Luvisol and Halpic Alisols are the dominant soil type in the catchment.

6.1.2 Modeling Koga Watershed.

Koga Watershed is one of the tributary flowing in to Gilgel Abay River. It has a catchment area of 271 Km^2 and the elevation ranging from 1884-3076 m.+MSL Modeling work has been carried out before joining Gilgel Abay River. To delineate the watershed, the first spatial input DEM grid was processed by SWAT in such away that the digitized stream network has been analyzed in burn in option and with a threshold area of 2000ha; the watershed is partioned in to seven sub watersheds and further 15 HRUs developed.

Table 6.4 Land use classification of Koga catchment used in SWAT

No.	Land use	SWAT Land use Class	Area (Km^2)	% of Total Area
1	Agriculture	AGRL	191	70.48
2	Agro- Pastoral	AGRC	78	28.78
3	Pastoral	PAST	2	0.74
Total			271	100

Table 6.5 Soil type of Koga catchment as per FAO-UNESCO soil classification system.

No.	Soil Type	Soil Classes defined in SWAT	Area (Km^2)	% of Total Area
1	Halpic luvisols	LVh	150	55.35
2	Halpic Alisols	ALh	64	23.62
3	Eutric vertisols	VRe	34	12.55
4	Halpic Luvisols	NTh	22	8.12
5	Eutric Rigosols	RGe	1	0.37
Total			271	100

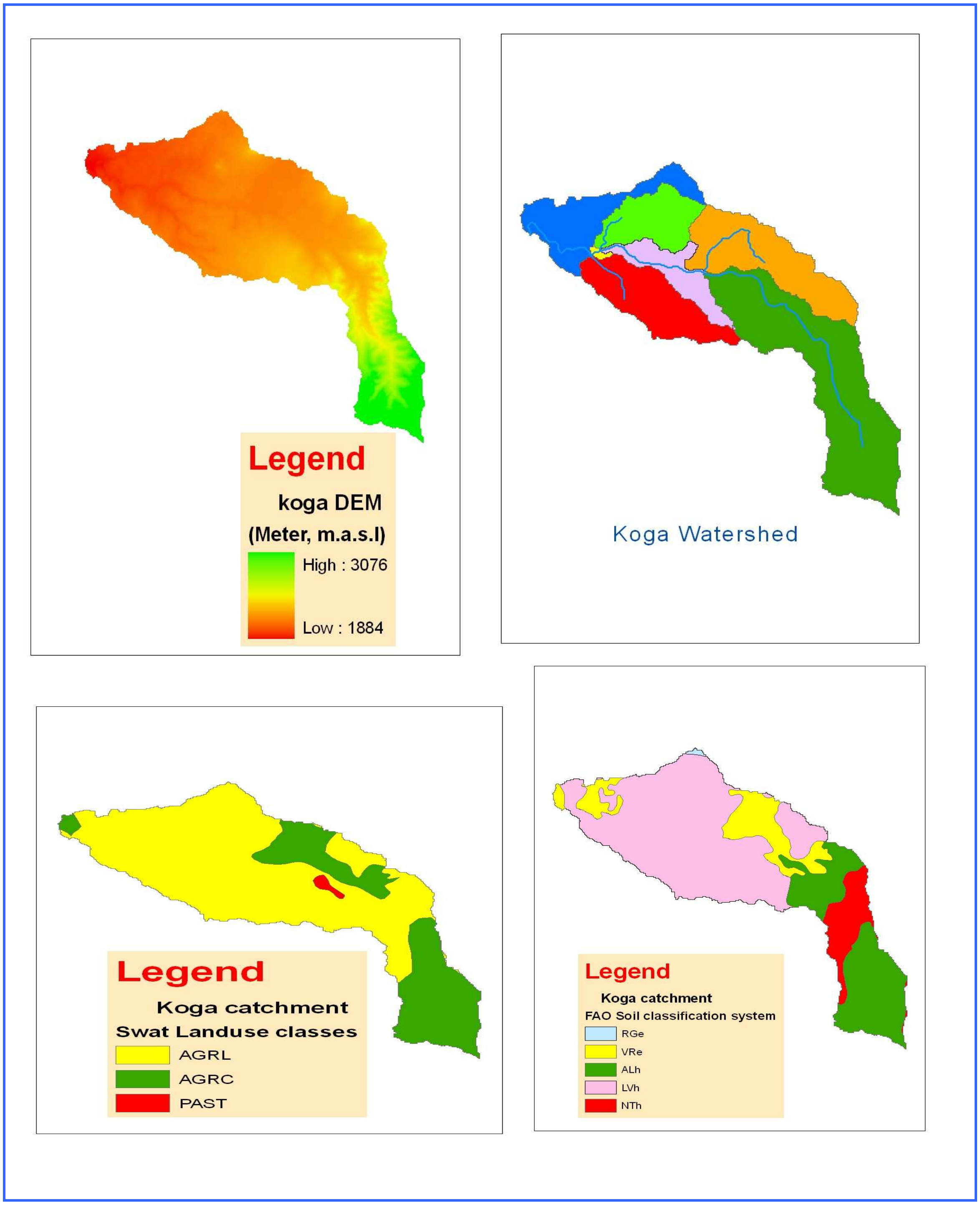


Fig 6.2 Spatial input of Koga Watershed used in SWAT Model.

6.1.3 Modeling Gumera Watershed.

Gumera watershed is another major river contributing inflow in to the lake. It has a catchment area of 1376 $Km^2$and its elevation ranges from 1800-3703 m. +MSL. The watershed delineated in to 15 sub watersheds with a threshold area of 6000ha and 42 HRUs

To simulate the runoff at the outlet of the catchment, DEM, land use and Soil map of the watershed used are clearly shown here below in fig 6.11 and table 6.16 & 6.17

Table 6.6 Land use classification of Gumera catchment used in SWAT Model.

No.	Land use	SWAT Land use Class	Area (Km^2)	% of Total Area
1	Agriculture	AGRL	892	64.83
2	Agro- Pastoral	AGRC	427	31.03
3	Pastoral	PAST	55	4.00
4	Urban	URLD	2	0.15
Total			1376	100

Table 6.7 Soil type of Gumera catchment as per FAO-UNESCO soil classification system

No.	Soil Type	Soil Classes defined In SWAT	Area (Km^2)	% of Total Area
1	Halpic Luvisols	LVh	836	60.76
2	Chromic Luvisols	LVx	343	24.93
3	Eutric Leptosol	LPe	114	8.28
4	Eutric Vertisols	VRe	57	4.14
5	Eutric Fluvisols	FLe	23	1.67
6	Urban	URLD	3	0.22
Total			1376	100

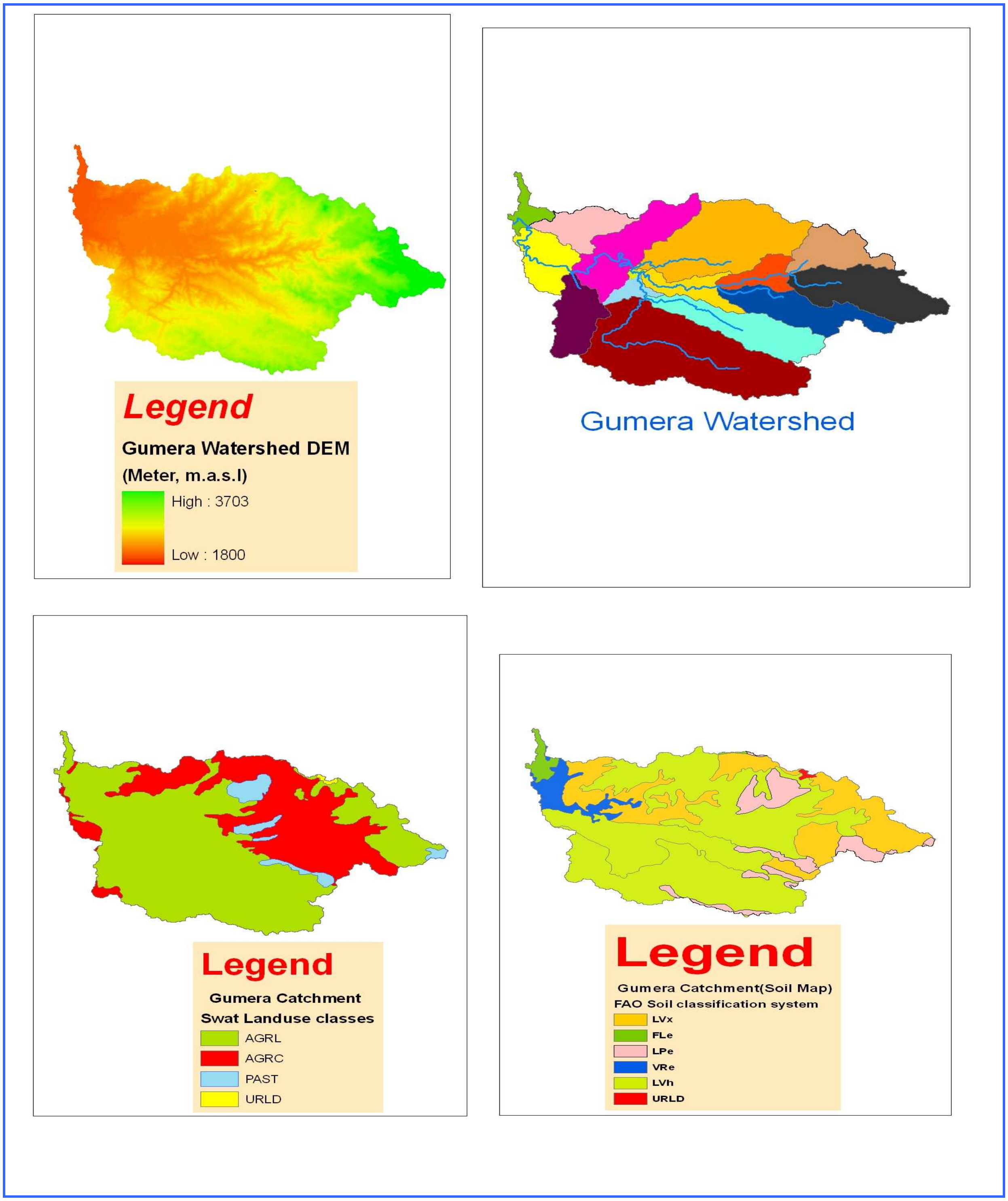


Fig 6.3 Spatial input of Gumera Watershed used in SWAT Model.

6.1.4 Modeling Rib Watershed

Rib watershed has a catchment area of 1592 Km2 and its elevation ranging from 1800-4108 m. +MSL. The watershed has been delineated in to 17 sub watersheds with a threshold area of 6000 ha and 44 HRUs developed.

Table 6.8 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	996	62.56
2	Pasture	PAST	203	12.75
3	Agro- Pastoral	AGRC	381	23.93
4	Forest Ever green	FRSE	9	0.57
5	Urban	URLD	3	0.19
Total			1592	100

Table 6.9 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	LPe	572	35.93
2	Halpic Nitisol	NTh	4	0.25
3	Chromic Luvisol	LVx	515	32.35
4	Eutric Fluvisol	FLe	460	28.89
5	Halpic Luvisol	LPh	40	2.51
6	Urban	URLD	1	0.06
Total			1592	100

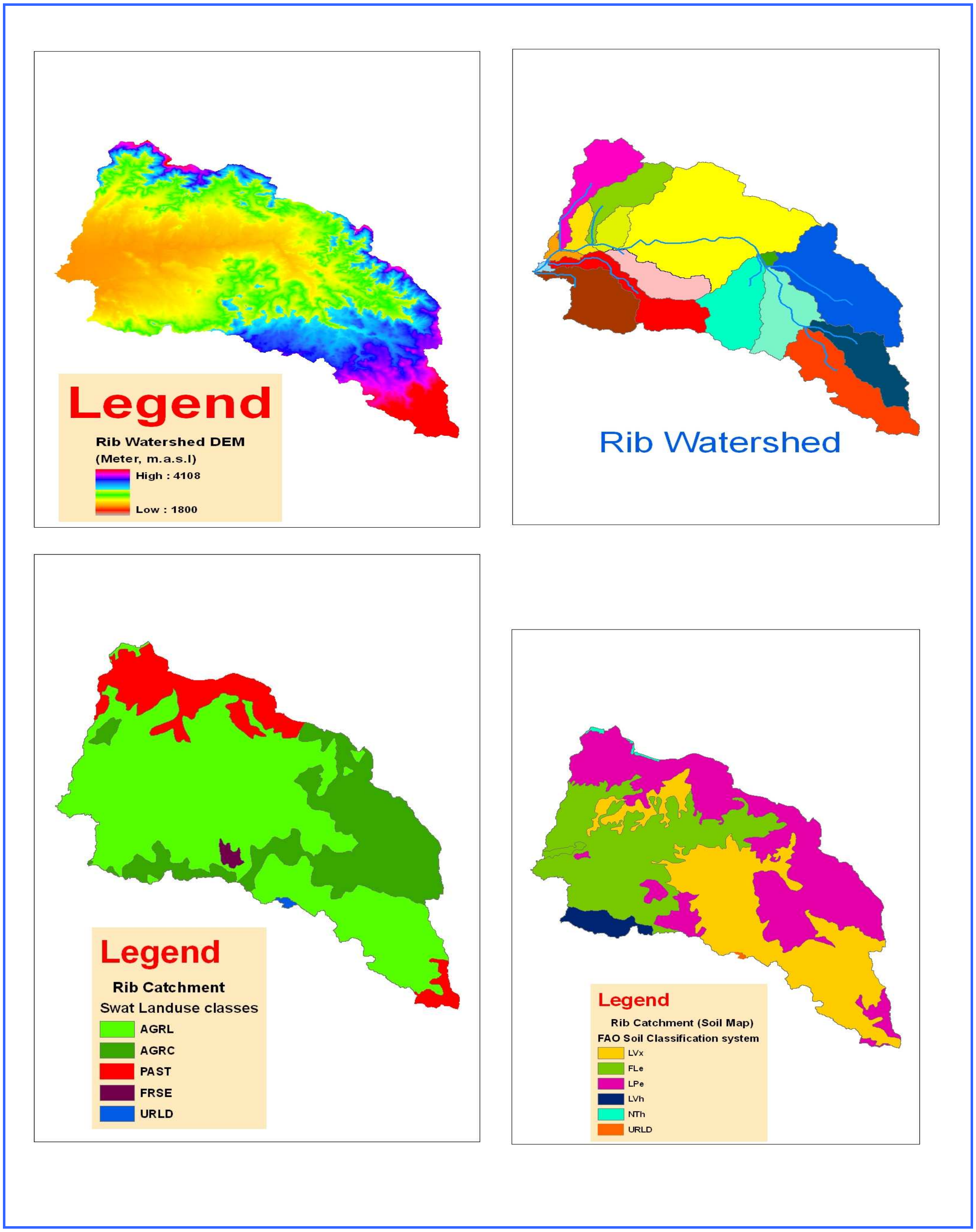


Fig 6.4 Spatial input of Rib Watershed used in SWAT Model.

6.1.5 Modeling Megech Watershed.

Megech watershed has a catchment area of 484 Km^2 and its elevation ranging from 1865-2938 .m + MSL. The watershed is delineated in to 15 sub watersheds with a threshold area of 2000 ha and 27 HRUs developed.

To simulate the runoff at the outlet of the catchment, DEM, land use and Soil map of the watershed used are clearly shown here in fig 6.21 and table 6.30 & 6.31

Table 6.10 Land use classification of Megech catchment used in SWAT

No.	Land use	SWAT Land use Class	Area (Km^2)	% of Total Area
1	Agriculture	AGRL	463	95.66
2	Agro- Pastoral	AGRC	13	2.69
3	Urban	URLD	5	1.03
4	Pasture	PAST	3	0.62
Total			484	100

Table 6.11 Soil type of Megech catchment as per FAO-UNESCO soil classification system .

No.	Soil Type	Soil classes defined in SWAT	Area (Km^2)	% of Total Area
1	Eutric Leptosols	LPe	400	82.64
2	Halpic Nitisols	NTh	39	8.06
3	Chromic Luvisols	LVx	25	5.17
4	Eutric Vertisols	VRe	16	3.31
5	Urban	URLD	4	0.83
Total			484	100

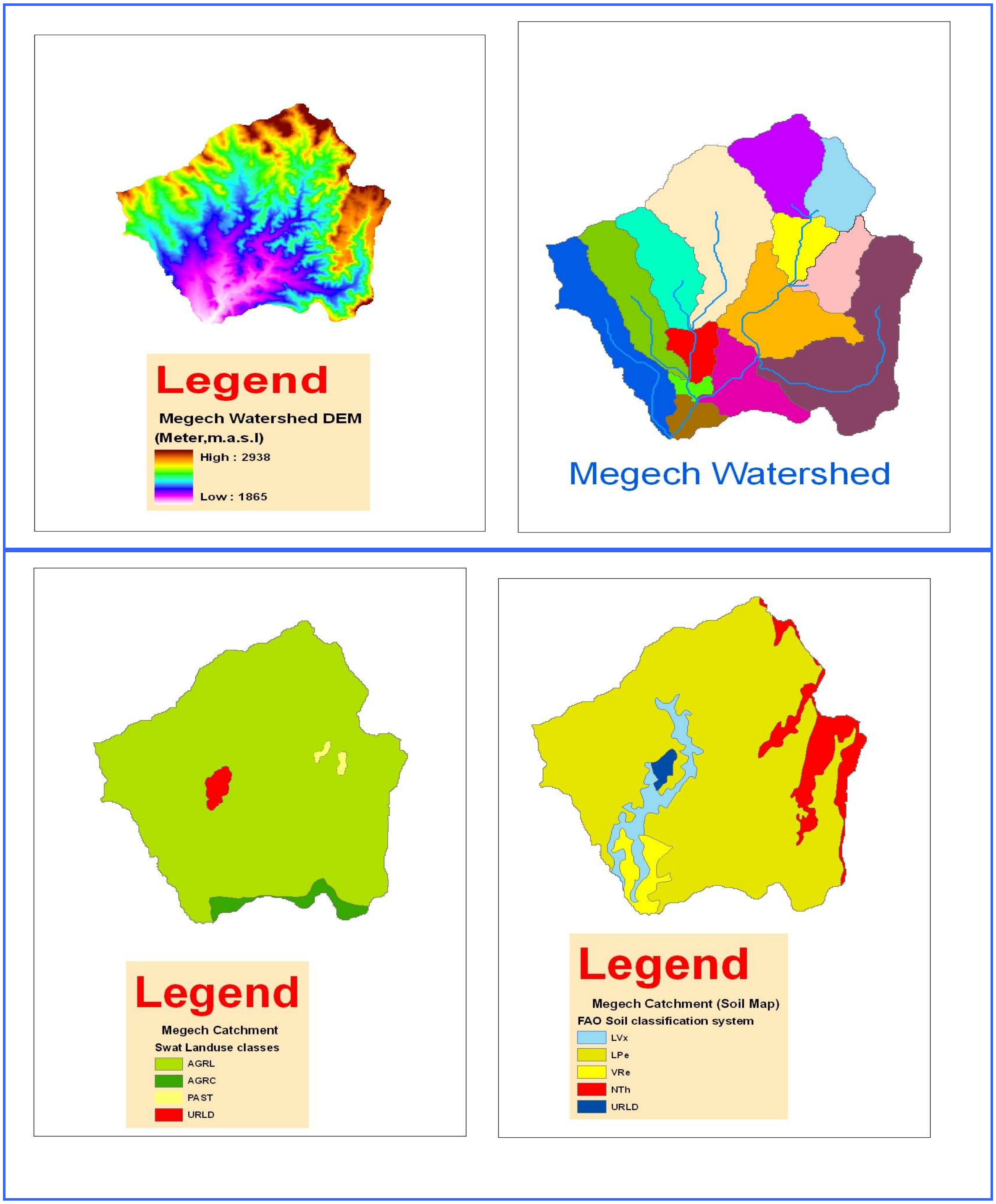


Fig 6.5 Spatial input of Megech Watershed used in SWAT Model.

Sensitivity Analysis

Sensitivity analysis has been done on the built in extension program embedded in SWAT. Sensitivity analysis has been carried out for 27 parameters. Only few sensitive parameters were considered and the parameters with their mean relative sensitivity value at the outlet for the runoff are presented in table 6.4 below.

Table 6.12 Result of the sensitivity analysis of flow in gauged watershed.

	Gilgel Abay catchment			
Rank	Parameters	Lower bound	Upper bound	Relative sensitivity value
1	CN2	-25%	+25%	1.7 (very high)
2	RCHRG_DP	0	1	1.07 (very high)
3	GWQMN	0	5000	0.714 (high)
4	SOL_AWC	-25%	+25%	0.47 (high)
5	SOL_K	-25%	+25%	0.286 (high)
6	SOL_Z	0	3000	0.177 (medium)
7	ESCO	0	1	0.123 (medium)
8	GW_REVAP	0.02	0.2	0.114 (medium)
9	CANMX	0	10	0.054 (medium)
	Koga catchment			
1	CN2	-25%	+25%	3.31 (very high)
2	SOL_AWC	-25%	+25%	0.86 (high)
3	GWQMN	0	5000	0.4 (high)
4	RCHRG_DP	0	1	0.37 (high)
5	SOL_K	-25%	+25%	0.309 (high)
6	SOL_Z	0	3000	0.256 (high)
7	ESCO	0	1	0.145 (medium)
8	CANMX	0	10	0.12 (medium)
9	SOL_ALB	0	1	0.075 (medium)
10	SLOPE	-25%	+25%	0.063 (medium)
	Gumera catchment			
1	CN2	-25%	+25%	2.2 (very high)
2	SOL_AWC	-25%	+25%	2.13 (very high)
3	GWQMN	0	5000	1.24 (very high)
4	RCHRG_DP	0	1	1.22 (very high)
5	SOL_K	-25%	+25%	0.294 (high)
6	SOL_Z	0	3000	0.189 (medium)
7	ESCO	0	1	0.169 (medium)
8	GW_REVAP	0.02	0.2	0.144 (medium)

9	SLOPE	-25%	+25%	0.075 (medium)
10	ALPHA_BF	0	1	0.054 (medium)
11	SOL_ALB	0	1	0.053 (medium)
	Rib catchment			
1	CN2	-25%	+25%	1.78 (very high)
2	SOL_AWC	-25%	+25%	0.628 (high)
3	SOL_K	-25%	+25%	0.257 (high)
4	GWQMN	0	5000	0.228 (high)
5	ESCO	0	1	0.133 (medium)
6	RCHRG_DP	0	1	0.125 (medium)
7	SOL-Z	0	3000	0.1 (medium)
	Megech catchment			
1	CN2	-25%	+25%	1.52 (very high)
2	SOL_AWC	-25%	+25%	0.807 (high)
3	ESCO	0	1	0.133 (medium)
4	GWQMN	0	5000	0.094 (medium)
5	SOL_K	-25%	+25%	0.082 (medium)
6	SOL-Z	0	3000	0.052 (medium)

Comparison of sensitivity analysis among catchments

The sensitivity analysis has been carried out for all modelled watershed. CN is the most sensitive parameter in all catchments, which indicating that the importance of this parameter during calibration. The deep aquifer percolation fraction (RCHRG_DP) was the second highest sensitive parameter which governs the base flow in Gilgel Abay catchment only. This is an indication that Gilgel Abay catchment has a highest ground water contribution to the flow. Except the RCHRG_DP most of the parameters in Gilgel Abay and Koga catchments have similar rank except the mean relative sensitivity value which governs both surface and sub- surface hydrology varies.

The mean relative sensitivity value of parameters in Gumera catchment also shows that SOL_AWC, GWQMN, RCHRG_DP have very high value as compared to Rib catchment. Though, the parameters rank in Gumera and Rib catchments were the same, the mean relative sensitivity value in Gumera catchment was very high and high in Rib catchment respectively. Thus, Gumera catchment also has better surface and base flow contribution than Rib catchment.

The mean relative sensitivity value in Megech catchment shows that except CN which was very high and SOL_AWC was high value, the rest parameters have medium mean relative values and hence, most of the parameters govern the surface flow in the catchment.

Generally, sensitivity of parameters varies from catchment to catchment in Lake Tana basin and even within the same catchment it varies from sub basin to sub basin.

Calibration

Historical observed stream flow of Gilgel Abay at Merawi, Koga at Merawi, Gumera at Bahirdar, Rib at Addiszemen and Megech at Azezo were calibrated from a period of 1996-2001.

Validation

An independent data set from a period of 2002- 2004 has been used to ensure that the calibrated parameters perform reasonably well under this data set.

Table 6.13 Initial and final adjusted value of optimized parameters for gauged catchments.

	Gilgel Abay catchment		
S.No.	Parameters	Initial and default value	Final adjusted value
1	CN2	Default	10 %
2	RCHRG_DP	0.05	0.2
3	GWQMN	0	30
4	SOL_AWC	From Literature	-20 %
5	SOL_K	From Literature	-20 %
6	SOL_Z	From Literature	Not adjusted
7	ESCO	0.95	0.75
8	GW_REVAP	0.02	0.1
9	CANMX	0	0.5
	Koga catchment		
1	CN2	Default	+10 %
2	SOL_AWC	Literature	-20 %

3	GWQMN	0	5
4	RCHRG_DP	0.05	0.2
5	SOL_K	From Literature	-20 %
	Gumera catchment		
1	CN2	Default	-15 %
2	SOL_AWC	From Literature	+5 %
3	GWQMN	0	0.42
4	RCHRG_DP	0.05	0.067
5	SOL_K	From Literature	+10 %
6	SOL_Z	From Literature	-10 %
7	ESCO	0.95	0.461
8	GW_REVAP	0.02	0.127
9	SLOPE	Default	+20 %
10	ALPHA_BF	0.048	0.325
	Rib catchment		
1	CN2	Default	-20 %
2	SOL_AWC	From Literature	+20 %
3	SOL_K	From Literature	-20 %
4	GWQMN	0	23.18
5	ESCO	0.95	0.25
6	RCHRG_DP	0.05	0.903
7	SOL-Z	From Literature	+20 %
	Megech catchment		
1	CN2	Default	-25 %
2	SOL_AWC	From Literature	not adjusted
3	ESCO	0.95	0.65
4	GWQMN	0	6.67
5	SOL_K	From Literature	+10 %
6	SOL-Z	From Literature	-10 %

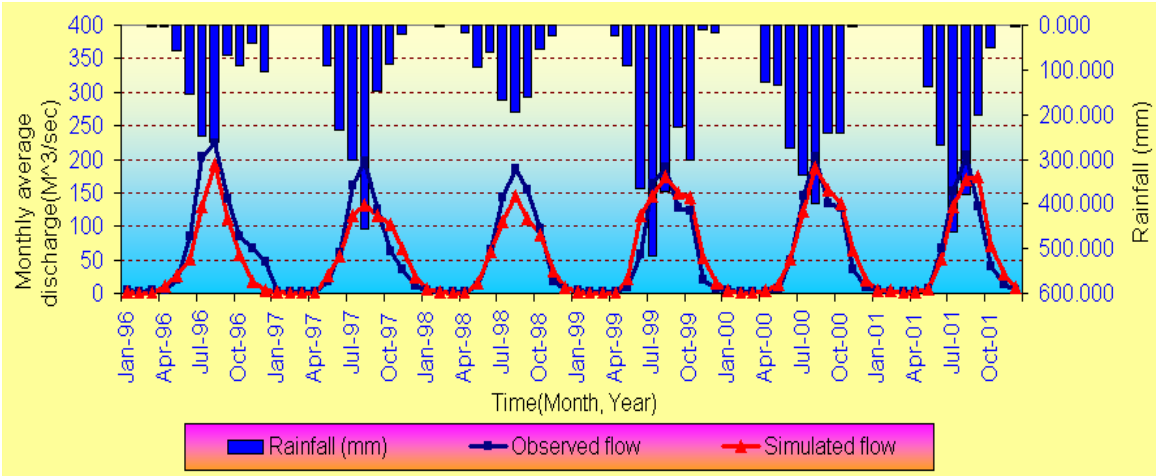


Fig 6.6 Calibration of Observed and simulated flow hydrograph of Upper Gilgel Abay River gauged at Merawi. Period (1996-2001)

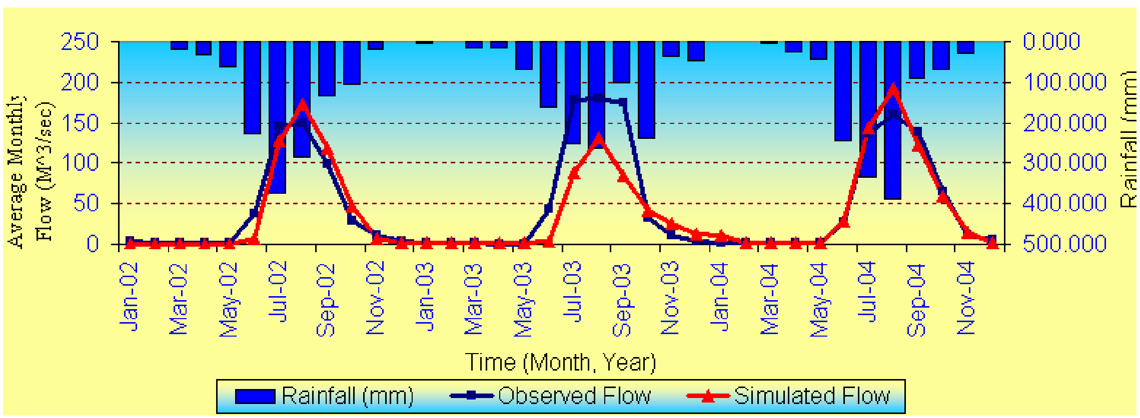


Fig 6.7 Validation of Observed and simulated flow hydrograph of upper Gilgel Abay River gauged at Merawi. Period (2002-2004)

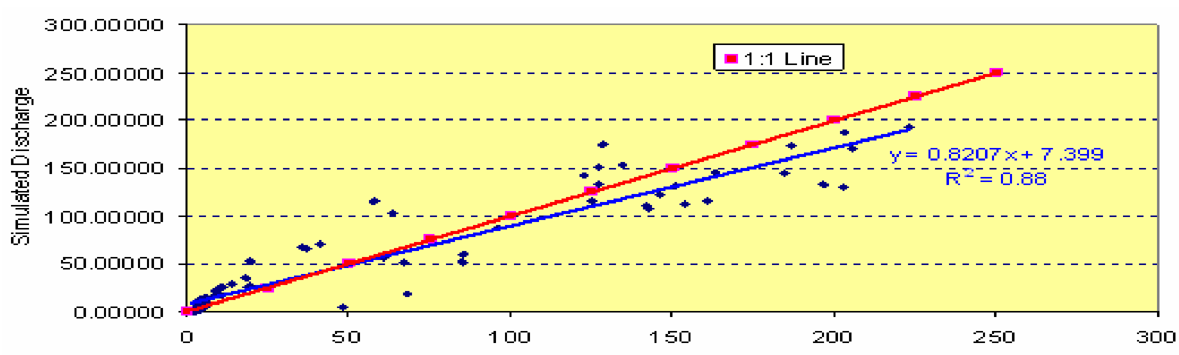


Fig 6.8 Scatter plot of observed and simulated discharge for Gilgel Abay River during calibration period.

Since modelling studies predict results with some error, it is useful to evaluate the general accepted level of model performance.

Over the calibration period 1996-2001 and validation period 2002-2004, Gilgel Abay catchment shows that the performance in simulation of trends NSE, in simulation of residual variation (RSR) and in simulation of volumetric fit in all cases a very good performance was rated.

As it was indicated in calibration and validation results, NSE values for the monthly stream flow of validation and calibration ranges from 0.83 to 0.88. According to the model evaluation guide lines, the model simulated the stream flow trends very good in both calibration and validation period. The residual variation (RSR) values ranges from 0.35 to 0.41 during calibration and validation. These values indicate that the model performance for stream flow residual ranged very good in both periods. The volumetric fit (% D), value also varied from 5.56 % to 12.55 % during calibration and validation period indicates that the model simulated the stream flow volumetric fit as good to very good range of performance during validation calibration period. As shown in fig 6.3 the poor hydrograph fit in 2003, may be attributed to many reasons. One of the likely reasons was in accuracy in measurements as flat hydrograph are not characteristics of the basin.

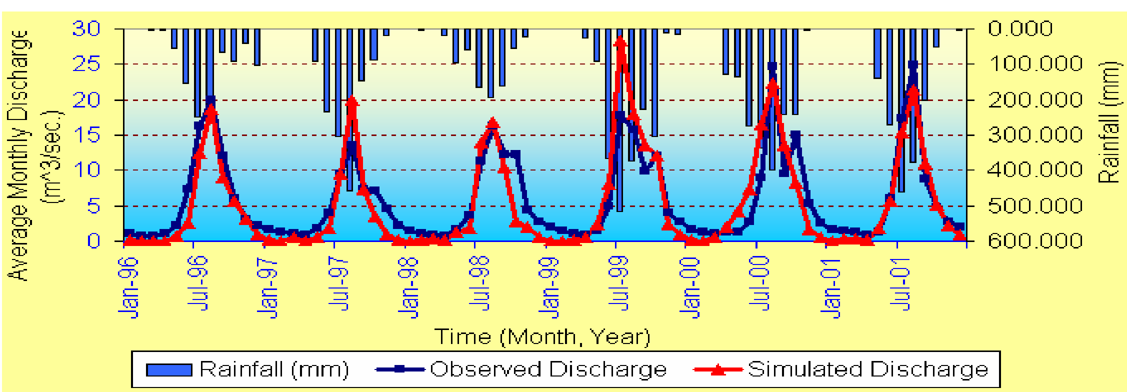


Fig 6.9 Calibration of observed and simulated flow hydrograph of Koga River gauged Merawi. Period (1996-2001)

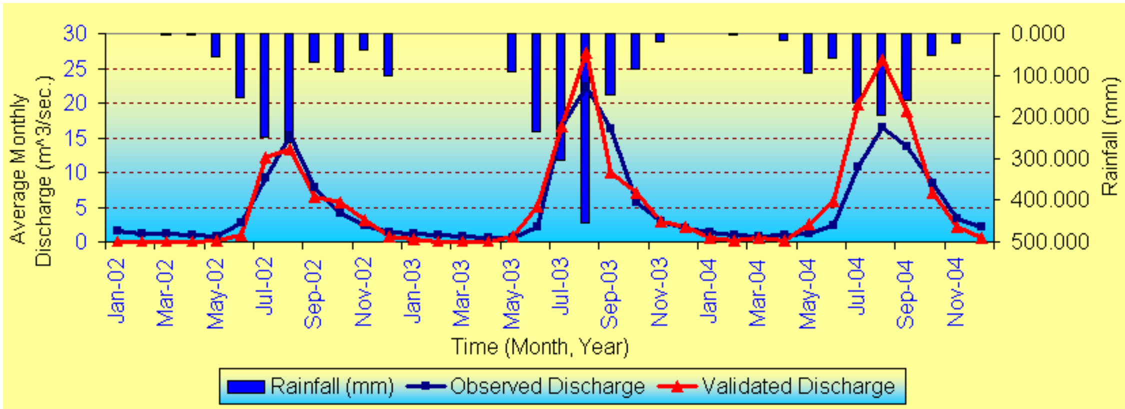


Fig 6.10 Validation of observed and simulated flow hydrograph of Koga River gauged at Merawi. Period (2002-2004)

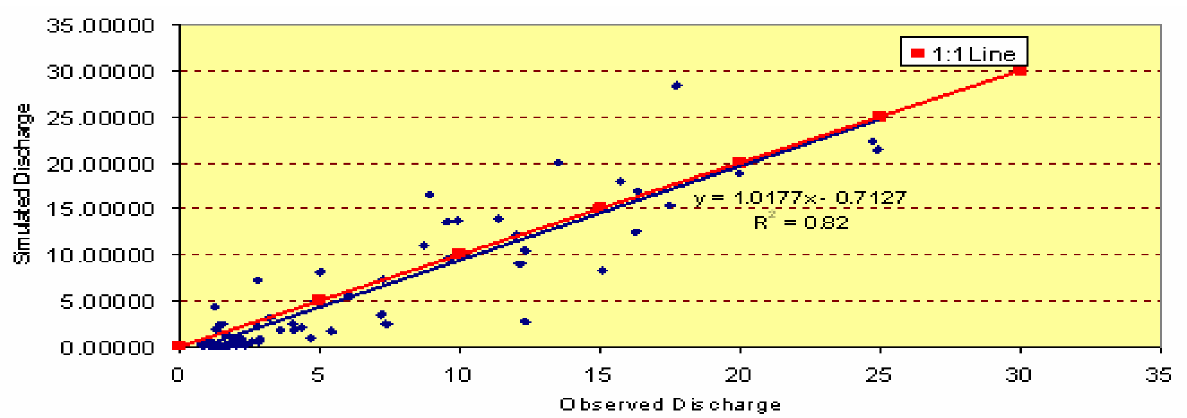


Fig 6.11 Scatter plot of observed and simulated discharge for Koga River during Calibration period.

The validation and calibration results of Koga watershed demonstrate that NSE for monthly stream flow values ranges from 0.74 to 0.76. Based on the model performance criteria, the model simulated the stream flow trend as good to very good performance. The residual variation (RSR) ranges from 0.49 to 0.51, during calibration and validation indicates that the model simulated residual variation as good to very good in validation and calibration periods. The volumetric fit which ranges from -9.27 % to 10.45 % indicates, an over estimation of the volume during validation period and the model simulated the volumetric fit as good to very good performance during calibration and validation periods respectively.

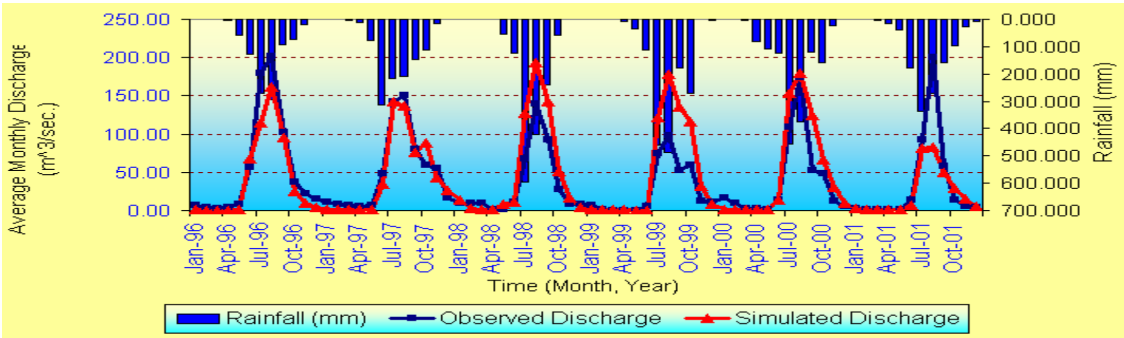


Fig 6.12 Calibration of observed and simulated flow hydrograph of Gumera River gauged at Bahirdar. Period (1996-2001)

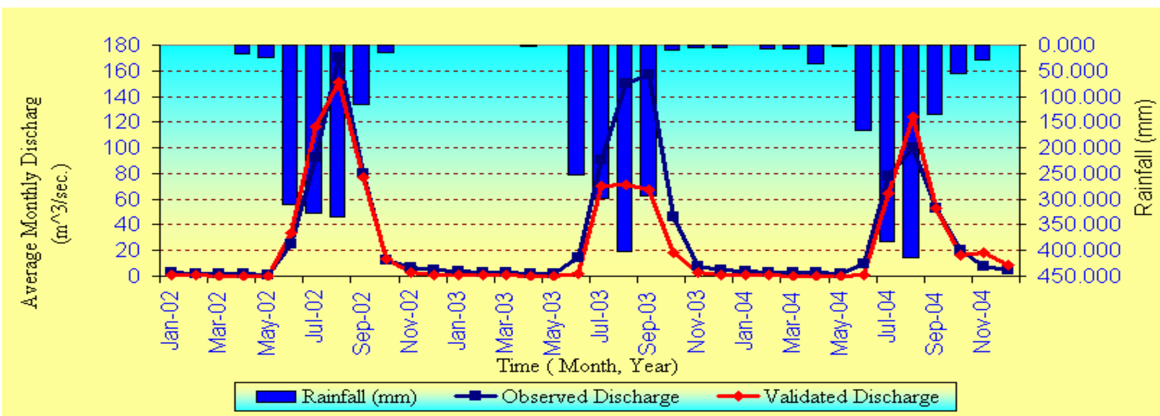


Fig 6.13 Validation of observed and simulated flow hydrograph of Gumera River gauged at Bahirdar. Period (2002-2004)

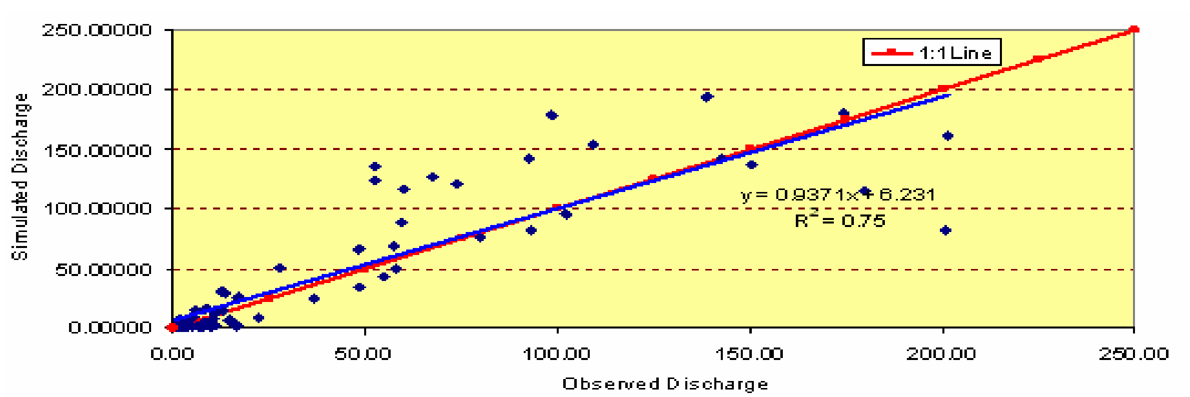


Fig 6.14 Scatter plot of observed and simulated discharge of Gumera River during calibration period.

The modelling results of Gumera watershed shows that NSE for the monthly stream flow ranges from 0.7 to 0.79 during calibration and validation periods. According to the performance rating criteria the model simulated the stream flow trends as good to very good range. The residual variation (RSR) also ranges from 0.46 to 0.55 during validation and calibration. The results indicate that the model simulated the residual variation as good to very good ranges in calibration and validation respectively. The volumetric fit also ranges from -9.75 % to 21 % indicates that the model overestimated the volume during calibration and underestimated the volume during validation and hence, the model simulated the volumetric fit as very good to satisfactory in calibration and validation periods respectively.

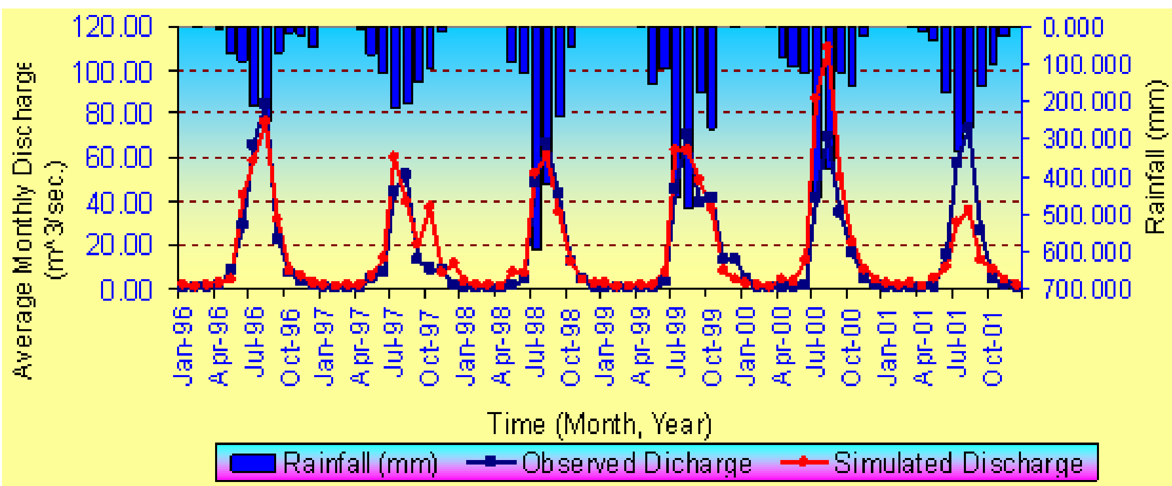


Fig 6.15 Calibration of observed and simulated flow hydrograph of Rib River gauged Addiszemn. Period (1996-2001)

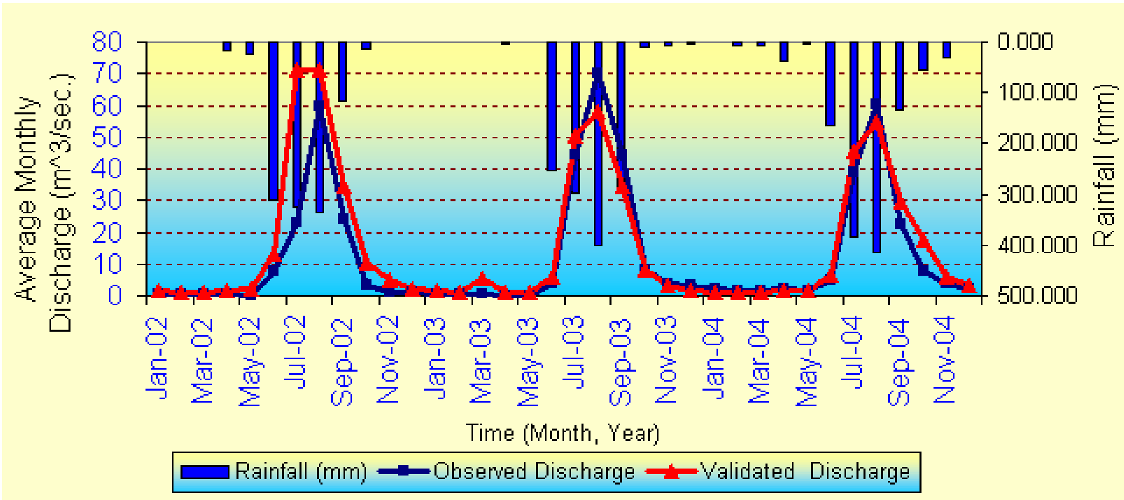


Fig 6.16 Validation of Observed and simulated flow hydrograph of Rib River gauged at Addiszemen. Period (2002-2004)

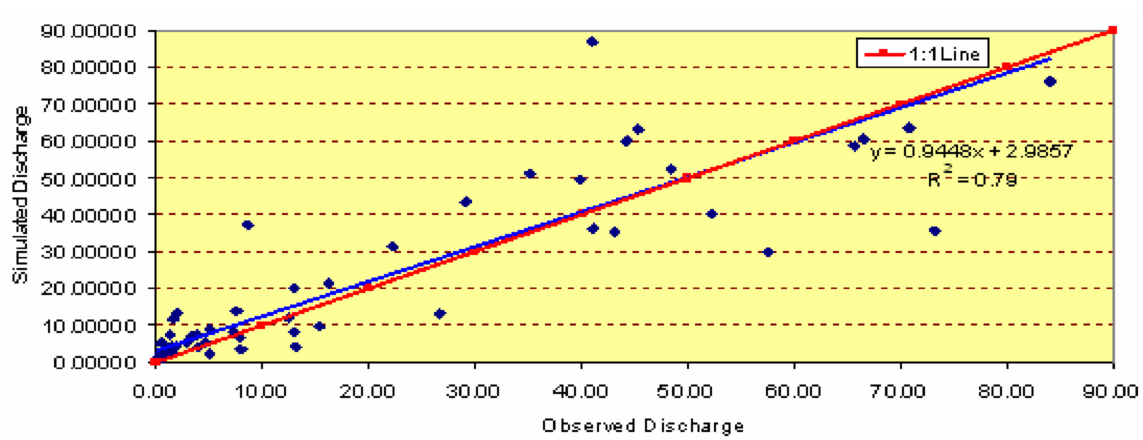


Fig 6.17 Scatter plot of observed and simulated discharge of Rib River during calibration Period.

The calibration and validation result of Rib watershed indicate that NSE for monthly stream flow ranges from 0.75 to 0.77 during calibration and validation. The model simulated the stream flow trends very good in both periods. The residual variation (RSR) also ranges from 0.48 to 0.5 during validation and calibration periods. These results indicate that the model simulated the residual variation as very good performance in both periods. The results of the volumetric fit on the other hand indicate that in both calibration and validation periods the model overestimated the volume of simulated flow, which ranges from -13.38 to -23.44 % during calibration and validation period. Thus the model simulated the volumetric fit as good to satisfactory ranges.

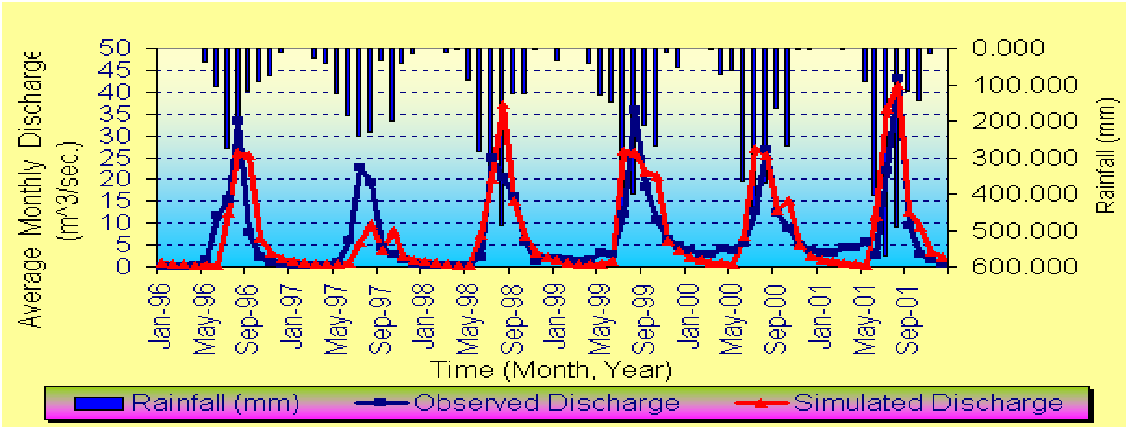


Fig 6.18 Calibration of Observed and simulated flow hydrograph of Megech River gauged Azezo. Period (1996-2001)

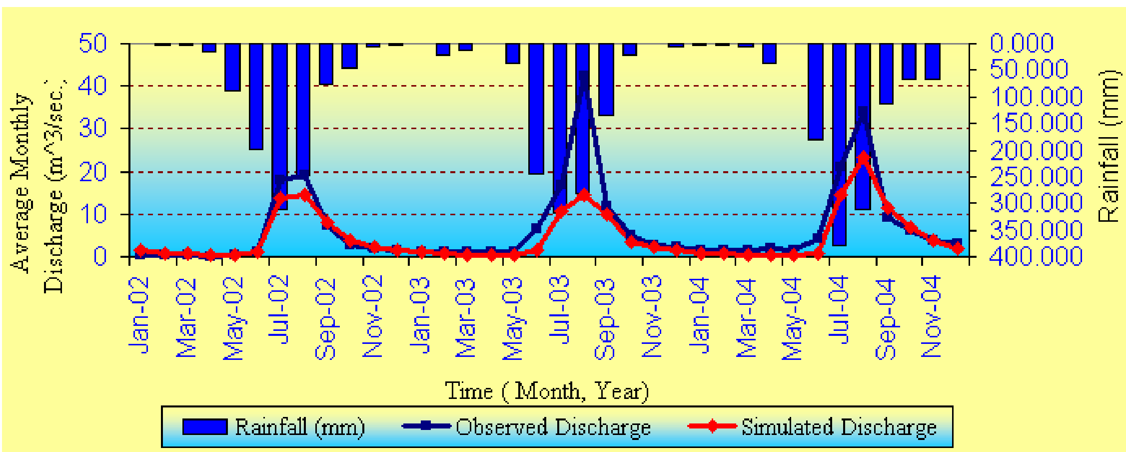


Fig 6.19 Validation of Observed and simulated flow hydrograph of Megech River gauged at Azezo. Period (2002-2004)

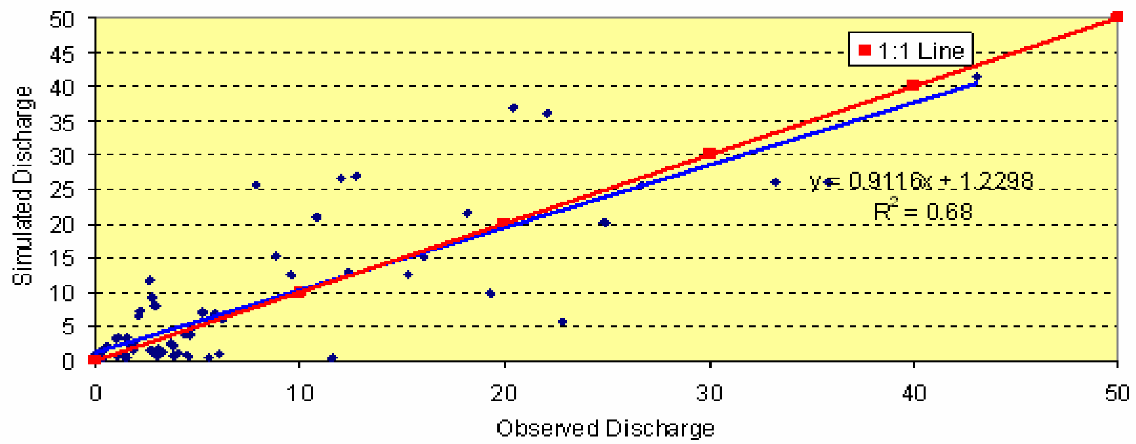


Fig 6.20 Scatter plot of observed and simulated discharge of Megech River during calibration period.

The calibration and validation result of Megech watershed indicate that NSE for monthly stream flow ranges from 0.61 to 0.68. The performance rating shows the model simulated the trends as satisfactory to good during calibration and validation periods. The residual variation (RSR) also ranges from 0.63 to 0.57 during calibration and validation period indicate that the model simulated the residual variation as satisfactory to good ranges. The volumetric fit result also ranges from -8.8 % to 31 % shows that an over estimated volume during calibration and under estimated volume during validation was observed. Thus the model simulated the volumetric fit as very good during calibration and unsatisfactory performance during validation.

For all modelled watershed the coefficient of determination ranges from 0.69 to 0.89 during calibration and 0.81 to 0.86 during validation indicates that the model reproduce the magnitude of measured data very well.

Generally, the overall model performance was satisfactory for all catchments during calibration. However, the validation result of 2003 for Gilgel Abay, Gumera, and Megech has been underestimated. The main reason for the under estimation of the peak was due to many missed measured rainfall data for the year 2003 that was filled by the embedded weather generator. The weather stations used Enjibara, Merawi, Wetet Abay, Debretabor has the whole missed rainfall data through out the year 2003, which attribute to the case for the under estimation of peak flow during validation period for the year 2003.

Table 6.14 Calibration & validation statistics of observed and simulated stream flow.

Average monthly flow (m^3/sec.)		Gilgel Abay River (Calibration period 1996-2001)			
Observed flow	Simulated flow	R^2	NSE	RSR	% D
59.82	56.5	0.89	0.88	0.35	5.56
Gilgel Abay River (Validation period 2002-2004)					
46.24	40.44	0.84	0.83	0.41	12.55
Koga River (Calibration period 1996-2001)					
5.83	5.22	0.82	0.79	0.49	10.45
Koga River (Validation period 2002-2004)					
5.08	5.55	0.86	0.74	0.51	-9.27
Gumera River (Calibration period 1996-2001)					
39.27	43.10	0.75	0.7	0.55	-9.75
Gumera River (Validation period 2002-2004)					
32.68	25.57	0.81	0.79	0.46	21.77
Rib River (Calibration period 1996-2001)					
15.8	17.91	0.79	0.75	0.5	-13.38
Rib River (Validation period 2002-2004)					
12.54	15.48	0.83	0.77	0.48	-23.44
Megech River (Calibration period 1996-2001)					
6.94	7.56	0.69	0.61	0.63	-8.8
Megech River (Validation period 2002-2004)					
6.53	4.49	0.81	0.68	0.57	31

Over the calibration period, the simulated basin wide water balance components on annual average basis are as follows:

Table 6.15 Annual basin water balance components of gauged Rivers.

Hydrologic parameters	Simulated value (mm) Period (1996-2001)				
	Gilgel Abay	Koga	Gumera	Rib	Megech
Precipitation	1846.8	1211.8	1493.9	1254.5	1498.80
Surface runoff	548.07	502.25	272.08	100.52	178.08
Lateral flow	19.26	3.59	31.13	241.16	202.90
Ground water flow (Base flow)	475.26	104.08	667.07	2.43	90.55
Revap. Shallow aquifer recharge	82.61	42.21	28.76	37	40.27
Deep aquifer recharge	136.53	33.77	41.52	438.98	495.01
Transmission losses	14.89	10.38	8.77	3.14	4.14
Total water yield	1027.7	599.54	961.51	340.98	467.38
Evapotranspiration	579.8	530.3	449.5	432.8	502.50
Potential Evapotranspiration	1006.8	1084.8	796.9	806.9	854.30

Note: Total water yield = (Surface runoff) + (Lateral flow) + (Ground water flow) – (Transmission losses)

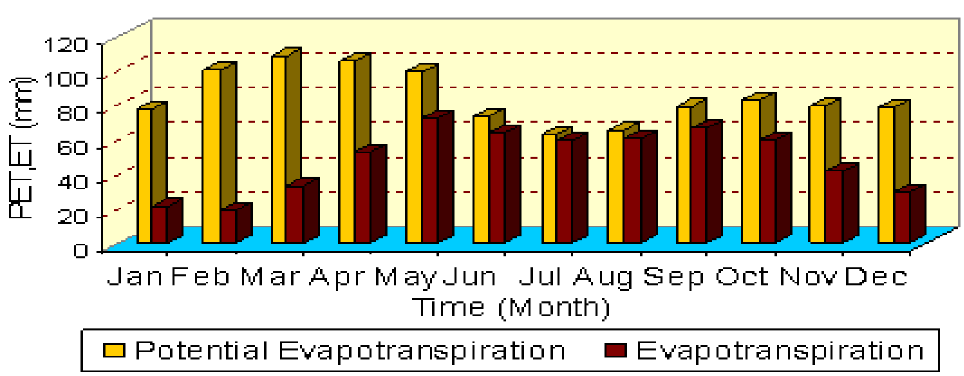


Fig 6.21 Monthly average Potential Evapotranspiration and Evapotranspiration of gauged Gilgel Abay catchment. Period (1996-2001)

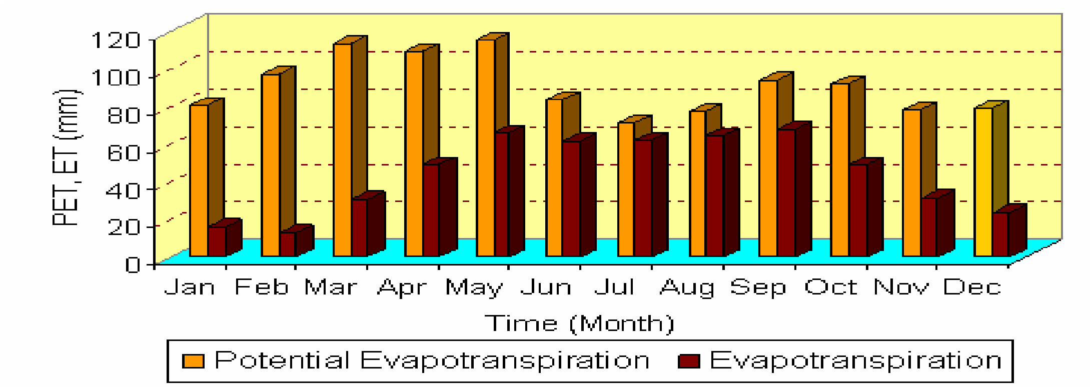


Fig 6.22 Monthly average Potential Evapotranspiration and Evapotranspiration of gauged Koga catchment. Period (1996-2001)

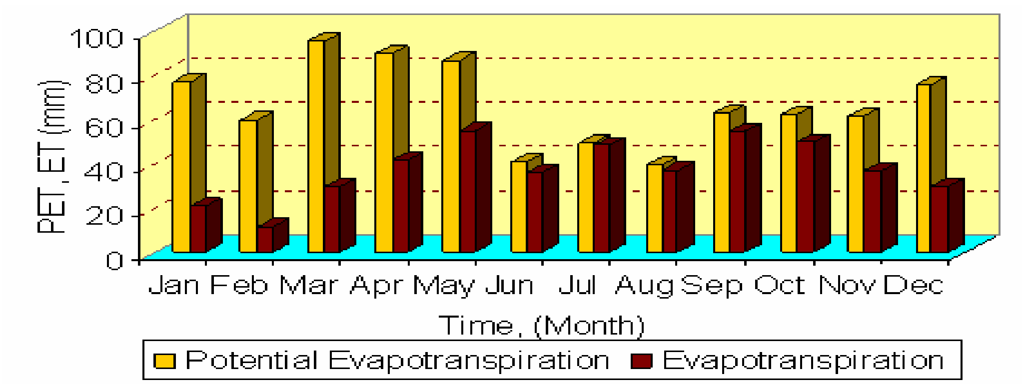


Fig 6.23 Monthly average Potential Evapotranspiration and Evapotranspiration of gauged Gumara catchment. Period (1996-2001)

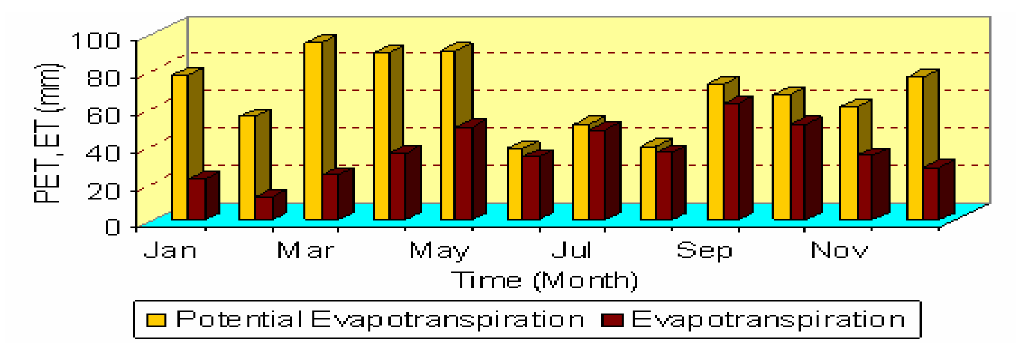


Fig 6.24 Monthly average Potential Evapotranspiration and Evapotranspiration of gauged Rib catchment. Period (1996-2001)

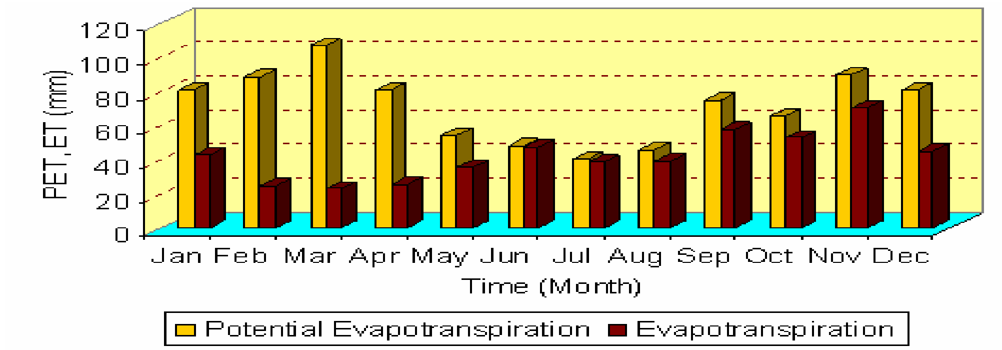


Fig 6.25 Monthly average Potential Evapotranspiration and Evapotranspiration of gauged Megech catchment. Period (1996-2001)

Detail of annual average basin value for gauged and un-gauged catchments are found in Appendix-G

6.2 Runoff estimation for ungauged catchments

Ungauged catchments are catchments with no or little river flow data. In Lake Tana basin as it was indicated in previous sections, most of the rivers inflow in to the Lake are not gauged and the runoff generated from ungauged watershed was not accurately estimated. To estimate the runoff from this un-gauged area, the optimized parameters that have been obtained during calibration was transferred to un-gauged part by simulation mode used in SWAT model.

SWAT model has great advantage to estimate runoff for un-gauged catchments by assigning HRUs in the sub-catchments. Sub-catchments with the same HRUs have the same responses for runoff generation and in this research work, after modeled the gauged watersheds lumped parameters were transferred directly to un-gauged part and hence, runoff from un-gauged part has been estimated.

Lumped parameters used for the estimation of runoff in ungauged catchments and simulated stream flow for ungauged catchments are found in appendix-D and F respectively.

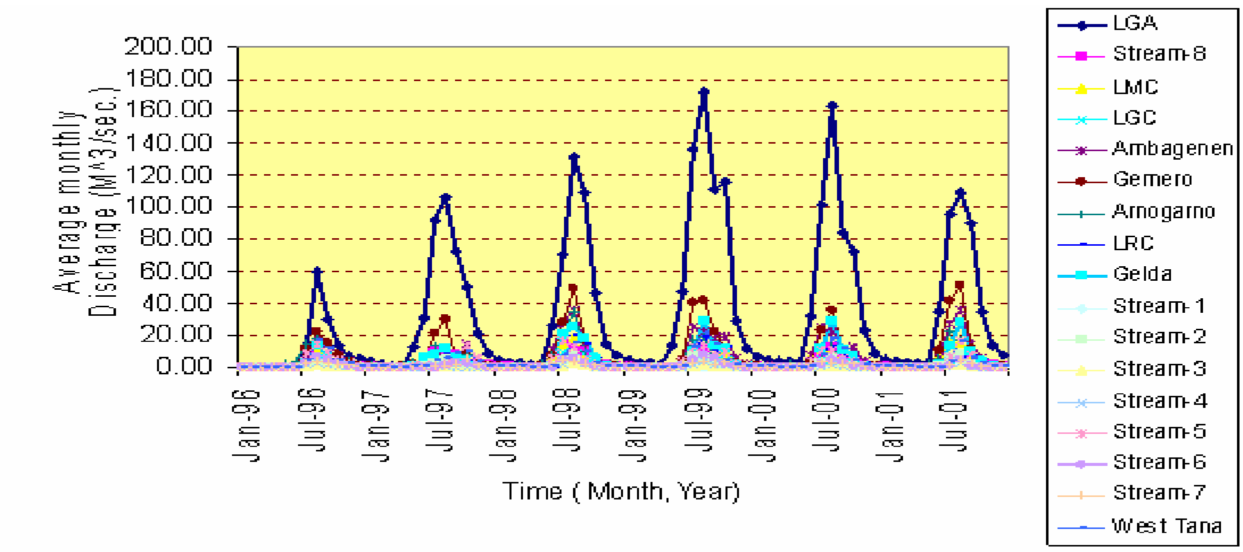


Fig 6.26 Hydrograph of ungauged catchments

Runoff contribution from gauged and ungauged catchments.

From the model out put it has been observed that over the calibration period 1996-2001 Gilgel Abay catchment was the major runoff contributor 909 MCM / year (54.56 %), Gumera 375 MCM / year (22.51 %), Rib 160 MCM / year. (9.61 %), Koga 136 MCM / year, (8.16 %), and Megech 86 MCM / year, (5.16 %). From the total average rainfall, this was falling on gauged catchments about 22 % of it converted in to surface runoff and the rest percentage mainly converted in to Evapotranspiration and ground water.

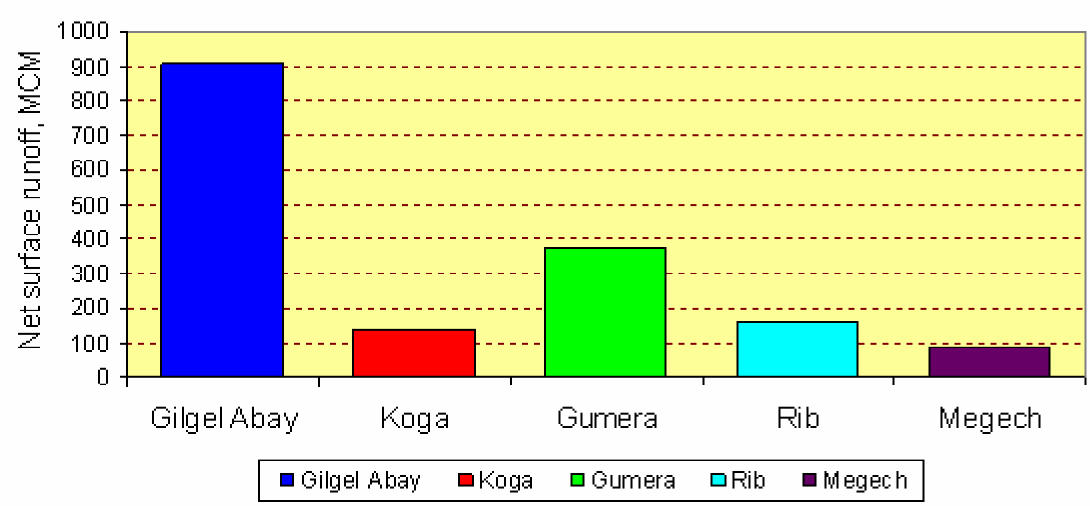


Fig 6.27 Net surface runoff generated from gauged catchments

Table 6.16 Surface runoff generated from gauged catchments in LTB from a period of 1996 - 2001

Catchment	Gauged area (Km^2)	Net Surface runoff (mm/year)	Net Surface runoff (MCM/year)
Gilgel Abay	1658	548.07	909
Koga	272	502.25	136
Gumera	1377	272.08	375
Rib	1592	100.52	160
Megech	484	178.08	86
Total	5383		1666

Detail of simulated stream flow for gauged catchments found in appendix-E

After transferring the calibrated parameters from gauged catchments it has been found that lower Gilgel Abay catchment (LGA), contribute larger proportion of net surface runoff 542.69 MCM / year, (32.49 %).

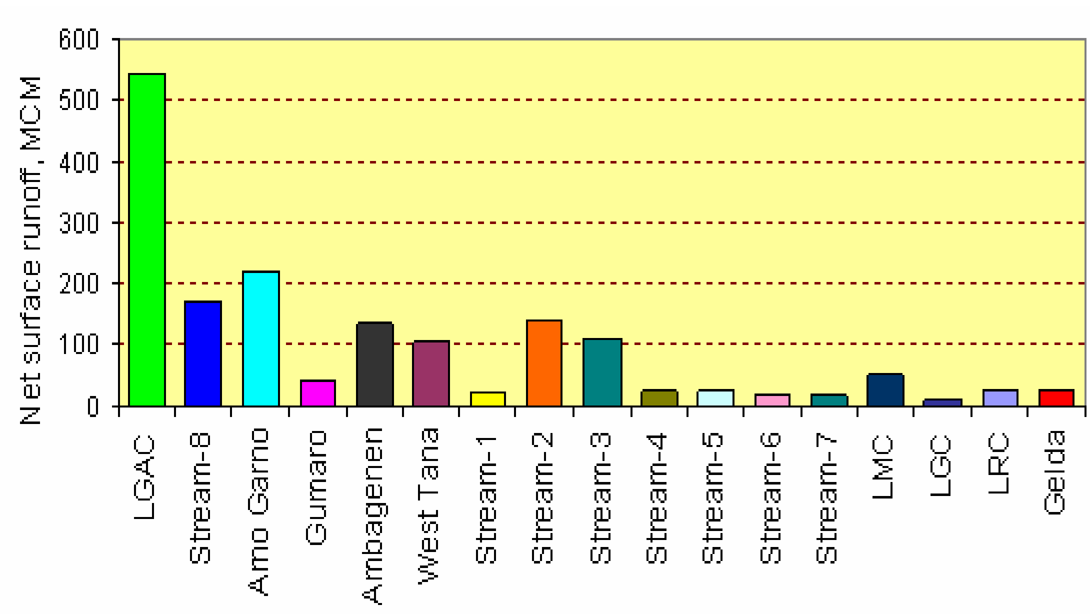


Fig 6.28 Net surface runoff generated from ungauged catchments

From the total average rainfall falling on ungauged catchments, about 18 % of the rainfall was converted in to surface runoff. Larger portion of the rainfall was converted in to Evapotranspiration and the rest proportion is to the ground water contribution. From the overall semi distributed modeling approach it can be concluded that the dominant hydrological variables in Lake Tana basin was the Evapotranspiration in which the greater portion of rainfall lost through it.

Table 6.17 Surface runoff generated from ungauged catchments in LTB from a period of 1996 - 2001

Catchment	Ungauged area (Km^2)	Net Surface runoff (mm/year)	Net Surface runoff (MCM /year)
Lower Gilgel Abay (LGAC)	2010	269.99	542.69
Stream-8	591	290.88	171.98
Gelada	834	260.72	217.51
Lower Gumera (LGC)	150	258.99	38.93
Lower Rib (LRC)	475	278.58	132.51
Lower Megech (LMC)	247	421.75	104.57
Arnogarno	260	81.49	21.19
Gemero	411	341.87	140.68
Ambagenen	399	280.31	112.12
Stream - 1	63	394.37	24.98
Stream - 2	54	427.44	23.27
Stream - 3	87	175.10	15.37
Stream - 4	80	206.94	16.71
Stream - 5	208	238.23	49.69
Stream - 6	100	88.97	8.94
Stream - 7	86	291.21	25.07
West Tana	626	38.49	24.11
Total	6681		1670

CHAPTER SEVEN

7. Water Balance Analysis of the Lake

7.1 The inflow hydrograph

Inflow series of gauged catchments were estimated during calibration in previous section. Once the model is calibrated and verified at the gauged location the model output during that period were quantified and taken as simulated inflow series. Later this inflow series will be used for water balance analysis. The inflow series of gauged catchments are found in appendix-E

Similarly, the inflow series for ungauged catchments were done by transferring calibrated parameters having the same HRUs as gauged catchments. The total inflow in to the Lake mouth was determined after having the inflow from gauged catchments and inflow from ungauged catchments separately and later the total inflow was taken as the aggregate of inflow series from gauged and ungauged catchments.

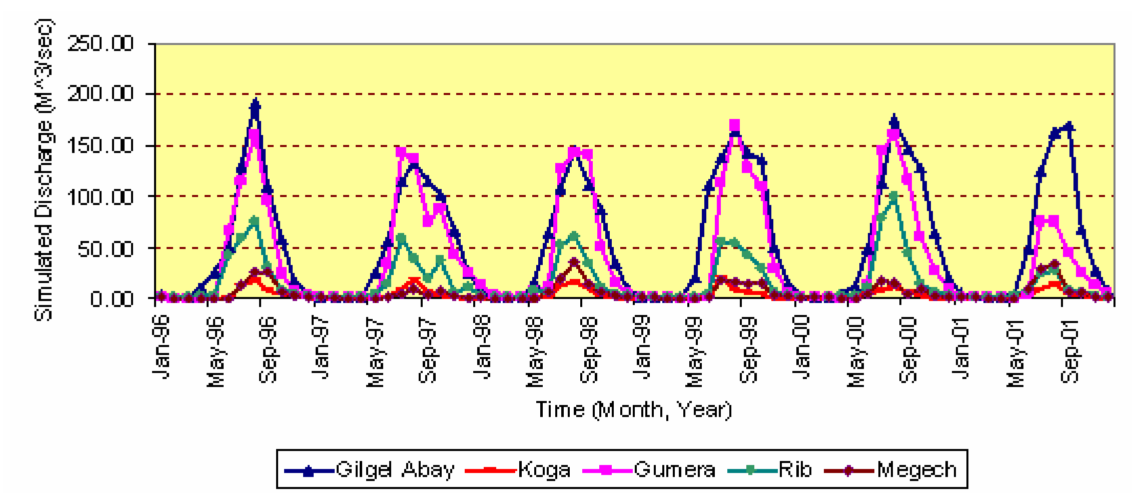


Fig 7.1 Inflow Hydrograph of gauged catchments

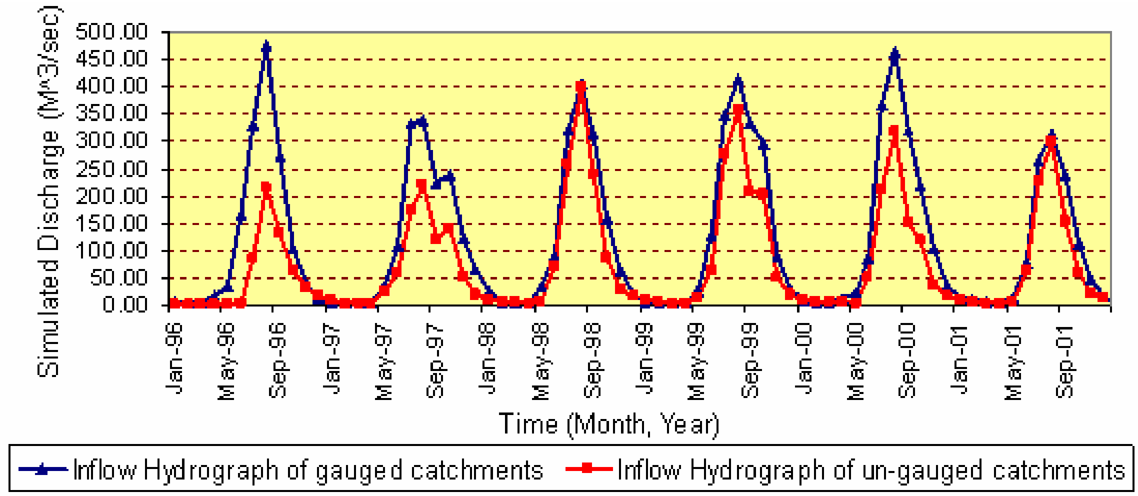


Fig 7.2 Total inflow Hydrograph of gauged and ungauged catchments

From the model result it was found that the inflow from gauged catchments was mainly contributed from Gilgel Abay (43.4%), Gumera (33.1%), Rib (13.7%), Megech (5.8%) and Koga (4%). It is also found that the inflow from ungauged catchments contributed mainly from lower Gilgel Abay catchment (42.99%) and the rest inflow percentage is contributed from the ungauged catchments, which described in appendix-J

Generally, about 61.8 % inflow was contributed from gauged catchments and about 38.2 % was contributed from ungauged catchments. Inflow series of ungauged catchments is found in appendix-E and percentage contribution from ungauged catchments are shown in table 7.1

Table 7. 1 Percentage contribution of inflow series from ungauged catchments.

Catchment	% contribution
Lower Gilgel Abay catchment (LGAC)	42.99
Stream-8	3.04
Lower Megech catchment (LMC)	3.98
Lower Gumera catchment (LGC)	2.03
Ambagenen	8.12
Gemero	9.26
Arnogarno	5.30
Lower Rib Catchment (LRC)	4.15

Gelda	5.25
Stream-1	0.72
Stream-2	1.49
Stream-3	0.48
Stream-4	0.83
Stream-5	4.11
Stream-6	1.65
Stream-7	1.63
West Tana	4.96

7.2 The Evaporation and Rainfall over the Lake

Monthly evaporation and monthly rainfall over the Lake have been estimated using Crop Wat model and Thiesen polygon respectively.

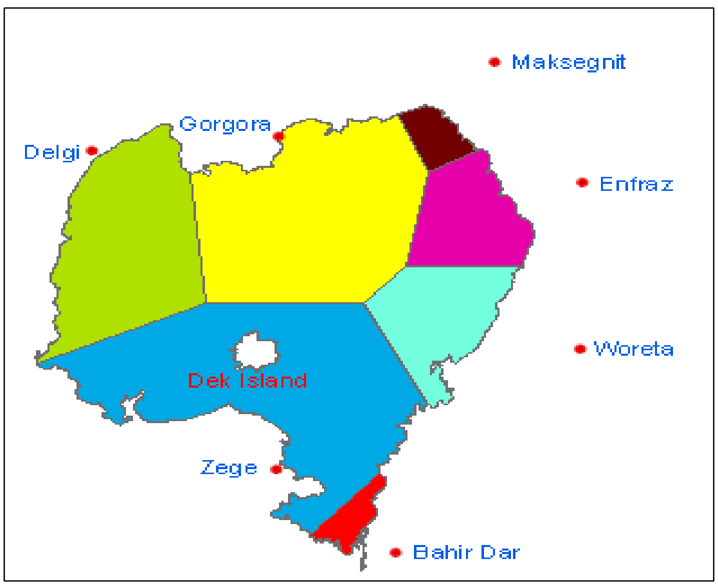


Fig 7.3 Thiesen polygon used for the estimation of monthly areal rainfall over Lake Tana

From the Thiesen polygon analysis, the annual average areal rainfall over the Lake found to be 1311.17 mm/year and from Crop Wat model the average annual evaporation for the simulation period 1996-2001 found to be 1624.19 mm/year. The detail of monthly areal rainfall and evaporation values are found in water balance result appendix-I

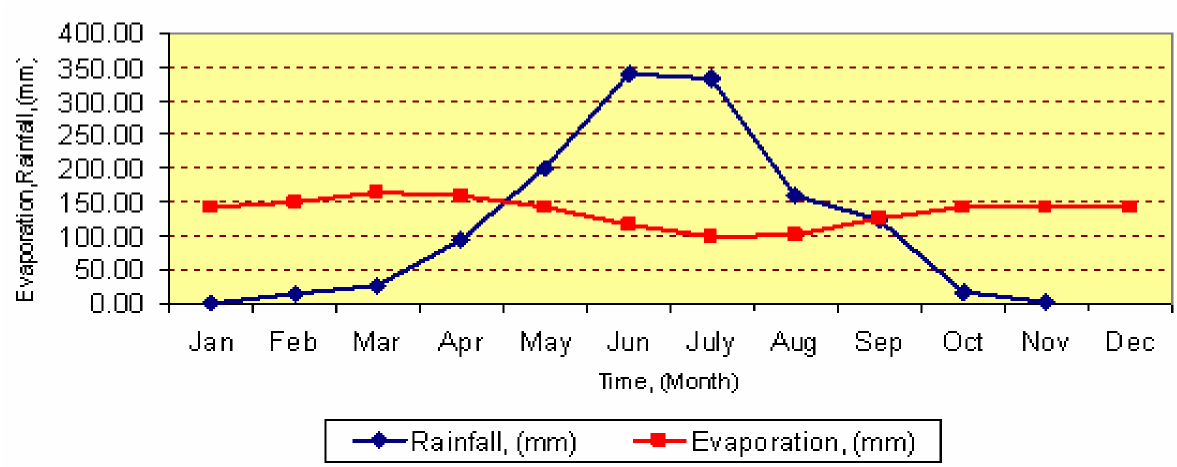


Fig 7.4 Average Monthly Rainfall and Evaporation over Lake Tana. Period (1996-2001)

7.3 Physical Characteristic data of the Lake

The Lake Tana is approximately 84 Km long and 66 Km wide, with mean and maximum depth of 7.2 and 14 m respectively. Abeyou,(2008)

The polynomial fitted bathymetry by Pietrangeli, (1990) cited in SMEC, 2007 and Abeyou, (2008) used in this research work is as follows:

Table 7.2 Elevation-Volume-Area relation ship as per Pietrangli and Abeyou

Pietrangeli	$E = 1.08*10^{-9}(V)^2+3.88*10^{-4}(V)+1775.58$, $R^2=1.0$
	$A = 6.20*10^{-8}(V)^2+1.72*10^{-2}(V)+2516.3$, $R^2= 0.997$
Abeyu	$E = 1.21*10^{-13}(V)^3-1.02*10^{-8}(V)^2+6.20*10^{-4}(V)+1774.63$, $R^2=0.999$
	$A = 7.93*10^{-11}(V)^3-5.81*10^{-6}(V)^2+1.65*10^{-1}(V)+1147.51$, $R^2=0.990$

Where E= Lake level elevation, m. +MSL

A= Surface area of the Lake, Km^2

V= Lake volume, MCM

The basic equation used in the water balance:

Change in storage = Total inflow – total outflow- losses-----------------Eq (7.1)

Further equation (7.1) can be written as:

$S_t = S_{t-1} + I(t) + P(t) - O(t) - E(t) + G_{in} - G_{out} - other$ losses-------------Eq (7.2)

Where: $S_t =$ Lake storage volume at the end of current month.

S_{t-1} = Lake storage volume at the end of previous month.

I (t) = Simulated inflow volume from gauged and un-gauged catchments at current month.

O (t) = Outflow volume at the Lake outlet.

P (t) = Areal rainfall volume on the Lake surface.

E (t) = Evaporation volume on the Lake surface.

G_{in} (t) = Ground water inflow in to the Lake at the end of current month.

G_{out} (t)= Ground water outflow from the Lake at the end of current month.

In this research work the ground water inflow and outflow, the evaporation term from the inundated flood plain have not been included. Due to lack of depth, volume information for the inundated area, it was difficult to analyze in SWAT and neglected in the water balance calculation.

The water balance terms were computed using EXCEL spread sheet model and the monthly water balance result obtained by using the relation ship developed by Abeyou, (2008) has been best fitted than Pietrangeli, (1990).

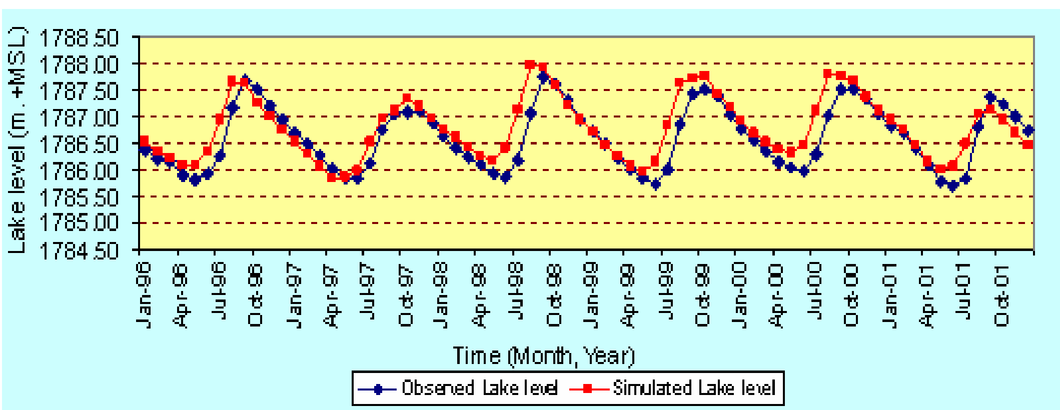


Fig 7.5 Observed and Simulated Lake level with out the implementation of development projects for the period 1996-2001.

Table 7.3 Performance rating of Lake level simulation from a period of 1996-2001

Researcher	R^2	Nash & Sutcliff	Maximum level difference from the Observed Lake level (cm)
Pietrangeli	0.73	0.45	140
Abeyou	0.76	0.65	96

From the above statistical values, the result of this thesis lake level simulation is best fitted on the relation ship developed by Abeyou and hence, the SWAT model output is applicable in simulating the Lake level even with a lot of uncertainty in input data for the model to run.

Table 7.4 Lake Tana Annual water balance components simulated from 1996-2001

Water balance components	mm/Year	MCM/Year
Lake areal rainfall	+1311	+3834
Gauged River inflow	+1329	+3909
Un-gauged river inflow	+827	+2431
Lake Evaporation	-1624	-4799
River outflow	-1766	-5258
Change in storage	77	117

Comparison of this thesis result with the previous researches

Many research works have been done in Lake Tana basin using different approach. However, significant variations of the Lake Tana water balance components have been obtained. Based on the reviewed results the inflow terms such as Lake areal rainfall varies between 1200 mm / year to 1678 mm / year, inflow volume varies between 4.18 BCM / year to 12.05 BCM / year and the out flow terms, evaporation varies between 1478 mm / year to 1965 mm / year , out flow 1113 mm / year to 3735 mm / year. As it is described in table 7.4 the result of this thesis was found between the above mentioned previous results. The annual inflow volume of (6.34 BCM) was obtained in this research nearly approaching to the research made by Abeyou, 2007 (6.69 BCM). Even though, reseaonable results were obtained, still the great variation of results which was done so far requires further research findings in the basin.

CHAPTER EIGHT

8. Conclusion and Recommendations

8.1 Conclusion

In this study work due emphasis have been given for the estimation of runoff contribution from gauged and ungauged catchments using semi distributed model known as SWAT. Based on SWAT watershed delineation at outlet of the Lake Tana, the catchment area was found to be 15,114 KM^2. Considering the whole watershed in the basin about 46.97 % of the total watershed is gauged and 53.03 % is ungauged. Hence, estimation of runoff from this huge percentage has become important for future developments. Major gauged Rivers, such as Gilgel Abay, Koga, Gumera, Rib and Megech have been modelled independently and parameters were derived by calibrating the simulated model output with the historical flow records. The performance rating criteria shows that the model in all catchments were satisfactory and with in an acceptable performance.

After modeling the gauged watershed, calibrated parameters were transferred to ungauged watershed by lumping the parameters having the same hydrologic response unit (HRUs). The model output indicates that, the annual inflow volume estimated to be 3909 MCM (61.8 %) contributed from gauged watershed and about 2431 MCM (38.2 %) contributed from ungauged watershed. The Lake areal rainfall, Evaporation and out flow for the simulation period (1996-2001) were found to be 3834, 4799, and 5258 MCM respectively. Annual average potential evapotranspiration, actual evaporation of the catchment, precipitation also estimated to be 978, 476, 1193 mm respectively.

The result of sensitivity analysis also shows that CN is the most sensitive parameter in all catchments. Except CN, the rest parameters level of sensitivity to runoff differs from one catchment to another catchment. Thus, this is an indication of the hydrological processes in the basin differ from one catchment to another catchment. In most of the gauged watershed after calibration it can be seen that base flow contribution is more and less in Rib catchment have been obtained. The lateral flow also more in Rib catchment and Megech catchment as compared to other catchments. This also a clear indication of the ground water component was the second dominant hydrological process next to Evapotranspiration in the basin.

The previous studies in the basin were hampered to account spatial and temporal variation of inputs and this study is an attempt of applying semi distributed model, which accounts spatial and temporal variation of inputs in the basin. This study has paramount importance as it is new and original contribution using SWAT semi distributed modelling approach, to mainly estimate runoff from gauged and ungauged part of the catchments and to study the Lake Water balance.

Generally, the data base created would enable for further research improvement or new research in monitoring Lake Water quality and sediment studies in the basin. SWAT model is applicable in Lake Tana basin and the result can be used for planning and management of water resources in the basin.

8.2 Recommendation

- SWAT model calibrated using observed flow data at gauging station. In order to improve the model performance, the weather stations should be improved both in quality and quantity. Hence, it is highly recommended to establish a good network of both hydrometric and meteorological stations.
- The study aims to estimate the runoff contribution from gauged and un-gauged catchments based on a semi distributed modelling approach. However, in water balance components, the sub-surface condition for the Lake Tana was not considered. Therefore, detail research work, which incorporates ground water, is recommended to understand the interaction of surface and sub-surface condition and Lake Water balance.
- It is essential to develop joint reservoir operation rule for all Dam projects with in the basin including Lake Tana. Hence, it will significantly important to manage and to set different management alternatives in the basin.
- Areal rainfall estimated by Thiessen polygon method was used for this study. In order to improve the result, either additional stations shall be established or augmented from already available satellite estimated rainfall.
- The database created in this study has paramount importance to conduct further research on water quality modelling and sediment studies. Therefore, it is recommended to use the database for further research work in the basin.
- The evaporation components from inundation area with in the basin have not been included. Therefore, different model which accounts evaporation is recommended to include in the water balance.
- Generally, it is the feeling of the author that flow measurement is likely affected by measurement error (as shown in fig 6.3 of 2003 record). The rating curve shall be established to check the measurements.

REFERENCES:

Abayneh, (2005), Assessment of cause of Lake Tana water level change & its impact on Tiss Abay Hydropower production & Tiss Issat fall, ArbaMinch University MSc. thesis.

Abeyou, (2008), Hydrological balance of Lake Tana, upper Blue Nile, Ethiopia, ITC Enschede, MSc Thesis.

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

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman. (1989). Operational estimates of evapotranspiration. Agron. J. 81:650-662

Acres International Limited (1995) Canada in association with Shawel Consult international (Ethiopia), Feasibility study of Birr and Koga Irrigation project.

Arnold, J.G., P.M Allen, R. Muttiah, and G. Bernhardt, November-December (1995): Automated base flow separation and recession analysis techniques. Ground Water vol 33(6): 1010-1018pp.

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., 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

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

BCEOM (1999), Abay River Basin integrated master plan, main report, MoWR, Addis Ababa, Ethiopia.

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

Conway, D., (2000). The climate and hydrology of the Upper Blue Nile River. The Geographical Journal 166, 49–62.

Cunderlik M. Juraj, October (2003). Hydrologic model selection fort the CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions, Project Report I, 40pp.

Dingman, S.L. (2002), Physical Hydrology (2nd ed.), Prentice Hall Inc., USA.

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

Green, W.H. and G.A. Ampt, (1911). Studies on soil physics, 1. The flow of air and water through soils. Journal of Agricultural Sciences 4:11-24.

Humphrey & associates, (1996).Feasibility Study of Tis Abbay II-Ethiopia

Hargreaves, G.H. and Z.A. Samani. (1985). Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1:96-99.

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.

Kebede. S., Travi, Y., Alemayehu, T., Marc, V., 2005 Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin Ethiopia, pp, 233-247 Journal of Hydrology 316.

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

Liden, R. and J. Harlin (2000), Analysis of conceptual rainfall-runoff modelling performance in different climates, Journal of Hydrology, 238: 231-247.

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

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 Report TR-193, 345pp.

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

Moriasi, D.N, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harem,T. L.Veith, (2007). Model evaluation guidelines for systematic quantification of accuracy in Watershed simulations. Vol. 50(3), 850-900pp. American society of Agricultural and Biological Engineers ISSN 0001-235

Morris.M.D., (1991). Factorial sampling plans for preliminary comp experiments. Tecnometrics. Vol.33 nr2

MoWR, (2005). Tana – Beles water systems, an over view of water resources Development potentials and issues, Addis Ababa, Ethiopia.

Nash, J. E., and J. V. Sutcliffe. (1970). River flow forecasting through conceptual models: Part 1. A discussion of principles. *J. Hydrology* 10(3): 282-290.

Neitsch (A), S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, K.W. King , (2002). Soil and Water Assessment Tool (SWAT) Theoretical Documentation, Version 2000, Grassland Soil and Water Research Laboratory, Black land Research Center, Texas Agricultural Experiment Station, Texas Water Resources Institute, Texas Water Resources Institute, College Station, Tex as, 506pp.

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.

Ponce, V.M, (1998). Engineering Hydrology. Principles and practice. Prentice Hall 640p.

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.

Rosenthal, W. D., R. Srinivasan, and J. G. Arnold. (1995). Alternative river management using a linked GIS-hydrology model. *Trans. ASAE* 38(3): 783-790.

Saleh, A., J. G. Arnold, P. W. Gassman, L. W. Hauck, W. D. Rosenthal, J. R. Williams, and A. M. S. McFarland. (2000). Application of SWAT for the upper North Bosque River watershed. *Trans. ASAE* 43(5): 1077-1087.

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. Water Resour. Assoc.* 37(5): 1169-88.

Semu Ayalew, (2007) Lecture notes on deterministic hydrology.

Shahin, M., (1988). Hydrology of the Nile basin, International Institute for Hydraulic and Environmental Engineering. Elsevier, The Netherlands.

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.

S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan, J. R. Williams, (2005). Soil and Water Assessment Tool (SWAT) User's Manual, Version 2005, Grassland Soil and Water Research Laboratory, Blackland Research Center, Texas Agricultural Experiment Station, Texas Water Resources Institute, Texas Water Resources Institute, College Station, Texas, 520pp.

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

Soil Conservation Service, (1972). Section 4: Hydrology *In* National Engineering Handbook. SCS.

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.

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

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

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.

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

Water Works Design And Supervision, **(2007)** Design of Dams in Lake Tana Sub-Basin Gilgel Abbay, Megech, Ribb, Gumera and Jemma Project Hydrological Study Final Report.

Williams, J. R. (1969). Flood routing with variable travel time or variable storage coefficients. *Trans. ASAE* 12(1): 100-103

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

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.

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

Web site sources:

http://www.brc.tamus.edu/swat/soft_links.html

APPENDICES

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

Station Name	X-Co-ordinate	Y-Co-ordinate	Elevation
Adet	332989	1246157	2080
Addiszemen	377034	1339957	1550
Ayikel	294609	1361596	2150
Bahirdar	331001	1282667	1770
Dangla	259914	1244754	2000
Debretabor	394353	1313350	2690
Delgi	289652	1352391	2692
Enfraz	356388	1346686	1500
Enjibara	272722	1216751	2650
Gonder	328323	1385551	1967
Georgia	315083	1354659	1830
Merawi	298154	1262951	2110
Maksegnit	344529	1367761	1450
Wereta	356249	1317931	1865
Zege	314729	1297140	1820
Feresbet	346965	1199638	4000
DekEstifanos	311756	1317114	1800
Wereta	287202	1257492	1830

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

Table –B-1

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), μ*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:

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

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 1 to 12 in the following tables represent the months from January to December and the alphabets A, B, C….M, indicate the description of weather generator parameters presented in appendix-B, Table B-1

STATION	LAT	LONG	ELEV	Rain-yrs	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Adet	11.27	37.47	2080.00	21.00	26.60	28.60	29.40	28.90	28.70	25.70	22.50	22.60	24.00	24.50
Bahirdar	11.60	37.45	1770.00	22.00	26.80	27.80	29.70	29.10	28.00	24.70	24.40	24.60	25.40	26.50
Dangla	11.00	37.00	2000.00	21.00	26.70	28.50	29.10	28.80	28.50	24.00	21.90	22.40	23.30	24.00
Debretabor	11.88	38.03	2690.00	21.00	21.10	21.10	20.70	24.90	23.30	22.10	16.60	18.50	20.30	20.40
Gonder	12.53	37.42	1967.00	21.00	28.70	30.50	30.80	30.80	25.60	23.50	23.10	23.60	22.40	26.80
STATION	A11	A12	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
Adet	24.80	26.00	5.50	6.80	9.30	10.60	11.50	11.70	12.00	12.20	10.80	10.40	8.00	6.00
Bahirdar	26.50	26.60	7.70	10.00	14.00	14.50	15.10	14.70	14.00	13.90	13.40	12.90	10.90	9.30
Dangla	25.30	26.10	4.60	7.30	9.40	11.10	11.40	12.70	12.70	12.50	11.70	10.10	7.90	4.80
Debretabor	21.90	22.10	7.10	6.60	5.80	10.50	11.10	10.60	10.30	10.30	9.60	9.20	7.60	7.60
Gonder	27.90	28.10	11.60	14.20	15.40	16.80	12.00	13.50	13.90	13.90	12.20	12.70	11.80	12.20
STATION	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	D1	D2
Adet	1.30	1.30	1.40	8.10	2.00	2.10	1.90	1.60	1.10	1.20	1.50	0.90	1.70	2.00

Bahirdar	1.30	1.30	2.10	3.30	2.40	3.50	1.40	2.70	1.20	1.10	2.70	1.30	1.70	2.60
Dangla	1.10	1.50	1.20	1.90	1.80	1.90	1.70	1.30	0.90	1.10	1.20	0.80	1.80	2.30
Debretabor	1.80	1.60	2.20	1.90	2.20	1.90	2.00	1.50	1.30	1.60	0.90	0.90	1.10	1.00
Gonder	1.20	1.40	1.30	1.90	2.60	1.80	1.50	1.50	1.80	1.30	1.20	0.80	2.00	2.20
STATION	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	E1	E2	E3	E4
Adet	3.00	2.70	1.90	1.30	1.10	1.00	1.30	1.70	2.30	1.90	2.90	5.30	35.50	34.80
Bahirdar	3.10	3.30	2.10	1.10	1.00	1.00	1.10	1.90	2.10	1.80	1.50	2.60	7.80	18.20
Dangla	2.60	2.70	2.10	1.10	1.10	1.00	1.20	2.10	2.10	1.90	0.90	2.30	11.70	25.60
Debretabor	1.20	0.90	1.30	1.00	0.80	0.80	0.90	1.20	1.30	1.20	4.00	1.20	19.00	29.00
Gonder	1.70	2.20	2.50	2.00	1.00	0.80	1.90	1.40	1.90	1.50	2.30	4.20	12.90	28.10
STATION	E5	E6	E7	E8	E9	E10	E11	E12	F1	F2	F3	F4	F5	F6
Adet	88.70	134.70	295.10	245.00	151.20	106.30	22.00	5.70	2.80	7.80	8.63	8.30	10.43	8.53
Bahirdar	57.20	155.20	347.40	312.10	157.10	85.20	10.60	1.70	2.53	6.17	9.02	7.65	12.28	13.34
Dangla	82.30	192.70	254.60	257.50	175.90	90.80	24.20	4.00	1.27	2.07	5.96	6.96	9.16	9.98
Debretabor	60.80	106.80	239.40	230.00	109.50	66.50	16.90	13.30	5.60	2.45	9.32	6.40	11.90	10.96
Gonder	68.10	168.50	298.50	263.80	94.00	87.20	16.70	7.20	6.75	4.84	9.10	7.26	8.17	11.73
STATION	F7	F8	F9	F10	F11	F12	G1	G2	G3	G4	G5	G6	G7	G8
Adet	11.15	9.93	8.15	8.79	5.87	3.63	1.76	3.35	1.69	3.57	2.79	2.65	1.70	1.93
Bahirdar	16.30	15.28	11.55	9.66	6.64	3.59	1.04	1.40	5.16	2.18	2.38	2.26	2.25	2.44
Dangla	11.64	10.37	9.45	10.54	8.20	5.43	0.64	0.84	2.66	2.04	1.68	1.63	2.17	1.43
Debretabor	12.09	11.04	9.44	14.20	7.33	12.52	3.41	0.97	2.82	1.58	2.47	3.26	1.36	1.25
Gonder	17.19	11.36	8.32	12.67	8.13	6.35	1.40	0.70	3.87	2.60	2.06	2.23	7.21	2.14
STATION	G9	G10	G11	G12	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
Adet	2.58	1.53	1.42	1.52	0.02	0.03	0.09	0.12	0.20	0.37	0.46	0.47	0.42	0.20
Bahirdar	2.21	1.71	1.39	1.13	0.01	0.01	0.05	0.07	0.12	0.30	0.25	0.30	0.31	0.17
Dangla	1.54	2.65	1.93	1.60	0.01	0.02	0.05	0.08	0.14	0.19	0.14	0.11	0.21	0.16
Debretabor	1.74	3.79	1.65	2.88	0.03	0.01	0.05	0.08	0.12	0.15	0.06	0.08	0.13	0.08
Gonder	2.03	2.26	2.29	3.69	0.01	0.02	0.07	0.10	0.23	0.36	0.33	0.34	0.26	0.22
STATION	H11	H12	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12
Adet	0.08	0.04	0.35	0.27	0.46	0.50	0.61	0.72	0.88	0.86	0.79	0.67	0.46	0.26
Bahirdar	0.04	0.01	0.33	0.18	0.32	0.34	0.55	0.68	0.92	0.89	0.76	0.62	0.30	0.17
Dangla	0.08	0.02	0.13	0.18	0.44	0.54	0.68	0.88	0.93	0.94	0.84	0.67	0.41	0.29
Debretabor	0.05	0.04	0.25	0.13	0.49	0.53	0.54	0.75	0.95	0.92	0.78	0.69	0.36	0.27
Gonder	0.08	0.04	0.33	0.22	0.23	0.47	0.51	0.72	0.91	0.89	0.66	0.49	0.22	0.33
STATION	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12	K1	K2
Adet	0.90	1.10	4.60	5.80	10.40	17.20	24.40	23.80	20.00	11.60	3.90	1.50	20.00	22.00
Bahirdar	0.50	0.50	2.00	3.00	6.60	14.60	23.30	22.50	16.70	9.60	1.70	0.50	21.00	22.00
Dangla	0.40	0.80	2.60	4.30	9.40	18.50	20.50	20.90	17.30	10.20	3.60	0.80	17.00	22.00
Debretabor	1.10	0.40	3.00	4.60	6.30	11.50	16.60	16.00	10.80	6.50	2.10	1.60	18.00	13.00

Gonder	0.40	0.90	2.50	4.90	9.80	17.00	24.40	23.50	13.20	9.30	2.80	1.60	20.00	22.00
STATION	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	L1	L2	L3	L4
Adet	22.00	22.00	23.00	19.00	17.00	17.00	20.00	20.00	18.00	19.00	16.07	16.94	17.86	17.90
Bahirdar	23.00	23.00	20.00	19.00	17.00	17.00	19.00	21.00	21.00	20.00	15.22	15.01	14.83	15.83
Dangla	22.00	22.00	21.00	18.00	15.00	16.00	18.00	19.00	19.00	19.00	13.69	4.32	16.67	16.17
Debretabor	20.00	20.00	20.00	10.00	15.00	10.00	18.00	16.00	14.00	18.00	9.31	9.95	10.55	12.44
Gonder	22.00	21.00	19.00	18.00	14.00	15.00	20.00	18.00	21.00	18.00	-1.12	-0.83	-0.61	-2.43
STATION	L5	L6	L7	L8	L9	L10	L11	L12	M1	M2	M3	M4	M5	M6
Adet	19.04	18.81	17.02	17.26	17.65	17.81	16.77	16.17	0.12	0.96	1.04	1.14	1.14	1.45
Bahirdar	17.98	20.17	18.60	19.30	6.75	20.13	18.29	16.35	0.39	0.49	0.64	0.71	0.70	0.67
Dangla	17.21	17.64	16.49	16.67	16.45	15.11	14.65	14.29	0.91	1.00	1.13	1.23	1.23	1.17
Debretabor	14.61	16.01	14.06	14.24	12.76	14.73	13.37	12.27	1.05	1.24	1.18	1.21	1.50	1.36
Gonder	9.29	15.28	12.40	2.08	1.10	0.57	-1.36	5.30	1.46	1.45	0.35	1.41	1.00	1.00
STATION	M7	M8	M9	M10	M11	M12								
Adet	0.53	0.80	0.82	0.68	0.31	0.71								
Bahirdar	0.57	0.53	0.51	1.05	0.45	0.35								
Dangla	1.10	1.10	0.95	0.82	0.69	0.74								
Debretabor	1.15	1.26	1.13	0.78	0.84	1.04								
Gonder	0.50	0.07	1.21	1.12	1.00	1.22								

Appendix-C 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	2006 2006
Addet	x	x	x	x	x	1986 1985 1997 1987 1996	2006 2006 2006 2005 2005
Bahirdar	x	x	x	x	x	1985 1985 1996 1982 1996	2005 2005 2005 2005 2005
Dangla	x	x	x	x	x	1988 1987 1996 1988 1996	2006 2006 2005 2005 2005
Debretabor	x	x	x	x	x	1980 1985 1996 1996 1996	2005 2005 2005 2005 2005
Dek Estifanos	x	-	-	-	-	1990	1995
Delgi	x	x	-	-	-	1997 -	2006 -
Enfranz	x	x	-	-	-	1997 1997	2005 2005
Enjibara	x	x	-	-	-	1987 -	2002 -
Fresbet	x					1985	2000
Gonder	x	x	x	x	x	1985 1985 1996 1996 1996	2006 2006 2005 2005 2005
Gorgora	x	x	-	-	-	1985	2005

						1985	2006
Maksegnit	x	x	-	-	-	1997 1997	2006 2006
Merawi	x	x	-	-	-	1982 2005	2006 2006
Wereta	x	x	-	-	-	1997 1985	2006 2006
Wetet Abay	x	-	-	-	-	1985	2002
Yifag	x	x	-	-	-	2004 -	2005 -
Zege	x	x	-	-	-	1997 1997	2006 2006

In the above table P, T, R.H, n and W.S are precipitation (mm), temperature (o_C), relative humidity (%), sunshine duration and wind speed (m/s) respectively.

Appendix-C1 Monthly Correlation matrix between rainfall stations in Lake Tana Basin

	Ayikel	Addiszemen	Bahirdar	Debretabor	Dangla	Delgi	Enjibara	Gorgora	Gonder	Maksegnit	Zege	Woreta	Enfraz	Yifag
Ayikel	1	0.81	0.88	0.89	0.92	0.90	0.91	0.80	0.90	0.83	0.86	0.82	0.82	0.76
Addiszemen	0.81	1	0.89	0.86	0.82	0.82	0.80	0.68	0.85	0.75	0.88	0.87	0.78	0.66
Bahirdar	0.88	0.89	1	0.90	0.87	0.91	0.86	0.72	0.91	0.78	0.94	0.89	0.80	0.68
Debretabor	0.89	0.86	0.90	1	0.82	0.88	0.88	0.78	0.91	0.86	0.89	0.88	0.85	0.79
Dangla	0.92	0.82	0.87	0.82	1	0.88	0.94	0.74	0.88	0.78	0.85	0.83	0.79	0.70
Delgi	0.90	0.82	0.91	0.88	0.88	1	0.88	0.80	0.90	0.81	0.89	0.87	0.78	0.73
Enjibara	0.91	0.80	0.86	0.88	0.94	0.88	1	0.79	0.87	0.74	0.85	0.80	0.73	0.67
Gorgora	0.80	0.68	0.72	0.78	0.74	0.80	0.79	1	0.80	0.82	0.73	0.72	0.65	0.71
Gonder	0.90	0.85	0.91	0.91	0.88	0.90	0.87	0.80	1	0.83	0.90	0.89	0.84	0.71
Maksegnit	0.83	0.75	0.78	0.86	0.78	0.81	0.74	0.82	0.83	1	0.79	0.78	0.76	0.82
Zege	0.87	0.89	0.94	0.89	0.86	0.90	0.85	0.73	0.90	0.80	1	0.92	0.82	0.68
Woreta	0.82	0.87	0.89	0.88	0.83	0.87	0.80	0.72	0.89	0.78	0.92	1	0.80	0.73
Enfraz	0.82	0.78	0.80	0.85	0.79	0.78	0.73	0.65	0.84	0.76	0.82	0.80	1	0.73
Yifag	0.76	0.66	0.68	0.79	0.70	0.73	0.67	0.71	0.71	0.82	0.68	0.73	0.73	1

Appendix-C2 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	1959	2006	1959	31	28	31	30	31	30						
			1960											30	31
			1961	31										30	
			1962				30	31	30					30	31
			1963	365											
			1964							31	31	30			
			1965										31	30	
			1966							31					
			1967				30		30	31					
			1969	31											
			1970	365											
			1975	31											
			1980								31	30	31	30	31
			1989							31			31	30	
			1999												20
			2000	31	29	7									
			2006								7	1			
Gilgel Abay@Merawi	1973	2006	1986	31							31		31	30	31
Koga @ Merawi	1973	2006	1980												
			1981	365											
			1982	365											
			1990								31	30			
			1991							31	31	30	31		
			2006							31	31	31	31	31	31
Megech@Azezo	1980	2006	1984											30	31
			1989									30	31		
			1991												31
			1992												31
			1998								5				

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
Rib @ Addiszemen	1964	2006	1966					31	30	31					
			1969							31					
			1970					31	30	31	31	30	31		
			1971		29					31	31				
			1975			31	30								
			1980										31	30	31

			1981						30	31					
			1988							31	31				
			1991					31	30	31	31				
Lake Tana water level@ Bahirdar	1959	2006	1959	31	28	31	30	14	5	8				1	
			1960			2			8	10					
			1963	365											
			1965				9	15							
			1991	7	28	31	8								
			1993									11			
Abay out flow@ Bahirdar	1973	2006	1982										22	24	
			1991		4	31	25	31	11						

Appendix-C3 Detail of Transverse Mercator Projection (UTM) used in Lake Tana Basin.

Projection	Universal Transverse Mercator
Spheroid	Clarke 1880
Datum	Adindan
Zone	37
Central Meridian	39
Reference Latitude	0
False -Northing	0
False- Easting	500000
Scale factor	0.9996
Latitude- of -origin	0.00
Linear Unit	Meter (1.00)

Appendix-D Lumped calibrated parameters used for the estimation of runoff in Ungauged catchments.

Catchment	CN	SLP	Ov-N	CNMX	ESCO	EPECO	GW-Delay	α-Base flow factor	GWQMN	GW-Revap	RevapMN	RCHRG -DP
	HRU : AGRL - LVh											
	Calibrated parameters											
Gilgel Abay	77	0.05	0.14	0.5	0.95	0.75	31	0.15	30	0.1	1.0	0.2
Koga	88.94	0.032	0.168	0.0	0.95	0.75	25	0.2	5.0	0.1	1.0	0.2
Gumera	72.42	0.177	0.169	3.0	0.176	0.36	11	0.205	9.0	0.114	4.0	0.055
Rib	61.6	0.078	0.14	7.0	0.67	0.75	16	0.5	15	0.1	22	1.0
Average value	74.99	0.084	0.154	2.63	0.68	0.65	20.75	0.264	14.75	0.104	7	0.455
	HRU : AGRL - VRe											
Gilgel Abay	87	0.05	0.14	0.5	0.95	0.65	31	0.15	30	0.1	1.0	0.2
Koga	95.7	0.032	0.168	0.0	0.95	0.65	25	0.3	5	0.1	1.0	0.2
Gumera	73.64	0.07	0.169	3.89	0.345	0.19	11	0.335	1.0	0.13	10	0.054
Megech	65.61	0.13	0.168	0.0	0.0	0.07	5	0.0746	7.0	0.196	1.0	0.799
Average value	80.48	0.071	0.161	1.09	0.56	0.39	18	0.189	10.75	0.132	3.25	0.313
	HRU : AGRL - NTh											
Gilgel Abay	77	0.093	0.14	0.5	0.95	0.5	31	0.15	30	0.1	1.0	0.2
Koga	88.94	0.168	0.168	0.0	0.95	0.5	25	0.2	5.0	0.1	1.0	0.2
Megech	58.06	0.332	0.168	0.0	0.95	0.01	5	0.0562	5.0	0.199	1.0	0.798
Average value	74.67	0.198	0.158	0.16	0.95	0.34	20.33	0.135	13.33	0.133	1.0	0.399

Catchment	HRU : AGRL - LPe											
	Calibrated parameters											
	CN	SLP	Ov-N	CNMX	ESCO	EPECO	GW-Delay	α-Base flow factor	GWQMN	GW-Revap	RevapMN	RCHRG -DP
Gumera	70.96	0.173	0.169	2.0	0.278	0.18	9.0	0.11	13	0.147	1.7	0.055
Rib	74.39	0.144	0.184	2.0	0.035	0.34	14	0.0525	8.0	0.19	3.0	0.91
Average value	72.67	0.158	0.176	2.0	0.156	0.26	11.5	0.081	10.5	0.168	2.35	0.48
	HRU : AGRL - LVx											
Gumera	72.42	0.077	0.169	3.89	0.345	0.19	9.0	0.206	0.8	0.105	8.0	0.057
Rib	68.40	0.091	0.184	3.0	0.022	0.33	20	0.0453	30	0.19	5.0	0.92
Megech	55.29	0.219	0.168	0.0	0.0	0.01	6.0	0.0512	6.0	0.2	1.0	0.778
Average value	65.37	0.127	0.174	2.29	0.122	0.176	11.67	0.1	12.26	0.165	4.67	0.585
	HRU : AGRL - RGe											
Gilgel Abay	67	0.079	0.14	0.5	0.0	0.0	31	0.15	30	0.1	1.0	0.2
	HRU: AGRL - LPq											
Megech	69.64	0.3	0.168	0.0	0.95	0.65	5.0	0.059	7.0	0.199	3.0	0.798
	HRU: AGRL - ALh											
Gilgel Abay	83	0.095	0.14	0.5	0.95	0.75	31	0.15	30	0.1	1.0	0.2
Koga	95.86	0.031	0.168	0.0	0.95	0.75	25	0.2	5.0	0.1	1.0	0.2
Average value	89.43	0.063	0.154	0.25	0.95	0.75	28	0.175	17.5	0.1	1.0	0.2
	HRU: AGRL - FLe											
Gumera	72.42	0.026	0.169	1.0	0.239	0.29	7.0	0.2	10	0.178	5.0	0.0632
Rib	66.55	0.192	0.154	4.0	0.018	0.54	18	0.055	30	0.188	4.0	0.92
Average value	69.48	0.109	0.162	2.5	0.128	0.41	12.5	0.127	20	5.0	4.5	0.492

Catchment	HRU : AGRC - LVh											
	Calibrated parameters											
	CN	SLP	Ov-N	CNMX	ESCO	EPECO	GW-Delay	α-Base flow factor	GWQMN	GW-Revap	RevapMN	RCHRG -DP
Gilgel Abay	73	0.031	0.14	0.5	0.95	0.0	31	0.15	30	0.1	1.0	0.20
Koga	83.5	0.031	0.14	0.0	0.95	0.0	25	0.20	5.0	0.1	1.0	0.20
Gumera	68.65	0.077	0.169	3.75	0.425	0.3	12	0.335	0.35	0.125	12	0.07
Average value	75.2	0.046	0.149	1.42	0.142	0.1	22.67	0.228	11.78	0.108	4.67	0.157
	HRU: AGRC - VRe											
Gilgel Abay	84	0.076	0.14	0.5	0.0	0.0	31	0.15	30	0.1	1.0	0.2
Koga	88.2	0.031	0.14	0.0	0.0	0.0	25	0.20	5.0	0.1	1.0	0.2
Gumera	79	0.07	0.169	5.56	0.3	0.2	8	0.313	0.50	0.16	15	0.105
Average value	83.73	0.059	0.449	2.02	0.1	0.06	21.33	0.221	11.83	0.12	5.67	0.168
	HRU: AGRC -ALh											
Gilgel Abay	81	0.24	0.14	0.5	0.95	0.0	31	0.15	30	0.1	1.0	0.20
Koga	93.56	0.168	0.168	0.0	0.95	0.0	25	0.20	5.0	0.1	1.0	0.20
Average value	87.28	0.204	0.154	0.25	0.95	0.0	28	0.575	17.5	0.1	1.0	0.20
	HRU: AGRC -LVx											
Gumera	72.27	0.177	0.169	3.2	0.85	0.27	7.0	0.20	6.0	0.13	5.0	0.0515
Rib	67.76	0.293	0.14	5.0	0.65	0.0	9.0	0.27	20	0.13	1.0	0.83
Average value	70.02	0.235	0.155	4.1	0.75	0.135	8.0	0.235	13	0.13	3.0	0.44
	HRU: AGRC -LPe											
Gumera	76.18	0.177	0.169	4.1	0.95	0.33	11	0.206	3.0	0.107	4.0	0.034
Rib	62.45	0.202	0.154	3.0	0.046	0.6	16	0.0657	30	0.187	6.0	0.95
Average value	69.32	0.189	0.162	3.55	0.513	0.465	13.5	0.135	16.5	0.147	5.0	0.495

Catchment	HRU : AGRC - LPq											
	Calibrated parameters											
	CN	SLP	Ov-N	CNMX	ESCO	EPECO	GW-Delay	α-Base flow factor	GWQMN	GW-Revap	RevapMN	RCHRG -DP
Megech	63.34	0.151	0.168	0.0	0.0	0.01	6.0	0.0789	8.0	0.197	1.0	0.789
	HRU: AGRC - NTh											
Koga	84.32	0.168	0.168	0.0	0.0	0.0	25	0.20	5.0	0.1	1.0	0.20
	HRU: PAST - ALh											
Gilgel Abay	79	0.095	0.15	0.5	0.0	0.0	31	0.15	30	0.1	1.0	0.20
	HRU: PAST - LVh											
Gumera	61.65	0.177	0.181	2.70	0.756	0.345	8.0	0.279	7.0	0.112	6.0	0.036
	HRU: PAST -LVx											
Gumera	61.65	0.215	0.181	3.3	0.132	0.225	13	0.219	1.05	0.106	7.0	0.049
	HRU: PAST -LPe											
Gumera	70.97	0.144	0.158	1.0	0.013	0.0	11	0.0112	15	0.198	2.0	0.90
Rib	70.57	0.25	0.181	3.0	0.267	0.32	8.0	0.211	7.0	0.12	13	0.087
Average value	70.77	0.197	0.169	2.0	0.14	0.16	9.5	0.11	11	0.159	7.5	0.494
	HRU: URLD - NTh											
Gumera	62.07	0.195	0.121	3.0	0.91	0.49	10	0.21	9.0	0.158	5.0	0.053
	HRU: URLD - LVx											
Gumera	65.34	0.186	0.121	3.80	0.386	0.23	16	0.30	1.2	0.13	8.0	0.08

Catchment	HRU: AGRL - LVh								
	Calibrated parameters								
	Sol_Z (mm)			Sol_AWC (mm/mm)			Sol_K (mm/hr)		
	Layer-1	Layer-2	Layer-3	Layer-1	Layer-2	Layer-3	Layer-1	Layer-2	Layer-3
Gilgel Abay	200	700	900	0.16	0.16	0.16	1.5	1.5	1.5
Koga	200	700	900	0.11	0.11	0.11	1.8	1.8	1.8
Gumera	180	630	810	0.12	0.12	0.12	1.8	1.8	1.8
Rib	200	700	900	0.19	0.19	0.19	1.5	1.5	1.5
Average	195	682	877	0.145	0.145	0.145	1.65	1.65	1.65
	HRU: AGRL - VRe								
Gilgel Abay	300	500	1000	0.15	0.15	0.15	0.6	0.6	0.6
Koga	300	500	1000	0.11	0.11	0.11	0.72	0.72	0.72
Gumera	270	450	900	0.12	0.12	0.12	0.79	0.79	0.79
Megech	200	356	695	0.16	0.16	0.16	1.8	1.8	1.8
Average	267	451	898	0.135	0.135	0.135	0.98	0.98	0.98
	HRU: AGRL - NTh								
Gilgel Abay	300	500	1000	0.16	0.16	0.16	1.5	1.5	1.5
Koga	300	500	1000	0.11	0.11	0.11	1.8	1.8	1.8
Megech	280	276	695	0.17	0.17	0.17	4.18	4.18	4.18
Average	293	425	898	0.15	0.15	0.15	2.493	2.493	2.493
	HRU: AGRL - LPe								
Gumera	300	700	-	0.16	0.16	0.16	2.76	2.76	2.76
Rib	216	510	-	0.23	0.23	0.23	8.83	8.83	8.83
Average	258	605	-	0.195	0.195	0.195	5.79	5.79	5.79
	HRU: AGRL - RGe								
Gilgel Abay	300	700	-	0.23	0.23	0.23	5.9	5.9	5.9
	HRU: AGRL - ALh								
Gilgel Abay	400	600	800	0.16	0.16	0.16	0.9	0.9	0.9
Koga	400	600	800	0.11	0.11	0.11	1.08	1.08	1.08
Average	400	600	800	0.135	0.135	0.135	0.99	0.99	0.99
	HRU: AGRL - LPq								
Megech	122	260	521	0.17	0.17	0.17	4.18	4.18	4.18
	HRU: AGRL - LVx								
Gumera	810	360	270	0.12	0.12	0.12	0.79	0.79	0.79
Rib	648	296	218	0.16	0.16	0.16	11.74	11.74	11.74
Megech	592	311	209	0.16	0.16	0.16	1.87	1.87	1.87
Average	683	322	233	0.15	0.15	0.15	4.8	4.8	4.8
	HRU: AGRL - FLe								
Gumera	180	360	450	0.18	0.18	0.18	1.19	1.19	1.19
Rib	145	364	435	0.18	0.18	0.18	16.36	16.36	16.36
Average	162	362	422	0.18	0.18	0.18	8.78	8.78	8.78

Catchment	HRU: AGRC - LVh								
	Calibrated parameters								
	Sol_Z (mm)			Sol_AWC (mm/mm)			Sol_K (mm/hr)		
	Layer-1	Layer-2	Layer-3	Layer-1	Layer-2	Layer-3	Layer-1	Layer-2	Layer-3
Gilgel Abay	200	700	900	0.16	0.16	0.16	1.5	1.5	1.5
Koga	200	700	900	0.11	0.11	0.11	1.8	1.8	1.8
Gumera	180	630	810	0.13	0.13	0.13	1.98	1.98	1.98
Average	193	676	870	0.13	0.13	0.13	1.76	1.76	1.76
	HRU: AGRC - VRe								
Gilgel Abay	300	500	1000	0.15	0.15	0.15	0.60	0.60	0.60
Koga	300	500	1000	0.11	0.11	0.11	0.72	0.72	0.72
Gumera	270	450	900	0.12	0.12	0.12	0.79	0.79	0.79
Average	290	483	967	0.13	0.13	0.13	0.70	0.70	0.70
	HRU: AGRC - ALh								
Gilgel Abay	400	600	800	0.16	0.16	0.16	0.90	0.90	0.90
Koga	400	600	800	0.11	0.11	0.11	1.08	1.08	1.08
Average	400	600	800	0.135	0.135	0.135	0.99	0.99	0.99
	HRU: AGRC - LVx								
Gumera	900	400	300	0.16	0.16	0.16	0.79	0.79	0.79
Rib	900	400	300	0.14	0.14	0.14	0.76	0.76	0.76
Average	900	400	300	0.15	0.15	0.15	0.78	0.78	0.78
	HRU: AGRC - LPe								
Gumera	300	700	-	0.16	0.16	0.16	3.04	3.04	3.04
Rib	216	510	-	0.16	0.16	0.16	7.19	7.19	7.19
Average	258	605	-	0.16	0.16	0.16	5.12	5.12	5.12
	HRU: AGRC - LPq								
Megech	139	243	521	0.17	0.17	0.17	0.79	0.79	0.79
	HRU: AGRC - NTh								
Koga	300	500	1000	0.14	0.14	0.14	1.80	1.80	1.80
	HRU: PAST - ALh								
Gilgel Abay	400	600	1000	0.16	0.16	0.16	0.90	0.90	0.90
	HRU: PAST - LVh								
Gumera	180	630	810	0.13	0.13	0.13	1.98	1.98	1.98
	HRU: PAST - LVx								
Gumera	810	360	270	0.17	0.17	0.17	0.79	0.69	0.79
	HRU: PAST - LPe								
Gumera	270	630	-	0.23	0.23	0.23	6.41	6.41	6.41
Rib	216	510	-	0.14	0.14	0.14	3.04	3.04	3.04
Average	243	570	-	0.18	0.18	0.18	4.73	4.73	4.73
	HRU: URLD - NTh								
Gumera	270	450	1620	0.17	0.17	0.17	1.98	1.98	1.98
	HRU: URLD - LVx								
Gumera	810	360	270	0.17	0.17	0.17	0.79	0.79	0.79

Appendix-E Time series data of observed and simulated stream flow of gauged Watershed from a period of 1996 - 2001

Month, year	Gilgel Abay River		Koga River		Gumera River	
	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)
Jan-96	3.58	3.07	1.14	0.24	7.45	0.97
Feb-96	2.27	0.54	0.80	0.03	3.59	0.58
Mar-96	4.08	0.69	0.81	0.02	3.40	0.35
Apr-96	3.91	12.18	1.06	0.05	3.46	0.28
May-96	19.74	26.90	2.18	0.79	8.15	1.54
Jun-96	85.19	51.07	7.35	2.50	57.26	68.24
Jul-96	202.98	129.70	16.26	12.43	179.93	115.30
Aug-96	223.52	192.40	19.95	18.73	201.62	161.20
Sep-96	141.70	110.80	12.15	8.95	102.05	95.36
Oct-96	85.51	59.20	6.05	5.58	36.97	24.48
Nov-96	68.07	17.40	3.18	3.11	22.14	8.98
Dec-96	47.88	4.55	2.19	0.86	15.24	3.73
Jan-97	2.94	1.16	1.64	0.27	10.78	1.81
Feb-97	1.93	0.43	1.25	0.03	8.00	0.98
Mar-97	1.75	0.36	1.08	0.59	6.63	0.85
Apr-97	1.67	0.28	0.88	0.07	4.98	0.83
May-97	18.39	25.81	1.83	0.57	7.56	1.05
Jun-97	60.79	56.20	4.08	1.85	48.37	34.29
Jul-97	160.86	115.60	9.59	9.47	142.58	142.30
Aug-97	196.73	132.70	13.45	19.93	150.36	137.10
Sep-97	125.08	115.10	7.25	7.29	80.05	76.45
Oct-97	63.56	102.50	7.18	3.49	59.28	89.00
Nov-97	35.67	67.22	4.66	0.93	54.69	42.83
Dec-97	10.54	25.34	2.27	0.17	16.90	25.82
Jan-98	4.48	7.70	1.551	0.03	10.33	13.51
Feb-98	2.53	1.45	1.106	0.15	9.76	3.16
Mar-98	1.85	0.57	0.885	0.35	9.68	1.16
Apr-98	1.28	0.45	0.752	0.25	1.62	0.85
May-98	10.13	16.71	1.658	1.34	1.89	8.07
Jun-98	64.30	63.54	3.588	1.76	10.71	11.01
Jul-98	142.70	107.90	11.354	13.92	67.58	126.90
Aug-98	184.56	144.30	16.285	16.89	138.95	193.50
Sep-98	153.73	112.00	12.288	10.48	92.85	142.10
Oct-98	96.14	86.96	12.315	2.66	27.79	50.78
Nov-98	18.32	34.58	4.325	2.07	8.48	16.47
Dec-98	6.54	9.09	2.825	0.50	8.37	4.36
Jan-99	3.72	2.58	2.03	0.08	6.51	1.63
Feb-99	2.14	0.69	1.44	0.02	1.61	1.24
Mar-99	1.43	0.58	1.08	0.26	0.68	0.98

Apr-99	1.71	0.71	0.93	0.49	0.51	0.77
May-99	8.91	22.05	1.49	2.39	0.68	0.64
Jun-99	57.74	115.10	5.01	8.08	4.96	0.60

Month, year	Gilgel Abay River		Koga River		Gumera River	
	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)
Jul-99	163.04	145.40	17.72	28.37	74.09	121.60
Aug-99	186.86	173.60	15.69	17.91	98.50	178.00
Sep-99	127.08	150.60	9.89	13.61	52.52	135.50
Oct-99	122.52	142.30	12.01	12.05	59.93	116.30
Nov-99	19.66	53.06	4.03	2.41	12.61	31.45
Dec-99	7.60	15.54	2.81	0.83	10.41	7.71
Jan-00	3.42	4.19	1.74	0.15	16.59	2.01
Feb-00	2.03	1.05	1.27	0.03	9.98	1.36
Mar-00	1.49	0.61	1.01	0.62	3.40	1.08
Apr-00	3.10	4.91	1.29	1.99	2.54	0.89
May-00	6.08	14.28	1.23	4.29	1.76	1.21
Jun-00	49.04	50.54	2.74	7.26	13.32	14.41
Jul-00	146.03	122.10	8.89	16.49	109.34	153.30
Aug-00	203.22	187.10	24.70	22.29	174.55	179.90
Sep-00	134.16	153.10	9.52	13.45	52.52	124.40
Oct-00	126.98	133.50	15.04	8.27	48.55	65.70
Nov-00	36.71	65.78	5.40	1.73	12.77	30.27
Dec-00	8.95	19.94	2.59	0.50	5.18	9.82
Jan-01	3.83	5.14	1.73	0.06	3.09	2.38
Feb-01	2.33	4.24	1.41	0.28	1.90	1.39
Mar-01	1.80	0.67	1.19	0.37	1.69	1.18
Apr-01	1.79	1.48	0.97	0.23	1.28	1.06
May-01	6.00	5.99	1.32	1.79	1.75	1.07
Jun-01	67.17	51.79	5.98	5.64	14.48	7.13
Jul-01	150.91	130.60	17.47	15.34	93.03	81.98
Aug-01	205.90	169.60	24.89	21.33	200.83	82.34
Sep-01	128.70	174.70	8.71	10.96	57.82	49.99
Oct-01	41.19	70.85	4.82	5.04	13.69	29.43
Nov-01	13.86	28.73	2.79	2.22	5.88	15.02
Dec-01	5.39	8.46	2.03	0.97	3.64	5.06

Month, year	Rib River		Megech River	
	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)
Jan-96	0.55	1.91	0.03	0.97
Feb-96	0.42	1.02	0.01	0.74
Mar-96	0.60	1.38	0.01	0.54
Apr-96	1.47	2.52	0.19	0.33
May-96	7.90	3.65	1.49	0.30
Jun-96	29.17	43.29	11.53	0.47
Jul-96	65.58	58.52	15.27	12.42

Aug-96	83.99	75.99	33.23	26.01
Sep-96	22.32	31.48	7.82	25.50
Oct-96	7.23	8.06	2.06	6.54
Nov-96	2.95	5.41	0.99	3.16
Dec-96	1.37	2.53	0.48	1.98

Month, year	Rib River		Megech River	
	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)
Jan-97	0.74	1.55	0.30	1.37
Feb-97	0.40	1.10	0.20	0.90
Mar-97	0.66	1.95	0.19	0.75
Apr-97	0.46	1.44	0.19	0.54
May-97	4.64	5.62	1.08	0.55
Jun-97	7.62	14.07	6.01	1.07
Jul-97	44.29	59.94	22.80	5.65
Aug-97	52.27	40.13	19.33	9.73
Sep-97	13.02	19.93	4.30	3.84
Oct-97	8.56	37.31	2.88	8.08
Nov-97	7.81	6.93	1.59	2.54
Dec-97	1.63	11.71	0.51	1.67
Jan-98	0.71	2.87	0.21	1.12
Feb-98	0.32	1.64	0.17	0.79
Mar-98	0.26	1.39	0.22	0.59
Apr-98	0.18	0.86	0.20	0.38
May-98	1.29	7.41	0.38	0.40
Jun-98	3.86	7.32	2.16	7.22
Jul-98	48.36	52.36	24.88	20.20
Aug-98	66.48	60.57	20.45	36.95
Sep-98	43.01	35.25	16.02	15.25
Oct-98	12.40	12.13	5.78	6.88
Nov-98	3.98	4.32	1.11	3.28
Dec-98	0.95	2.57	2.04	2.07
Jan-99	0.81	2.25	1.77	1.57
Feb-99	0.49	1.17	1.45	1.02
Mar-99	0.36	0.94	1.39	0.76
Apr-99	0.30	1.66	1.50	0.63
May-99	0.39	1.75	3.03	0.66
Jun-99	3.42	7.26	2.85	1.40
Jul-99	45.27	63.05	11.99	26.56
Aug-99	70.81	63.57	35.81	26.05
Sep-99	39.86	49.43	18.19	21.58
Oct-99	41.03	36.24	10.79	20.87
Nov-99	12.96	8.21	6.17	6.08
Dec-99	13.08	4.24	4.63	3.67
Jan-00	5.05	2.37	3.80	2.08
Feb-00	0.47	1.51	2.68	1.47
Mar-00	0.30	1.07	2.83	0.97

Apr-00	0.99	3.93	4.01	0.92
May-00	0.68	3.02	3.79	0.68
Jun-00	2.01	13.26	5.20	6.94
Jul-00	40.95	86.70	12.71	27.00
Aug-00	69.72	110.20	26.66	25.51
Sep-00	35.08	51.30	12.41	12.82
Oct-00	16.20	21.34	8.79	15.21
Nov-00	5.19	8.89	4.66	4.98
Dec-00	1.50	4.05	3.65	2.61

Month, year	Rib River		Megech River	
	Observed (m^3/sec)	Simulated (m^3/sec)	Observed (m^3/sec)	Simulated (m^3/sec)
Jan-01	0.80	2.39	3.09	1.73
Feb-01	0.48	1.55	3.25	1.20
Mar-01	0.49	2.45	4.45	0.82
Apr-01	0.43	1.14	4.55	0.63
May-01	0.53	5.26	5.51	0.46
Jun-01	15.31	9.60	2.58	11.69
Jul-01	57.55	29.93	22.06	36.05
Aug-01	73.22	35.54	43.07	41.40
Sep-01	26.70	13.20	9.56	12.54
Oct-01	5.06	9.17	2.74	9.23
Nov-01	1.84	4.11	1.46	3.37
Dec-01	0.88	1.93	0.56	2.17

Appendix-F Time series data of simulated stream flow of ungauged watershed in LTB, from a period of 1996 – 2001.

Month	LGAC	Stream-8	LMC	LGC	Ambagenen	Gemero
Jan-96	0.00	0.00	0.00	0.00	0.00	0.00
Feb-96	0.00	0.00	0.00	0.00	0.00	0.00
Mar-96	0.00	0.00	0.00	0.00	0.00	0.00
Apr-96	0.00	0.00	0.00	0.00	0.00	0.00
May-96	0.02	0.00	0.00	0.00	0.00	0.03
Jun-96	0.11	0.00	0.00	0.00	0.02	0.25
Jul-96	13.36	1.00	5.97	0.99	7.97	11.69
Aug-96	60.36	6.37	10.27	4.83	20.67	22.06
Sep-96	29.82	3.23	6.77	2.66	14.94	15.64
Oct-96	13.25	2.21	3.40	1.23	7.97	7.87
Nov-96	6.91	1.40	1.46	0.63	3.70	3.55
Dec-96	5.93	0.97	0.17	0.44	1.08	0.96
Jan-97	3.49	0.51	0.06	0.25	0.52	0.56
Feb-97	1.76	0.22	0.05	0.12	0.34	0.36
Mar-97	1.44	0.10	0.04	0.06	0.26	0.46
Apr-97	1.30	0.04	0.03	0.03	0.21	0.65
May-97	12.50	0.66	0.28	0.02	0.44	2.21

Jun-97	30.63	2.42	0.91	3.63	1.12	4.70
Jul-97	91.82	9.76	4.11	2.80	5.65	21.39
Aug-97	106.40	9.04	6.07	4.66	11.79	29.95
Sep-97	72.71	7.26	1.18	2.12	3.54	4.94
Oct-97	50.25	8.04	6.94	1.52	14.22	8.08
Nov-97	21.33	3.20	1.92	0.74	5.33	2.27
Dec-97	8.48	1.80	0.18	0.51	1.07	0.88
Jan-98	4.91	1.21	0.07	0.31	0.43	0.56
Feb-98	3.33	0.75	0.05	0.15	0.30	0.37
Mar-98	2.56	0.38	0.04	0.07	0.23	0.29
Apr-98	2.07	0.17	0.03	0.04	0.18	0.28
May-98	1.88	0.08	0.07	0.04	0.16	0.75
Jun-98	25.74	1.10	6.68	0.04	10.30	7.86
Jul-98	70.43	5.31	14.37	9.84	27.82	28.32
Aug-98	131.00	14.42	18.10	12.11	35.87	48.95
Sep-98	109.60	9.18	6.51	8.59	15.64	17.53
Oct-98	46.33	3.93	2.38	2.44	5.08	3.95
Nov-98	14.94	2.00	0.28	1.01	1.50	1.21
Dec-98	7.53	1.26	0.11	0.58	0.89	0.73
Jan-99	5.09	0.79	0.08	0.38	0.60	0.46
Feb-99	3.42	0.40	0.06	0.21	0.46	0.31
Mar-99	2.67	0.19	0.05	0.11	0.36	0.21
Apr-99	2.24	0.10	0.05	0.06	0.28	0.16
May-99	13.54	0.26	0.29	0.04	0.28	0.35
Jun-99	48.62	0.94	3.17	0.04	4.15	5.43
Jul-99	139.90	13.07	15.75	5.38	29.29	44.32
Aug-99	176.70	15.64	13.99	13.94	27.09	46.75
Sep-99	114.00	8.01	9.70	6.69	21.00	25.41
Oct-99	118.70	6.79	11.30	8.05	22.55	14.35
Nov-99	29.26	2.43	2.00	1.92	6.15	3.70
Dec-99	11.52	1.44	0.72	0.82	1.96	1.44
Jan-00	6.51	0.95	0.14	0.51	0.97	0.68
Feb-00	4.66	0.51	0.09	0.31	0.66	0.44
Mar-00	3.60	0.26	0.07	0.16	0.49	0.30
Apr-00	3.75	0.14	0.14	0.11	0.40	0.38
May-00	3.08	0.12	0.06	0.14	0.34	0.33
Jun-00	32.13	0.26	6.30	0.21	8.15	3.87
Jul-00	104.00	9.92	14.38	7.61	27.96	25.73
Aug-00	167.70	16.62	12.67	10.12	26.17	40.56
Sep-00	86.30	6.49	6.05	4.68	13.26	12.99
Oct-00	74.31	5.27	7.31	3.23	14.37	8.97
Nov-00	23.61	2.58	1.33	1.27	3.97	1.90
Dec-00	8.85	1.47	0.22	0.65	1.21	0.80
Jan-01	5.37	0.98	0.11	0.45	0.77	0.49
Feb-01	3.96	0.54	0.09	0.26	0.54	0.32

Mar-01	3.17	0.27	0.07	0.14	0.42	0.23
Apr-01	2.62	0.15	0.06	0.08	0.32	0.19
May-01	2.59	0.10	0.06	0.05	0.25	0.44
Jun-01	35.51	0.52	7.20	0.14	7.77	11.67
Jul-01	98.52	5.44	18.19	4.30	30.41	45.07
Aug-01	113.40	11.22	19.71	6.30	39.61	55.12
Sep-01	91.74	8.83	6.78	4.31	16.28	13.32
Oct-01	35.18	3.47	2.80	2.14	6.14	4.50
Nov-01	13.59	1.83	0.38	0.96	1.70	1.40
Dec-01	7.43	1.27	0.14	0.57	1.01	0.85

Month	Arnogarno	LRC	Gelda	Stream-1	Stream-2	Stream-3	Stream-4
Jan-96	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb-96	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Mar-96	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Apr-96	0.07	0.00	0.00	0.00	0.00	0.00	0.00
May-96	1.48	0.00	0.00	0.00	0.00	0.00	0.00
Jun-96	3.43	0.00	0.00	0.01	0.00	0.00	0.01
Jul-96	14.31	0.68	3.16	1.26	1.51	0.98	1.71
Aug-96	18.38	5.77	13.06	2.33	2.99	1.88	3.26
Sep-96	8.46	4.84	5.83	1.62	2.00	1.27	2.21
Oct-96	4.69	2.18	1.30	0.83	1.05	0.66	1.14
Nov-96	3.83	0.99	0.26	0.33	0.50	0.30	0.55
Dec-96	1.41	0.51	0.03	0.05	0.13	0.06	0.12
Jan-97	0.48	0.30	0.03	0.02	0.04	0.02	0.03
Feb-97	0.26	0.21	0.03	0.01	0.03	0.01	0.01
Mar-97	0.45	0.13	0.02	0.06	0.06	0.01	0.01
Apr-97	0.58	0.07	0.02	0.10	0.10	0.00	0.00
May-97	2.81	0.03	0.93	0.29	0.35	0.00	0.00
Jun-97	4.56	0.55	5.82	0.65	0.74	0.01	0.05
Jul-97	13.25	2.94	7.52	2.61	3.37	0.45	0.92
Aug-97	10.41	8.46	11.97	3.41	4.38	0.86	1.42
Sep-97	2.30	5.35	5.44	0.51	0.65	0.17	0.28
Oct-97	7.64	4.18	3.65	0.74	1.07	0.20	0.38
Nov-97	1.06	2.12	1.42	0.14	0.32	0.05	0.09
Dec-97	0.60	0.83	0.18	0.04	0.09	0.01	0.02
Jan-98	0.39	0.44	0.06	0.02	0.05	0.01	0.01
Feb-98	0.17	0.24	0.05	0.02	0.04	0.00	0.01
Mar-98	0.71	0.15	0.05	0.02	0.04	0.00	0.01
Apr-98	0.15	0.08	0.05	0.01	0.03	0.00	0.00
May-98	1.66	0.11	0.05	0.10	0.13	0.00	0.01
Jun-98	7.66	0.14	1.32	0.72	0.79	0.31	0.68
Jul-98	18.97	18.70	20.18	2.86	3.84	1.35	2.34
Aug-98	34.70	20.39	24.69	5.16	6.51	3.13	5.40
Sep-98	9.98	14.95	18.74	1.72	2.19	1.58	2.65

Oct-98	3.58	5.76	5.46	0.23	0.35	0.24	0.39
Nov-98	1.38	2.75	0.88	0.05	0.10	0.05	0.09
Dec-98	0.77	1.04	0.18	0.03	0.06	0.02	0.03
Jan-99	0.54	0.50	0.08	0.02	0.05	0.01	0.02
Feb-99	0.21	0.28	0.08	0.02	0.04	0.01	0.01
Mar-99	0.09	0.18	0.08	0.01	0.03	0.01	0.01
Apr-99	0.08	0.10	0.07	0.01	0.03	0.01	0.01
May-99	0.59	0.21	0.07	0.01	0.03	0.00	0.01
Jun-99	5.18	0.57	0.07	0.72	0.82	0.01	0.05
Jul-99	21.28	12.23	13.96	4.71	6.37	1.16	2.16
Aug-99	24.10	24.35	34.10	5.14	6.63	2.18	3.79
Sep-99	6.71	12.39	15.95	2.46	3.12	1.07	1.84
Oct-99	13.52	14.98	14.03	1.14	1.40	1.30	2.23
Nov-99	1.70	4.29	2.35	0.22	0.41	0.29	0.46
Dec-99	1.12	1.76	0.50	0.06	0.14	0.06	0.12
Jan-00	0.50	0.74	0.12	0.03	0.07	0.02	0.03
Feb-00	0.28	0.38	0.10	0.02	0.06	0.01	0.01
Mar-00	0.14	0.23	0.09	0.02	0.05	0.01	0.01
Apr-00	2.03	0.15	0.09	0.04	0.05	0.01	0.01
May-00	0.51	0.19	0.15	0.02	0.04	0.00	0.01
Jun-00	3.97	0.56	0.47	0.18	0.10	0.01	0.06
Jul-00	13.04	13.24	14.49	2.42	3.27	0.42	0.87
Aug-00	16.56	17.03	33.46	4.32	5.71	1.36	2.28
Sep-00	4.74	9.12	12.68	1.22	1.47	0.53	0.82
Oct-00	3.44	7.27	8.80	0.47	0.76	0.09	0.17
Nov-00	0.80	3.33	1.64	0.06	0.13	0.02	0.03
Dec-00	0.52	1.29	0.30	0.03	0.07	0.01	0.02
Jan-01	0.23	0.60	0.12	0.02	0.05	0.01	0.01
Feb-01	0.10	0.34	0.11	0.02	0.05	0.00	0.01
Mar-01	0.07	0.22	0.11	0.01	0.04	0.00	0.00
Apr-01	0.40	0.14	0.10	0.01	0.03	0.00	0.00
May-01	1.64	0.09	0.10	0.10	0.06	0.00	0.00
Jun-01	6.33	0.33	2.91	0.95	1.30	0.01	0.08
Jul-01	25.68	7.74	16.48	4.56	5.97	1.89	3.42
Aug-01	21.27	10.40	32.46	5.78	7.59	1.74	2.83
Sep-01	3.26	8.93	11.50	1.26	1.64	0.32	0.51
Oct-01	1.53	5.26	4.34	0.27	0.42	0.06	0.14
Nov-01	0.64	2.55	1.05	0.06	0.11	0.02	0.03
Dec-01	0.34	0.99	0.21	0.04	0.08	0.01	0.01

Month, year	Stream-5	Stream-6	Stream-7	West Tana	Month, year	Stream-5	Stream-6	Stream-7	West Tana
Jan-96	0.00	0.00	0.00	0.00	Jul-97	0.41	0.16	0.78	4.60
Feb-96	0.00	0.00	0.00	0.00	Aug-97	2.13	0.75	1.36	6.24
Mar-96	0.00	0.00	0.00	0.00	Sep-97	2.76	2.74	1.54	8.80
Apr-96	0.00	0.00	0.00	0.00	Oct-97	13.64	2.84	5.55	9.49
May-96	0.00	0.00	0.00	0.02	Nov-97	5.68	1.08	1.95	3.84
Jun-96	0.00	0.02	0.01	0.11	Dec-97	0.41	0.30	0.91	1.41
Jul-96	8.29	2.96	2.42	4.85	Jan-98	0.10	0.22	0.44	0.95
Aug-96	14.92	7.16	3.86	17.35	Feb-98	0.03	0.17	0.10	0.67
Sep-96	10.07	5.22	2.81	11.95	Mar-98	0.02	0.14	0.13	0.50
Oct-96	5.14	2.46	2.29	5.04	Apr-98	0.02	0.11	0.02	0.38
Nov-96	2.05	1.14	1.74	2.56	May-98	0.09	0.15	0.35	0.38
Dec-96	0.20	0.40	0.72	1.18	Jun-98	5.37	0.21	3.09	0.51
Jan-97	0.06	0.29	0.34	0.79	Jul-98	16.14	4.58	5.00	7.79
Feb-97	0.02	0.23	0.14	0.51	Aug-98	13.00	6.24	3.64	15.63
Mar-97	0.01	0.18	0.05	0.36	Sep-98	5.25	3.17	2.32	9.98
Apr-97	0.01	0.14	0.02	0.28	Oct-98	1.08	0.94	1.45	3.11
May-97	0.98	0.32	1.08	0.63	Nov-98	0.10	0.37	0.62	1.41
Jun-97	0.80	0.15	0.58	1.22	Dec-98	0.03	0.29	0.26	0.97

Month, year	Stream-5	Stream-6	Stream-7	West Tana	Month, year	Stream-5	Stream-6	Stream-7	West Tana
Jan-99	0.03	0.23	0.05	0.67	Jul-00	10.46	1.58	3.72	7.89
Feb-99	0.02	0.17	0.01	0.48	Aug-00	10.42	5.26	3.12	18.72
Mar-99	0.02	0.14	0.00	0.36	Sep-00	5.59	3.93	2.10	11.94
Apr-99	0.02	0.11	0.00	0.29	Oct-00	3.96	1.30	2.88	4.39
May-99	0.02	0.09	0.04	0.27	Nov-00	1.00	0.62	0.94	2.25
Jun-99	4.03	0.55	2.06	0.80	Dec-00	0.12	0.34	0.50	1.34
Jul-99	12.24	4.53	3.05	12.90	Jan-01	0.05	0.27	0.20	0.95
Aug-99	13.60	7.87	3.73	21.64	Feb-01	0.04	0.21	0.04	0.68
Sep-99	7.79	5.79	2.13	14.74	Mar-01	0.03	0.16	0.01	0.51
Oct-99	9.55	2.27	3.70	4.93	Apr-01	0.03	0.13	0.00	0.40
Nov-99	1.84	0.71	1.37	2.08	May-01	0.03	0.10	0.00	0.36
Dec-99	0.22	0.35	0.73	1.20	Jun-01	0.06	0.13	0.01	0.44
Jan-00	0.08	0.27	0.32	0.84	Jul-01	6.51	0.91	1.63	3.50
Feb-00	0.03	0.21	0.13	0.58	Aug-01	16.35	4.81	4.47	16.64
Mar-00	0.03	0.16	0.03	0.43	Sep-01	8.18	1.15	2.83	5.78
Apr-00	0.04	0.14	0.16	0.36	Oct-01	0.88	0.37	1.21	2.60
May-00	0.03	0.13	0.01	0.36	Nov-01	0.13	0.27	0.62	1.25
Jun-00	3.47	0.13	2.06	0.75	Dec-01	0.06	0.22	0.27	0.91

Appendix-G Annual average basin value of Hydrological variables for gauged and ungauged catchments in LTB

Catchment	PET (mm)	ET (mm)	Rainfall (mm)	Runoff (mm)	Lateral flow (mm)	Base flow (mm)
LGAC	1064.5	537.9	1481	270	270	311
Stream-8	1194.8	580.8	1323	291	10	264
Arno Garno	903	376.7	994	82	450	66
Gumaro	888	432	1434	342	95	276
Ambagenen	875	461	1348	280	44	289
West Tana	1055	506	965	77	49	126
Stream-1	895	451	1417	394	35	286
Stream-2	894	421	1417	427	34	289
Stream-3	897	389	939	175	7	194
Stream-4	897	389	939	207	16	184
Stream-5	910	426	1028	238	4	200
Stream-6	895	426	921	89	52	139
Stream-7	915	421	1062	291	3	198
LMC	873	432	1388	422	8	280
LGC	1198	524	1280	259	14	272
LRC	891	418	1260	279	8	318
Gelda	1173	546	1341	261	8	330
Gigel Abay	1007	598	1847	548	19	475
Koga	1085	530	1212	502	4	104
Rib	807	433	1255	100	241	2.43
Gumera	797	450	1494	272	31	667
Megech	854	503	1499	178	203	91

Appendix-H1 Average simulated inflow (m3/sec) of Lake Tana contributed from Gauged catchments, period 1996 – 2001.

Year	Jan	Feb	Mar	May	APr	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1996	7.16	2.90	2.97	15.36	33.17	165.57	328.37	474.33	272.09	103.86	38.05	13.64	121.46
1997	6.16	3.44	4.51	3.15	33.60	107.48	332.96	339.59	222.61	240.38	120.45	64.71	123.25
1998	25.22	7.19	4.07	2.79	33.93	90.85	321.28	452.21	315.08	159.41	60.71	18.58	124.28
1999	7.30	3.72	3.18	3.84	24.74	119.19	346.48	413.22	333.65	294.98	91.08	28.79	139.18
2000	9.72	4.88	3.91	11.37	21.13	83.16	365.03	472.50	319.56	219.62	100.48	33.23	137.05
2001	10.53	7.80	4.95	4.09	13.11	77.26	264.51	315.19	235.25	111.34	48.10	16.73	92.41
Average	11.02	4.99	3.93	6.77	26.61	107.25	326.44	411.17	283.04	188.26	76.48	29.28	122.94

Appendix-H2 Average simulated inflow (m3/sec) of Lake Tana contributed from un-Gauged catchments, period 1996 – 2001.

Year	Jan	Feb	Mar	May	APr	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1996	0.00	0.02	0.01	0.07	1.55	3.98	83.09	215.52	129.35	62.70	31.90	14.37	45.21
1997	7.79	4.31	3.69	3.60	23.52	58.54	172.54	219.30	122.27	138.42	52.55	17.71	68.69
1998	10.18	6.47	5.34	3.64	6.01	72.52	257.83	398.95	239.57	86.70	28.73	14.76	94.23
1999	7.77	5.02	3.67	2.95	13.05	62.53	277.26	357.39	209.62	203.13	49.54	19.57	100.96
2000	10.34	6.86	4.92	6.46	4.47	50.76	211.41	317.58	148.98	119.06	36.84	14.37	77.67
2001	8.65	5.92	4.43	3.79	4.85	61.04	226.97	299.46	151.17	57.76	21.53	11.66	71.44
Average	7.45	4.77	3.68	3.42	8.91	51.56	204.85	301.36	166.83	111.30	36.85	15.41	76.37

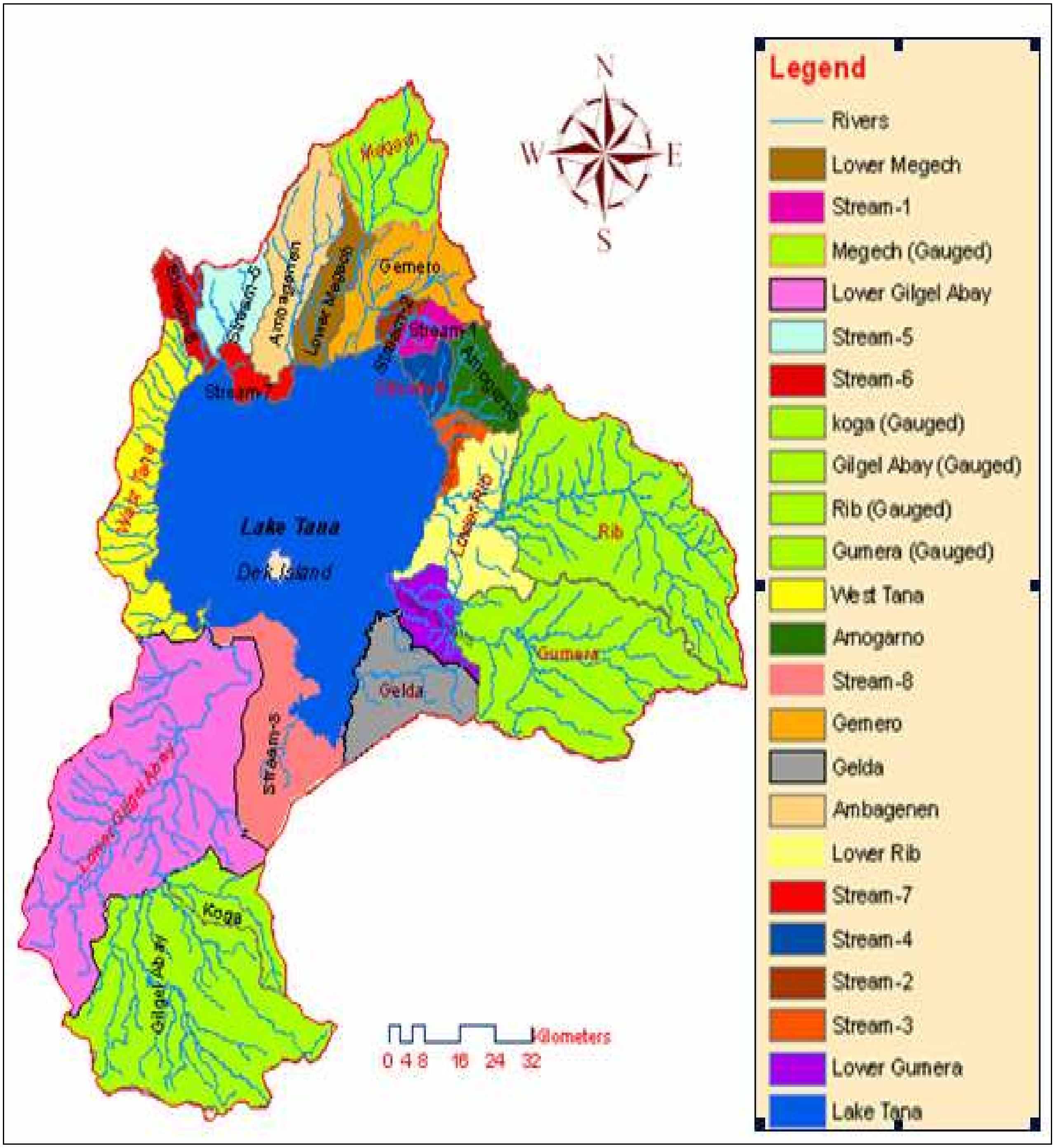
Appendix-I Detail of Monthly Water balance simulation from a period of 1996-2001

(With out the implementation of development projects)

Month	Area (KM^2)	Total Inflow (MCM)	Rainfall (mm)	Outflow (MCM)	Evaporation (mm)	Simulated Volume (MCM)	Observed volume(MCM)	Observed Water level (m)	Simulated Water level (m)
Dec-95							28097.81	1786.68	1786.68
Jan-96	2955.83	19.17	0.11	70.53	142.85	27624.52	27186.24	1786.38	1786.52
Feb-96	2932.50	7.33	0.06	65.31	154.51	27113.61	26626.21	1786.19	1786.35
Mar-96	2918.73	7.98	38.74	65.64	165.17	26686.93	26515.51	1786.15	1786.21
Apr-96	2916.06	40.00	50.87	62.58	168.48	26321.38	25735.99	1785.89	1786.09
May-96	2897.49	93.00	121.50	66.59	129.46	26324.73	25503.58	1785.82	1786.09
Jun-96	2892.04	439.47	251.67	75.70	117.36	27076.92	25849.31	1785.93	1786.34
Jul-96	2900.16	1102.06	363.16	68.21	110.48	28843.59	26862.70	1786.27	1786.93
Aug-96	2924.50	1847.68	310.72	297.95	106.02	30991.97	29584.37	1787.18	1787.65
Sep-96	2997.15	1040.53	215.68	1395.93	130.32	30892.41	31108.42	1787.69	1787.62
Oct-96	3045.17	446.14	23.75	1144.65	157.73	29785.91	30596.74	1787.52	1787.25
Nov-96	3028.31	181.32	39.73	626.92	141.12	29033.28	29596.34	1787.18	1786.99
Dec-96	2997.51	75.03	0.11	440.52	145.08	28233.24	28868.51	1786.94	1786.73
Jan-97	2976.67	37.37	0.00	286.45	142.10	27561.16	28124.80	1786.69	1786.50
Feb-97	2956.54	18.76	0.00	202.66	146.83	26943.14	27548.96	1786.50	1786.30
Mar-97	2941.63	21.96	16.34	299.69	167.40	26221.04	26823.77	1786.26	1786.06
Apr-97	2923.55	17.51	14.92	261.93	148.32	25586.63	26070.18	1786.01	1785.84
May-97	2905.39	152.99	190.47	255.73	143.96	25619.01	25584.00	1785.84	1785.85
Jun-97	2893.93	430.31	161.91	251.83	108.36	25952.46	25581.02	1785.84	1785.97
Jul-97	2893.86	1353.91	271.70	183.41	102.67	27612.11	26419.81	1786.12	1786.52
Aug-97	2913.75	1496.93	176.14	368.83	111.23	28929.34	28310.77	1786.75	1786.96
Sep-97	2961.48	893.94	160.07	512.70	138.96	29373.10	29237.08	1787.06	1787.11
Oct-97	2987.07	1014.57	250.88	626.76	142.48	30084.72	29290.99	1787.08	1787.35
Nov-97	2988.62	448.41	33.11	591.70	142.56	29614.33	29359.87	1787.10	1787.19
Dec-97	2990.60	220.74	2.59	413.95	149.17	28982.76	28694.63	1786.88	1786.98
Jan-98	2971.87	94.82	0.28	360.97	143.59	28290.70	27944.83	1786.63	1786.75
Feb-98	2951.82	33.07	0.00	92.29	142.46	27810.95	27282.14	1786.41	1786.59
Mar-98	2934.90	25.20	26.19	48.35	167.03	27374.44	26763.89	1786.24	1786.44
Apr-98	2922.09	16.66	5.86	78.28	164.88	26848.17	26303.21	1786.08	1786.27
May-98	2910.95	106.99	62.95	117.96	146.94	26592.71	25843.35	1785.93	1786.18
Jun-98	2900.02	423.44	219.92	39.36	127.80	27243.93	25670.41	1785.87	1786.40
Jul-98	2895.95	1551.08	383.57	233.54	84.82	29426.64	26545.43	1786.16	1787.13
Aug-98	2916.78	2279.75	406.84	690.82	94.86	31925.55	29174.18	1787.04	1787.96
Sep-98	2985.27	1437.66	167.63	1695.76	119.16	31812.13	31239.05	1787.73	1787.93
Oct-98	3049.60	659.17	72.52	1469.38	143.96	30784.05	30906.31	1787.62	1787.58
Nov-98	3038.41	231.83	2.23	857.30	144.72	29725.62	29940.24	1787.30	1787.23
Dec-98	3007.79	89.31	0.87	497.75	136.52	28909.16	28868.51	1786.94	1786.95
Jan-99	2976.67	37.94	17.30	360.17	144.34	28208.80	28229.79	1786.73	1786.72

Feb-99	2959.32	20.70	0.00	310.04	156.25	27457.06	27536.97	1786.50	1786.47
Mar-99	2941.33	17.26	0.00	176.40	163.31	26817.58	26692.05	1786.21	1786.25
Apr-99	2920.33	16.38	9.17	163.15	169.20	26203.47	26064.20	1786.00	1786.05
May-99	2905.25	93.43	39.98	62.70	143.22	25934.27	25566.13	1785.84	1785.96
Jun-99	2893.51	434.70	195.83	122.78	116.64	26475.31	25209.05	1785.72	1786.14
Jul-99	2885.18	1558.36	367.43	251.13	95.23	28567.88	26067.19	1786.00	1786.84
Aug-99	2905.32	1929.20	411.57	484.52	104.53	30904.60	28571.69	1786.84	1787.62
Sep-99	2968.51	1305.35	119.00	1058.25	119.52	31150.14	30292.61	1787.41	1787.70
Oct-99	3018.65	1239.65	204.80	1256.95	132.06	31352.43	30593.76	1787.52	1787.77
Nov-99	3028.21	336.68	5.99	916.35	145.44	30350.46	30194.12	1787.38	1787.43
Dec-99	3015.58	120.31	2.87	533.81	142.48	29515.96	29084.30	1787.01	1787.16
Jan-00	2982.72	50.49	0.00	357.54	142.85	28782.83	28400.75	1786.78	1786.91
Feb-00	2963.89	27.86	0.00	226.07	150.68	28138.01	27653.91	1786.53	1786.70
Mar-00	2944.31	22.32	0.20	89.84	174.84	27556.29	27075.37	1786.34	1786.50
Apr-00	2929.75	42.75	77.47	213.16	138.96	27205.72	26503.55	1786.15	1786.38
May-00	2915.77	62.14	58.98	50.98	147.31	26959.31	26111.99	1786.02	1786.30
Jun-00	2906.39	321.56	189.44	16.62	119.88	27466.43	25971.66	1785.97	1786.47
Jul-00	2903.06	1428.31	357.34	274.20	100.07	29367.41	26895.64	1786.28	1787.11
Aug-00	2925.31	1965.02	340.56	630.47	95.23	31419.62	29165.19	1787.04	1787.79
Sep-00	2985.02	1117.66	117.40	1156.26	122.04	31367.18	30596.74	1787.52	1787.78
Oct-00	3028.31	837.81	140.23	1178.44	132.80	31049.02	30572.90	1787.51	1787.67
Nov-00	3027.54	325.82	14.98	861.45	138.96	30138.04	30080.66	1787.34	1787.36
Dec-00	3012.08	117.12	0.14	471.03	137.27	29371.08	29213.12	1787.05	1787.11
Jan-01	2986.39	47.94	0.00	133.51	143.59	28856.70	28511.72	1786.82	1786.94
Feb-01	2966.88	30.91	0.05	187.35	144.14	28272.74	28112.81	1786.69	1786.74
Mar-01	2956.22	23.51	0.66	444.72	151.78	27404.80	27246.17	1786.40	1786.45
Apr-01	2934.00	19.14	7.11	478.92	158.76	26500.07	26297.23	1786.08	1786.15
May-01	2910.81	44.02	90.94	351.11	138.38	26054.87	25402.37	1785.78	1786.00
Jun-01	2889.68	334.26	179.71	360.96	100.08	26258.27	25128.81	1785.69	1786.07
Jul-01	2883.31	1230.16	294.89	542.75	94.12	27524.58	25533.36	1785.83	1786.49
Aug-01	2892.74	1542.56	346.45	545.03	96.35	29245.58	28466.73	1786.81	1787.06
Sep-01	2965.66	929.00	173.76	888.68	126.72	29425.41	30176.21	1787.38	1787.12
Oct-01	3015.03	417.87	47.34	719.89	144.34	28830.93	29742.92	1787.23	1786.93
Nov-01	3001.85	165.96	8.21	468.79	140.04	28132.35	29015.38	1786.99	1786.69
Dec-01	2980.78	70.68	4.19	387.26	144.34	27398.02	28235.78	1786.73	1786.45

Appendix-J Gauged and ungauged catchments analyzed in SWAT for runoff estimation



Appendix-K Elevation-Volume-Area relation ship of Lake Tana with out the implementation of development projects.