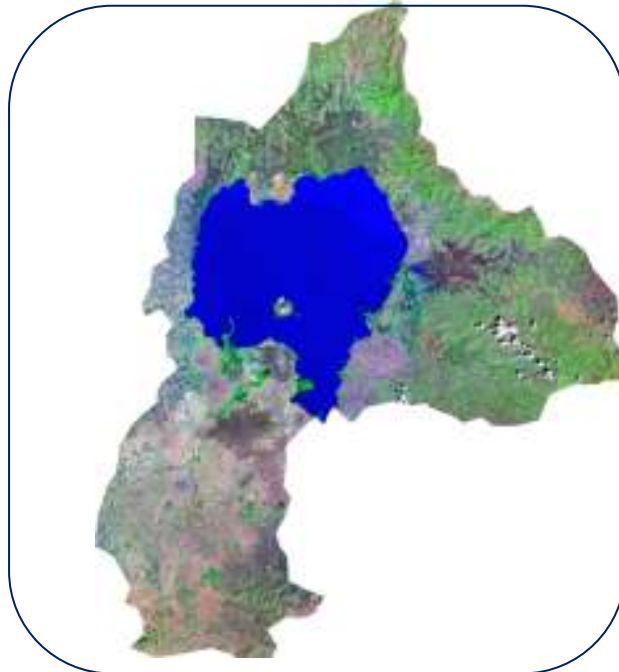




**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCES**

BASEFLOW ANALYSIS OF RIVERS IN LAKE TANA SUB BASIN



**A THESIS SUBMITTED TO SCHOOL OF GRADUATE STUDIES IN
PARTIAL FULFILMENT OF THE REQUIREMENTS FOR DEGREE OF
MASTER OF SCIENCE IN HYDROGEOLOGY**

**By
Getachew Zewdie
February, 2010**

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SCHOOL OF GRADUATE STUDIES
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UPPER BLUE NILE BASIN

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HYDROGEOLOGY*

Advisor: Seifu Kebede (PhD)

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February, 2010

Addis Ababa

DECLARATION

I declare the BASEFLOW ANALYSIS OF RIVERS IN LAKE TANA SUB BASIN , UPPER BLUE NILE BASIN is my own work, that it has been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledge by complete reference.

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Signature_____

This thesis has been submitted for examination with my approval as a university advisor

Seifu Kebede (PhD)

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Place and Date of Submission

Addis Ababa University School of Graduate Studies

February, 2009

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LISTS OF ACRONYMS

Adj. R2	Adjusted coefficient of Determination
AET	Actual evapotranspiration
BFI	Baseflow index
CN	Curve number
Dd	Drainage density
DEM	Digital Elevation Model
GSE	Geological Survey of Ethiopia
HMS	Hydrological Modeling System
ITCZ	Inter Tropical Convergence Zone
MER	Main Ethiopian Rift
MoWR.	Ministry of Water Resources
NMA	National Meteorological Agency
NA	Not Applicable
PEPF	Percentage Error in Flow Peak
PET	Potential evapotranspiration
PEV	Percent volume error
R	Correlation Coefficient
r2	Coefficient of determination
SCS	Soil Conservation Service
S.E. of Estimate	Standard error of intercept
SMA	Soil Moisture Accounting

ABSTRACT

The Lake Tana sub basin is situated on the northwestern plateau of Ethiopia at the headwaters of the Blue-Nile basin, west of the Afar depression. The drainage area of the lake is approximately 15,000 square kilometers, of which 3062 is the lake area. Topographic high surrounding the basin forces the major River systems to drain toward Lake Tana. The altitude of the basin ranges between 1765m to 3000 m a.m.s.l. The climate of the region is ‘tropical highland monsoon’ with one rainy season between June and September. The rainfall data for 23 long-term records of rainfall stations lying within or around the Tana sub Basin are used for the computation of rainfall. The Tana sub Basin receives an average annual rainfall of 1329 mm. The air temperature shows small seasonal changes with an annual average of 20°C. The major geological formations that outcrops in Lake Tana sub-basin and its adjacent areas are Tertiary and Quaternary volcanic rocks and alluvial along the major tributaries of the Lake Tana sub-basin. Alluvial sediments have limited distribution within Lake Tana sub-basin dominant at the eastern and northern side of the Lake. The understanding and knowledge of hydrology and hydrogeologic systems is very crucial for every activities involving economic development in the Lake Tana sub basin. Groundwater recharge is one of the most important factors governing the sustainable yield of groundwater and surface water exploitation. The recharge estimation of the Lake Tana sub basin was carried out based on the principle of base flow separation using HMS – SMA for gauged catchments on daily bases. The hydrological and meteorological data used for the period of 1992 to 2006. StatistiXL Multiple linear regression was used to estimate the runoff for ungauged catchments. A level of significance of 0.05 was used for the forward and backwards stepwise regressions. Climate and physical characteristics of the catchments were used in multiple regression to predict the flow characteristics of ungauged catchments. The amount of rainfall, topographic setting and geology are the main controlling factors of climate and physical characteristics of the catchments. The groundwater contribution from gauged catchments is about 161.17mm/yr or 12.1% of the total rainfall of the basin. The ungauged catchments contribute a total of 28.18 mm/yr or 2.28% of the total rainfall of the basin.

CHAPTER ONE

INTRODUCTION

1.1. Background

The Blue Nile drains a large area of the Ethiopian highlands and is the largest tributary of the Nile River. The hydrology of the Blue Nile has received less attention in scientific literature in contrast to the abundant information about the history of the White Nile sources (Livingstone, 1980). Lake Tana sub-basin is one of the richest water resources and high potential land for agriculture and livestock development is located at the head water of this basin. The agricultural activity and energy supply in the country is highly dependent on the rainy season. Now a day due to climate changes in the world, the rainfall pattern retarded the increasing grows of agriculture, water supply and hydroelectric power which are play a great role in the economic development of the country. Wetlands, natural springs and surface waters are drying now a day. The alarming increasing of population density, poor extensive cultivation, uncontrolled settlement in the basin poses a problem on the natural ecosystems. Land use practices involving deforestation in any farm causes a reduction in the infiltration capacity, and groundwater recharge, increases in surface runoff and erosion, increase in evaporation from the soil and surface storages. These problems are common in the region of heavy population growth. To overcome these problems and for sustainable development, large funds are being invested in the Lake Tana sub basin for the proper land use management and development of both surface and groundwater resources for drinking, irrigation and hydroelectric power (Engida *et.al*, 2007). The irrigation project conducted on the Ribb, Gummera and Koga, extensive investigation of groundwater resources and hydroelectric power on the Tana – Beles are among the activities carried out in the sub basin. The understanding and knowledge of hydrology and hydrogeologic systems is very crucial for every activities involving economic development in the basin. Groundwater recharge is one of the most important factors governing the sustainable yield of groundwater and surface water exploitation.

The knowledge of the water utilization and system of managing the available water depends on the understanding and controlling factors of the amount that enters and leaves the basin.

The amount of water that extracted from an aquifer and surface water without causing depletion is primarily dependent upon the amount and rate of recharge. Quantification of the rate of natural recharge is a basic pre-requisite for efficient ground water and surface water resource management. It is particularly important in the sub-basin with large demands for ground water and surface water supplies, where such resources are the key to economic development. Since the basin is relevant for Ethiopia and North-eastern countries, it is highly beneficial to carry out the recharge estimation in Lake Tana sub-basin continuously in the future.

1.2 Objective

General objective

Recharge estimation of the Tana sub basin is one of the key factors necessary for effective and rational management of groundwater resources. Therefore, this study focuses on the recharge estimation in the Tana sub basin.

Specific Objective

- Quantification of the recharge in the Tana sub basin
- To identify catchment characteristics that can be used for predicting flow characteristics of ungauged catchments

1.3 Previous works

BCEOM (1998). The Abay River Basin Integrated Development Master Plan Project. This study in its Climatology, Hydrology and Hydrogeology has valuable information regarding the overall Abay basin. In its Hydrogeology part the study was conducted with the following objectives. The assessment of the recharge is based on hydric balance which includes rainfall, evapotranspiration, direct runoff and working hypothesis over the distribution of the soil retention capacity. This hypothesis is cross checked through water table

fluctuation. The result obtained for Gilgel Abay, Koga, Ribb, Gummera and Megach was 305mm, 203mm, 35mm, and 90,55mm respectively.

Getachew (2008). Ground water contribution and Recharge estimation in the upper Blue Nile flows. According to this study ground water recharge of the basin was estimated by baseflow, rainfall-runoff simulation using BASF model and by a chemical balance method (chloride as a tracer's chemical species).

The results from chemical analysis. BASF model and baseflow separation using Eckhardt (2005) model were selected to represent the natural groundwater recharge of the basin and thus, the value was found vary between 70mm to 120mm per annum.

Kebede et al. (2006). Established the water balance of Lake Tana and its sensitivity to fluctuations in rainfall (1960-1992) on monthly basis. In flow from the ungauged catchments is estimated from a runoff coefficient ($\alpha=0.22$). The inflow from ungauged catchments is estimated to contribute less than 7% of the total inflow.

Kebede, et al. (2005). Groundwater recharge, Circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. This study uses Geochemical and environmental isotopes to gain the first regional picture of groundwater recharge, circulation and its hydrochemical evolution in the Upper Blue Nile basin of Ethiopia. According to their study two major structurally deformed regions with distinct groundwater circulation and evolution history were identified.

SMEC (2007). Simulated water balance of the Lake Tana from the period 1960 to 1995 using a simple monthly spreadsheet model. In flow from the ungauged catchment is estimated to be 1.41 times the inflow from five gauged catchments.

Wale (2008). The hydrological balance of Lake Tana Upper Blue Nile Basin. In this study the Lake Tana hydrological system shows a gap with respect to major lake water balance components where 48% of the catchment is ungauged. In this paper daily lake level is simulated giving due emphasis on runoff from ungauged catchments using rainfall-runoff and spreadsheet water balance model. Daily flows from ungauged catchment are estimated by transferring model parameters of gauged catchments using semi-distributed conceptual model HBV. Calibrated model parameters of gauged catchments with a relative volume error less than $\pm 5\%$ and Nash-

Sutcliffe coefficient greater than 0.6 are transferred to ungauged catchments based on regional model, spatial proximity and catchment area, the result of ungauged flow simulation indicates that 42%, 47% and 46% of the inflow is coming from ungauged catchments respectively.

1.4 Research frame work

To quantify the spatial and temporal variability of the recharge, recharge estimation method need to be selected in order to achieve the objectives using limited data sets available in the study area. In attempt to meet the primary and the specific objectives mentioned above, an outline of research process is illustrated in Figure 1.1. The data sets of climate, geomorphology, soil and vegetation are necessary because they influence synthetically the processes of recharge.

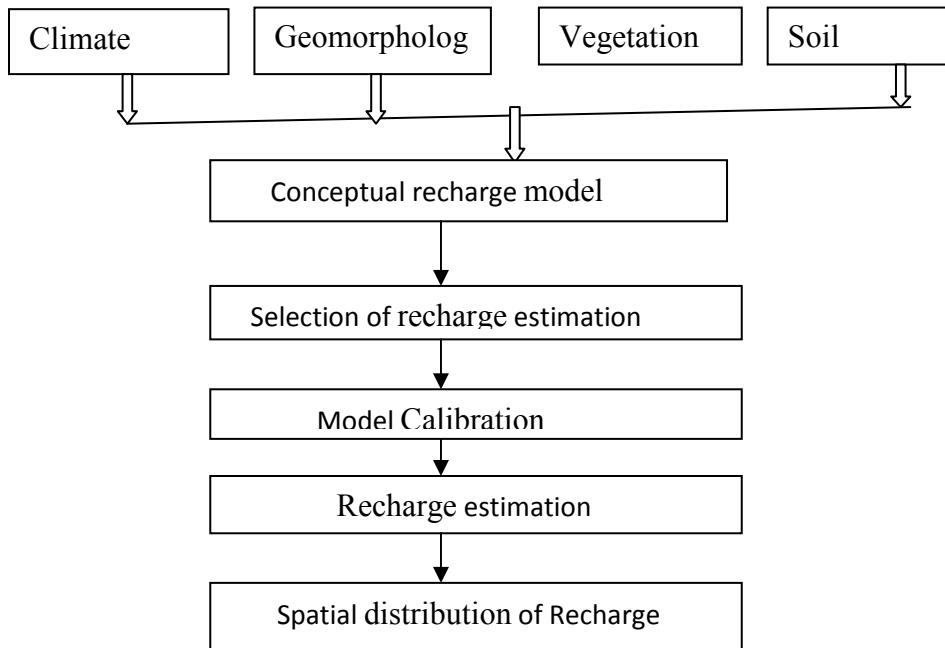


Figure 1.1 Flow diagram for study of recharge estimation in the Tana Sub Basin

CHAPTER TWO

LOCALITY DESCRIPTION

2.1. Location and extent of the study area

The Lake Tana basin is situated on the northwestern plateau of Ethiopia at the headwaters of the Blue-Nile basin, west of the Afar depression. The drainage area of the lake is approximately 15,000 square kilometers, of which 3062 is the lake area. The geographical location of the Tana basin extends from 10° 57'N to 12° 47'N latitude and from 36°53'E to 38°15'E longitude. The area is accessed through the Addis to Bahir Dar and Gonder asphalt paved road. There are many all weather roads running through the basin.

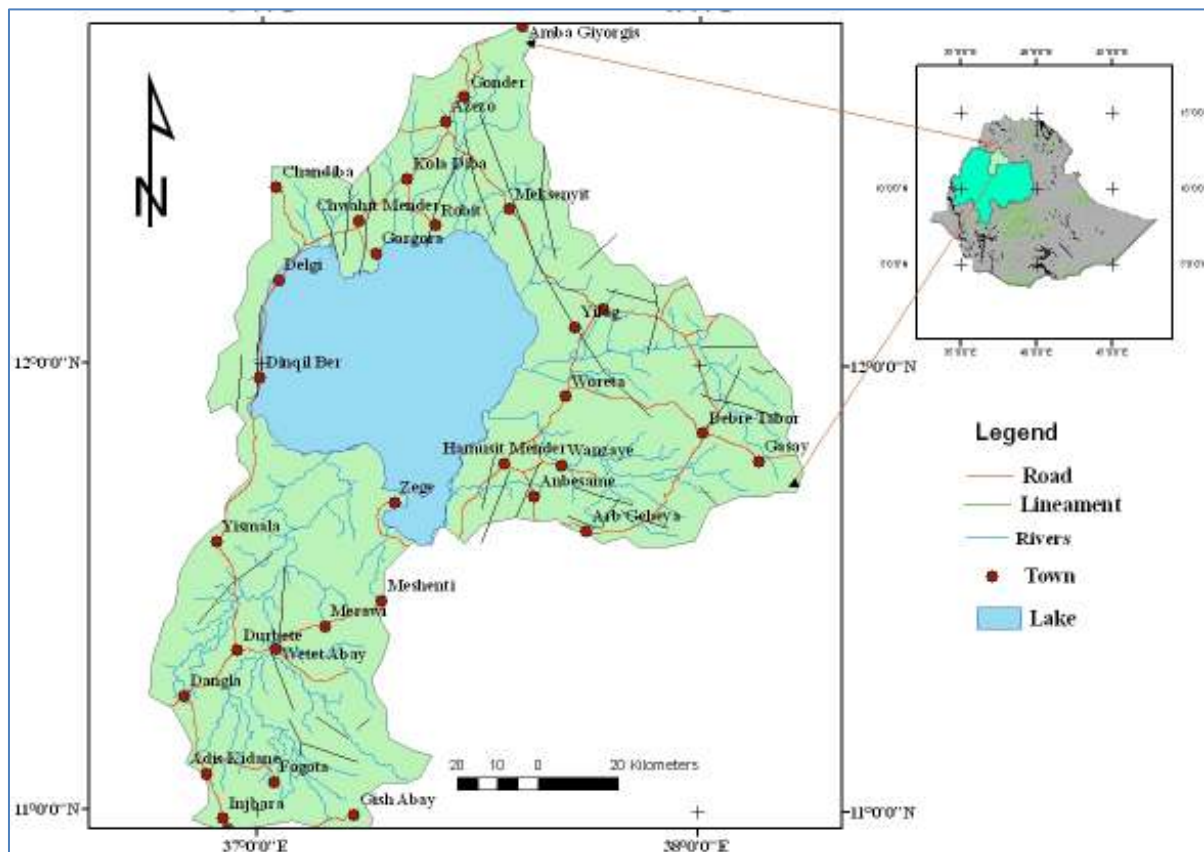


Figure 2.1 Location map of Lake Tana sub basin

2.2. Topographic characteristics

The Tertiary and Quaternary volcanic eruption, together with erosion due to steep streams and large Rivers play a major role for the present topographic setting of the area. Lake Tana was formed primarily by recent volcanic activity which made a natural dam as it poured lava across the valley outlet. The basin is perched on a topographic high. New data from digital elevation modeling and satellite imagery analysis confirm the basin's location at the junction of three grabens: the Dengel Ber (buried), Gondar (exposed by erosion) and Debre Tabor (reactivated), (J.Chorowicz *et al*, 1998). Around Lake Tana the topography is strongly controlled by faulting and major lineaments. Topographic high surrounding the basin forces the major River systems to drain toward Lake Tana. The altitude ranges between 1765m to 3000 m a.m.s.l. The eastern and the southern margin of the basin are elevated above 2000 m. The surface geology of the basin is characterized by the outcropping of Tertiary and Quaternary volcanic rocks. Mountain Choke and Guna make a solid boundary in the South and East of the basin. The Chilga mountain ridge and Gonder graben form the boundary in the West. The Gilgel Abay rises in elevated terrain that occurs off the flanks of Mt Choke and flows across largely basaltic terrain into the Lake Tana. Gummera is one of the main Rivers on the east side flowing to Lake Tana. It drains mountain Guna and drops its load in the low land to the mouth of Lake Tana. Megach River drains Northern highlands and flows toward Lake Tana. The River changed its course in kola Diba village and deposited large sediment in the flat land. Ribb River drains highlands of Debre Tabor and flows across the flat land from Woreta to Lake Tana. There are extensive flood plains in the downstream ends of Ribb and Gumera River, which prone to long term flooding. The slopes of the Basin are generally converged into Lake Tana.

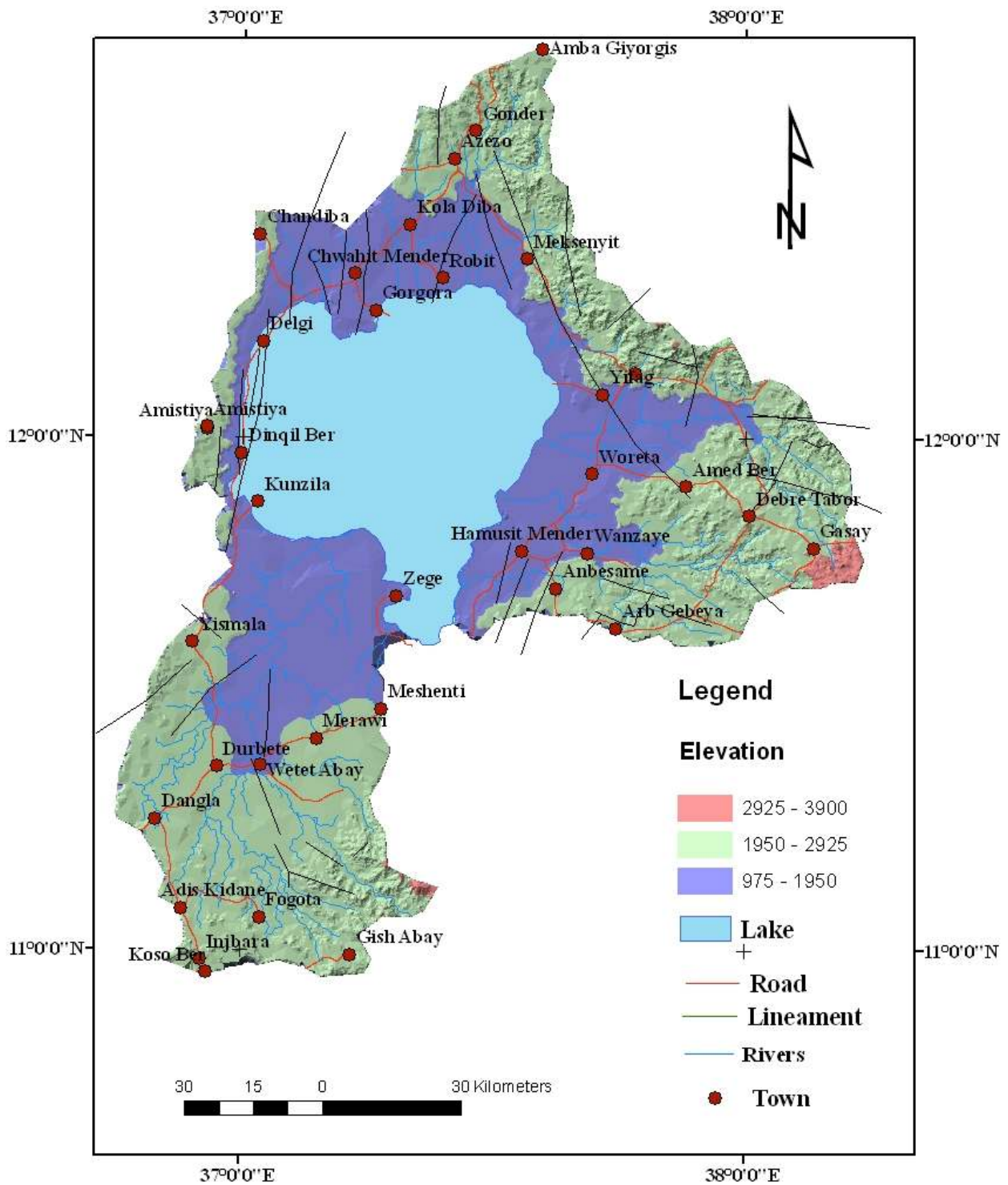


Figure 2.2 Topographic setting of the study area.

2.3. Climate

The climate of the region is ‘tropical highland monsoon’ with one rainy season between June and September. The air temperature shows small seasonal changes with an annual average of 20°C. The seasonal distribution of rainfall is controlled by the northward and southward movement of the inter-tropical convergence zone (ITCZ). Moist air masses are driven from the Atlantic and Indian Oceans during summer (June–September). During the rest of the year the ITCZ shifts southwards and dry conditions persists in the region between October and May. Generally, the southern part of the Lake Tana basin is wetter than the western and the northern parts (Kebede *et.al.*, 2006).

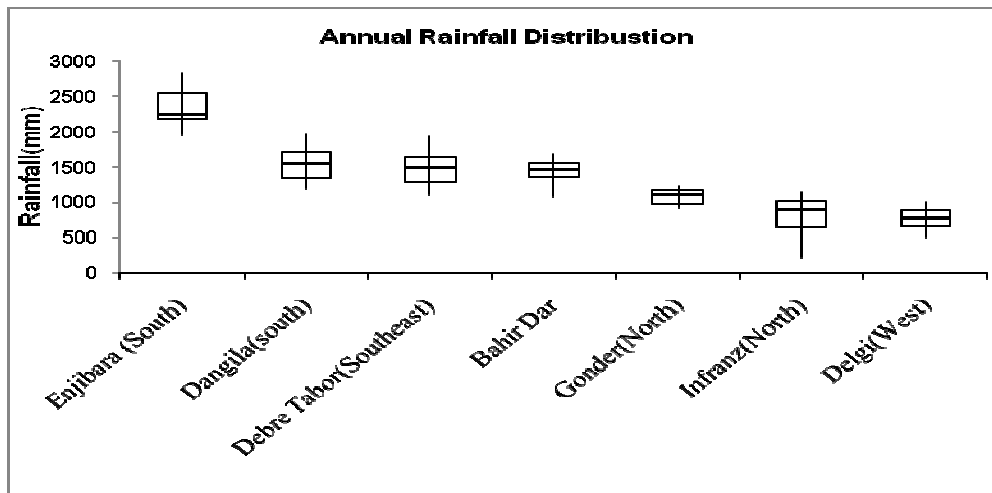


Figure 2.3 The box & whisker plot displays annual rainfall, and shows the mean for the data by the horizontal line, the quantiles by the box, and the range by the vertical lines.

2.4. Drainage and Catchment characteristics

2.4.1. Drainage Pattern

The drainage pattern in the basin is mainly characterized by dendritic pattern and controlled by structures. There are four major perennial rivers, which drain in to Lake Tana. Drainage density (Dd) of the area is derived by dividing the total stream length within a catchment by the

catchment area, and is regarded as an important landscape characteristic .It is a measure of how dissected a basin is, and it is expected that drainage density affects the transformation of rainfall into runoff (REDDY, 2001). The drainages of the basin are generated by using GeoHMS ArcGIS extension. The streams density is compared with topographical map of the study area.

The total stream length for each catchment is then estimated using standard routines available in most GIS packages. . In general the central part of the basin has the lowest Dd values, while the Northern Highland region has relatively the highest values.

Table 2.1 Characteristics of catchments.

Catchments	Area(Km2)	Drainage density	Shape factor	Elongation ratio	Width(Km)	overland flow(Km)
Gauged Megach	492	0.2	3.0	0.6	12.7	2.1
Ungauged Megach	315.3	0.3	7.2	0.4	6.6	1.7
Gauged Gummera	1394	0.2	5.9	0.5	14.5	2.1
Ungauged Gummera	127	0.2	5.3	0.5	4.8	2.8
Gauged Ribb	1592	0.3	5.8	0.5	14.6	1.7
Ungauged Ribb	418	0.2	5.2	0.5	9.0	2.3
Koga	301.55	0.3	5.6	0.5	7.3	2.0
Kility	698.36	0.2	4.2	0.5	12.9	2.2
Gauged Gilgel Abay	1640	0.3	4.1	0.6	19.8	1.9
Ungauged Gilgel Abay	1481	0.2	6.4	0.4	15.3	2.1

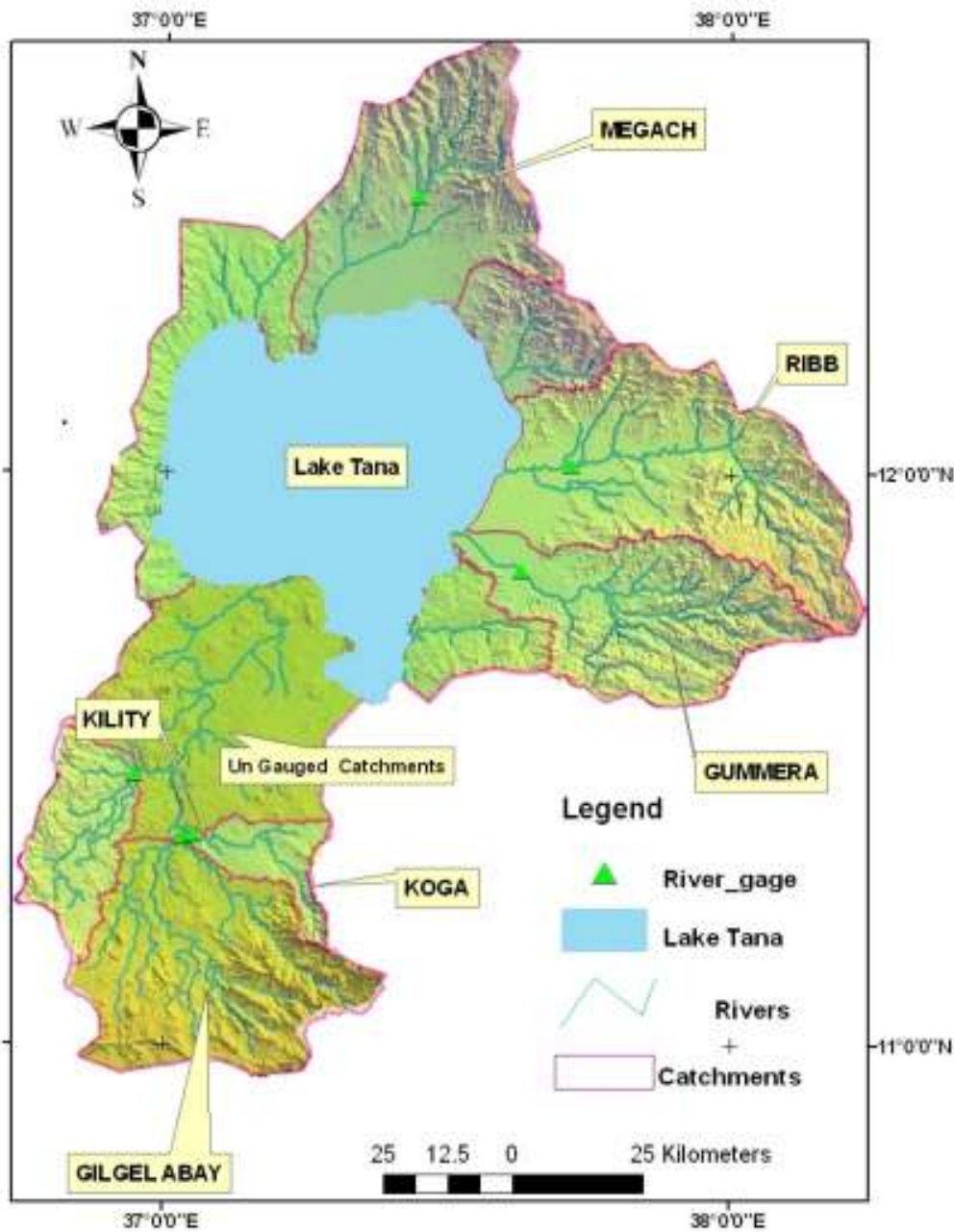


Figure 2.4 Drainage systems in Lake Tana sub basin.

2.4.2. Slope

Slope is an important characteristic of a catchment as it gives an indication of the kinetic energy available for water to move towards the basin outlet, and it has been found to be related to total runoff and base flows (REDDY, 2001). The main purpose of the slope in this study is to determine the amount of surface depression storage. Slope roughness causes friction between the

ground and air passing over it and causes atmospheric turbulence that increases evapotranspiration. Steep slopes promote the formation of runoff. Areas with steep slopes generally have high altitudes and high rainfall, e.g. south and south east high land of the study area.

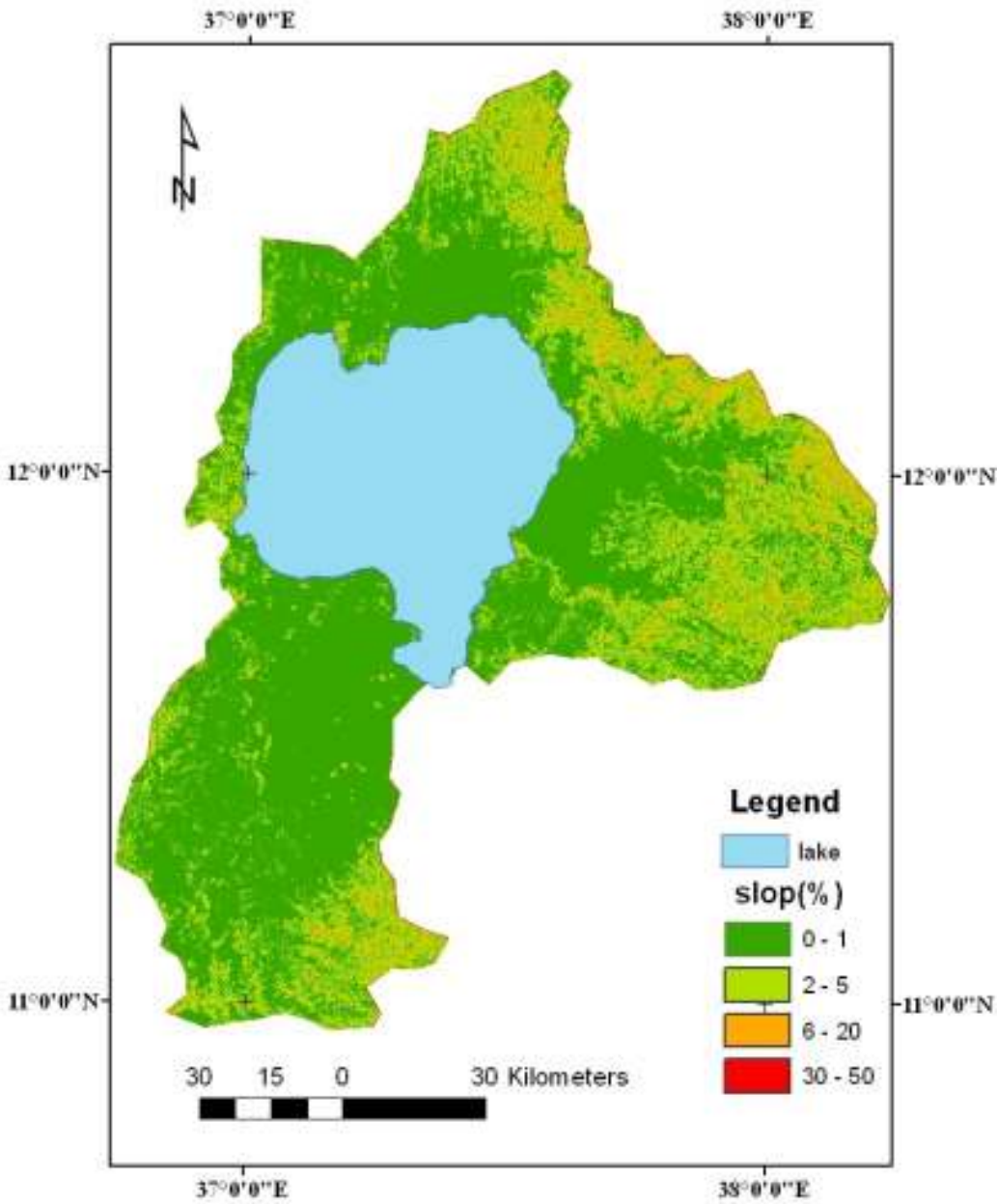


Figure 2.5 slope map of the study area.

2.5. Land Use and land cover

Land cover has been shown in several studies to affect flow characteristics. The amount of evapotranspiration is also related to the percent vegetation cover, density, type, species, and spatial composition and growth stage. The land use and land cover is one of the parameter used to initialize the model to estimate recharge. The land use and land cover governs both flow characteristics and evaporation condition of the model. Most of the Lake Tana Sub Basin is characterized by cropland with scarce woodlands while only few limited areas of highlands are forested (less than 1% of the basin). The major land cover types are cropland 45%, woody land 18% water body (20%), Grass land (13%), and bare land (2%) Forest (1%), and urban and built 0.2 %,(Wale, 2008).

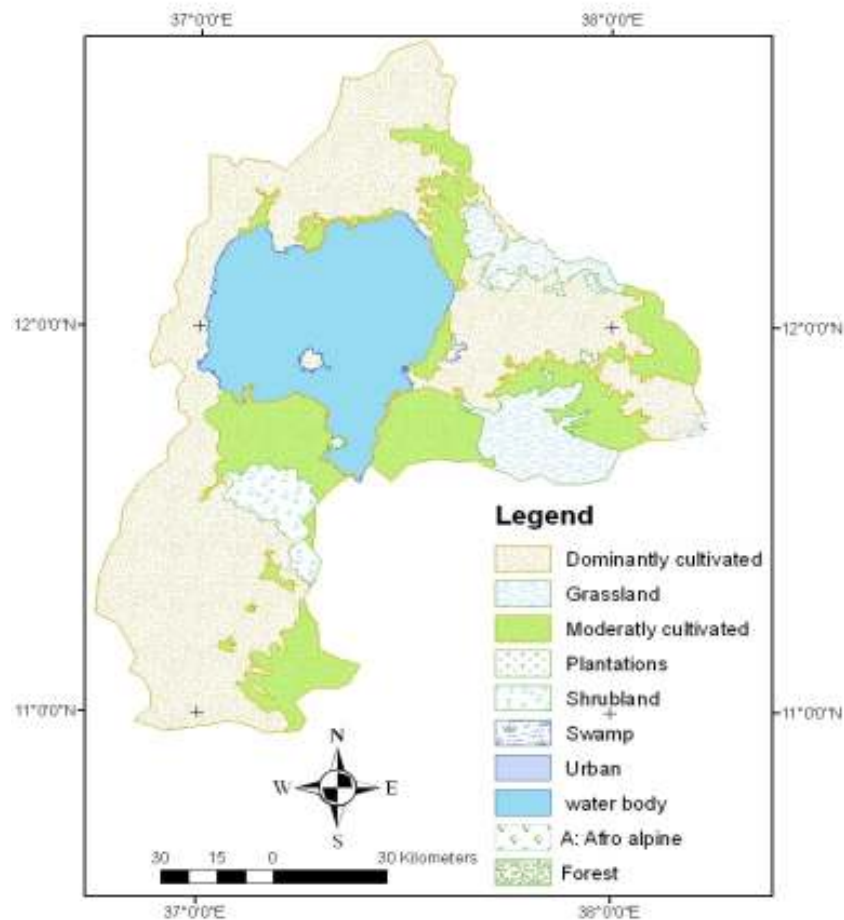


Figure 2.6 Land cover and land use of Lake Tana sub basin (source: MoWR).



Plate 2.1 Localized vegetation in the mountain areas.

2.6. Soils

Soil stores water in its pores before water recharges the aquifer system. Water stored in upper layer evaporates directly; it stored in deeper layer is absorbed by vegetation root then transpires to leaves and to be evaporated. The amount of evapotranspiration from soil is controlled by the soil attribute such as soil texture, soil structure and soil moisture content because ability of soil stores water and transports water is different for every soil. Deeper soil has a larger soil moisture reserve than thinner soil, which can supply more water to evaporate. Therefore, soils of the same hydrologic conditions are grouped together for the purpose of the model simulation. Soils in most of the Lake Tana Sub Basin are derived from weathered basalt profile and are highly variable. In low lying areas particularly north and east of Lake Tana and along part of Gilgel Abay, soils have been developed on alluvial sediment (SMEC, 2007).

Table 2.2 Soil properties of Tana sub Basin (SMEC, 2007).

Major Soil Group	Soil Texture	Drainage condition	Infiltration Category
Eutric Luvisols s	Silty clay	Moderately well drained	B
Eutric Leptosols	Clay loam to clay	Moderately deep to deep	C
Fluvisols	Clay to silty clay	Well drained	B
Haplic Nitisols	Silty clay to clay	Well drained	B
Eutric Vertisols	clay	Poorly drained	D



Plate 2.2 Agricultural land around Woreta.

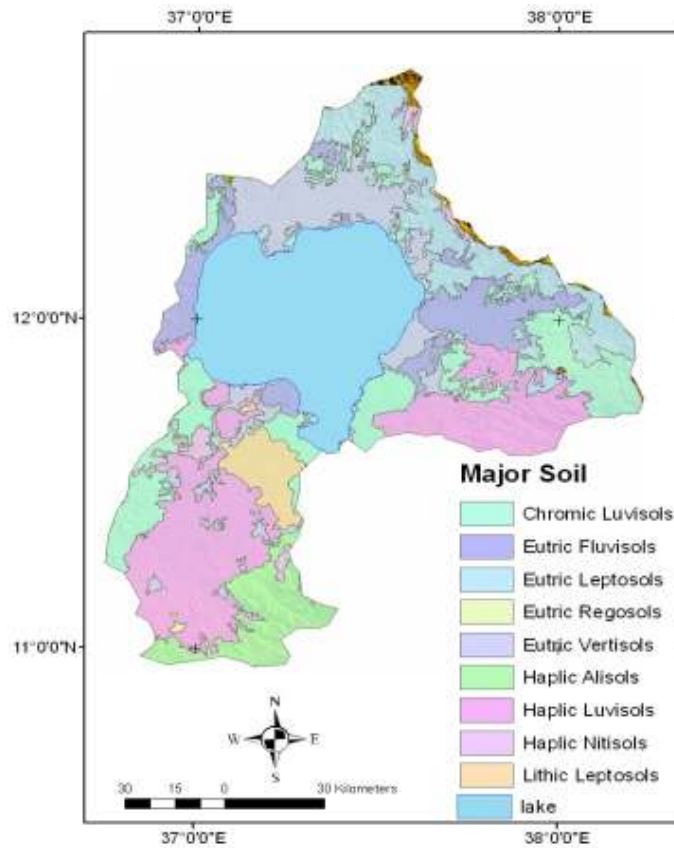


Figure 2.7 Soil map of the of Lake Tana sub basin (source: MoWR).

2.7. Regional Geology

The Ethiopian volcanic province is composed of tertiary (Trap series) and quaternary (Aden series) basaltic succession with thicknesses varying from 700 to 2000 at the plateau-rift margins and about 300000 km³ size (Mohr, 1988). The volcanic province is sub divided into three major geographical and geomorphological parts: the Ethiopian plateaus (northwestern, southwestern and southeastern), the Main Ethiopian Rift (MER) and the Afar Rift (Kazmin, 1979). Although the post-rift volcanism has been concentrated mainly along the axis of MER, it also occurred in the Tana graben (Kazmin, 1972) and along the Yere-Tulu Wellel volcano-tectonic lineaments between northwestern and southwestern plateaus (Abebe et al., 1998).

The Blue Nile basin is situated in the Northwestern Ethiopian plateau. The basin contains approximately 1400m thick section of Mesozoic Sedimentary rocks unconformably overlying Neoproterozoic basement rocks and unconformably overlain by Early-Late Oligocene and quaternary volcanic rocks. The Cenozoic is characterized by extensive faulting accompanied by widespread volcanic activity and uplift. Several shield volcanoes, also consisting of alkali basalts and fragmental material, cover the center and the upper part of the Blue Nile basin. Over two third of the upper Blue Nile is covered by Cenozoic basalts and ashes (kebede et al., 2006).

The geology of Lake Tana Basin comprises a basement of Precambrian bedrock, overlain by Mesozoic sediments, Tertiary volcanics and minor sediments, Quaternary volcanics and recent alluvial sediments (SMEC, 2007). Ongoing tectonic activities has controlled the distribution of the rock formation and controlled the current configuration of the basin.

The basement rocks in the Tana Basin comprise Precambrian metamorphic and granitic rocks which occur in the sub-surface of the basin. They are overlain by extensive deposits of Sedimentary rock that do not outcrop in the Tana Basin, but are observed in the Blue Nile gorge to the southeast. The areas surrounding Lake Tana are made up of tertiary basalts and much of south of Lake Tana areas covered by Quaternary volcanics, which overlie the older tertiary volcanics (SMEC, 2007).The thickness of sediments overlying the Precambrian basement and underlain 0-250 m thick continental flood basalts averages 1.5-2 km, which is comparable to the Blue Nile Stratigraphic section, south of the area (Engida et al., 2007).



Plate 2.3 Quaternary volcanic rocks near Lake Tana.

2.8. Hydrogeology

The major geological formations that outcrop in Lake Tana sub-basin and its adjacent areas are Tertiary and Quaternary volcanic rocks and alluvial along the major tributaries of the Lake sub-basin. Alluvial sediments have limited distribution within Lake Tana sub-basin dominantly at the eastern and northern side of the Lake. The thickness reaches more than 50m. The grain size of the sediment becomes coarser away the Lake. The static water level is very shallow in most areas less than one meter. Bore hole drilled (depth 53m) for Woreta town showed significant discharge with relatively low drawdown ($Q = 7$ l/s, drawdown =4 m) (Engida, 2007). Quaternary volcanic rocks are distributed at the southern part of the Lake basin, which has wide distribution to south beyond the Lake basin. The volcanic rock is vesicular basalt of plain topography with very low drainage network, indicating that this formation is highly pervious. Gilgel Abay River, where almost all its watershed is found in this formation has a very big base flow. In general the static water is very shallow in this formation, which is manifested by a large number of springs that emerges from this formation. The static water level becomes shallower towards the Lake and the springs discharge increases and even forms big swampy area near the Lake shore. The recharge estimation based on base flow separation showed that about 20% of the rainfall infiltrates to this formation (BCEOM, 1997). Big springs (Arek and Lomi), currently water supply source of Bahir Dar town discharge more than 200 l/s emerge from this formation. If the thickness of the formation is more than hundred of meters, then there could be a large stored groundwater in the vesicular basalt due its high porosity. Tertiary scoriaceous basalt (Tarmaber basalt) is widely distributed in the Lake Sub-basin and adjacent areas. At the southern part of the Lake basin it is overlain by the quaternary basalt and it has also wide distribution along the Choke mountain plateau. Its thickness increases from the south in the north direction with a probable maximum thickness in Gilgel river basin. Although, there are not deep bore holes drilled in this formation where it outcrops, the groundwater could be relatively deep as compared to the quaternary basalt. The yield of the boreholes drilled in to this rock varies between 5.59 l/s and 9.9 l/s. The bore holes data at Dangla shows that this formation has high discharge 25l/s with a drawdown of 12.5m (CES and Tropics, 2003).

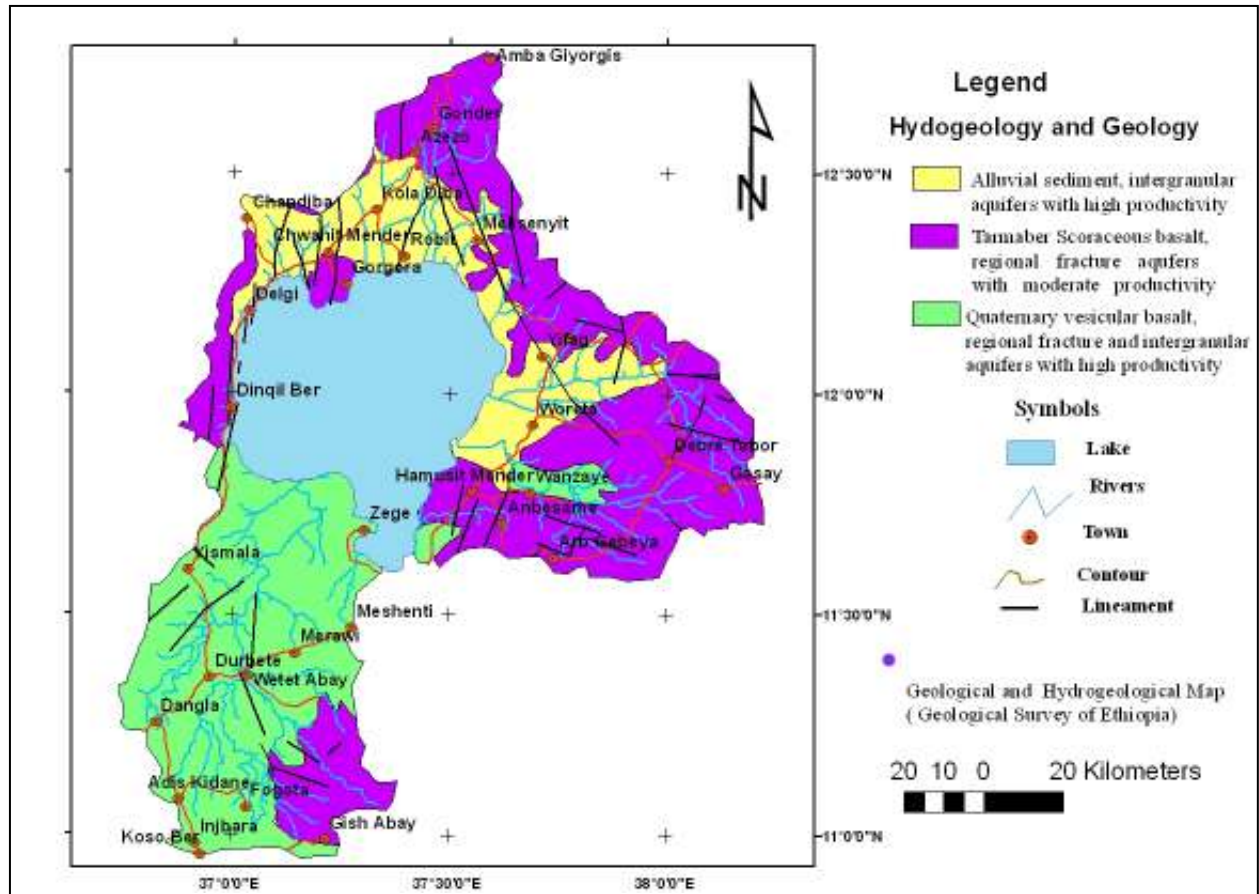


Figure 2.8 Geological and Hydrogeological map of Lake Tana sub basin Source: (Bayisa, 2003)

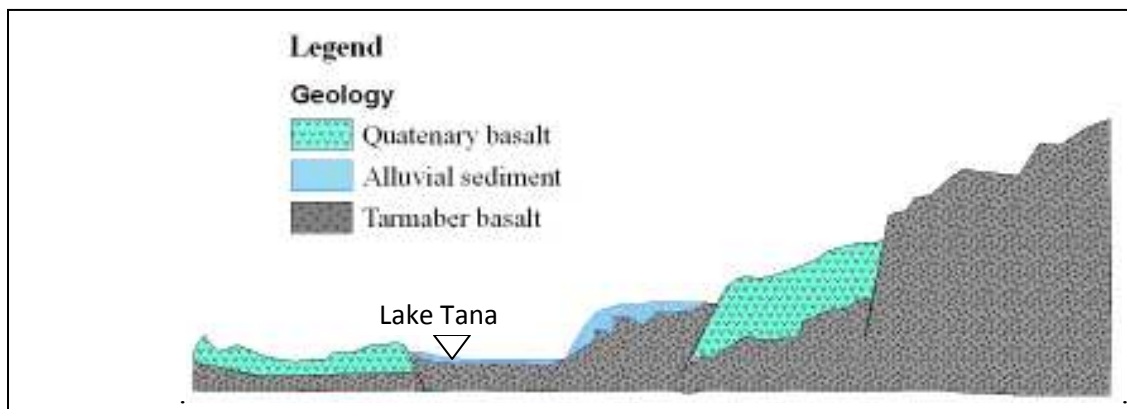


Figure 2.9 Conceptual geological cross section of Lake Tana Sub basin from W – E.

CHAPTER THREE

METHODOLOGY AND APPROACH OF THE STUDY

The approach to the recharge estimation of the Lake Tana sub-basin is carried out by dividing the time table in to office, field and post field works. HEC- HMS is the major tool used to estimate the recharge of the basin. For the purpose of modelling, it is required that the entire basin be divided into discrete catchments. ArcGIS and its extension GeoHMS are used to generate the Lake basin, major catchments and the catchments characteristics such as slope, area, and stream length. StatistiXL Multiple linear regression was used to estimate the runoff for ungauged catchments. A level of significance of 0.05 was used for the forward and backwards stepwise regressions.

3.1. Desk study

The desk study involved review of all relevant available information, including:

- □A literature review of previous studies of the Tana Lake sub basin (including hydrogeological maps, geological maps, recharge and other data).
- Model selection of the Tana Lake sub basin

3.1.1. Data collection

Daily climate data, including precipitation, relative humidity, sunshine hours, temperature and wind speed are obtained from National Meteorological Agency (NMA) and Bahir Dar meteorological stations. The stream flow for the year 1990- 2006, and land cover/ land use are collected from Ministry of Water Resources (MoWR). Geological map and hydrogeological map of Northern Ethiopia is accessed from Geological Survey of Ethiopia (GSE).

3.1.2. Data analysis of Rainfall and runoff

The calibration of a rainfall runoff model is most sensitive to the rainfall data.

If the volume of rainfall is incorrect or the rain days are not representative of the peaks in flow then calibration may be difficult with very poor results.

Catchment average rainfall and selection of appropriate rainfall sites are things that need to be considered in the preparation of rainfall data. The catchment average rainfall can be estimated by Thiessen polygon method. The selection of rainfall sites are based on proximity to the catchment, correlation with flow peaks, the number of sites used and difference in average annual rainfall as compared to the catchment average annual rainfall.

The coefficient of variation (CV) for monthly average rainfall, calculated for the Bahir Dar, Dangila, Sekela, Enjebara, Gonder and Debre Tabor is compared in figure 3.1. The coefficient of variation (CV) from June to September for all rainfall sites is similar. There is a fluctuation of coefficient of variation for the rest of the months. These aspects suggest that the spatial distribution for rainfall in each site is homogeneous during rainy season from June to September. On the other hand, during the dry season it is very heterogeneous.

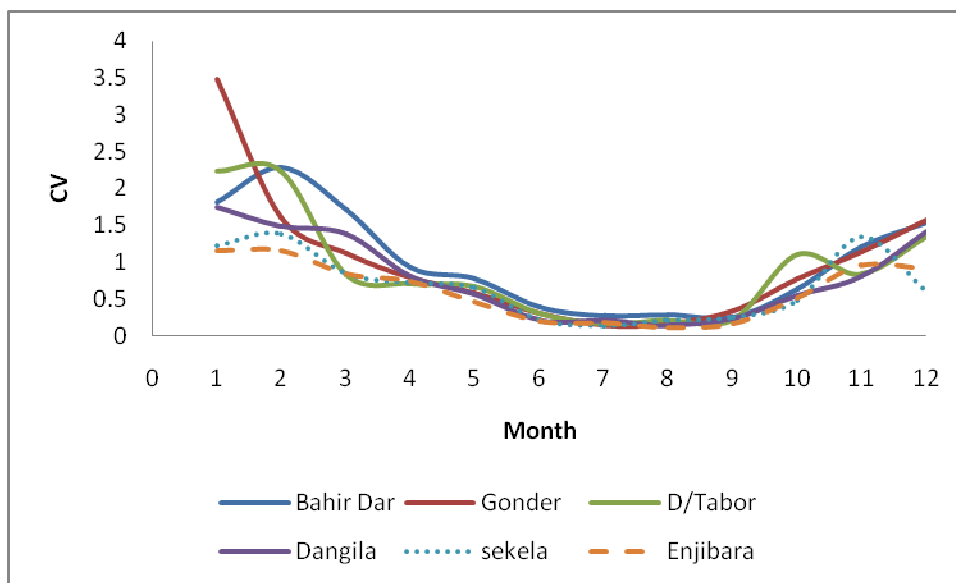


Figure 3.1 Coefficient of variation (CV) for monthly average rainfall in selected stations.

If the difference in average annual rainfall is great (e.g. more than 20%) then the rainfall process for the catchment and selected site are probably quite different and this is not a good station to use (Geoff Podger, 2004). The relation of rainfall and runoff from individual station and a number of stations is assessed in order to select appropriate daily data for the calibration of the model. A good method for assessing how well a rainfall station represents the flow from the

catchment is to plot the rainfall and flow on similar scales. The rainfall peaks can then be checked against the flow peaks to see if the size of peaks correlates with the amount of rainfall and that the peaks occur at about the same period or after certain time. The monthly rainfall and flow are relatively correlated and the size of the peaks occurred at the same months. The daily rainfall and flow correlation is quiet difficult. The relation is highly dependent on the location and distribution of raingauge stations in the catchments. The location of river gauging at Ribb and Gummera is not appropriate. The site is frequently affected by flooding. As the figure 3.1 shows, the Ribb River gauging station is highly affected by flooding. The flow at this station is both underestimated and overestimated due to flooding effect. The hydrograph of the stations show some irregularities. Gonder station represents the daily peak flow and rainfall on the daily time steps. The location of the Dangila station is far from Gauged catchments of Gilgel Abay by 4 Kms. The Dangila rainfall station is the only gauging recording all elements of climate in the upstream of Gilgel Abay. The Gummera and Ribb catchments have not daily recording station. The Debre Tabor station is relatively closes to the catchments, but the rainfall–runoff evaluation on daily base has some difficulties. The relation of peaks flow and rainfall duration has a time lag between them. Overall, both raingauge and river gauging stations are located along the highway. The reliability of these stations on the water resource evaluation and management is challenging and considers great attention during data collection and analysis.

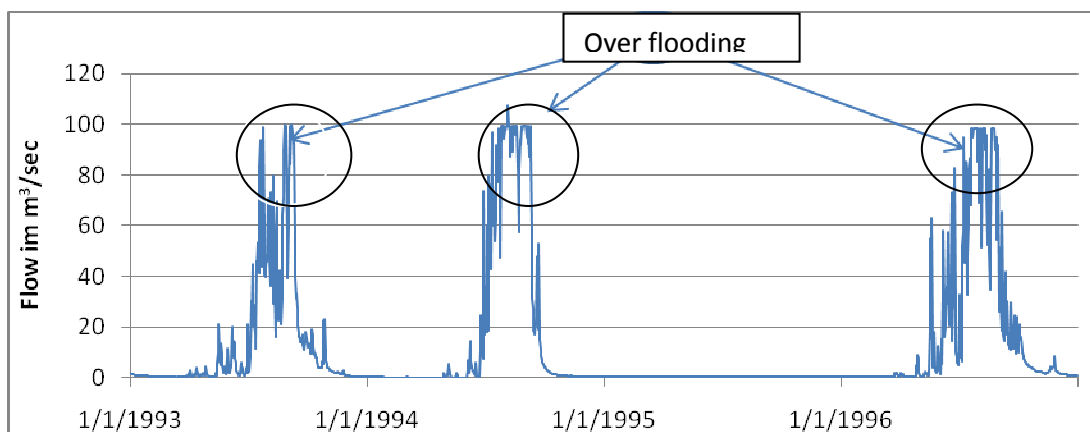


Figure 3.2 Hydrograph at Ribb station for the period 1993 – 1996.

3.1.3 .DEM processing and catchment Generation

The digital elevation model (DEM) is processed by 3 DEM and Arc Hydro tools to fill the gap. The processed DEM is further optimized by HEC GeoHMS to generate drainage area, drainage line, stream length, longest flow length, slope, etc. The generated data are used as the base map for HEC – HMS and used to generate initial parameters of HMS – SMA. The basin is further classified into small subbasins to utilize by HMS to run rainfall runoff model.

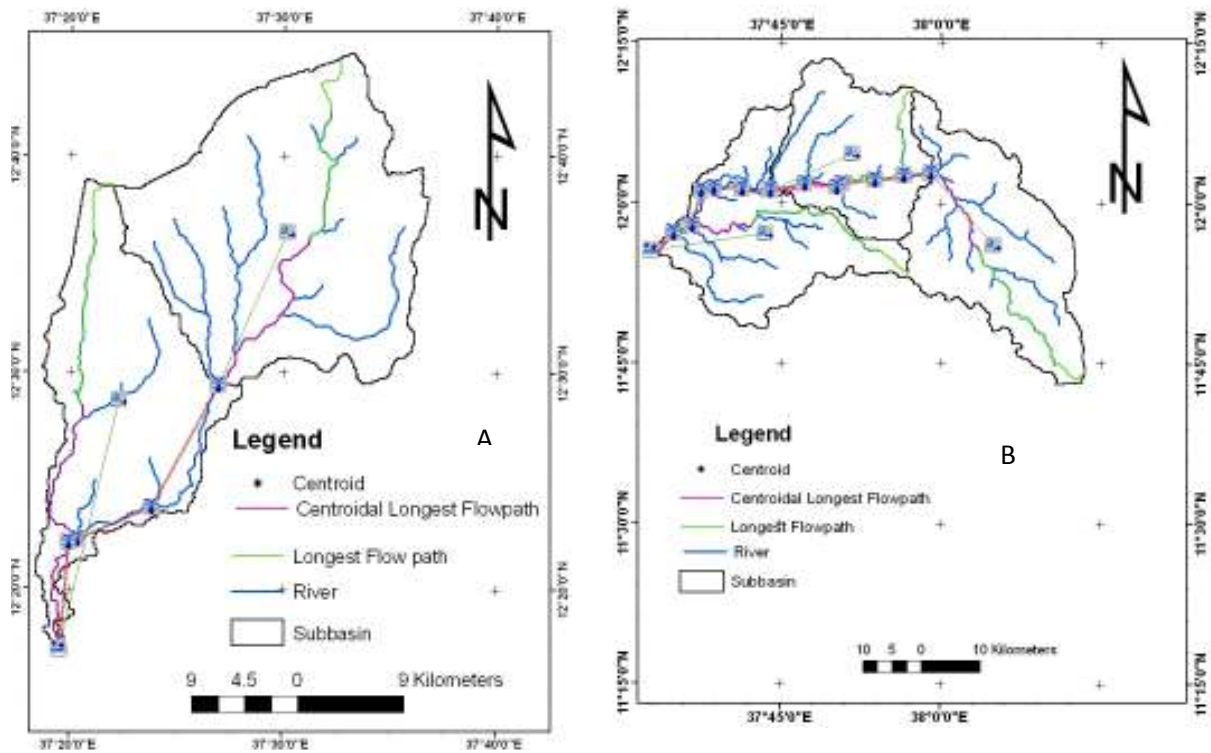


Figure 3.3 Physical descriptions of catchments in Lake Tana sub basin generated by HEC-GeoHMS (A). Megach, (B). Ribb.

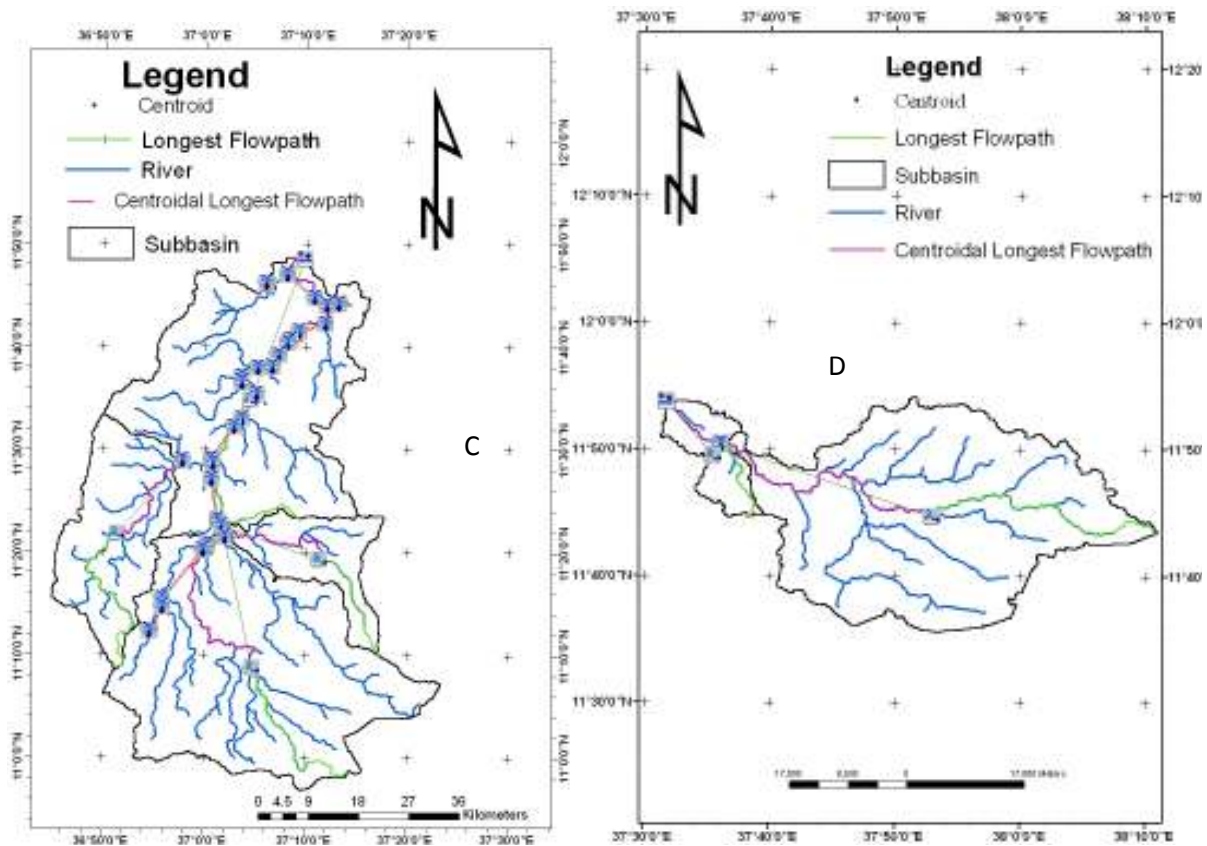


Figure 3.4 Physical descriptions of catchments in Lake Tana sub basin generated by HEC-GeoHMS (C). Gilgel Abay,(D). Gummera.

3.2. Field Works

A field survey was conducted to collect ground truth data and to have a general understanding of the study area. The topographic setting, Regional geology, land cover/ land use, location of raingauge and stream flow are accessed during field season.

3.3. Model Description

Soil Moisture Accounting

The model simulates the movement of water through and storage of water on vegetation, on the soil surface, in the soil profile, and in groundwater layers. Given precipitation and potential

evapotranspiration (PET), the model computes basin surface runoff, groundwater flow, losses due to evapotranspiration, and deep percolation over the entire basin.

The soil moisture accounting loss rate method uses five layers to represent vertical water movement in the watershed. Precipitation first falls into the canopy layer. The canopy layer must fill and then any additional precipitation overflows to the surface layer. The surface layer begins to fill and immediately starts infiltrating to the soil. Once the surface layer is full, continuing precipitation in excess of the infiltration rate will become excess precipitation and be routed by the transform. Water in the soil layer can percolate into the groundwater layers, but only from the upper zone section of the soil. Evapotranspiration, or plant water use, first empties the water in canopy storage. Once the canopy storage is empty, water will be removed from the surface layer. After the surface layer is empty, evapotranspiration will remove water from the both zones in the soil layer. Evapotranspiration cannot remove water from the groundwater layers.

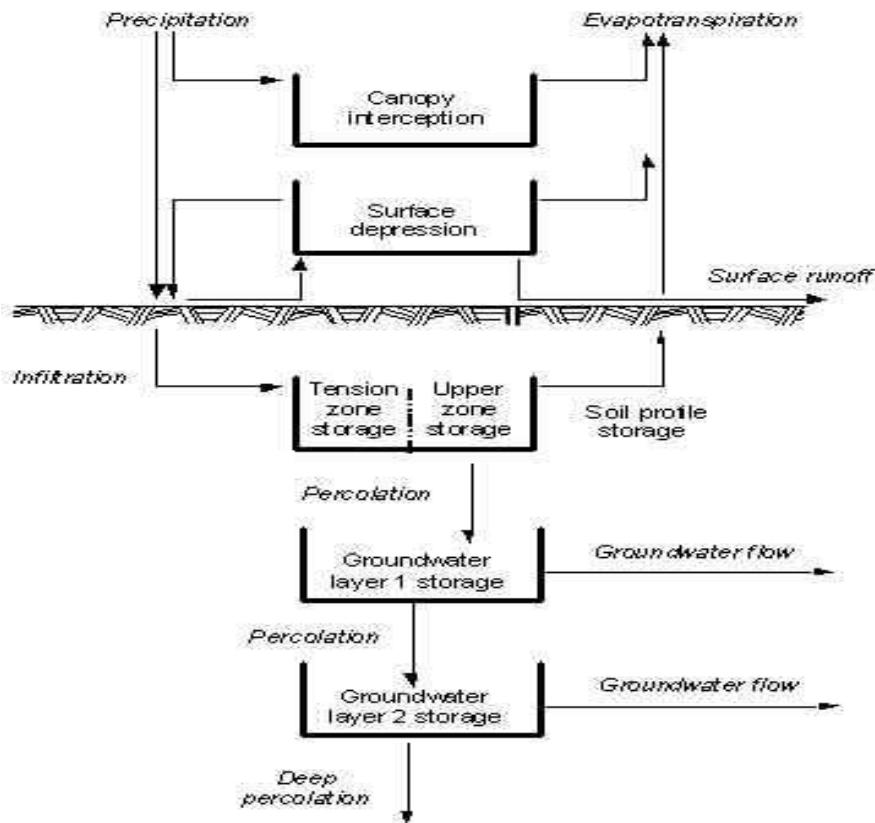


Figure 3.5 Conceptual schematic of the continuous soil moisture accounting algorithm (Bennett, 1998).

CHAPTER FOUR

HYDROMETROLOGY AND HYDROLOGY

4.1. Precipitation

The spatial and temporal variation of rainfall in Ethiopia is controlled by the movement of the position of the Inter Tropical Convergence Zone, ITCZ (Tenalem and Tamiru, 2001). The climate in the study area is largely influenced by westerlies air from Atlantic Ocean and minor rain is influenced by air movement from Indian Ocean. The rainfall data for 23 long-term records of rainfall stations lying within or around the Tana sub Basin are used for the computation of rainfall. The four rainfall stations in the sub basin are considered for the estimation of potential evapotranspiration and runoff. They record all principal components of climate. The Lake Tana sub Basin receives an average annual rainfall of 1329 mm. The annual rainfall in the study area is range from 900mm to 2346mm. Rain falls in a single rainy season mostly from June to September and receives minor rain from April to May. The figure 4.1 shows the temporal variation of rainfall in the study area. The dry season ranges from October to February. The maximum mean monthly rainfall is observed in the July month having a value of 364.5mm and minimum rainfall is recorded in the January. Within the study area, the distribution of rainfall varies locally, where there is higher amount of rainfalls in the South and Southeast mountainous side and relatively low rainfall in the northern and western part, which indicates that precipitation increases with altitude.

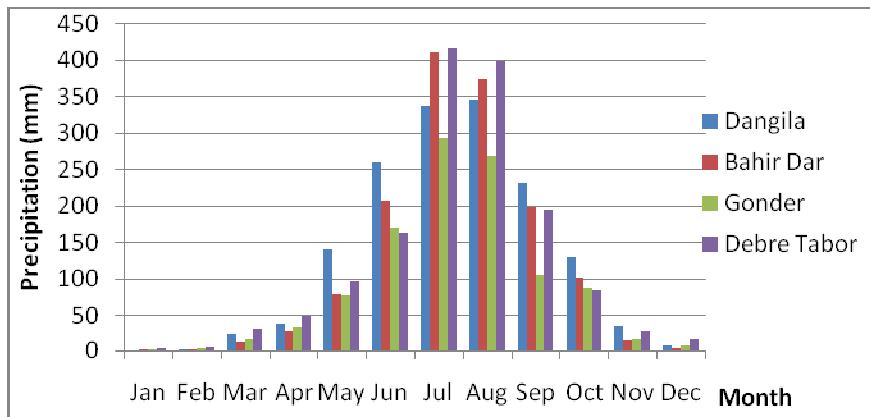


Figure 4.1. Monthly mean rainfall of different station.

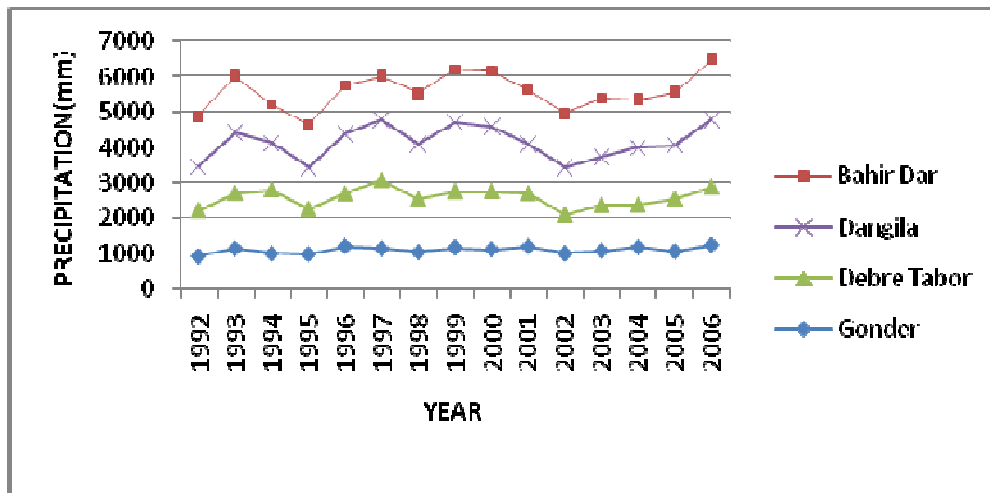


Figure 4.2. Variation of rainfall in the basin for the period of (1992 – 2006).

The rainfall in the Tana Sub basin is erratic both in spatial and temporal. From the figure there is the increasing trend of rainfall for Bahir Dar, and constant rainfall for the Gonder station. In all stations year 1995, 1998 and 2002 show the low amount of rainfall. The rainfall shows increase from 1235mm to 1618mm for the year 2002 to 2006.

4.2. Aerial Depth of precipitation

Since most hydrological problems require a knowledge of the average depth of rainfall over a significant area such as a river basin, some procedure must be used to connect the rainfall measured, at individual rain gauges to the areal average, (REDDY, 2001). However, the availability of class 1 rain gauge is limited in the study area, the distribution of rain gauges station based on the World Meteorological Organization norm is fair. Thiessen method is the appropriate method to evaluate the average areal distribution of rainfall in the area affected by topography. To compute the areal distribution of the Lake Tana Sub Basin, 23 meteorological stations are used. The stations in and around the Sub Basin are included. The areal depth of precipitation estimated is, 1329mm for Thiessen polygon.

Table 4.1 Meteorological stations in and around the Lake Tana Sub Basin.

stations	Easting	Northing	Precipitation
Adis Zemen	377034	1339957	1068
Aykel	288107	1385819	1175
Debre Tabor	392163	1310040	1494
Delgi	285688	1352646	809
Infranz	356388	1346686	971
Gonder	328336	1387763	1081
Bahir Dar	327729	1282685	1416
DeKI Istefanos	311575	1315964	1676.57
Dangila	265059	1245367	1557.67
Enjebara	270512	1213353	2266
Sekala	305053	1216952	1566
Zege	316783	1292357	1605
Woreta	357993	1318144	1236.7
Merawi	298085	1263464	1572.3
Kunzila	285329	1313299	1126.8
Gorgra	314919	1353457	1107.4
Maksagnt	347821	1371441	1144.241
Tlili	281496	1200567	1942.4
Finoteselam	292446	1181578	1034.7
Mota	376442	1226519	1144.6
Dembech	332556	1169129	1311.1
Gimbet	251113	1228418	1898.4
Tis Abay	322850	1270195	1144.8
Fasiledes	348591	1241289	1258.9
Adet	333822	1246985	1272.4
Nifasmewcha	442272	1297413	1104.9

4.1.2. Thiessen Polygon Method

Thiessen polygon method attempts to make allowance for irregularities in gauge locations by weighting the record of each gauge in proportion to the area which is closer to that gauge than to any other gauge. However, this method does not make any allowance for orographic influences in the basin; it gives appropriate depth of rainfall in the basin. The average depth of rainfall is

Computed using the following formula:
$$P = \frac{A_1P_1 + A_2P_2 + \dots + A_nP_n}{A_1 + A_2 + \dots + A_n}$$

Where P_1, P_2, \dots, P_n are the rainfall recorded at rain gauge stations with A_1, A_2, \dots, A_n as the polygon areas. The average depth of rainfall computed using Thiessen method is about 1329mm, which is appropriate value for the basin (Annex -1).

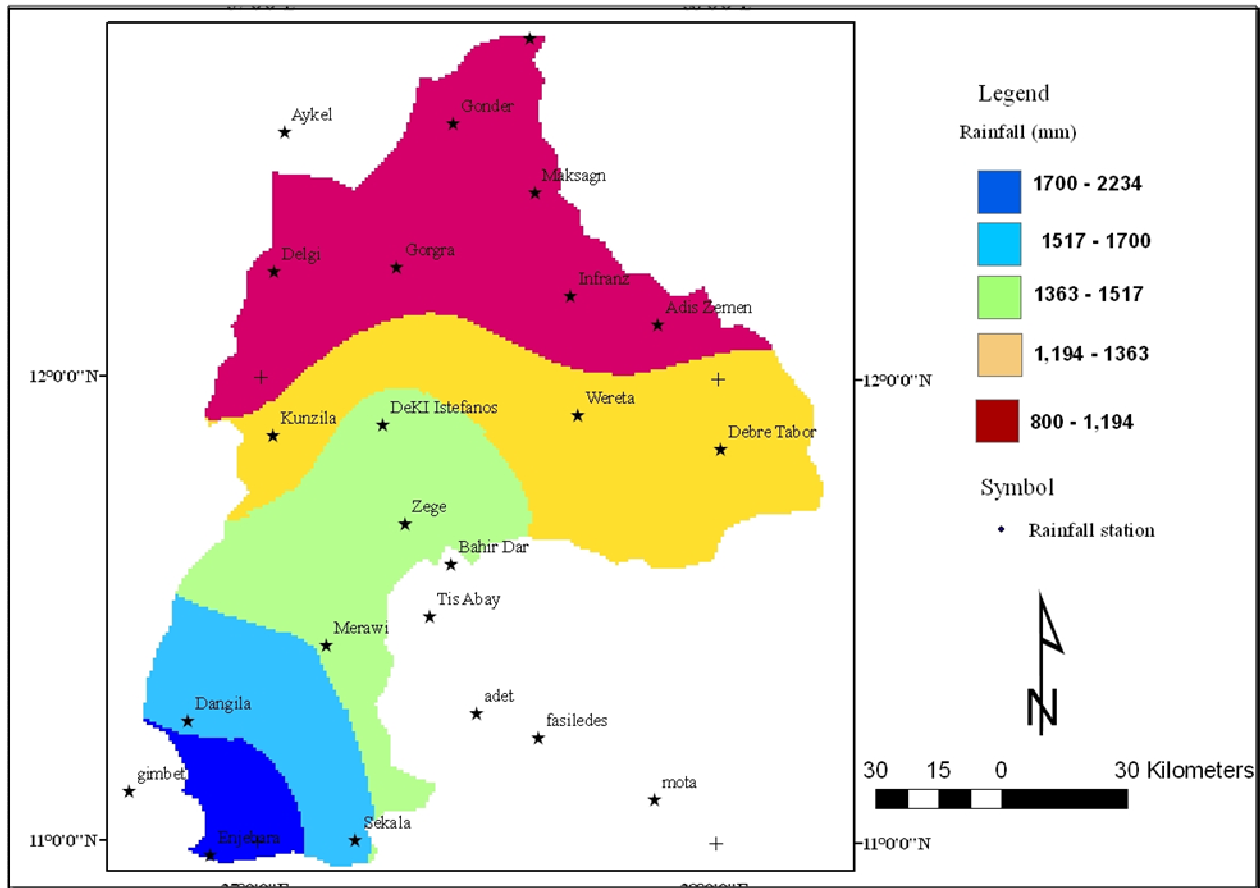


Figure 4.3 Spatial distribution of rainfall.

4.2. Temperature

The air temperature shows small seasonal changes with an annual average of 20°C. The average temperature ranges from 15°C to 20°C. The figure 4.4 confirms the seasonal variation of temperature is more or less constant through the year. The mean temperature recorded in the major stations is relatively similar. The highest mean temperature is recorded in the Gonder station and minimum temperature is recorded in the Debre Tabor station. The hot months occur in December, January and February. Temperature in August and July is relatively low. Temperature is high in the Northern and Western part of the sub basin, whereas low temperature

is observed in the South and South East of the study area. Temperature is usually the most important factor to the evapotranspiration. The evaporation will continue to increase at an increased rate as the temperature rises as long as there is water to evaporate.

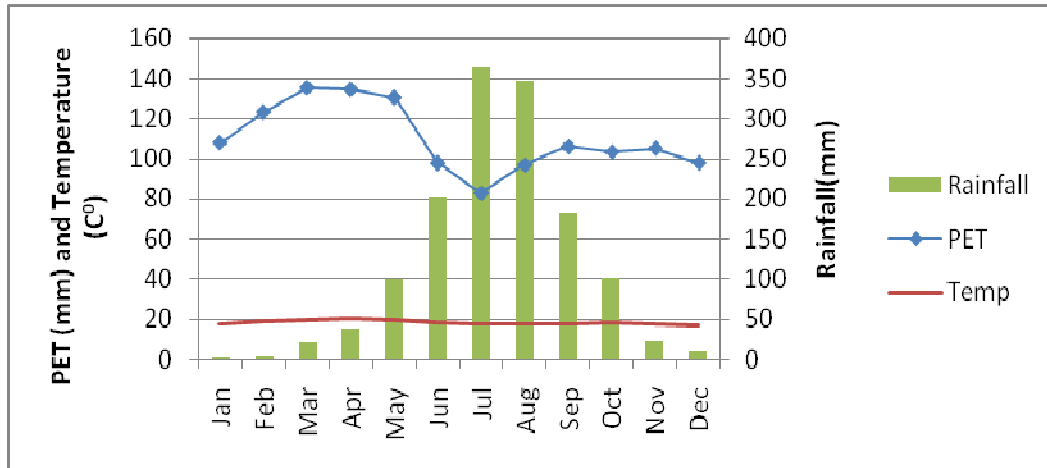


Figure 4.4 Average monthly temperatures, potential evapotranspiration and rainfall for Gonder, Debre Tabor, Dangila and Bahir Dar stations.

4.3. Sunshine hours

Sunshine hour is one of the climates that affects the rate of evaporation. The maximum sun shine hour is recorded in the Bahir Dar station. The minimum sunshine hour is observed in the Debre Tabor station. The sunshine hour decreases from May to August and rise from September to January.

Table 4.2: Mean monthly sunshine hours (hr/day) of the area.

No.	station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.00	Dangila	9.1	9.0	8.2	8.2	7.7	6.1	4.1	4.2	6.3	6.6	8.4	8.82
2.00	Bahir Dar	9.8	9.7	9.23	9.16	8.4	6.9	4.8	4.8	7.0	8.3	9.3	9.82
3.00	Gonder	9.4	8.9	8.4	7.3	7.2	5.1	4.2	4.7	7.2	7.4	8.6	8.93
4.00	Debre Tabor	8.3	7.7	7.4	6.3	6.3	5.2	4.8	5.1	6.5	6.9	7.4	8.57

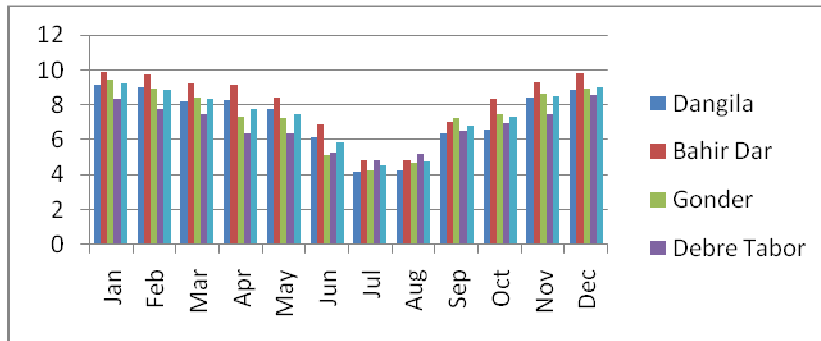


Figure 4.5 Monthly sunshine hours in the study area.

4.4. Relative humidity

Relative humidity and evapotranspiration are closely related because if the relative humidity is close to its holding capacity, the ability of plants to transpire may be inhibited. The higher the relative humidity, the slower the evaporation rate; the drier the air above the surface, the faster the evaporation. So the seasonal trend of evapotranspiration within a given climatic region follows the seasonal trend of solar radiation and air temperature. Minimum evapotranspiration rates generally occur during the coldest months of the year; maximum rates, which generally coincide with the winter season, when water may be in short supply. The relative humidity (RH) expresses the degree of saturation of the air as a ratio of the actual (e_a) to the saturation ($e^\circ(T)$) vapour pressure at the same temperature (T) is:

$$RH = 100 \frac{e_a}{e^\circ(T)}$$

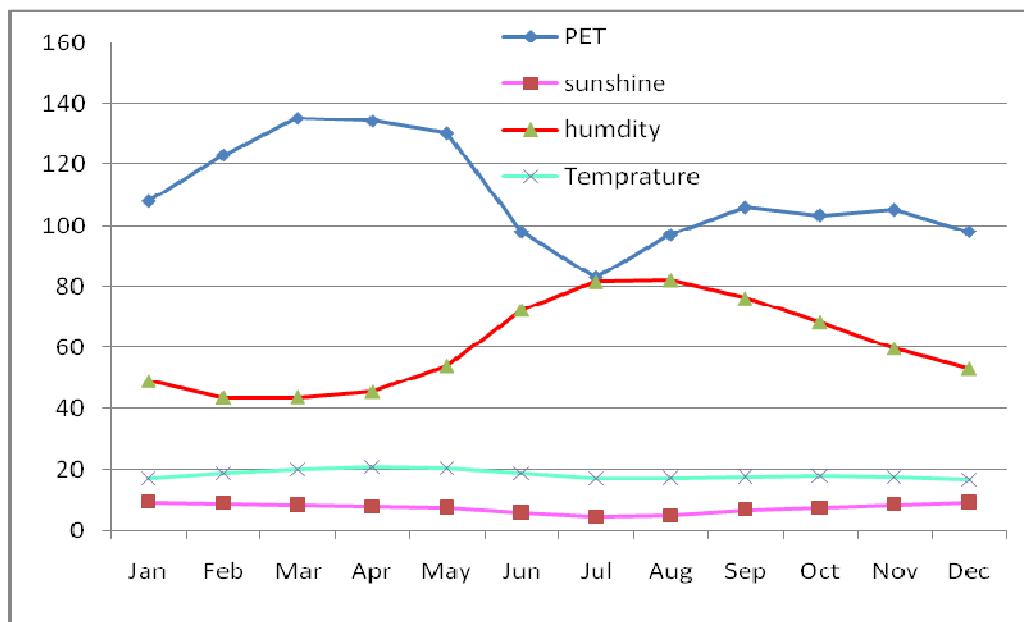


Figure 4.6 Mean monthly sunshine hour, potential evapotranspiration, temperature and Relative humidity.

Table 4.3: Relation of mean monthly sunshine hour, potential evapotranspiration, temperature and Relative humidity.

Descriptive Statistics				
Variable	Mean	Std Dev.	Std Err	N
PET	110.177	16.842	4.862	12
sunshine	7.363	1.603	0.463	12
humidity	60.897	14.691	4.241	12
Temperature	18.265	1.359	0.392	12
wind	1.202	0.181	0.052	12

Correlation Matrix (R)					
	PET	sunshine	humidity	Temperature	wind
PET	1.000	0.537	-0.789	0.862	0.678
sunshine	0.537	1.000	-0.871	0.143	0.079
humidity	-0.789	-0.871	1.000	-0.514	-0.494
Temperature	0.862	0.143	-0.514	1.000	0.836
wind	0.678	0.079	-0.494	0.836	1.000

4.5. Wind Speed

Wind speed plays a role in controlling the evapotranspiration rates by influencing the moisture gradient. Evaporation has a direct relation with the wind speed. As water vaporizes into the atmosphere, the boundary layer between earth and air becomes more and more saturated so that the water vapor has to be removed and replaced with drier air continuously. Moisture -laden air is forced to rise over a mountain barrier, producing more rainfall on the windward side than on the leeward side.

Table 4.4: Monthly average wind speed at 2m above ground surface (m/s).

No	station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Dangila	1.0	1.2	1.2	1.3	1.2	1.3	1.2	1.2	1.0	0.9	0.8	0.9
2	Bahir Dar	0.9	1.1	1.3	1.4	1.3	1.1	0.8	0.7	0.7	0.7	0.8	0.9
3	Gonder	1.6	1.7	1.8	1.7	1.9	1.9	1.3	1.2	1.4	1.3	1.4	1.4
4	Debre Tabor	1.2	1.3	1.3	1.3	1.4	1.4	1.1	1.2	1.2	0.9	1.0	1.1

4.6. Evapotranspiration

Evapotranspiration is the process in which water is returned to atmosphere by a combination of evaporation and transpiration. The principal weather parameters affecting the Evapotranspiration are radiation, air temperature, humidity and wind speed. Evapotranspiration is two types: potential evapotranspiration and actual evapotranspiration. Potential evapotranspiration is the water loss that will occur under given climate condition with no deficiency of water for the vegetation while actual evapotranspiration is the amount of water that actually returns to atmosphere depending on the availability of water.

4.6.1 Estimation of Potential evapotranspiration

Potential evapotranspiration is determined by using Penman combination approach. Thornthwaite approach under estimate the potential evapotranspiration in the study area. Thornthwaite approach is best estimates for the Gonder station which has high temperature record. Penman use standard climatologically records of sunshine, temperature, humidity and wind speed to calculate evapotranspiration. The physical principle used by Penman combines the mass transfer (or aerodynamic) method and the energy budget methods. High potential evapotranspiration is estimated from Bahir Dar station and minimum is from Debre Tabor. The average potential evapotranspiration is 1322mm per year and it is less than the average annual rainfall of the basin. The average monthly evapotranspiration values are shown in Figure 4.8 indicate that the lowest values occur in June and July. The highest mean monthly values occur in April and May. The monthly average value in July is about 82.9mm.

The basic equation for calculating PET from vegetated surface is:-

$$PET = \frac{\left(\frac{\Delta}{\gamma}\right) H_T + E_{at}}{\frac{\Delta}{\gamma} + 1}$$

Where H_T is the available Heat, E_{at} is the Energy for evaporation; PET is Potential evapotranspiration, Δ slope of saturation vapour pressure curve at air temperature, γ psychrometric constant. Annual potential evapotranspiration of four stations is given below.

Table 4.5: Mean annual potential evapotranspiration of the study area.

Stations	PET (mm)
Debre Tabor	1217.171
Bahir Dar	1456.71
Gonder	1333.094
Dangila	1283.615

Table 4.6 Monthly mean potential evapotranspiration.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
108	123	135	135	130.4	97.9	82.9	97	106	103	105.184	98.06998

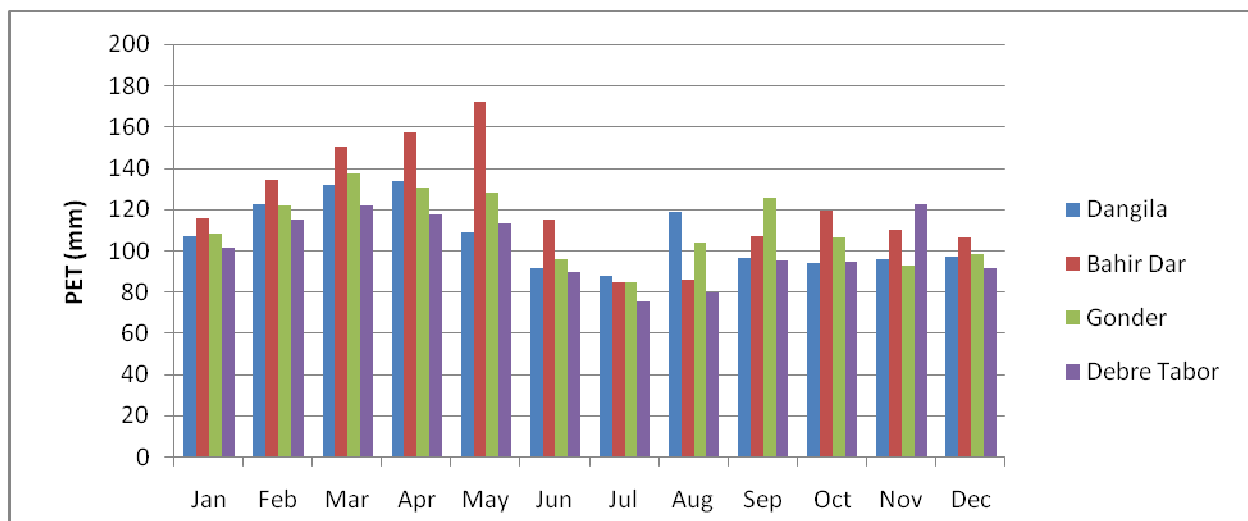


Figure 4.7 Monthly mean potential evapotranspiration of four stations (1992 -2006).

4.6.2. Actual evapotranspiration

Actual evapotranspiration is the evaporation from a vegetal cover under the natural or given condition of supply of moisture. It is used to describe the amount of evaporation that occurs under field condition and depends on the availability of water to meet the atmospheric demand. Actual evapotranspiration is estimated using Thornthwaite soil moisture balance.

Table 4.7: Monthly mean actual evapotranspiration of Tana sub basin.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Megach	3.662	7.65	32.477	65.73	155.8	95.72	84.665	103.9	209.4	177	31.8	13.7	982
Gummera	9.959	6.89	25.676	39.41	77.9	102.3	79.73	82.7	101.1	96.5	54.7	24.6	701
Ribb	21.2	15.7	30.806	42.31	78.9	77.59	120.72	119.5	86.6	26.7	58.1	47.8	726
Gilgel													
Abay	19.52	13.5	24.358	20.72	108.6	91.47	87.532	118.6	96.29	94	56.3	50.7	782

4.7. Rainfall and Runoff relationship

The Tana Lake is fed by four large perennial rivers. They contribute more than 95% of the total annual inflow (Livingstone, 1980). These rivers form four major catchments in the Lake Tana sub basin. The drainage systems in the Lake Tana basin are controlled by topography and structural setting. The Gonder, Debre Tabor, and Dengel Ber grabens together form a triple junction at the centre of the Tana basin (J.Chorowicz *et al*, 1998). The convergence of the three grabens toward the Tana Lake plays a major role in driving the rivers to flow toward Lake Tana.

Megach river drains the northern highlands where as Gilgel Abay drains the southern parts of the sub basin. Gummera and Ribb drain the Debre Tabor and Guna highlands. The average annual runoff in the basin is variable. The runoff in the basin varies from 379.49mm/yr to 1046mm/yr. The variability of the runoff can be primarily attributed to the patterns of precipitation. The patterns of runoff are shown in figure 4.8. The largest portion of the runoff is derived from Gilgel Abay and Gummera catchments in the south and south east part of the Tana Lake Sub basin where the high elevation promote greater precipitation. The annual rainfall and runoff diminishes toward the north and west of the Tana Lake sub basin. This revealed that the runoff of the basin is highly controlled by topography and precipitation. The runoff is also seasonal. The runoff increases during rainy season and drops when the rainfall is ceased. The maximum discharge of the major catchments is recorded in the August month. The occurrence of minimum discharge is variable for the catchments. Gummera and Gilgel Abay rivers have the highest discharge year in 1996 and Megach and Ribb Rivers in 2006. Generally the highest flows are typically during the mid June, July, August and mid September. The lowest flows are occurred during winter season. During April and May there is relatively moderate discharge. The seasonal nature of rainfall and runoff means groundwater recharge can occur in one half of the year and the other half is a discharge period. The recharge estimation in such areas needs to consider this recharge – discharge relationship.

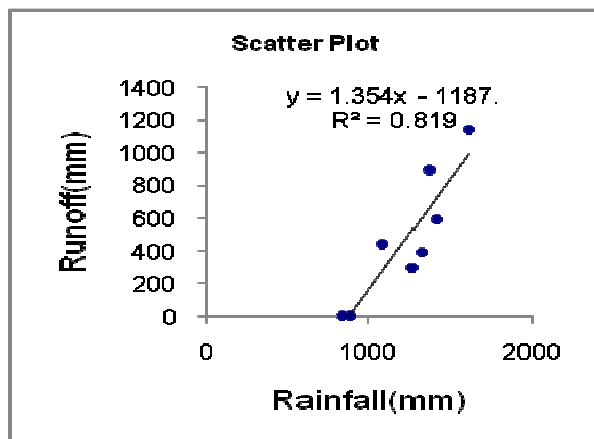


Figure 4.8 Rainfall and runoff relation of the basin.

Table 4.8: Rainfall and runoff of the main catchments in Tana sub basin (1992 -2006).

Catchments	Area(Km2)	Rainfall(mm/yr)	Runoff(mm/yr)	Runoff coefficient
				(%)
Gilgel Abay	1640	1557	1046	67.2
Koga	301	1500	618	42.9
Kility	698	1561	389	25.6
Gummera	1394	1333	891	66.8
Megach	492	1081	437.4	40.5
Ribb	1592	1283	302.6	24

The runoff in the study area shows increasing trends with increasing precipitation. The runoff coefficient (the ratio of runoff to precipitation) is also increased with increasing precipitation. Runoff coefficient is the simplest way to relate the precipitation and runoff of the catchments.

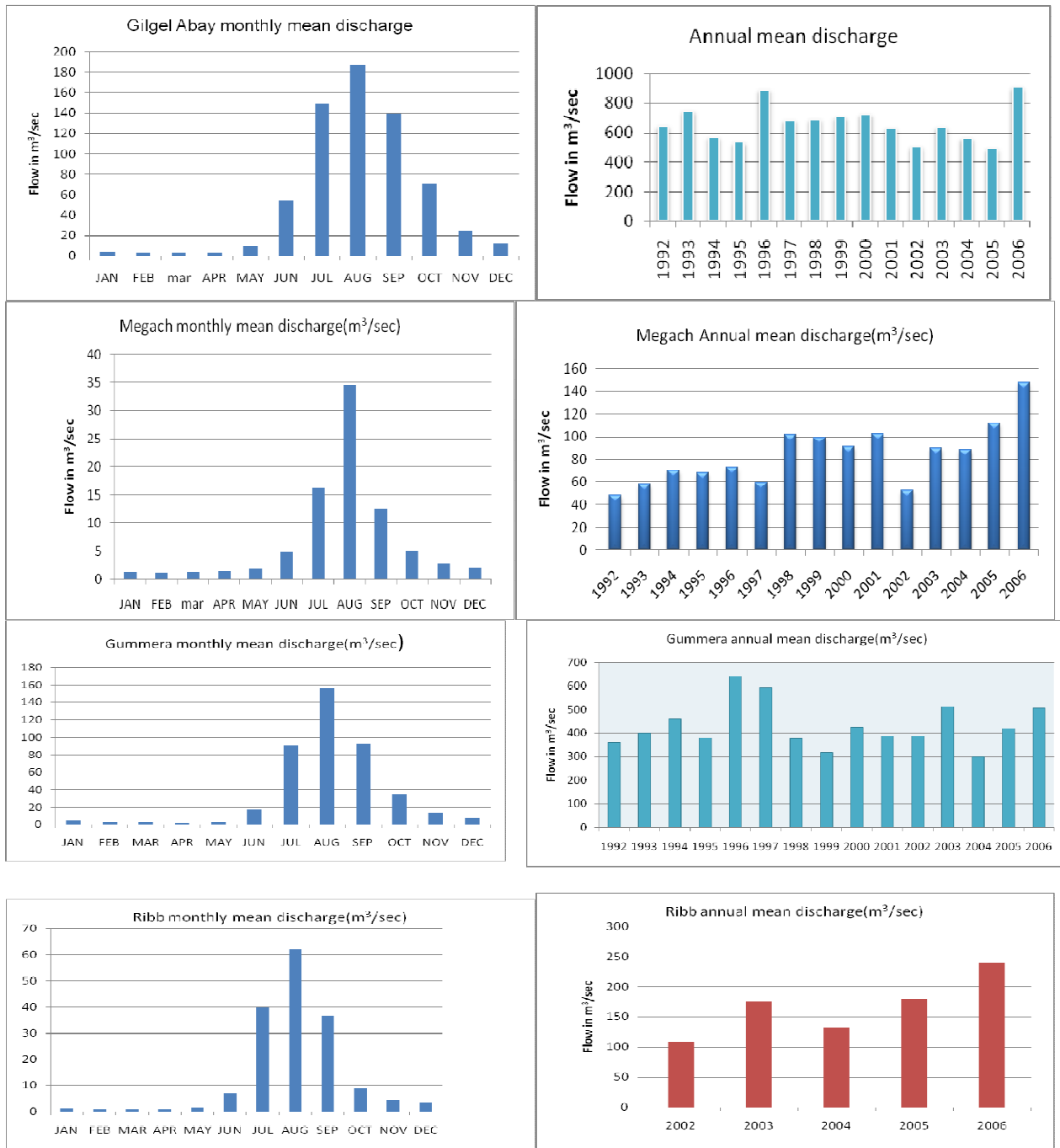


Figure 4.9 Patterns of runoff in the Tana Lake sub basin.

4.8 Flow Duration Curve

Flow-duration data commonly are used to statistically characterize streamflow and it removes information on the sequence of recorded flows. Flow-duration data are daily mean flow values measured over a specified time interval that have been exceeded various percentages of the specified time interval. However, in most cases, it is better to estimate the flow duration curve based on one or two years of record, the uncertainty in the flow duration curve will decrease as the record length increases. Daily flows, Q_t , for each catchment are divided by the average daily flow (Q) to give dimensionless flows so as to exclude the effects of catchment size (Dominic MAZVIMAVI,2003).

The equation used to compute the exceedence probability, which also is referred to as the flow-duration percentile, is given as:

$$P = 100 * \left(\frac{m}{(n+1)} \right)$$

Where

P is the exceedence probability,

m is the ranking, from highest to lowest, of all daily mean flows for the specified period of record, and

n is the total number of daily mean flows.

To determine the flow for a specific flow duration percentile, interpolation between the discharges associated with percentiles on either side of the specific percentile may be needed. Flows that are equal to each other also would be given separate m rank values. With the equation above, high flows are assigned low percentiles and low flows are assigned high percentiles.

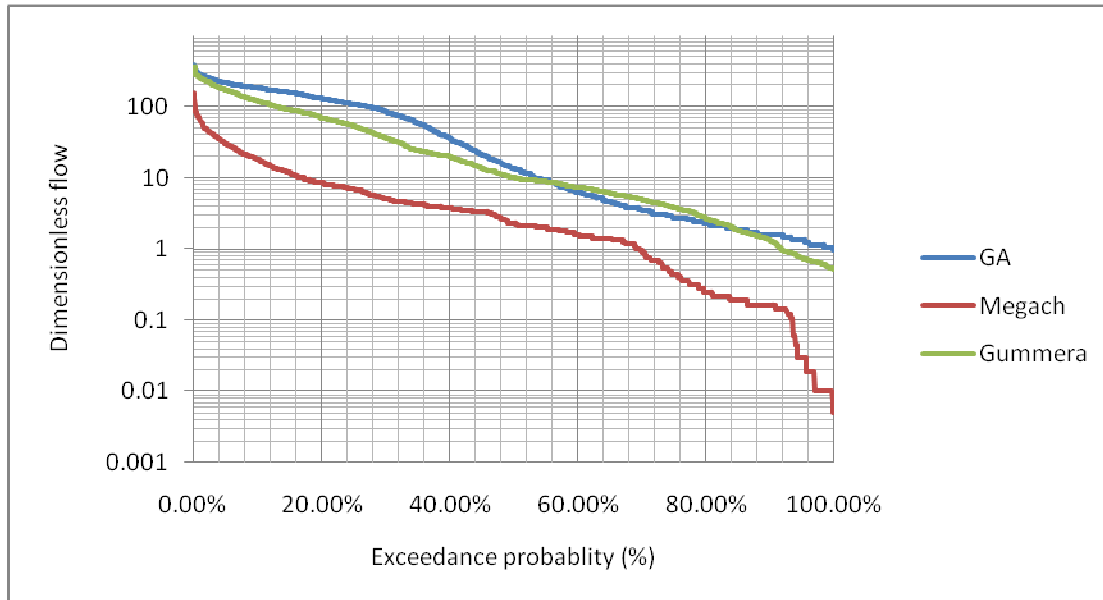


Figure 4.10 Semi-log plot of Stream flow duration curves from different climatic regions.

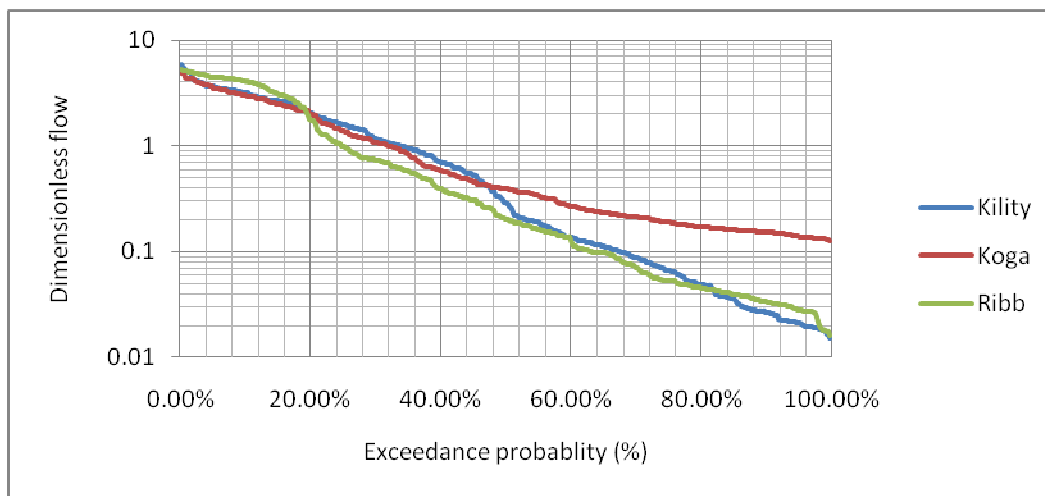


Figure 4.11 Semi-log plot of Stream flow duration curves from at different stations on annual mean daily discharge.

When flows are expressed as a percentage of the long term mean flow (standardized), the dependencies on the climatic variability across the basin and on the scale effect of catchment

area are minimized. The shape of the standardized flow duration curve indicates the characteristic response of the catchment to rainfall. The geology of Gilgel Abay, Koga and Kility is Quaternary volcanic rocks. These rocks are highly permeable and characterized by high hydraulic conductivity. The bore holes and springs data obtained from these unit indicated that the Quaternary volcanic rocks were considered as highly productive aquifers and large groundwater storage. The geology of Gummera Megach and Ribb is Tertiary volcanic rocks. These rocks were classified as moderate productive aquifers in regional hydrogeological map of Northern Ethiopia (Bayisa, 2003). The climate of the Lake Tana sub basin is spatially variable. The south part of the basin receives large amount of rainfall and characterized by low potential evapotranspiration. The south east of the basin (Ribb and Gummera) receives moderate rainfall. The north and west catchments of the basin (Megach) are characterized by low amount of rainfall. The annual rainfall amount in the catchments is less than the annual potential evapotranspiration. The flow duration curve of the catchments indicated that Gilgel Abay and Koga are considered as large baseflow catchments. The flow in Kility, Megach, and Ribb Rivers gradually decreases with season. Smakhtin (2001) indicated that the “design” low flow range of a flow duration curve is the 70%-99% range, or the Q70 to Q99 range. To relate the BFI to a usable flow statistic, a relationship was derived between BFI and Q95, the point on the flow duration curve at which flows are exceeded 95% of the time. Q95 was chosen because it is positively correlated with BFI of the catchments with correlation coefficient of 0.787.

CHAPTER FIVE

RECHARGE ESTIMATION

Groundwater recharge in the basin is controlled by various factors like: climate, geomorphology and geology. Climate controls hydrological behavior of an area especially the rainfall distribution. Variation in geomorphology reflects differences in topography, soils and vegetations which in turn affect recharge. The shape and the size are some geometric factors control the peak of runoff. In the Lake Tana sub basin, recharge is generally considered to occur in topographic high areas while discharge occurs along the rivers and in the topographic low areas.

5.1 Principle of recharge estimation methods

The soil moisture accounting loss rate method uses five layers to represent vertical water movement in the watershed. Precipitation first falls into the canopy layer. The canopy layer must fill and then any additional precipitation overflows to the surface layer. The surface layer begins to fill and immediately starts infiltrating to the soil. Once the surface layer is full, continuing precipitation in excess of the infiltration rate will become excess precipitation and be routed by the transform. Water in the soil layer can percolate into the groundwater layers, but only from the upper zone section of the soil.

Percolation calculations are carried out approximately the same for all transitions between layers. For example, the infiltration from surface into the soil is done the same way as percolation from the soil to the upper groundwater layer. The amount of percolation is calculated as a linear reduction based on the storage in the upper source layer and the storage in the lower receiving layer. The maximum percolation happens if the upper layer is completely full, and the lower layer is completely empty. No percolation will happen if the upper layer is empty. Some fraction of the maximum possible percolation happens when both layers are partially full. The only water in the soil layer that can percolate is the water in upper or gravity storage; that is, the water represented by maximum storage minus the tension storage. This represents the fact that soil spends most of the time partially saturated. The SMA model simulates both wet and dry weather behavior, and is based on the Precipitation - Runoff Modeling system of (Leavesley et al., 1983).

In this model, the river basin is represented by a series of interconnected storage layer. There are four different storages in the SMA model:

Canopy-interception storage (precipitation captured on trees, grasses, etc ...).

Surface- depression storage (water held in shallow surface depression.)

Soil- profile storage - water stored in the top layer of the soil; the upper zone represents water held in soil pores and the tension zone water attached to soil particles.

Ground water storage - Groundwater layers are intended to represent shallow flow processes and not deep aquifers .The model can include either one or two groundwater layers. In this research two groundwater layers are used based on the information of the geological log collected from the basin. The geological logs of more than 30 borehole data are linearly correlated to demarcate the layers. The unsaturated or saturated weathered/ fractured part above the massive layer is considered as groundwater layer 1, whereas the layer below is considered as groundwater layer 2.The assumption of classification is restricted to shallow aquifer.

The movement of water into, out of, and between the storages is administered by the following processes (USACE, 2000b):

- **Precipitation**- The process represents an input into the SMA system.
- **Evapotranspiration**- in the HEC-HMS, evapotranspiration is modeled as vaporization of weather directly from the soil and vegetative surface, transpiration through plant leaves.
- **Infiltration** - The potential infiltration volume, PIV, is calculated in the SMA method as:

$$PIV = If \frac{CSs}{Ss} If$$

Where, **If** is the maximum soil infiltration rate, CSs is the current soil storage, and **Ss** is the maximum volume of the soil storage.

- **Percolation** - The percolation rate from the soil profile into groundwater layer 1, CSp , is computed as:

$$CSp = Sp \left(\frac{CSs}{Ss} \right) \left(\frac{1 - CGs}{Gs} \right)$$

Where, Sp is the maximum soil percolation rate, CSs is the current soil storage, Ss is the maximum soil storage, CGs is the current storage in groundwater layer1, and Gs is the maximum storage in groundwater layer1.

Similarly, the percolation rate from groundwater layer 1 to layer 2, CGp , is given by:

$$CGp = Gp \left(\frac{CGs}{Gs} \right) \left(\frac{1 - CGs}{Gs} \right)$$

Where, GP is the maximum groundwater percolation rate.

- **Surface runoff**- Surface runoff is the water that exceeds the infiltration rate and overflows the surface storage.
- **Groundwater flow** - The SMA method models groundwater flow as:

$$GW = \left(\frac{CSp + Gst - pGpi - 0.5Gwt.T}{RGsi + 0.5TS} \right)$$

Where Gw_t , is the groundwater flow rate at the beginning of the time interval t , CSP is the actual soil percolation, PGp_i , is the potential percolation from groundwater layer I, and T is the simulation time step. The volume of groundwater flow from the river basin is computed as:

$$GW = 0.5(GW_{t+1} + GW_t)T$$

This volume is then an input into the HEC-HMS baseflow component.

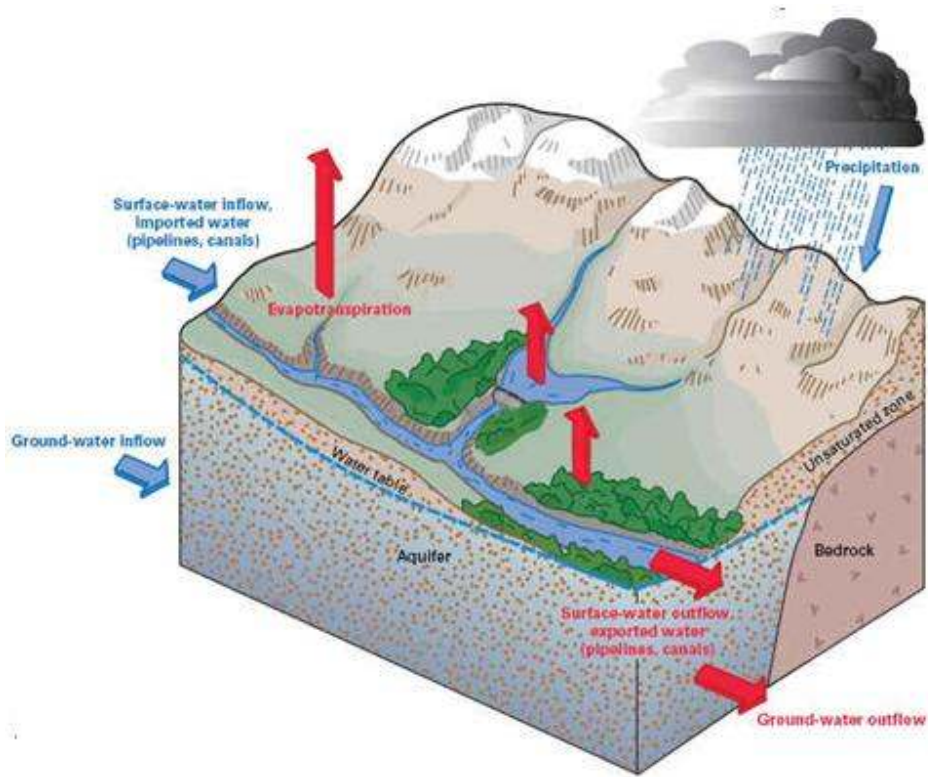


Figure.5.1: Conceptual hydrologic cycle model (USGS, circular 1308).

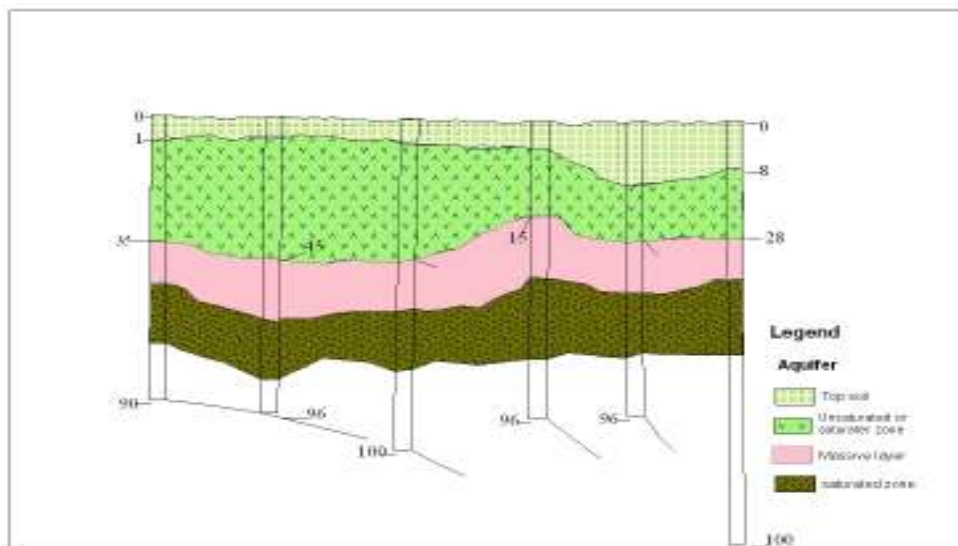


Figure 5.2: The correlation of selected geological logs in the study area (not to scale).

To run SMA model, 12 parameters are needed, of which some are measurable parameters and some cannot be measured by indirect/direct means. Data requirement for processing includes: soil map and its related information like saturated hydraulic conductivity, porosity, hydraulic

Table 5.1: SMA parameters and suggested sources to acquire.

Layers	Parameters (units)	Sources
Canopy interception storage	Storage capacity (mm);	GIS processing
Surface depression storage	Storage capacity (mm);	GIS processing
Soil profile storage	Soil infiltration Max.rate (mm/hr);	GIS processing
	Storage capacity (mm);	GIS processing
	Tension zone capacity (mm) ;	GIS processing
Groundwater layer-1 storage	Percolation Max.rate (mm/hr);	GIS processing
	Storage capacity (mm);	Stream flow analysis
	Percolation Max.rate (mm/hr);	GIS processing
Groundwater layer-2-storage	Storage coefficient (hr);	Stream flow analysis
	Storage capacity (mm);	Stream flow analysis
	Percolation Max.rate (mm/hr);	Model calibration
	Storage coefficient (hr);	Stream flow analysis

Model parameterization

The GIS processing is implemented in this study simply as map overlaying. The land use map, and soil map with relevant attributes are processed using ArcGIS.

- The saturated hydraulic conductivity of the first soil layer is used as the maximum infiltration rate;
- The porosity and field capacity values were simply multiplied by the depth of soil layer to obtain maximum soil profile and tension zone depths respectively. The average porosity of 0.4 and 0.5 is used. The depth of the soil varies from place to place. In order to use for the model run the average depth of 0.65m is selected. The field capacity of different soils is obtained from Soil-Plant-Atmosphere-Water field and pond Hydrology, SPAW model (Saxton, K. E., 2007).
- The average hydraulic conductivity for whole soil layers was used as percolation rate for soil zone and groundwater 1.

The interception storage is one of the parameters that required for the model simulation. Interception storage of the catchments was referred from Fleming (2002).

Table 5.2: The interception values for each of land use type.

Land use type	interception storage(mm)
Agriculture-mixed	1.27
Agriculture-crop	2.032
Agriculture-trees and agriculture trees – smack	2.54
Bare soil and urban	0

Therefore, the study area is classified under agriculture-mixed and agriculture-crop based on the area coverage.

The surface depression storage was calculated based on the surface slope. Most surface slope of the Lake Tana sub basin ranges from moderate to gentle slopes and flat. The value given in the table below is used as the surface storage as an input for SMA.

Table 5.3 Surface depression storage (Fleming and Neary, 2004).

Description	Slop (%)	Surface Storage (mm)
Paved Impervious Areas	NA	3.18-6.35
Steep. Smooth slopes	>30	1.02
Moderate to Gentle Slopes	5-30	6.35-12.70
Flat, Furrowed Land	0-5	50.8

Stream flow analysis

The soil moisture accounting (SMA) approach needs stream flow analysis to identify groundwater storage capacity and storage coefficient to accomplish its model parametrisation. Stream flow originating from groundwater discharge is referred to as base flow. During periods of precipitation stream flow is derived primarily from surface runoff, whereas during extend dry periods all stream flow may be contributed by base flow. Typically, base flow is not subject to wide fluctuations and is indicative of aquifer characteristics within a basin (Nathan and McMahon, 1990).

The baseflow-recession equation $Q = Q_0 e^{-at}$ indicates that Q_0 (the initial stream flow at the start of recession segment) varies logarithmically with time, t . A plot of a stream hydrograph with time on an arithmetic scale and discharge on a logarithmic scale will therefore yield a straight line for the baseflow recession (Linsley *et al.*,1958). The slope of this line should represent the recession constant K , depends on the time unit selected, which is usually used as an indicator of the extent of the baseflow (Nathan and McMahon, 1990). The recession constant K , for the catchments ranges from 0.96 to 0.987. If the storage - discharge is assumed to be linear, the integrated form of the classic recession function is:

$$S = kQ$$

Where S is represent groundwater storage and Q is discharge and k is constant having dimension of time (day). The storage coefficient of groundwater can be obtained by solving $\frac{-1}{\ln K}$.

Direct runoff component

The SCS Unit hydrograph was chosen in order to transform excess precipitation into surface runoff. The SCS lag parameter was calculated based on a formulation SCS Lag Method and Dingman. The overland flow, slope and other basin characteristics are extracted using ArcGIS Geo-HMS. The linear reservoir is adapted for base flow calculation methods because this module is suitable with the soil moisture accounting model. The time-of concentration (T_c) is used in the SCS methods, to determine how the runoff is distributed over time (Nezar and Ali, 2007).

The T_c is most often defined as the time required for a particle of water to travel from the most hydrological remote point in the basin to the point of collection. There are several methods available for calculating T_c , one of them is the SCS Lag Method:

$$TL = \frac{L^{0.8} \left[\left(\frac{1000}{CN} \right) - 9 \right]^{0.7}}{1900S^{0.5}}$$

$$T_c = 1.67 TL$$

Where T_c is the time of concentration (minutes); TL is the Watershed lag time (minutes); L is the length of longest Watercourse (ft); S is the mean slope of the basin (%); and CN is the curve number.

The basin parameter CN can be determined from empirical information.

The SCS has developed tables of initial curve number (CN) values as a function of the basin soil type and the land cover/use/condition. The hydrologic soil groups are defined in accordance to the standard SCS soil classification procedures, which establish a range from classification A for sand and aggregated silts with high infiltration rates, to classification D for soils that swell significantly when wet and have low infiltration rates (Nezar and Ali, 2007). On the basis of the

soil information for Lake Tana sub basin and the visible ground coverage, a CN of 78 was chosen.

The other method is also used to compute the time of concentration to compare with the SCS Lag Method:

$$T_c = \frac{0.7(L * L_c)^{0.38}}{S^{0.5}}$$

Where T_c is the time of concentration (hr), L_c is the distance from the outlet to the center of the catchment (Km), L is length of the main stream (Km), and S is the slope of the maximum flow distance path (Dingman, 2002). The calculated Watershed lag time is used for the initialize of the model and it further determined through calibration.

Table 5.4: Lag time and time of concentration of the catchments.

Catchments	Time of concentration(hr)	Lag time(min)
Gauged Megach	17.8	667.5
Ungauged Megach	25	937.5
Gauged Gummera	33.5	1256.25
Ungauged Gummera	14.03	526.13
Gauged Ribb	31.9	1196.25
Ungauged Ribb	23.14	867.75
Koga	22.6	847.5
Kility	30.26	1134.75
Gauged Gilgel Abay	37.84	1419
Ungauged Gilgel Abay	43	4308.6

5.2 Calibration

The calibration procedure involved a combination of both manual and automated calibrations. A manual calibration was used to determine the limits for the automated optimization. The univariate gradient search method of the HMS optimization manager was applied in the automated model calibration to optimize the set of initial model parameters within the limits obtained by manual calibration. Several statistical measures were used to assess the performance

of the hydrologic model, including error in peak flow, error in volume, and coefficient of determination. Each optimization output was assessed according to the above described criteria. If the output was acceptable, the calibration process was completed, otherwise the initial optimization parameters were altered and the process repeated.

The systematic manual calibration relied on the measured and estimated values of the model parameters available from the Basin. This ensured that a physically meaningful set of initial parameters constant. A 10% increased/ decreased step was used to linearly change parameter values until the soft limits were reached, (Fleming and Neary, 2004).

The input data for the continuous model are available in a daily time step. Since HMS control specifications setup is greater than the lag time of some sub basins in the study area, therefore the model computation step was changed to 6 hours. Suitable simulation period of the catchments is selected based on the data reliability. The simulation started from the dry season in order to initialize the model and to reduce the complexity of the parameters.

The period October 1, 1995 to December31, 2000 is selected for Megach catchments. The period of 1 November, 1993 to 31December 1997 is for Gummera, 1Jan 2002 to 31December 2004 for Ribb and period 1Dec 1995 to 31December 2000 is selected for Gilgel Abay. Since the stream flow at the Ribb is highly affected by flooding, the period of 1Jan 2002 to 31December 2004 were chosen from the stream record for the period 1992 to 2006. At the beginning of the simulation the initial storage contained in both the Canopy and Surface Storage layers was set to 0 percent because the simulation begins when the precipitation is minimum or not available. The precipitation during dry period has either evaporated or infiltrated into the soil. The initial storage for the GW 1 layer was set to 0 percent because the hydrograph shows a relatively flat baseflow hydrograph which indicates a slower responding input to baseflow. Before calibration of the model the sensitivity of each parameter to the model was identified. The least sensitive parameters were calibrated first followed by highly sensitive parameters. The canopy and surface storage are less sensitive to the model. The period of simulation and the vegetation density does not favor much canopy storage. Soil storage, tension storage, and maximum soil infiltration rate

are the most sensitive parameters. The A 10% increased/ decreased step was used to linearly change parameter values until the soft limits were reached.

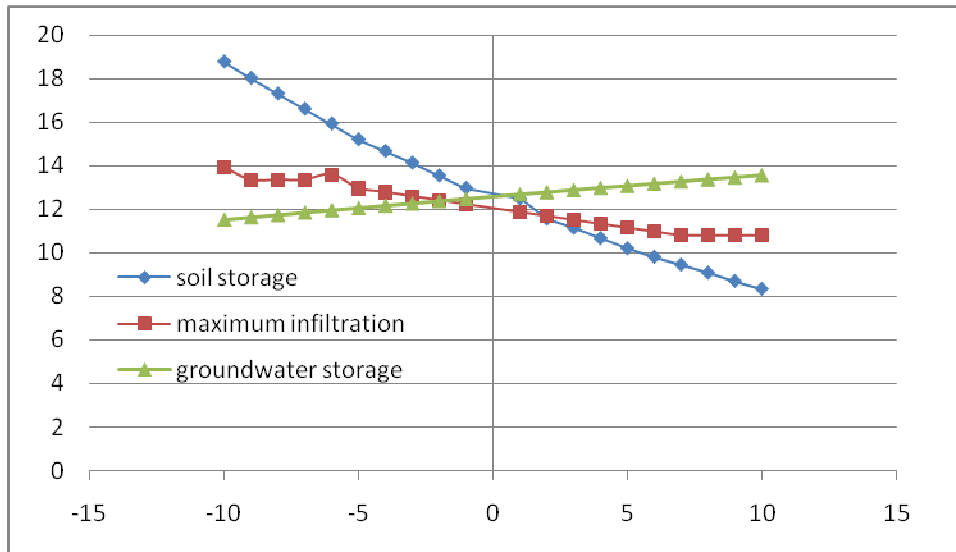


Figure 5.3: Sensitivity of soil, groundwater storage and soil infiltration rate on 10% increased/ decreased step against percent volume error.

The statistical performance of the model was evaluated for each modeled catchments. The HMS –SMA is highly sensitive to rainfall duration. The multiple flow peak observed at each hydrograph is due to the erratic pattern of rainfall. The erratic pattern of rainfall is one of the challenges in the calibration of the model. Rainfall data analysis prior to the calibration is the pre-requisites to get appropriate results. The flow condition analysis in the case of Ribb is challenging. The flow year which is not affected by flooding was used for calibration. The irregularities in the stream flow causes overestimation and underestimation of the flow. The high rainfall amount in the year 1996 in the Gilgel Abay also initiate high flow peak. The model performance for the other catchments is in the acceptable range. Normal Probability Plot is useful in examining the possible non-normality of residuals. There is departure from normality line at both the low and high ends of the residual values. In this case, a departure from normality is likely to be due to the outliers and sensitivity of modeled flow to rainfall amount.

Table 5.5: Statistical performance measure of selected catchments.

Catchments	PEV	PEPF	r^2	R	Adj. R^2	S.E. of Estimate
Gilgel						
Abay	-1.69	16.2	0.958	0.979	0.958	15.885
Ribb	5.56	8.2	0.723	0.911	0.830	8.999
Gummera	1.82	-9.5	0.876	0.936	0.877	21.236
Megach	-4.67	-0.5	0.864	0.930	0.864	5.696
Kility	-0.67	6.6	0.98	0.990	0.940	2.251
Koga	-0.18	3.9	0.96	0.998	0.925	0.492

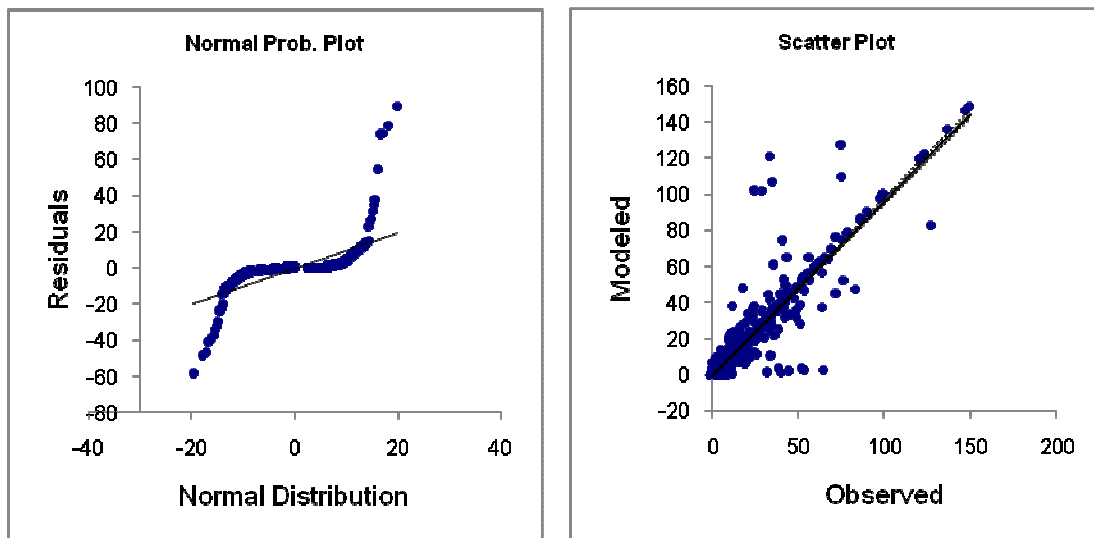


Figure 5.4: Normal probability distribution and scatter plot of Megach River.

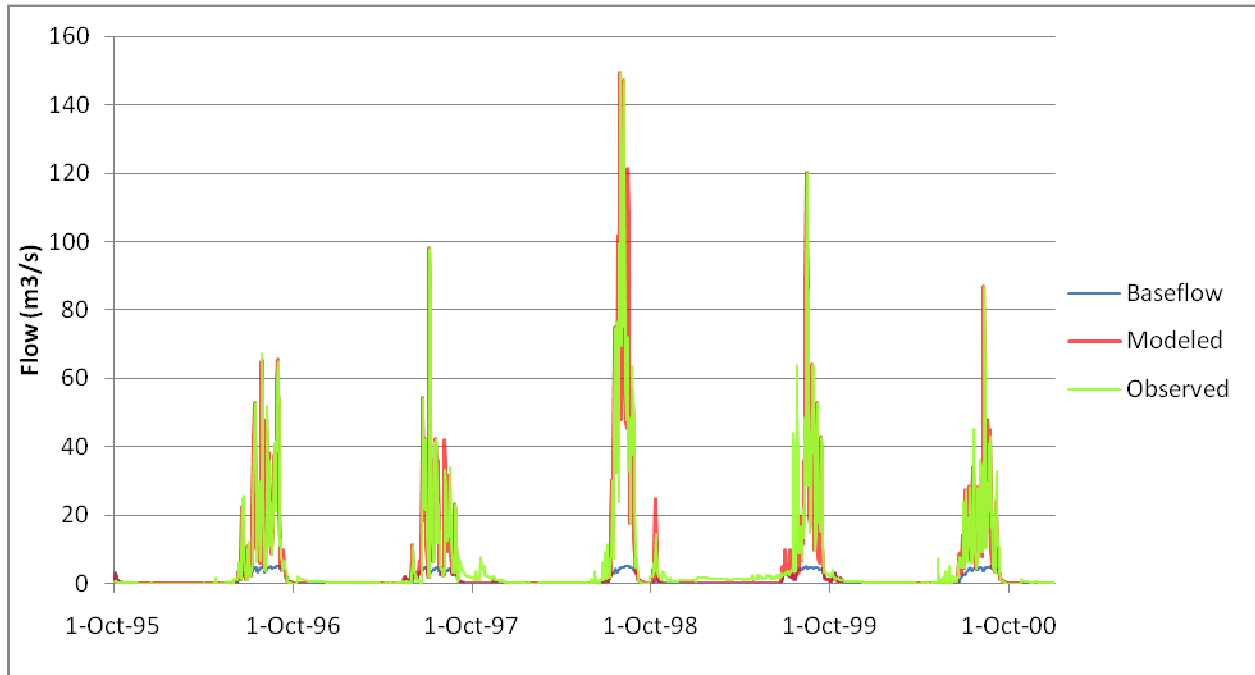


Figure 5.5: Observed and modeled hydrograph for the period October 1, 1995 to December31, 2000 at Megach.

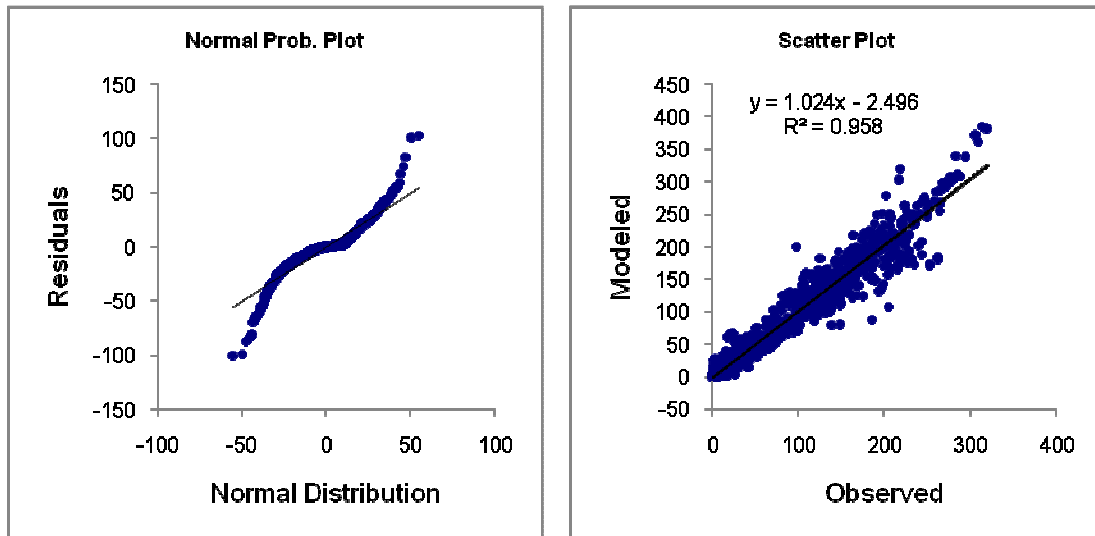


Figure 5.6: Normal probability distribution and scatter plot of Gilgel Abay River.

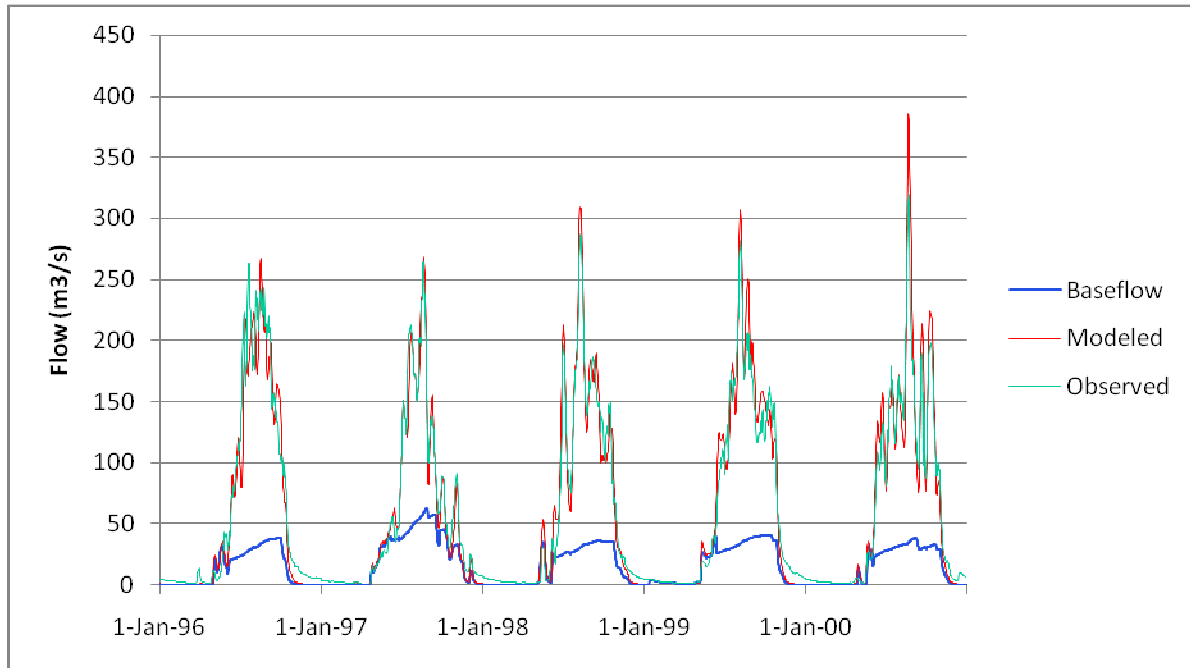


Figure 5.7: Observed and modeled hydrograph for the period December 1, 1995 to 31December 2000 at Gilgel Abay.

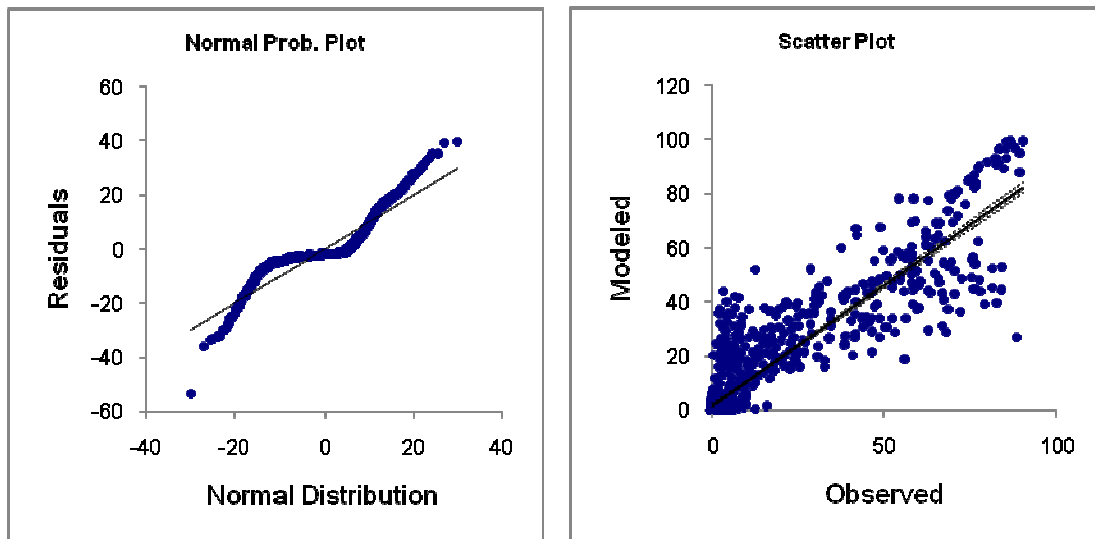


Figure 5.8: Probability distribution and scatter plot of Ribb River.

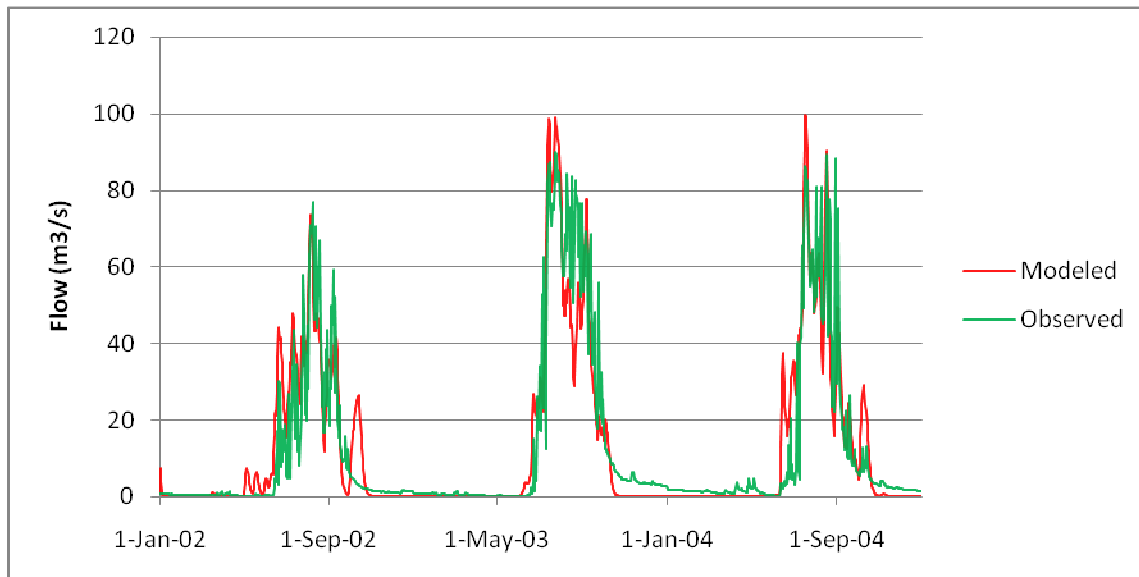


Figure 5.9: Observed and modeled hydrograph for the period 1Jan 2002 to 31December 2004 at Ribb.

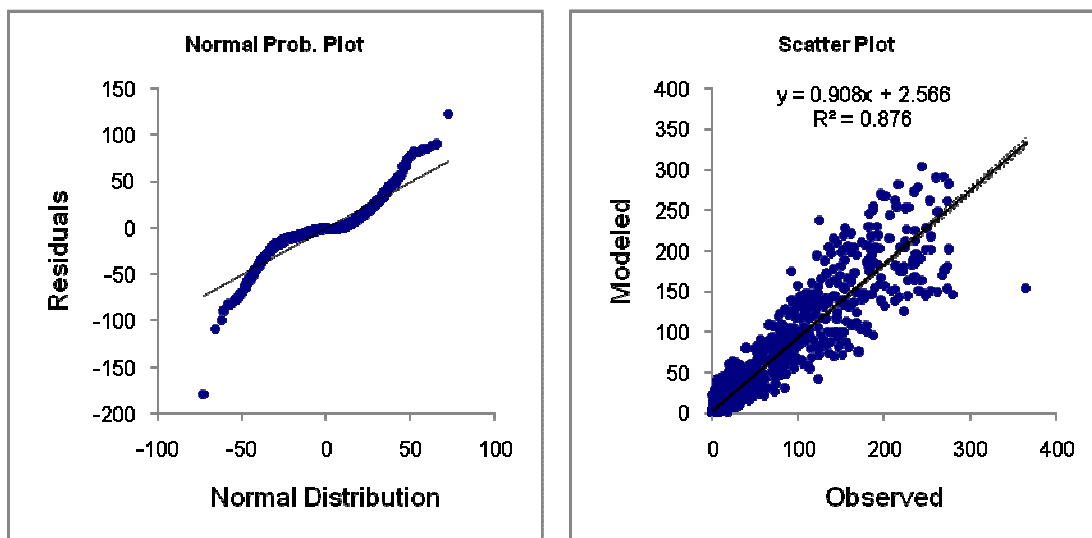


Figure 5.10: Normal probability distribution and scatter plot of Gummera River.

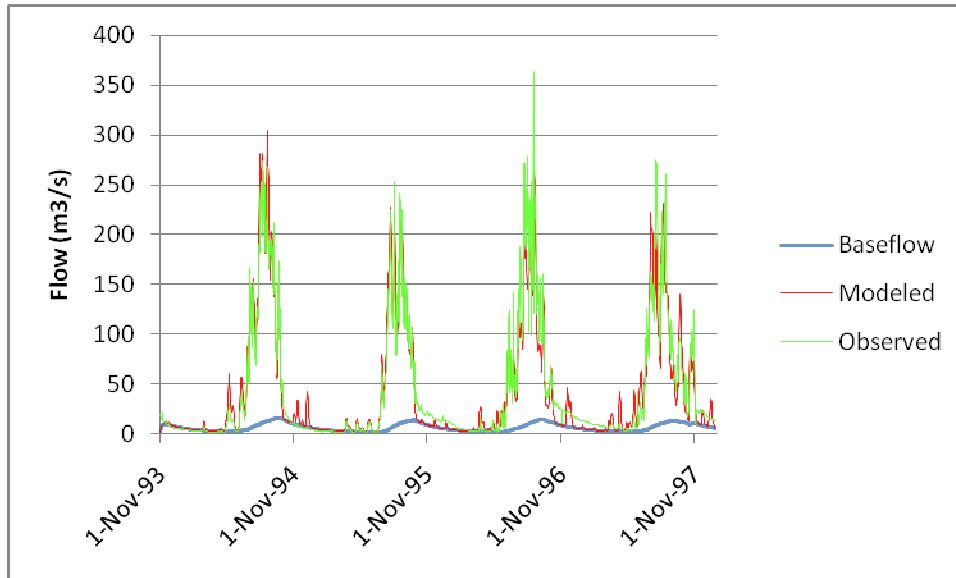


Figure 5.11: Observed and modeled hydrograph for the period November 1, 1993 to November 1, 1997 at Gummera.

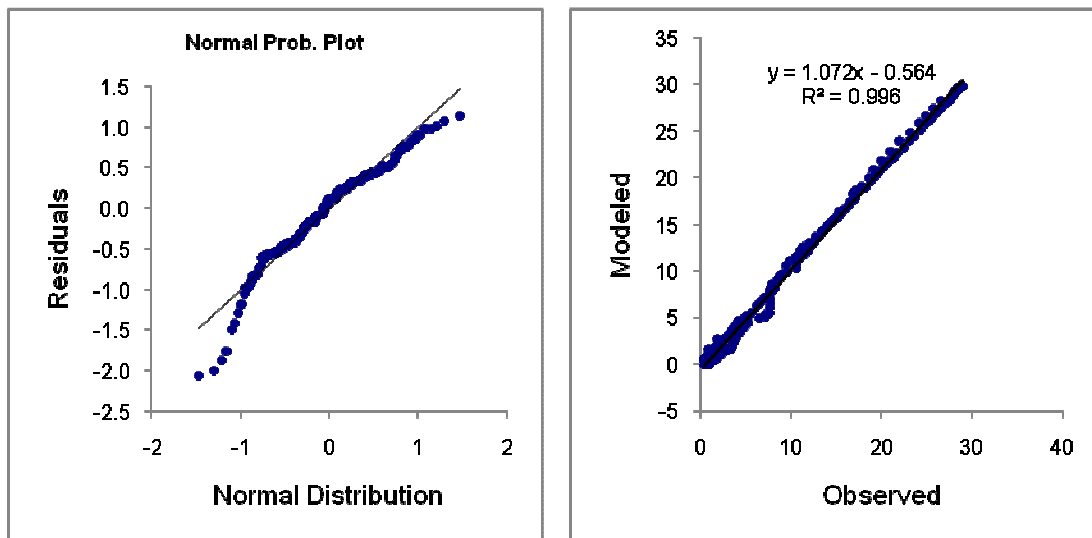


Figure 5.12 Normal probability distribution and scatter plot of Koga River.

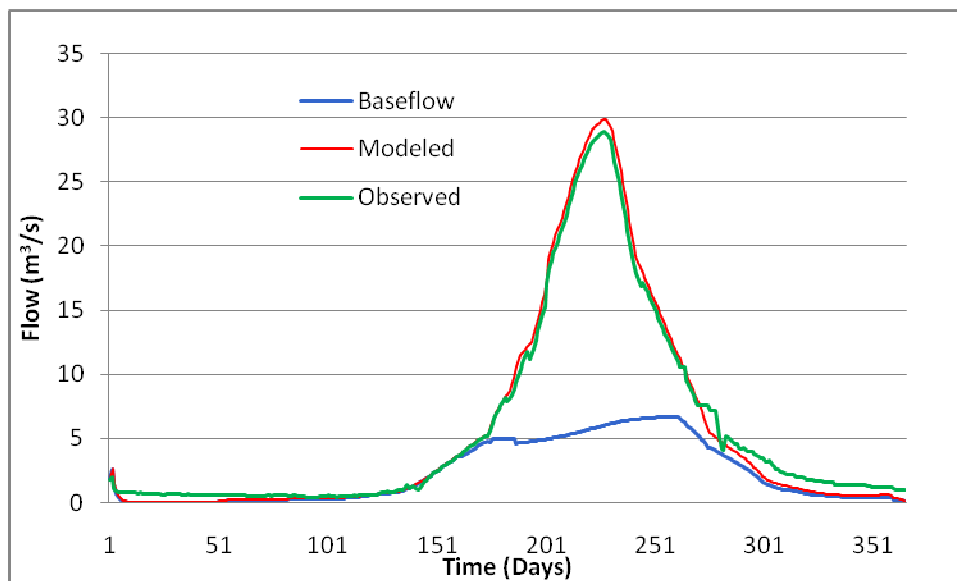


Figure 5.13 Observed and modeled hydrograph for average daily flow at Koga.

5.3 Recharge estimation Results

The quantity of water that infiltrates from the land surface to the aquifer is an essential input for simulation of flow in the aquifers. Recharge has been defined as the water added to the saturated groundwater body; in the context of river recharge it is the water that leaves a river and crosses the water table. The sense in which it is used here agrees with the definition in the AGI Glossary (1973), namely recharge comprises the processes involved in the absorption and addition of water to the zone of saturation. The term also means the volume of water added to the zone of saturation. Recharge is a complex process, but quantification is critical in order to understand the total water availability in the Lake Tana sub basin.

The recharge estimation of the Lake Tana sub basin was carried out based on the principle of base flow separation using HMS – SMA for gauged catchments and multiple linear regression for ungauged catchments. Base flow is water that enters the stream from the persistent, slowly varying sources and maintains stream flow between inputs of direct flow (Sophocleus, 2002). Although the concept of base flow does not imply a strict origin, hydrologists generally agree that most base flow originates largely by saturated flow from groundwater storage, and long-term

base flow rates are, as a consequence, commonly invoked as indicator of basin wide groundwater recharge rates (Meyer, 2005). The model result indicated that the groundwater contribution is restricted to shallow aquifer.

Table 6.1: Catchment characteristics of six gauged catchments in the Lake Tana sub basin.

Catchments	Area (Km ²)	Mean annual Rainfall (mm/yr)	Mean annual runoff(mm/yr)	Baseflow (mm/yr)	Baseflow as % of rainfall	Runoff as % of Rainfall	BFI
Gilgel							
Abay	1640	1614.34	1144.659	379.094	23.48291	70.9057	0.331
Gummera	1394	1291.5	891	158.21	12.2501	68.98955	0.177
Megach	492	1081	437.4	61.88	5.724329	40.46253	0.141
Ribb	1592	1263	302.6	77	6.096595	23.95883	0.254
Koga	301.55	1409.78	599.57	233.6	16.56996	42.52933	0.38
Kility	698.36	1321.77	393.71	57.25	4.331313	29.78657	0.145

The base flow results for the catchments shows that large amount of groundwater contribution is found in the south part of the Lake Tana sub basin. Gilgel Abay gauged at Merawi contributes 33.1% of the total runoff or 23.48% of the mean annual rainfall goes to base flow. Megach catchment contributes 14.1% of the total runoff and 5.72% of the mean annual rainfall which is attributed to less amount of rainfall in the north side of the basin. Ribb catchment on the east of Lake Tana contributes 25.2% of the total runoff or 6.096% of the mean annual rainfall. Gummera Catchment on the southeast of Lake Tana contributes 17.7% of the total runoff and 12.25% of the mean annual rainfall. Koga catchment is located on the shoulder of Gilgel Abay on the east contributes relatively large amount of base flow. Kility is found to the west of Gilgel Abay contributes 14.5% of the total runoff and 4.33% of the mean annual rainfall. Generally the groundwater contribution from gauged catchments varies from 14.1% to 33.1% of the total runoff. The high rainfall amount, high hydraulic gradient and outcrop of Tertiary volcanic in the high topographic setting contribute large amount of runoff. Koga River drains some part of the Tertiary volcanic rocks and Quaternary volcanic rocks in the downstream. The local fracture and fissure at the Tertiary volcanic rocks favor downward circulation of precipitation. The dense vegetation and low potential evaporation also play great role infiltration. These areas permit

sustainable baseflow to the river. Gilgel Abay is characterized by high slope which increases the hydraulic gradient for the movement of water. The local fracture and fissure at the foot of Choke mountain favor downward circulation of precipitation which sustains the flow of Gilgel Abay River. The Kility River drains Quaternary volcanic rocks from the south to Lake Tana. The Kility River is characterized by low slope which favor downward circulation rather than Lateral flow. The baseflow from Kility catchment is smaller than that of Gilgel Abay and Koga with same climatic zone. This could be due to the slope, geology of the Kility Catchment. Megach, Ribb and Gummera catchments drain Tertiary volcanic rocks. The distribution of rainfall and slope is quite different. The baseflow from Megach catchment is low as compared with Ribb and Gummera Catchments. The Megach catchment is characterized by low precipitation amount but by high potential evapotranspiration. Megach catchment is relatively compacted shape which facilitates short storage time of rainfall. These factors indirectly affect baseflow of the catchment.

The simple scatter plot of rainfall and baseflow rate shows the positive correlation between them.

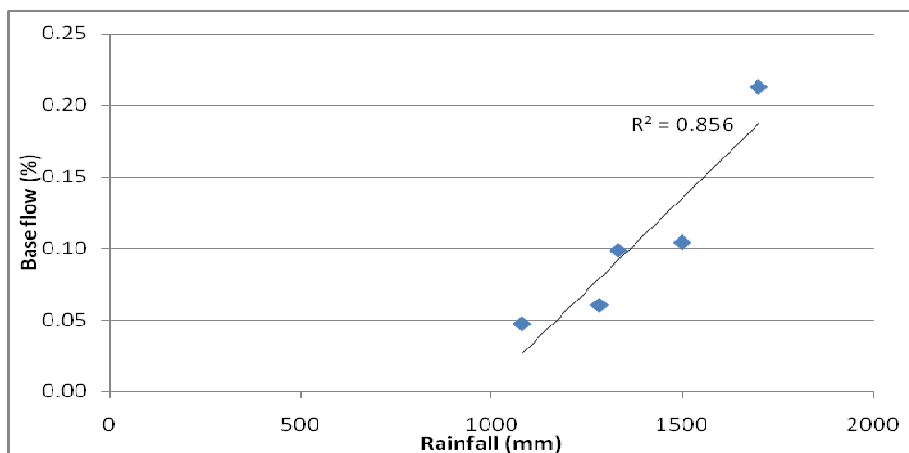


Figure 6.1 Recharge rates (%) versus precipitation.

Catchment characteristics for prediction of flow at ungauged catchments

Variations of flow characteristics in space and time are influenced by catchment characteristics such as climate, geomorphology, lithology, and land cover. Climate sets the broad limits to the

transfer of water between the atmospheric system and the drainage basin. Other factors affect the transformation of net rainfall into various transfer processes and storages that occur within a drainage basin hydrological system. Flow characteristics are indicators of the status of some of these processes and storages. Consequently, prediction of each of the flow characteristics requires identification of influential factors. Estimation of flow characteristics of ungauged catchments is usually based on transferring or extrapolating information from gauged to ungauged sites, a process called regionalization (Nathan and McMahon, 1990a). Several regionalization approaches have been used, and the most common method involves derivation of empirical relationships between flow and catchment characteristics (Gan *et al.*, 1990).

Linear multiple regression analysis is method of estimating streamflow statistics at ungauged sites. Multiple regression is used to create equations that relate streamflow statistics of gauged sites in a region with the climatic and physical characteristics of their upstream drainage areas.

The equation describing a linear multiple regression analysis is:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + \dots + b_k X_k$$

Where Y is the dependent variable, b_0 to b_k are the regression model coefficients determined in the analysis, X_1 to X_k are the independent variable (basin characteristics) for site.

The selection of independent variables, or basin characteristics, for the regression equations in the 9 regions was determined. Climate index (climate index, often denoted as aridity/humidity index, is the ratio of mean annual precipitation to potential evapotranspiration), fraction of vegetation coverage, and drainage density are selected using Stepwise regression analysis available using statistiXL Version 1.7, released 17 June 2007. The hypsometric integral (I) is the area beneath the curve which relates the percentage of total relief to cumulative percent of area. This provides a measure of the distribution of landmass volume remaining beneath or above a basal reference plane. Integration of the hypsometric curve gives the hypsometric integral I. It is proved mathematically that the elevation-relief ratio (E) which is defined as (Pike and Wilson, 1971):

$$E = \frac{\text{Mean elevation} - \text{min elevation}}{\text{Max elevation} - \text{min elevation}}$$

is identical to the hypsometric integral I but has the advantage that it is much more easy to obtain numerically. In this work, E is therefore used instead of I . The hypsometric integral was eliminated from the equation by backwards stepwise regressions.

Stepwise regression is included in many statistical software packages and is a procedure that helps determine an optimal selection of independent variables for a multiple regression equation. In a forward stepwise regression process, variables are added one by one. During each step, all unused variables are examined in order to determine which explains the largest amount of unexplained variation. After the addition of a variable, all variables selected are evaluated to ensure that each meets a predetermined level of significance in explaining the variation. Any variables found to be no longer significant are removed. These steps are repeated until none of the remaining unselected variables explain a significant amount of the remaining unexplained variation and all selected variables are significant. In a backward stepwise regression, the procedure begins with all possible variables included in the equation. On the bases of null hypothesis, H_0 is that the coefficient relating the explanatory (x) variable to the dependent (y) variable is 0. In other words that there is no relationship between the explanatory variable and the dependent variable. The alternative hypothesis H_1 is that the coefficient relating the x variable to the y variable is not equal to zero. In other words there is some kind of relationship between x and y . With each step, the least significant variable is eliminated. This step is repeated until all remaining variables in the equation are determined to be significant. A level of significance of 0.05 was used for the forward and backwards stepwise regressions. The forward and backward stepwise regression analysis created two equations for each regression dataset. Sometimes, the two equations were identical, but generally the equation created by the backward stepwise regression method had more independent variables than the equation created by the forward stepwise regression method. Higher values of the coefficient of determination generally are desirable in a regression analysis, especially when the dataset does not contain an outlier. StatistiXL provides the direct statistic for testing outliers.

The Base Flow Index (BFI) is used as a measure of the base flow characteristics of catchments. It provides a systematic way of assessing the proportion of base flow in the total runoff of a catchment. It indicates the influence of soil and geology on river flows, and is important for low flow studies. Therefore, the selected independent variables were correlated with baseflow index.

Table 6.2: Catchment characteristics of gauged catchments in the Lake Tana sub basin.

Catchments	Vegetation	Drainage density(km/km ²)	Hypsometric integral(I)	Climate index(CI)	BFI
Gilgel					
Abay	0.2111	0.26	0.348	1.39	0.331
Gumera	0.1811	0.236	0.257	1.05	0.177
Megach	0.0432	0.237	0.33	0.79	0.141
Ribb	0.1236	0.3	0.298	1.13	0.254
Koga	0.154	0.25	0.359	1.3	0.38
Kility	0.2722	0.228	0.83	1.029	0.145
Gumero	0.0864	0.426	0.5	0.76	0.22
Garno	0.1193	0.449	0.46	0.75	0.16
Gelda	0.1923	0.455	0.47	0.76	0.15

Table 6.3: statistiXL Pearson Correlations of catchment characteristics.

	BFI	Vegetation	Drainage density(km/km ²)	Hypsometric integral(I)	Climate index
BFI	1.000	0.071	-0.273	-0.368	0.811
Vegetation	0.071	1.000	-0.243	0.512	0.455
Drainage density(km/km ²)	-0.273	-0.243	1.000	0.112	-0.655
Hypsometric integral	-0.368	0.512	0.112	1.000	-0.238
Climate index	0.811	0.455	-0.655	-0.238	1.000

Table 6.4: statistiXL Regression Coefficients.

Source	Coefficient	Std Error	Std Beta	-95% C.I.	+95% C.I.	t	P.
Intercept	-0.309	0.104		-0.577	-0.042	-2.975	0.031
Vegetation(V)	-0.519	0.192	-0.411	-1.013	-0.025	-2.703	0.043
Drainage density(Dd)	0.439	0.160	0.494	0.029	0.850	2.753	0.040
Climate index(CI)	0.470	0.069	1.322	0.292	0.649	6.769	0.001

From the above statistical results, all independent variables are highly significant with probability $P < 0.05$, and so none can be removed in a further step, so the backward stepwise regression equation is:

$$\text{BFI} = 0.47 \text{CI} + 0.439 \text{Dd} - 0.519 \text{V} - 0.309 \quad R^2 = 0.909$$

Where BFI is baseflow index, CI is climate index, Dd is drainage density, and V is fraction of vegetation coverage.

Table 6.5: Predicted baseflow and runoff from multiple regressions for Ungauged Catchments.

Catchments	Area(Km ²)	Rainfall (mm)	Runoff (mm)	Baseflow(mm)	Climate index	Slope (%)	Vegetation coverage	BFI
Gilgel Abay	1481	1470	394.9	63.184	1.083426	17	0.18	0.16
Gummera	121	1326.35	250.62	30.57564	1.002089	17	0.16	0.122
Ribb	418	1318	297.05	38.6165	1.082839	28	0.13	0.13
Megach	315.3	1059.976	74.39	7.439	0.795125	18	0.031	0.1
West Tana	1065	1000	26.51	1.0604	0.699301	20	0.01	0.04

For some of the flow characteristics, multiple regression methods are capable of identifying the influential catchment characteristics (Chow, 1964). The runoff for the catchment has shown strong correlation with mean annual rainfall ($r^2 = 0.8$) and slopes ($r^2 = 0.75$) of the catchments. Base flow index (BFI) has also a strong relationship with mean annual rainfall catchments. The base flow index used here is obtained from the model results of gauged catchments. Drainage density and slopes within a catchment have a considerable effect on base flows. Subsurface water can only contribute to runoff if a hydraulic gradient exists. The slope of the water table usually conforms to the slope of the land above (Freeze and Cherry, 1979). According to Darcy's Law catchments with steep slopes will have high hydraulic gradients, resulting in high base flow rates. Besides the effect of slope on the hydraulic gradient, steep slopes occur in mountainous and hilly parts of catchments. Some of these hills and mountains have substantial fractures and fissures that store water during the rainy season, and then release it as base flow during the dry season. The shield volcanoes (Guna, and choke shield) are the principal site of recharge to the

Lake Tana sub basin (Kebede *et al*, 2005). Thus, steep slopes may also indirectly reflect areas with substantial subsurface storage due to these fractures and fissures. The downstream of the catchments is relatively flat and characterized by low drainage density and gentle slopes. Hence, these ungauged catchments contribute small amount of baseflow.

The regional geology and hydrogeology of these ungauged catchments are quite similar to their gauged catchments. The thickness of the alluvial deposit is increased around the Lake Tana. The catchments within the same region have the same geology and hydrogeological condition but they have different hydrological condition. The rainfall distribution is associated with elevation. The rainfall amount decreases toward the low land. Thus, the distribution of rainfall, drainage density, shape and the slopes are the major controlling factor keeping the other characteristics similar. Table 6.4 summarizes the general hydrology and hydrogeology of Lake Tana sub basin.

Table 6.6: Base flow amount at different catchments with respect to Lake Tana.

Location	Runoff (mm)	Baseflow(mm)	Geology	Hydrogeology
West Tana	26.51	1.06	Tarmaber basalt	Moderate productive fracture aquifer
SouthTana	2532.839	733.128	Quaternary vesicular basalt	Highly productive fracture and intergranular aquifer
NorthTana	511.79	69.319	Tarmaber basalt	Moderate productive fracture aquifers
East Tana	1741.27	304.4021	Tarmaber basalt	Moderate productive fracture aquifers

The springs discharges and swamp condition in the low lands are an indication of discharge condition in the downstream. The four big rivers are delivering large amount of water to Lake Tana through the year. The contribution of Lake Tana to the rivers is insignificant. Groundwater collected for isotope analysis from around the southern, eastern and northern parts of the lake do not show any sign of enrichment ($\sigma^{18} O$) by mixing of lake water into them. This lack of groundwater outflow from the lake is the result of the lake ward dipping block of rocks that favor groundwater flow to the lake rather than the loss of lake water into the surrounding aquifers (Kebede *et al.*, 2005). Large amount of baseflow is contributed from southern part of the Lake Tana whereas less amount of base flow derived from western parts.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The recharge estimation of the Lake Tana sub basin was carried out based on the principle of base flow separation using HMS – SMA for gauged catchments. The calibration procedure involved a combination of both manual and automated calibrations. A manual calibration was used to determine the limits for the automated optimization. The hydrological and meteorological data used for the period of 1992 to 2006. StatistiXL Multiple linear regression was used to estimate the runoff for ungauged catchments. A level of significance of 0.05 was used for the forward and backwards stepwise regressions. Climate and physical characteristics of the catchments were used in multiple regression to predict the flow characteristics of ungauged catchments. The amount of rainfall, topographic setting and geology are the main controlling factors of climate and physical characteristics of the catchments. The base flow results for the catchments shows that large amount of groundwater contribution is found in the south part of the Lake Tana sub basin. Gilgel Abay gauged at Merawi contributes 33.1% of the total runoff or 23.48% of the mean annual rainfall goes to base flow. Megach catchment contributes 14.1% of the total runoff and 5.72% of the mean annual rainfall which is attributed to less amount of rainfall in the north side of the basin. Ribb catchment on the east of Lake Tana contributes 25.2% of the total runoff or 6.096% of the mean annual rainfall. Gummera Catchment on the southeast of Lake Tana contributes 17.7% of the total runoff and 12.25% of the mean annual rainfall. Koga catchment is located on the shoulder of Gilgel Abay on the east contributes relatively large amount of base flow. Kility is found to the west of Gilgel Abay contributes 14.5% of the total runoff and 4.33% of the mean annual rainfall. The groundwater contribution from gauged catchments is about 161.7mm/yr or 12.1% of the total rainfall of the basin. The topography toward the Lake is flat, which favors low hydraulic gradient, and the base flow indexes of downstream catchments define that the upward movement is more facilitated rather than downward movement. The ungauged catchments contribute about of 28.18 mm/yr or 2.28% of the total rainfall of the basin.

6.2 Recommendation

The overall distribution of rain gauge and river gauging stations are located along the highway. The reliability of these stations on the water resource evaluation and management is challenging, so that great attention should be taken to monitor the appropriate function of existing stations and looking for the additional stations.

Groundwater level monitoring is relatively simple, which is relevant for recharge estimation in the area where gauging stations are scarce. Since groundwater well is not affected by flooding, it has capability in evaluating rainfall departure within the season to estimate recharge.

The intention of using monitored water point as gaining stations should be adopted to evaluate water resource.

Using of isotope for deep groundwater circulation assessment should be conducted for detail investigation of recharge.

Detail investigation of geology, hydrogeology land use/land cover should be carried out in this area which is rich in natural resources. These are also important for groundwater recharge estimation.

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ANNEXES

Annex 1- Thiessen Polygon Method Calculated Annual Rainfall.

Station	Thiessen Polygon Method of Rainfall Calculation			
	Area (Km ²)	Weighted Area (%)	Rainfall (mm)	Weighted (mm)
Adet	18.944914	0.0	1272.4	1.6
Adis Zemen	692.88531	0.0	1068.0	48.3
Arbe Gebeya	1204.8	0.1	1204.8	94.7
Aykel	115.3103	0.0	1175.0	8.8
Bahir Dar	217.79169	0.0	1416.0	20.1
Dangila	1025.3971	0.1	1557.67	102.9
Debre Tabor	1573.3691	0.1	1494.0	153.4
DeKI				
Istefanos	1036.6084	0.1	1676.6	113.4
Delgi	712.71173	0.0	809.0	37.6
Enjebara	348.91553	0.0	2266.0	51.6
Gimjabet	8.229435	0.0	1898.4	1.0
Gonder	910.36816	0.1	1081.0	64.2
Gorgra	1228.4841	0.1	1107.4	88.8
Infranz	830.75653	0.1	971.0	52.7
Kunzila	1089.3087	0.1	1126.8	80.1
Maksagnt	619.33917	0.0	1144.2	46.3
Merawi	1453.5673	0.1	1572.3	149.2
Nifasmewcha	1.34431	0.0	1104.9	0.1
Sekala	751.85876	0.0	1616	76.9
Tis Abay	66.090309	0.0	1144.8	4.9
Tlili	11.21783	0.0	1942.4	1.4
Woreta	678.19324	0.0	1236.7	54.7
Zege	724.52936	0.0	1605.0	75.9
Total	15320.0213			1328.872001

Annex 2- Inverse square distance relationship of the stations and catchments.

Catchments	Weight of the station to the catchment			
	Bahir Dar	Dangila	Gonder	Debre Tabor
Gelda	0.701	0.046	0.043	0.21
Garno	0.142	0.044	0.565	0.249
Gumero	0.062	0.023	0.822	0.092
Koga	0.447	0.456	0.036	0.061
Megach Gilgel	0.009	0.004	0.976	0.011
Abay	0.144	0.802	0.021	0.033
Gummera	0.115	0.02	0.03	0.835
Ribb	0.021	0.006	0.014	0.96

Annex 3-Daily average Discharge (m³/s) from 1992 – 2006.

Day	Gilgel Abay	Gummera	Megach	Ribb	Koga	Kility
1	5.13	5.85	1.40	1.78	1.673	1.08
2	4.96	5.73	1.38	1.70	1.657	1.10
3	4.87	5.64	1.36	1.66	1.633	1.08
4	4.81	5.62	1.35	1.66	1.594	1.05
5	4.76	5.52	1.35	1.63	1.58	1.06
6	4.65	5.45	1.35	1.61	1.564	1.00
7	4.60	5.44	1.33	1.61	1.582	0.99
8	4.56	5.32	1.32	1.59	1.552	0.97
9	4.50	5.24	1.32	1.56	1.517	1.32
10	4.48	5.18	1.31	1.53	1.479	0.99
11	4.42	5.11	1.29	1.53	1.478	0.95
12	4.38	5.05	1.30	1.53	1.47	0.94
13	4.34	4.98	1.31	1.52	1.459	0.93
14	4.38	4.92	1.29	1.47	1.45	0.89
15	4.27	4.90	1.27	1.05	1.457	0.86
16	4.18	4.80	1.27	0.85	1.436	0.85
17	4.12	4.79	1.26	0.83	1.419	0.82
18	4.08	4.66	1.25	0.83	1.412	0.79
19	4.04	4.60	1.26	0.83	1.365	0.76
20	3.91	4.53	1.24	0.86	1.381	0.84
21	3.87	4.47	1.24	0.82	1.377	0.90
22	3.86	4.39	1.24	0.83	1.375	0.87
23	3.77	4.23	1.20	0.83	1.365	0.86
24	3.70	4.15	1.21	0.83	1.353	0.78
25	3.62	4.10	1.20	0.79	1.334	0.75
26	3.59	4.04	1.22	0.78	1.317	0.73
27	3.57	3.97	1.21	0.76	1.303	0.71
28	3.47	3.88	1.21	0.77	1.287	0.75
29	3.43	3.90	1.20	0.75	1.283	0.73
30	3.38	3.88	1.18	0.72	1.27	0.67

Daily average Discharge (m³/s) from 1992 – 2006 continued

31	3.35	3.85	1.18	0.71	1.272	0.68
32	3.34	3.81	1.18	0.71	1.267	0.65
33	3.28	3.75	1.17	0.69	1.261	0.65
34	3.20	3.75	1.17	0.70	1.243	0.64
35	3.17	3.65	1.16	0.66	1.237	0.62
36	3.14	3.37	1.15	0.65	1.24	0.60
37	3.06	3.14	1.14	0.66	1.257	0.57
38	3.01	3.08	1.15	0.64	1.241	0.57
39	2.98	3.07	1.23	0.62	1.209	0.55
40	2.96	3.02	1.14	0.61	1.195	0.56
41	2.93	2.98	1.14	0.60	1.17	0.60
42	2.89	2.96	1.12	0.60	1.16	0.61
43	2.86	2.91	1.10	0.61	1.172	0.57
44	2.81	2.90	1.09	0.60	1.16	0.53
45	2.80	2.89	1.09	0.57	1.158	0.51
46	2.76	2.86	1.08	0.57	1.146	0.50
47	2.68	2.78	1.08	0.55	1.137	0.55
48	2.60	2.78	1.07	0.52	1.106	0.43
49	2.60	2.72	1.07	0.53	1.1	0.37
50	2.58	2.69	1.07	0.52	1.078	0.41
51	2.54	2.66	1.05	0.51	1.053	0.42
52	2.51	2.62	1.04	0.50	1.083	0.41
53	2.49	2.61	1.04	0.49	1.053	0.45
54	2.48	2.61	1.04	0.48	1.038	0.42
55	2.45	2.63	1.09	0.48	1.028	0.33
56	2.47	2.58	1.15	0.47	1.017	0.31
57	2.47	2.54	1.15	0.49	1.02	0.32
58	2.49	2.51	1.13	0.50	1.012	0.33
59	2.48	2.47	1.14	0.47	1.001	0.32
60	2.37	2.43	1.13	0.49	1.034	0.31

Daily average Discharge (m³/s) from 1992 – 2006 continued

61	2.32	2.39	1.13	0.43	0.987	0.30
62	2.31	2.71	1.12	0.41	0.969	0.31
63	2.31	3.21	1.12	0.45	0.958	0.33
64	2.30	3.17	1.12	0.41	0.944	0.41
65	2.21	3.20	1.12	0.34	0.939	0.34
66	2.21	2.29	1.11	0.32	0.916	0.44
67	2.20	2.30	1.10	0.30	0.903	0.43
68	2.17	2.25	1.10	0.28	0.922	0.42
69	2.17	2.23	1.10	0.27	0.919	0.28
70	2.13	2.24	1.10	0.25	0.917	0.27
71	2.10	2.25	1.11	0.28	0.913	0.33
72	2.09	2.27	1.32	0.27	0.887	0.26
73	2.06	2.35	1.23	0.43	0.975	0.26
74	2.10	2.51	1.35	0.42	0.962	0.22
75	2.19	2.54	1.35	0.45	0.929	0.26
76	2.28	2.42	1.31	0.68	1.029	0.23
77	2.34	2.43	1.37	0.72	1.049	0.22
78	2.32	2.55	1.28	0.66	1.011	0.23
79	2.20	2.79	1.25	1.14	1.019	0.24
80	2.27	2.70	1.24	0.68	0.996	0.24
81	2.25	2.74	1.24	0.60	0.962	0.25
82	2.26	2.59	1.22	0.68	0.966	0.24
83	3.12	2.79	1.24	0.68	0.946	0.18
84	4.22	2.99	1.22	0.64	0.945	0.19
85	3.86	2.79	1.20	0.62	1.003	0.18
86	2.88	3.47	1.23	0.60	0.963	0.16
87	2.47	2.53	1.28	0.54	0.93	0.14
88	2.26	2.37	1.26	0.50	0.89	0.16
89	2.13	2.17	1.24	0.42	0.884	0.17
90	2.07	2.12	1.23	0.42	0.876	0.18
91	2.06	2.13	1.21	0.53	0.839	0.17

Daily average Discharge (m³/s) from 1992 – 2006 continued

92	2.06	2.03	1.20	0.50	0.828	0.17
93	2.07	2.24	1.20	0.44	0.819	0.17
94	2.06	2.03	1.22	0.53	0.8	0.16
95	1.99	1.96	1.21	0.43	0.822	0.17
96	2.24	1.95	1.34	0.43	0.808	0.22
97	2.21	1.98	1.34	0.44	0.815	0.20
98	2.19	2.03	1.37	0.59	0.815	0.19
99	2.20	2.41	1.34	0.64	0.831	0.19
100	2.29	2.41	1.29	0.70	0.816	0.20
101	2.36	2.46	1.25	0.64	0.905	0.20
102	2.40	2.24	1.23	0.60	0.837	0.18
103	2.06	1.96	1.29	0.72	0.806	0.19
104	1.91	1.97	1.20	0.57	0.775	0.14
105	1.91	2.08	1.23	0.54	0.749	0.19
106	2.05	2.37	1.22	0.46	0.772	0.17
107	1.99	2.23	1.29	0.53	0.789	0.19
108	2.29	1.97	1.54	0.88	0.805	0.16
109	2.12	2.00	1.39	0.96	0.807	0.17
110	2.09	1.89	1.45	0.88	0.806	0.17
111	2.19	1.77	1.40	0.84	0.844	0.15
112	2.60	1.71	1.32	0.84	0.83	0.13
113	2.76	1.92	1.49	1.21	0.935	1.19
114	3.79	1.93	1.43	1.11	0.833	0.45
115	3.88	1.91	1.66	1.51	0.857	0.28
116	4.51	1.98	1.66	0.98	0.925	1.17
117	4.46	1.99	1.73	1.34	0.908	0.46
118	4.40	2.18	1.39	1.23	1.001	0.24
119	3.71	1.90	1.29	1.46	0.945	0.20
120	4.04	2.42	1.17	1.34	0.896	0.24
121	2.86	1.87	1.32	0.89	0.864	0.24
122	2.93	1.87	1.38	0.76	0.893	0.25

Daily average Discharge (m³/s) from 1992 – 2006 continued

123	3.74	2.23	1.35	0.73	0.856	0.24
124	3.66	2.38	1.50	1.00	0.918	0.24
125	4.16	2.24	1.28	1.18	1.044	0.22
126	3.97	2.61	1.30	0.97	0.991	0.23
127	4.70	2.18	1.46	1.17	0.955	0.37
128	4.38	2.12	1.50	1.08	1.079	0.34
129	8.16	2.25	1.40	0.94	0.946	0.45
130	5.26	2.00	1.98	0.97	0.938	0.41
131	8.37	2.20	1.56	0.76	0.933	0.50
132	7.93	2.95	1.56	0.72	0.996	0.46
133	12.47	2.57	1.58	0.75	1.306	1.05
134	7.33	2.18	1.65	1.67	1.144	1.54
135	7.85	2.11	1.72	1.19	1.085	1.14
136	5.15	2.49	1.64	1.52	1.197	0.73
137	7.65	2.56	1.90	2.33	1.362	1.17
138	7.76	3.00	1.89	4.37	1.105	0.68
139	8.12	4.07	1.94	7.64	1.167	0.82
140	8.56	5.30	1.77	4.15	1.266	1.46
141	8.47	4.02	1.68	7.41	1.083	0.90
142	7.10	3.94	2.28	2.31	1.006	0.52
143	9.39	4.98	1.74	1.42	1.083	0.62
144	12.35	3.33	2.08	1.20	1.385	1.42
145	16.45	3.31	2.10	2.90	1.68	2.53
146	21.09	2.76	1.64	1.26	1.707	0.94
147	15.29	4.35	2.12	1.51	1.413	1.50
148	16.18	2.97	1.37	1.48	1.5	1.69
149	17.40	2.61	4.80	1.46	1.289	1.78
150	17.62	3.35	2.38	2.36	1.334	1.09
151	22.89	6.68	2.19	2.62	1.614	1.72
152	22.72	4.56	1.78	1.53	1.724	1.92
153	21.65	5.82	2.66	1.34	1.854	3.63
154	23.44	4.36	1.56	1.77	2.204	3.99
155	35.58	4.79	2.00	2.14	1.728	4.99
156	44.73	5.79	2.01	1.86	1.884	3.23
157	39.85	11.13	2.37	4.43	1.88	7.76
158	51.01	10.34	2.11	8.20	2.097	7.03
159	40.04	10.95	1.88	3.93	2.185	8.26
160	53.41	10.55	5.03	4.07	2.553	4.59
161	40.33	12.33	3.01	3.44	2.253	7.11

Daily average Discharge (m³/s) from 1992 – 2006 continued

162	41.01	11.81	7.14	5.22	2.301	8.78
163	32.35	11.18	2.13	6.10	2.584	4.56
164	46.30	18.79	2.62	5.58	2.389	4.71
165	47.87	17.61	1.90	5.75	2.187	8.61
166	52.98	11.04	2.15	4.89	1.504	5.81
167	41.31	10.71	2.35	3.47	2.963	6.13
168	39.48	11.91	2.42	4.01	3.778	5.88
169	42.35	15.29	3.44	4.43	3.848	5.74
170	58.74	15.04	5.72	7.75	4.649	7.49
171	62.22	17.19	5.09	9.32	3.451	7.47
172	65.28	18.94	21.48	4.09	3.706	6.52
173	77.39	27.14	8.05	9.51	3.369	7.60
174	67.12	22.01	6.11	13.07	4.855	6.10
175	83.50	22.32	6.06	11.82	5.359	12.68
176	78.06	27.05	4.70	11.22	3.922	7.81
177	78.63	39.50	5.14	15.51	4.616	7.93
178	98.67	41.94	7.36	17.97	5.165	14.40
179	87.91	39.47	10.63	14.16	6.199	9.73
180	85.37	35.05	4.93	15.52	6.587	7.10
181	87.62	39.19	6.83	19.63	7.206	12.45
182	96.75	35.65	5.25	16.14	6.923	10.00
183	109.18	36.72	9.98	19.93	6.83	14.68
184	135.07	42.78	6.16	18.01	5.948	8.88
185	100.99	56.84	7.76	17.36	6.976	9.21
186	120.61	54.12	9.20	28.06	6.938	8.89
187	109.81	74.65	7.50	36.04	9.65	9.57
188	124.54	65.40	14.86	35.71	9.809	8.98
189	140.53	75.12	9.56	40.28	8.186	10.68
190	141.23	64.91	14.70	42.64	9.84	9.06
191	137.59	64.70	10.87	38.30	9.376	8.18
192	143.99	66.75	14.07	39.61	10.646	30.50
193	149.32	75.19	13.02	45.69	13.73	43.44

Daily average Discharge (m³/s) from 1992 – 2006 continued.

194	152.21	78.36	21.66	52.67	15.075	23.19
195	141.43	93.00	20.71	43.40	14.907	16.31
196	170.04	87.60	14.08	44.27	13.956	19.71
197	166.70	81.77	11.16	45.52	13.114	17.70
198	157.66	101.99	11.06	47.94	1.087	14.80
199	164.23	94.19	9.18	46.72	13.038	28.51
200	173.28	97.18	16.91	47.50	13.437	24.15
201	177.62	111.18	16.97	57.01	14.328	23.06
202	167.75	101.24	14.70	51.63	15.822	25.68
203	170.72	105.77	30.99	47.13	14.289	29.75
204	159.87	112.99	15.39	64.61	15.054	23.05
205	151.23	133.57	16.56	58.33	15.316	43.19
206	182.64	146.14	14.29	59.97	15.279	29.14
207	173.15	133.80	22.15	68.32	19.062	20.10
208	164.76	114.90	26.76	66.88	18.856	26.20
209	149.95	122.51	34.52	69.26	20.009	28.53
210	184.92	127.75	21.22	64.48	20.362	25.66
211	166.69	134.67	34.06	69.09	19.444	34.41
212	160.60	133.70	28.74	61.91	17.739	29.69
213	174.75	145.80	33.20	65.05	17.725	28.94
214	177.95	144.20	26.52	62.10	17.567	24.87
215	173.90	162.68	19.90	68.84	20.79	27.83
216	178.30	163.50	67.57	74.44	18.351	30.11
217	181.82	166.23	39.26	68.71	20.728	23.41
218	186.26	144.58	36.26	68.12	21.875	22.54
219	172.52	149.83	38.61	79.09	20.824	24.75
220	164.26	177.93	27.73	81.88	20.473	29.39
221	203.80	166.89	38.52	77.88	26.012	34.69
222	186.78	166.57	26.95	74.90	21.969	51.49
223	191.45	158.79	30.16	79.85	22.509	29.29
224	205.95	180.58	35.77	77.30	22.956	35.33

Daily average Discharge (m³/s) from 1992 – 2006 continued.

225	212.23	154.76	48.55	72.59	25.736	33.92
226	200.04	169.32	36.45	67.99	20.321	43.00
227	214.76	185.57	48.68	73.56	25.08	45.45
228	217.13	184.53	34.94	80.95	28.871	29.23
229	222.65	176.37	30.86	77.06	27.04	30.93
230	187.46	176.00	34.09	70.34	26.279	46.73
231	192.22	143.70	36.69	69.90	25.814	36.95
232	188.07	137.04	36.87	75.17	23.627	34.98
233	178.79	156.97	28.96	71.65	23.926	22.45
234	175.28	153.74	46.18	74.13	23.496	22.94
235	187.18	135.74	27.10	66.63	24.623	27.32
236	185.90	144.22	40.01	72.41	22.533	31.86
237	171.81	137.53	25.38	74.81	20.562	29.95
238	184.54	137.64	40.80	69.81	29.195	24.80
239	179.00	149.21	26.91	69.99	22.506	31.54
240	172.60	136.47	22.12	66.85	19.355	25.59
241	169.86	136.81	31.34	63.25	17.465	36.49
242	180.22	137.98	28.71	65.07	19.007	32.01
243	181.93	162.27	25.04	67.93	18.654	32.75
244	168.28	143.79	23.04	62.73	19.339	24.49
245	163.64	149.75	27.78	61.35	18.176	31.62
246	154.75	138.88	28.98	63.23	18.263	32.06
247	162.41	118.63	19.02	59.28	17.753	22.35
248	189.77	124.54	16.63	55.06	16.869	30.14
249	171.75	126.39	20.66	57.88	16.391	27.83
250	163.13	124.91	22.47	65.81	18.072	22.68
251	171.37	107.03	16.19	54.76	15.483	23.23
252	146.63	98.15	14.64	49.41	16.421	23.30
253	134.28	104.03	14.40	49.27	16.512	20.53
254	142.38	94.15	14.80	50.88	16.767	25.84
255	139.33	91.65	13.40	43.45	16.329	23.03
256	164.06	100.57	10.89	36.58	16.434	19.91

Daily average Discharge (m³/s) from 1992 – 2006 continued

257	140.34	98.02	10.66	31.83	14.15	22.67
258	145.07	93.59	10.96	27.13	12.892	28.23
259	134.11	94.80	10.34	29.77	14.697	22.82
260	151.96	101.56	9.07	26.61	13.774	21.76
261	135.64	83.83	9.62	24.79	12.961	19.61
262	132.77	83.37	9.56	21.85	13.049	16.60
263	105.68	81.47	7.25	20.03	12.001	13.98
264	118.53	78.41	6.95	17.33	11.672	17.52
265	133.64	76.09	7.57	20.31	13.077	15.85
266	129.78	68.78	7.07	22.13	13.99	17.67
267	119.71	64.95	6.22	19.47	12.04	17.94
268	123.95	68.35	6.83	16.51	10.517	16.79
269	108.36	64.09	7.77	13.66	9.927	14.05
270	100.16	58.44	5.87	13.46	10.038	13.20
271	100.36	56.08	6.12	16.50	11.634	16.10
272	107.33	53.52	5.67	14.86	9.436	13.56
273	99.97	48.19	5.15	12.88	9.226	14.44
274	100.14	47.32	4.74	12.94	8.838	13.16
275	95.87	53.50	5.00	11.38	8.272	13.15
276	101.89	43.36	5.08	11.25	8.145	11.46
277	88.90	39.92	5.36	11.79	8.724	21.50
278	74.98	43.60	4.79	12.39	7.476	12.17
279	94.00	47.40	5.00	10.60	8.142	13.61
280	84.32	45.71	5.27	9.14	7.669	13.74
281	91.86	42.91	5.00	8.70	7.297	12.78
282	85.52	46.89	4.54	10.65	7.248	12.30
283	88.20	42.91	7.45	11.90	7.708	14.54
284	85.89	45.09	6.21	14.47	8.67	27.37
285	82.84	44.35	5.41	11.92	8.49	15.89
286	71.90	34.15	4.55	11.13	7.44	12.65
287	63.49	31.28	4.27	8.92	7.33	15.60
288	54.05	27.26	4.68	9.15	6.973	11.06

Daily average Discharge (m³/s) from 1992 – 2006 continued

289	58.02	27.35	4.11	8.55	6.391	14.89
290	52.24	32.49	4.08	8.26	6.329	9.14
291	63.31	29.07	7.08	10.68	6.539	11.79
292	52.20	26.58	4.75	11.80	6.395	9.83
293	66.98	28.44	4.80	11.89	6.068	13.15
294	66.84	28.85	4.73	11.86	6.303	14.78
295	75.53	27.18	4.31	11.79	6.214	10.70
296	61.67	28.53	4.01	9.92	5.97	9.59
297	49.94	29.39	5.82	9.83	5.881	8.55
298	56.28	27.24	5.21	9.65	5.657	9.17
299	61.40	29.59	5.01	9.90	5.748	8.61
300	58.88	28.15	5.57	10.52	5.787	9.76
301	46.01	35.19	4.29	9.73	5.248	7.40
302	59.15	25.82	3.86	10.93	5.323	19.24
303	57.96	22.94	4.27	9.01	5.571	10.21
304	46.22	23.63	3.66	7.70	4.999	8.11
305	40.33	19.62	3.45	6.50	4.645	8.03
306	37.46	21.78	3.31	6.17	4.348	6.91
307	38.09	19.37	3.20	5.88	4.3	7.05
308	32.13	16.73	3.08	5.54	4.1	6.38
309	33.13	15.81	3.05	5.31	3.962	5.94
310	28.14	14.25	3.61	5.01	3.824	5.71
311	27.56	16.09	3.68	4.79	3.772	5.30
312	29.46	14.94	3.17	5.02	3.606	5.37
313	25.66	17.60	2.68	4.76	3.678	5.37
314	29.82	16.28	2.59	6.14	3.551	5.40
315	28.30	15.70	2.52	8.66	3.417	5.50
316	30.78	14.12	2.55	7.99	3.521	5.98
317	25.39	13.12	2.51	7.42	3.36	4.81
318	24.02	13.37	2.45	7.34	3.339	5.19
319	22.34	13.65	2.49	6.81	3.243	4.83
320	26.63	12.69	2.41	6.40	3.138	4.76
321	24.69	14.91	2.37	5.75	3.223	4.53
322	21.94	11.74	2.35	5.46	3.175	4.21
323	19.60	11.80	3.48	5.43	3.078	4.00
324	19.50	11.53	2.50	5.18	3.006	3.94
325	19.11	12.16	2.34	5.00	2.989	3.67

Daily average Discharge (m³/s) from 1992 – 2006 continued

326	19.19	11.98	2.33	5.35	2.967	3.60
327	18.35	11.21	2.28	4.85	2.963	3.47
328	15.54	13.13	2.32	4.83	2.866	3.23
329	14.14	13.09	2.28	3.85	2.782	3.00
330	13.01	10.62	2.25	4.02	2.776	2.87
331	13.79	12.50	2.30	3.49	2.723	2.83
332	16.06	12.06	2.34	3.27	2.707	2.67
333	15.34	11.38	2.29	3.32	2.598	2.91
334	14.69	9.70	2.23	3.20	2.583	2.51
335	15.82	9.16	2.21	3.17	2.559	2.42
336	15.30	9.21	2.15	3.17	2.538	2.30
337	16.57	10.39	2.11	2.97	2.52	2.16
338	14.61	8.83	2.13	2.92	2.498	2.01
339	14.25	8.78	2.10	2.88	2.453	1.90
340	13.89	8.60	2.12	2.79	2.429	1.77
341	14.20	8.69	2.14	2.74	2.383	1.72
342	13.89	8.27	2.07	2.76	2.4	1.72
343	13.56	8.31	2.10	2.90	2.406	1.66
344	13.47	8.23	2.10	3.04	2.444	1.84
345	12.82	8.21	2.15	3.04	2.394	1.81
346	12.32	7.83	2.09	2.77	2.397	1.70
347	12.11	7.69	1.98	2.65	2.385	1.67
348	11.89	7.89	2.02	2.71	2.311	1.66
349	11.72	7.94	1.98	2.61	2.276	1.59
350	11.51	7.45	1.95	2.56	2.23	1.54
351	11.28	7.26	1.93	2.49	2.203	1.48
352	11.13	7.30	1.91	2.51	2.196	1.41
353	10.81	7.10	1.90	2.43	2.167	1.37
354	10.67	6.93	1.87	2.42	2.149	1.34
355	10.43	6.89	1.88	2.38	2.105	1.32
356	10.34	6.86	1.86	2.39	2.068	1.27
357	10.30	6.68	1.82	2.36	2.063	1.26
358	10.14	6.70	1.82	2.31	2.056	1.20
359	9.87	6.55	1.77	2.21	2	1.17
360	9.78	6.46	1.84	2.18	1.964	1.16
361	9.65	6.30	1.77	2.14	1.947	1.09
362	9.45	6.23	1.76	2.18	1.933	1.04
363	9.31	6.34	1.75	2.18	1.908	1.01
364	9.37	6.27	1.74	2.16	1.904	1.04
365	9.20	6.16	1.72	2.13	1.878	0.97

Annex 4 - Geological Log.

West of Azezo

Depth(m)	Layer Description	Static water level
0 - 8	Soil	12.5
8.0- 65.0	Basalt, locally weathered	
65 - 115	Massive basalt and minor Trachyte	
115 - 118	Massive basalt	
118 - 133	Fractured Basalt	
133 - 138	Fractured Basalt	
138 - 150	Massive Basalt	

AZEZO

Depth(m)	Layer Description	Static water level(m)
0- 2	Soil	24
2.0-18.0	Fresh to slightly weathered basalt	
18- 27	Slightly weathered Trachyte	
27 - 52	Fractured basalt	
52 - 53	Clay	
53 - 75	Basalt locally fractured	
75 - 80	Scoraceous basalt	
80 - 107	Massive basalt	

North Gonder

Depth(m)	Layer Description
0.0 - 1	Highly weathered basalt
1.0 - 12.0	Slightly weathered basalt
12- 54.0	Silicic volcanic rocks with few basalt
54 - 72	Trachyte
72 - 78	Brown vesicular Trachyte
78 - 85	Basalt
85 - 91	Brown vesicular Trachyte
91 - 100.7	Basalt

Mariam Deber E= 328452m, N= 1383042m

Depth(m)	Layer Description	Static water level(m)
0.0 - 3.7	brown clay	46
3.7 - 5	Weathered basalt	
5.0 -25.0	Slightly weathered to fresh basalt	
25.0 -31	Slightly weathered Trachyte	
31 - 56	Fresh basalt	
56 - 59	Gravel clay	
59 - 79	compact and cemented gravel with clay	
79 - 89	Fresh basalt	
89 - 93	Fractured vesicular basalt	
93 -114	Fresh massive basalt	
114 - 115	Slightly weathered Trachyte	
115 -127	Fresh basalt with secondary minerals	
127 - 135	Fractured vesicular basalt	
135 - 144	Massive basalt	

SMA Initial Parameters

Parameter	Gilgel		
	Abay	Gummera	Megach
Canopy Storage Capacity	0	0	0
Surface Storage Capacity	0	0	0
Soil Storage Capacity	95	120	65
Soil Tension Storage Capacity	55	45	20
Soil Maximum Infiltration Rate	3.8	3.8	2.3
Soil Maximum Percolation Rate	15	12	12
Groundwater 1 Storage Capacity	0	0	0
Groundwater 1 Max. Percolation Rate	15	12	15
Groundwater 1 Storage Coefficient	135	300	200
Groundwater 2 Storage Capacity	1017	630	450
Groundwater 2 Max. Percolation Rate	57	23	15
Groundwater 2 Storage Coefficient	1680	1880	510
Initial Canopy Storage	0	0	0
Initial Surface Storage	0	0	0
Initial Soil Storage	50	55	27
Initial GW1 Storage	0	0	0
Initial GW2 Storage	3	2.5	1.3

