Jimma University
School of Postgraduate Studies
Jimma Institute of Technology
Faculty of Civil and Environmental Engineering
School of Hydraulic and Water Resources Engineering
Masters of Science Program in Hydraulic Engineering
On

Stream flow prediction of ungauged catchment using Hydrological model the case of Geba Sub-Basin: Tekeze River Basin, Ethiopia

Thesis submitted to the School of postgraduate Studies of Jimma Institute of Technology in Partial fulfillment of the requirements for the Degree of Masters of Science in Hydraulic Engineering.

By: Getachew Smur

March, 2018
Jimma, Ethiopia

Jimma University

School of Postgraduate Studies

Jimma Institute of Technology

Faculty of Civil and Environmental Engineering

School of Hydraulic and Water Resources Engineering

Masters of Science Program in Hydraulic Engineering

On

Stream flow prediction of ungauged catchment using Hydrological model the case of Geba Sub-Basin: Tekeze River Basin, Ethiopia

Thesis submitted to the School of postgraduate Studies of Jimma Institute of Technology in Partial fulfillment of the requirements for the Degree of Masters of Science in Hydraulic Engineering.

By: Getachew Smur

Main Advisor: Fiseha Behulu (PhD)

Co-Advisor: Mamuye Busier (Ass.Prof)

March, 2018

Jimma, Ethiopia

Dedicated to:

My beloved Family;

My wife Desta Hadish;

and my son Fana Getachew;

Declaration

I, the undersigned, declare that this thesis is my own original work and that it has not been presented and will not be presented by me to any other university for similar or any other degree award. And that all sources of materials used for this thesis have been appropriately acknowledged .Any copying or publication of this for commercial purposes or financial gain is not allowed without my written permission.

Getachew Smur ------------------ -----------/---------/----------
Submitted by Signature Date

Fiseha Behulu (PhD) -------------------- -----------/-----------/----------
Advisor Signature Date

Mr. Mamuye Busier (Ass.Prof) --------------------- -----------/----------/-----------
Co-advisor Signature Date

Approval Page

As member of the board of Examiners of the M.Sc. thesis open defense Examination, we certify that we have read, evaluated the thesis prepared by Getachew Smur G/giorgs and examined the candidate. We recommended that the thesis be accepted as fulfilling the requirement for the degree of Master of Science in Hydraulic Engineering.

Approved by Board of Examiners

Dr.Ing. Kassa Tadele -------------------- ---------/--------/---------
External Examiner Signature Date

Dawud Temam (PhD Candidate) --------------------- --------/--------/---------
Internal Examiner Signature Date

Mr. Andualem Shigute (M.Sc.) --------------------- -------/--------/-----------
Chair Person Signature Date

Final approval and acceptance of the thesis is contingent upon the submission of final copy of the thesis to council of Graduate Studies (CGS) through the Department or School Graduate Committee (DGC or SGC) of the candidate**.**

Abstract

Prediction of stream flow of ungauged catchment is important for water resources design, planning and management system. Runoff estimation in interest catchment is probably one of the most basic and oldest tasks of hydrologists. This long-standing issue has received increased attention recently due to the prediction in ungauged basin initiative by the International Association Hydrological Science. In developing countries like Ethiopia most of the rivers are ungauged. Therefore, applying regionalization techniques on an ungauged or poorly gauged river basin is crucial. This thesis deals with stream flow prediction in an ungauged catchments using hydrological model in Geba Sub-Basin. The HBV-96 model is selected to simulate discharge for four gauged catchments on a daily basis in the period of 1998-2008 and with data input such as precipitation, air temperature, potential evapotranspiration, and Geographical zones.

Four regionalization methods were applied to transfer model parameter values from the gauged to the interest catchments. Those methods are regional model, sub basin mean, area ratio and proximity methods. In regional model, gauged catchments model parameters and physical catchment characteristics of ungauged catchments were used to develop the equations in order to estimate stream flow from ungauged catchments. To have better understanding of model parameter performance, the sensitivity analysis of eight model parameters were performed manually by trial and error. The evaluation shows that the model parameters, runoff coefficient (Beta), recession coefficient of upper reservoir zone (Khq), limit for evapotranspiration (LP), and Field capacity (FC) are more sensitive than the others. The model performance was evaluated using Nash Sutcliff efficiency and Relative volume error. The result shows that the four gauging river have good agreement and distribution since Nash Sutcliff efficiency greater than 0.67 and relative volume error lies between +10% and -10%. In predicting model parameters from ungauged catchments in regional model method $p\text{-value} \leq 0.05$ *for 95% confidence interval and determination coefficient* (R^2) ≥ 0.98 *were obtained. Stream flow from ungauged catchments simulated by regional model, spatial proximity, area ratio and sub-basin mean contribute high and less runoff volume respectively.*

Key words; *HBV-96, Regionalization, Geba Sub-basin, Ungauged Catchment, Rainfall-Runoff Modelling, Stream flow, Simulation.*

Acknowledgement

First and above all praise to be almighty God, for endless love and for he gives me healthy to think and to complete this thesis work and great thanks be to him forever.

For most, my grateful acknowledgment extends to my advisor Dr.Fiseha Behulu who were sharing his valuable time, critical comment, dedicated and knowledge guidance throughout the thesis work. Next, my thanks go to my co-advisor Mr Mamuye Busier (Ass.Prof) for his guidance to right way throughout the thesis work.

My gratitude also goes to the Ministry of Water, Irrigation and Electricity and Tigray water resources development Bureau, particularly for staff members of MoWIE under the Department of Hydrology and GIS and also National Meteorological Agency (NMA) for providing hydrological and meteorological data for free.

I acknowledge the debt I owed to the University of Gondar and Jimma University for providing me this opportunity to continue my higher studies and for full financial and materials supports for my study.

I feel a deep sense of gratitude my mother Ametetsion and father Smur, my brother Hagose and my uncle Yohannes with your wife Letay for their ultimate support throughout my life and lovely and for best friends (G/micael, Mussie, Mohemmed, and Semahgn) for their moral support, encouragement.

Last, but not least, I would like to forward the leading and loving thanks to my helpful wife desta Hadish (mamaye) for her never ending concern, support, encouragement and appreciation. Our new son Fana Getachew will benefit deepest from the love we have to each other!

Table of Contents

List of Table

List of Figure

List of Acronyms

Alfa	Parameter defined the non-linearity of quick runoff reservoir in HBV model
amsl	above mean see level
Beta	Parameter in soil moisture routing in HBV model
DEM	Digital Elevation Model
DR	Direct Runoff
Ea	Actual evapotranspiration
GIS	Geographical Information System
IAHS	International Association of Hydrological Science
IHMS	Integrated Hydrological Modeling system
IN	Infiltration
Khq	Recession coefficient for upper zone reservoir
K4	Recession coefficient for lower zone reservoir
Lp	Limit for potential evapotranspiration
Lz	Lower zone storage reservoir
HBV-96	Hydrologiska Byråns Vattenbalansavdelning (Hydrological Bureau water balance)
MoWIE	Ministry of Water, Irrigation and Electricity
MP	Model Parameter
NSE	Nash- Sutcliffe Efficiency
NMSA	National Meteorological Service Agency
PCCs	Physical Catchment Characteristics
PET	Potential evapotranspiration
PUB	Prediction in Ungauged Basin
RVE	Relative Volume Error
SMHI	Swedish Meteorological and Hydrological Institution
SRTM	Shuttle Radar Topographic Mission
SWAT	Soil and Water Assessment Tool
UZ	Upper zone storage for quick runoff

1. Introduction

1.1 Background

Stream flow prediction for ungauged catchments is important for water resources design, planning and management system. According to (Sivapalan *et al*, 2003), ungauged basins are ones with inadequate records (in terms of both data quantity and quality) of hydrological observations. A catchment is ungauged or poorly gauged with respect to a variable of interest. The International Association of Hydrological Science (IAHS) initiated the decade 2003-2012 with Prediction in Ungauged Basins (PUB), defined as the prediction or forecasting of the hydrological responses of ungauged or poorly gauged basins and its associated uncertainty(Sivapalan *et al*, 2003).

Hydrological modeling play an important roles in the study of water resources and water management mainly in ungauged catchments. Moreover, sustainable water resources planning and management requires data to enable quantification of water quality and quantity (Beven, 2012). Lack of information about the quantity and quality of water resources arises from poorly developed hydrological networks in one hand and improper documentation in another. Inadequate hydrological data results in uncertainty both in design and management of water resources systems. In fact, regardless of the challenges, hydrological study remains to be the back bone of most engineering works. So, detail hydrological study is necessary before constructing any type of water infrastructures. As such, modeling the rainfall-runoff behavior of ungauged catchments is important both for understanding systems' behavior and sustainable water resources management. The main challenge with rainfall-runoff modeling in ungauged catchments is the lack of local runoff data to calibrate the model parameters.

Stream flow prediction for the present study are usually based on transferring information from gauged basin to the catchment under question through a standard procedure called Regionalization (Bloschl *et al*, 1995). In fact, the area ratio, spatial proximity, sub-basin mean and regional model regionalization methods are often used to predict discharge in catchments with lack of data. The most common approach that has been used for stream flow prediction of ungauged catchments was the use of conceptual rainfall-runoff models whose parameters can be regionalized. This is based on the fact that catchments with similar characteristics show similar hydrological behavior (Seibert, 1999).

The issue of ungauged catchment study in Ethiopia's context is challenging. The common reasons include: (i) there are no evenly distributed hydrometric stations, (ii) large areas lack gauging stations; and (iii) only a few years of data are available. Many of Ethiopian river basins are ungauged. Geba sub-basin is one of such basins draining part of Tekeze River Basin which is not well equipped with hydro meteorological data recording gauges. Accordingly, there quite limited hydrological and meteorological data series, this makes the Geba sub-basin is less studied compared to others.

In this study, a semi-distributed conceptual hydrological model called HBV-96 was applied. The model is used for continuous stream flow simulation which was originally developed by SMHI in the 70's to assist hydropower operations (SMHI, 2006). It is flexible and robust in solving water resources problems and applications and also needs only few input variables such as rainfall, evapotranspiration, and temperature and elevation zone data to simulate stream flow for ungauged catchments.

1.2 Statement of the problem

There are many reasons why we need to model the relation between rainfall and runoff processes of hydrological system. The main reason among others is a result of the limitations of hydrological measurement techniques. In fact, from current knowledge and technical capacity it is not fully possible to measure everything variables about processes in hydrological systems. There is only limited range of measurement techniques and a limited range of measurements in space and time.

A better understanding of the hydrological characteristics of different sub-basins of Tekeze River Basin has got a considerable importance. This is because of the country's interest in the utilization of its water resources, the need to improve and expand development and management activities of these resources, and the potential danger from negative impacts of climate change in the future. Most of the Ethiopian river basins are ungauged even though there is some gauged sub basins, they are not operational as a result of meandering of river flow regime from time to time (Gebeyehu, 2013). Tekeze River Basin is one of these river basins which has limited rain gauge coverage, very short records of temperature, wind, relative humidity and evapotranspiration. The basin is large and has complex characteristic which together with lack of data, creates severe constraint to the application of hydrological models. However, the country is on the way of exploiting its water resources potential. Full exploitation of the available water resources potential requires knowledge of the basin water balance. This in turn requires knowledge of the contribution of ungauged catchments of the basin. Since, in the Geba sub-basin, hydrometric network is not evenly distributed, large area lack gauging stations and only few gauging stations have long years of data. Due to the fact that Geba sub-basin is less study area and most parts are ungauged, consequently, there is a need to develop a method for predicting flow at the ungauged sites. Thus in this study, an attempt is made to estimate runoff in gauged and ungauged catchments to understand the temporal and spatial variability of water yield since it has a great comportment on local developments and downstream users.

1.3 Objective of the study

1.3.1 General objective

The general objective of this study is to predict stream flow of ungauged catchments in Geba Sub-Basin by applying a hydrological model and Regionalization techniques.

1.3.2 Specific objective

1. To identify catchment characteristics that can be used for predicting stream flow for Geba sub-basin.
2. To determine HBV-96 model parameters required to simulate stream flow for ungauged catchments.
3. To simulate stream flow for ungauged catchments using conceptual HBV-96 model.

1.4 Research Questions

1. How to identify catchment characteristics that can be used for predicting stream flow for Geba sub-basin?
2. What are the most appropriate parameters of HBV-96 model to simulate the stream flow for catchments of interest?
3. How to simulate the stream flow of ungauged catchments using HBV.96 model?

1.5 Significances of the study

Prediction of stream flow for interest catchments is important for hydrologist and improve the scientific and more information about the hydrology. In addition it is important to improve the skill to determine stream flow for ungauged catchment by using regionalization technique. This study improves sufficient hydrological information at interest catchment of Geba sub- basin. It provides better understanding of hydrological characteristics of different catchments in the river basin and sub basin in order to know the stream flow of ungauged and gauged catchments. It improves water resources development system, provides mitigation measure against various structural failure and use effective management of water resources system development in the study area.

1.6 Scope of the study

Rainfall-runoff models are often used to predict stream flow in space and time domain for operational and scientific investigations. Extrapolation and regionalization enable us to simulate response of catchments for which time-series are not available. Due to the presence of several factors, prediction of discharge regimes in ungauged and gauged catchments involves some degree of uncertainty.

In predict stream flow at gauged catchments, factors that cause include different model structures representing the real world differently, inadequacy of the data required by the models and the model calibration parameter. This introduces high degree of uncertainty in stream flow prediction at ungauged and gauged catchments. Most established hydrological models are data intensive, yet Geba sub-basin has limited rain gauge coverage, few flow gauged station, very scarce daily data of flow and meteorological data. For better water management these predictions should be done accurately by reducing the uncertainties. In ungauged catchments the observed data are not available or not sufficient for model calibration, hence, to predict the model parameters in ungauged catchments depends on other sources of information.

1.7 Outline of the thesis

The thesis consists five chapters. **Chapter one** deals with introduction which contains the rationale of the research, statement of the problem, objective and scope of the study area. **Chapter two** deals with literature review that describes mainly about hydrology of ungauged basins, hydrological modeling techniques, HBV model structure and previous study related to the present study. **Chapter three** focus mainly on materials and methods which includes detail description about the study area, climate, topography and slope, LULC, geology and soil types, data collection, assembling and gap-filling which includes hydrological and meteorological data, missing data completion and estimation of areal rainfall, homogeneity and consistency of data, physical catchment characteristics, selection of physical catchment characteristics, model parameter sensitivity analysis, calibration, validation, regionalization, establishing the regional model and simulate stream flow from ungauged catchments. **Chapter Four** describe about the results and discussion and finally **Chapter Five** deals about conclusion and recommendation.

2. Review of Literature

2.1 Hydrology of Ungauged Basin

Drainage basins are a fundamental landscape unit for the cycling of water, sediment and dissolved geochemical and biogeochemical constituents. As such, they integrate all aspects of the hydrological cycle within a defined area that can be studied, quantified and acted upon. The drainage basin, thus is a metaphor for integration of hydrological processes related to surface water, groundwater, evapotranspiration etc. And the explicit coupling of hydrology, geochemistry and ecology (Sivapalan *et al*, 2003).

A drainage basin which has insufficient records of various hydrological observation in terms of both quantity and quality for analysis at the appropriate spatial and temporal scale and up to a good level of accuracy for application in practical fields is known as ungauged basins (Sivapalan *et al*, 2003) If the parameter of interest is not available for the required period of time for prediction or modelling, that basin is an ungauged basin with respect to the variable. Variables of interest can be rainfall, runoff, erosion rates etc. So every basin is ungauged in some respect.

Accurate and timely predictions of high and low flow events at any ungauged catchments location can provide stakeholders the information required to make strategic, informed decisions. Whenever data is not available, hydrological models are important to establish baseline characteristics and determine long term impacts which are difficult to calculate (Lenhart *et al*, 2002). The aim of modelling is to reduce the uncertainty in hydrological predictions, prediction of runoff water in ungauged catchment area is vital for various practical applications such as the design of drainage structure and flood defenses, runoff forecasting and for catchment management tasks such as water allocation and climate impact analysis.

Recently, flow prediction in ungauged catchments got more attention. The IAHS decade (2003-2012) on Predictions in Ungauged Basins, or PUB, is a new initiative launched by the International Association of Hydrological Sciences (IAHS), aimed at formulating and implementing appropriate science programs to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make predictions in ungauged basins (Sivapalan *et al*, 2003).

2.2 Hydrological modeling for ungauged basins and its importance

Hydrological modeling is a powerful technique of hydrologic system investigation for both the research hydrologists and practicing water resources engineer involved in the planning and development of integrated approach for management of water resources. Hydrologic models are symbolic or mathematical representation of known or assumed functions expressing various components of the hydrologic cycle (Schultz, 1993). The term hydrological model is often misunderstood to be only as a computer based mathematical model. The main function of these models are hydrologic prediction and understand various hydrologic processes.

Hydrological models for interest basins try to simulate the catchment behavior by solving the equations that govern the physical processes occurring within the catchment. Therefore hydrological modes are usually used to simulate the catchment response for a give input. The hydrologic models take time series data and produce another time series as output. The importance of hydrological modeling in a catchment is;

To understand the spatial rainfall distribution over the catchment, To get information about catchment characteristics such as slope, soil type, land use, underlying geology, Surface-groundwater interactions, water allocation, etc. can be better understood through hydrological modelling, accurate stream flow forecasts are an important component of watershed planning and sustainable water resource management (Brooks *et al*, 2003).

One of the most frequently used events in hydrology is the relation between rainfall and runoff. It determines the runoff signal which leaves the watershed from the rainfall signal received by the basin (Kumar D. and Bhattacharjya, 2011). In it a part of the hydrological cycle has been studied to express the runoff from the catchment as a function of the rainfall and other catchment characteristics. It helps to extend stream flow time series both spatially and temporally to evaluate management strategies and catchment response to climate.

2.3 Hydrological process

The continuous movement of all forms of water on the earth is called hydrologic cycle. This includes condensation of vapor pressure in atmosphere that give rise to precipitation. Precipitation partly intercepts by vegetation and partly reaches the surface. Evaporation takes place from intercepted water by vegetation and from surface storage. Water also flows through stream and reach lakes and reservoirs from where evaporation and seepage to ground water occurs. Precipitation that infiltrate to the soil could also leave by evapotranspiration or reach stream by through flow and partly percolate to ground water. The depletion of water in the surface and sub-surface due to evaporation and evapotranspiration causes ground water to move upward directions through the process called capillary rise. Some of it evaporates or moves to streams as base flow or to the ocean and lakes through routs. Unsaturated flow, macro pore flow and perched flow perform due to the contribution of precipitation. The process of percolation will occur when the unsaturated flow recharges the ground water. Macro pore and perched flow allow passing the water and this water will recharge the ground water flow and cause rise of the water table. Percolation is a process when rainwater reaches ground water and this ground water in to the channel flow which is base flow and evaporation. But, in most cases most part of the ground water will be as groundwater or it contributes to the groundwater storage. Groundwater is contribution of catchment runoff and channel flow will contribute to catchment runoff (Chow *et al*, 1988).

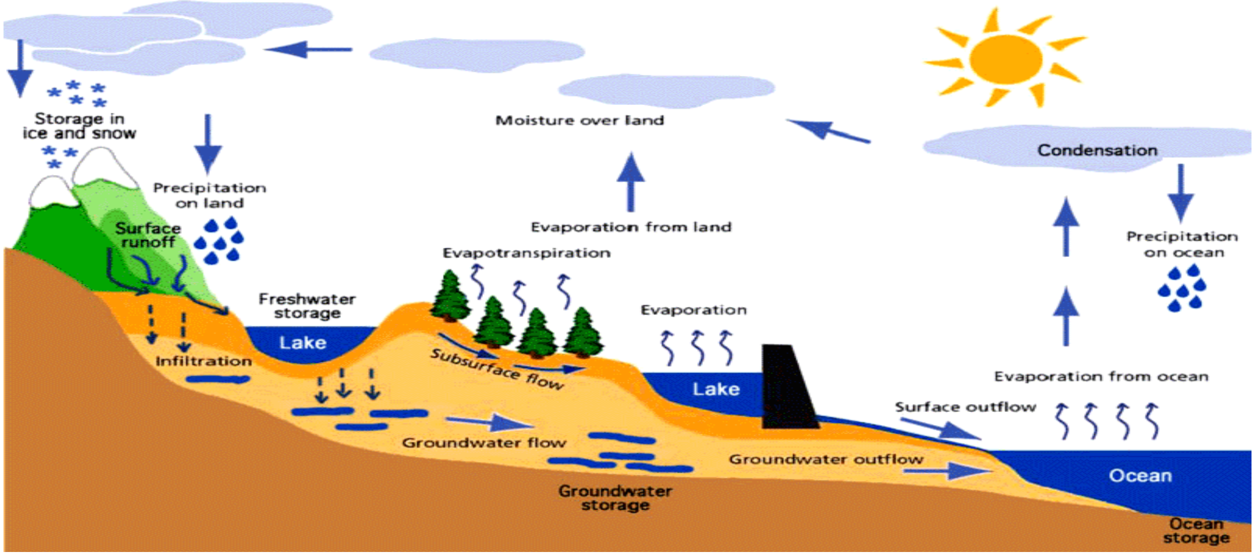


Figure 2.1: Hydrologic cycle (Chow et al, 1988)

2.4 Rainfall-Runoff Process

Hydrological models have been used in different river basins across the world for better understanding of the hydrological processes and the water resources availability. It is important to use hydrological model today to assess and predict the water availability of river basins due to land use change to develop a strategies in order to cope up with the changing environment. The surface subsystem of the hydrologic cycle is where the rainfall and runoff interaction takes place. The input to this system are the rainfall and snow along with solar energy and the output takes as the runoff, base flow, evapotranspiration and infiltration in the system

2.4.1 Rainfall

In the hydrologic cycle, moisture comes from the atmosphere to the surface as precipitation. The rainfall pattern and intensity greatly influences the runoff. The rainfall intensity is lower than infiltration capacity of the soil all water that infiltrate on the ground as form of infiltration. Whereas the increasing the rain fall intensity that means infiltration capacity lower than rain fall intensity runoff will be generated immediately and forms as surface runoff termed as surface flow.

When the soil is dry, a rainfall intensity less than infiltration rate produces no surface runoff. Gradually, as the rain progresses, the soil saturates and the infiltration rate reduces to a steady rate. The relation between rainfall intensity and runoff, strictly speaking, is not linear, which means that doubling the rainfall intensity does not produce a doubling of the hydrograph peak value. However, this phenomenon is more pronounced for small watersheds, such as an urban area. However in the catchment scale, due to the uncertainty of all the hydrological parameters, it might be assumed that the rainfall-runoff relation follows a linear relationship.

Rainfall is extremely variable both in time and space. The variation is brought about by differences in the type and scale of development of precipitation-producing processes, and is also strongly influenced by local and regional factors, such as topography and wind direction at the time of rainfall. It is, however, assumed that each individual rain-gauge is representative of a very considerable area around it. This assumption is not correct. Because of the very considerable spatial variation of precipitation depth and intensity, particularly for short durations and for sever convectional storms as is the case in most parts of Ethiopia (Tamalew, 2015).

To account the spatial and time variation of rainfall, one can derivate the areal rainfall from a number of point rainfall data. The simplest and most obvious initial approach to the derivation of areal rainfall is to calculate using the arithmetic mean method (Chow *et al*, 1988). This method is satisfactory if the gauge is uniformly distributed over the area and the individual gage measurements do not vary greatly about the mean.

2.4.2 Runoff

Surface runoff also known as overland flow is the flow of water that occurs when excess storm water, melt water, or other resources flows over the earth’s surface.

This might occur because soil is saturated to full capacity, because rain arrives more quickly than soil can absorb it. Surface runoff is a major component of the water cycle. It is the primary agent in soil erosion by water. Runoff that occurs on the ground surface before reaching a channel is also called a nonpoint source. A land area which produces runoff that drains to a common point is called a drainage basin (Chow *et al*, 1988).

2.4.2.1 Runoff Generation

Surface runoff can be generated either by rainfall, snow fall or by the melting of snow, or glaciers. Snow and glacier melt occur only in areas cold enough for these to form permanently. Typically snowmelt will peak in the spring and glacier melt in the summer, leading to pronounced flow maxima in rivers affected by them. The determining factor of the rate of melting of snow or glaciers is both air temperature and the duration of sunlight. In high mountain regions, streams frequently rise on sunny days and fall on cloudy ones for this reason. In areas where there is no snow, runoff will come from rainfall. However, not all rainfall will produce runoff because storage from soils can absorb light showers(Chow *et al*, 1988).

2.4.2.2 Infiltration excess overland flow

This occurs when the rate of rainfall on a surface exceeds the rate at which water can infiltrate the ground, and any depression storage has already been filled. This more commonly occurs in arid and semi-arid regions, where rainfall intensities are high and the soil infiltration capacity is reduced because of surface sealing, or in paved areas. This occurs largely in city areas where pavements prevent water from flooding (Subramanya, 1998).

2.4.2.3 Saturation excess overland flow

When the soil is saturated and the depression storage filled, and rain continues to fall, the rainfall will immediately produce surface runoff. The level of antecedent soil moisture is one factor affecting the time until soil becomes saturated. This runoff is called saturation excess overland flow or saturated overland flow (Subramanya, 1998).

2.4.2.4 Subsurface return flow

After water infiltrates the soil on an up-slope portion of a hill, the water may flow laterally through the soil, and infiltrate (flow out of the soil) closer to a channel.

This is called subsurface return flow or through flow. Precipitation falling on the surface, resulting in a flow of water over the land surface by means of a thin water layer sheet flow is called overland flow. Two types of overland flows can be distinguished based on the conditions of the soil which the precipitation bears. These are the Horton overland flow and the saturation excess overland flow.

The Horton overland flow occurs when the intensity of the rainfall is greater than the infiltration capacity of the soil and when the rainfall causes storage of water at the land surface. This happens when rainfall events are heavy and where mountainous slopes are bare or covered by thin vegetation.

The saturation excess overland flow occurs when the soil becomes saturated due to the rise of the phreatic ground water level up to the land surface. Since the infiltration capacity becomes zero, the precipitation cannot infiltrate anymore and will runoff on top of the land surface. It is mostly generated at the bottom part of hill slopes with shallow phreatic groundwater level (Subramanya, 1998).

2.5 Hydrological model

Hydrological model is a mathematical model used to simulate river or stream flow and calculate water quality calculations. These models generally come in to use in the 1960's and 1970's when demand for numerical forecasting of water quality was driven by environmental legislations in the United States and United Kingdom. At about this time computers became more widely accessible and powerful enough to significantly assist in modelling processes. There are numerous hydrological models and they can be grouped by pollutant addressed, complexity of pollutant sources, whether the model is steady state or dynamic, and the time period modelled. Also important in determining the selection of model is whether it is distributed (i.e. capable of predicting multiple points within a river) or lumped (Kim and Kalaurachchi, 2008).

Hydrological models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrological prediction and for understanding hydrological processes. Models often address individual steps modularly in the simulation process. Typically subroutines for surface runoff include components for a land use type, topography, soil type, vegetation cover, precipitation and land management practice (regular agricultural activities e.g. pesticide or fertilizer application). Whenever data is not available, hydrological models are important to establish baseline characteristics and determine long term impacts which are difficult to calculate (Lenhart *et al*, 2002).

2.5.1 Classification of hydrological models

Many different types of hydrological models have been developed. Many of these models share structural similarities because of underlying assumptions, while some of the models are distinctly different. Therefore, these models are classified according to different criteria. There are many criteria which can be used for choosing the “right’’ hydrologic model. These criteria are eternally project-dependent; since all projects have its own specific necessities and needs. Another criteria is also user dependent (and therefore subjective), such as the personal preference for graphical user, computer operation system, input-output management and structure or user’s added expansibility. On the basis of process description, the hydrological models can be classified in to three main categories (Cunderllk, 2003).

Lumped models: Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins. The parameters often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. These models are not usually applicable to event-scale processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models.
Distributed models: Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modelling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behavior. Distributed models generally require large amount of (often unavailable) data. However, the

governing physical processes are modelled in detail, and if properly applied, they can provide the highest degree of accuracy.

Semi-distributed models: Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin in to a number of smaller sub-basins. The main advantage of these models is that their structure is more physically-based than the structure of lumped models, and they are less demanding on input data than fully distributed models. SWAT (Arnold, *et al*, 1993), HEC-HMS (US-ACE, 2001), HBV (Bergström, 1995), are considered as semi-distributed models.

2.5.2 Hydrological model selection

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

Hydrologic models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events. Event-driven models are designed to simulate individual precipitation-runoff events. Their emphasis is placed on infiltration and surface runoff. Typically, event models have no provision for moisture recovery between storm events and, therefore, are not suited for the simulation of dry-weather flows. On the other hand, continuous-process models simulate instead a longer period, predicting watershed response both during and between precipitation events. They are suited for simulation of daily, monthly or seasonal stream flow, usually for long-term runoff-volume forecasting and for estimates of water yield (Cunderllk, 2003).

Many comprehensive spatially distributed hydrological models have been developed in the past decade due to advances in hydrological sciences. Among the many hydrological models developed in the past decade, HBV-96 model originally developed by SMHI in the 70's to assist hydropower operations has been used extensively by researchers. This is because HBV model;

1. Users readily available a few inputs of data
2. Allows considerable spatial detail for basin scale modelling
3. It is capable of simulating changing in catchment characteristics

Hence, HBV model was used in this study to simulate the discharge in ungauged catchments.

2.6 HBV model and it's structure

HBV-96 model is a semi-distributed conceptual hydrological model for continuous stream flow simulation which was originally developed by SMHI in the 70's to assist hydropower operations (SMHI, 2006). The model is designed to run on a daily time step and simulate runoff in river basins of various sizes. It is standard forecasting tool in Sweden, where some 75 catchments, mainly in small and unregulated rivers are calibrated for national warning service. Additional forecasting for the hydropower companies are made in some 80 catchments. Furthermore, operational or scientific applications of the HBV-model have been reported from more than 50 countries around the world. The model consists of 6 modules, which are;-

Precipitation accounting routine, representing rainfall, snow accumulation and melt, soil moisture routine, representing actual evapotranspiration, quick runoff routine, representing quick flow, base flow routine, representing slow flow, transformation function, representing quick flow and slow flow delay and attenuation, routing routine, representing flow through river reaches.

The HBV-96 model generates rainfall-runoff using precipitation, temperature and potential evapotranspiration and geographical zone as data input. The model's basis is referred to catchments, which can be divided into a number of sub-catchments. The model is semi-distributed, since differences can be made between areas with different altitudes and geographical zones in terms of forest or field. The parameters to be used can be specified for an individual sub-catchment, or for the catchment as a whole.

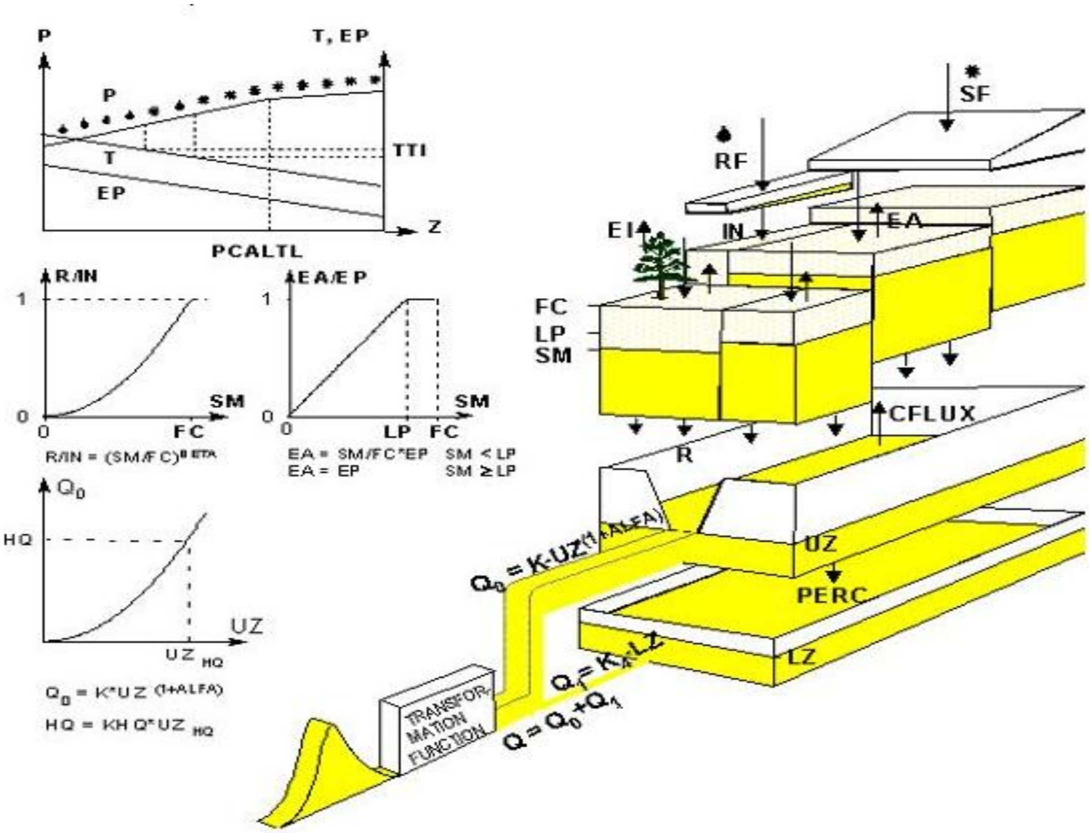


Figure 2.2: Schematic presentation of the HBV model for one sub basin (SMHI, 2006)

Where:

P= Precipitation

T= Temperature

SF= Snow fall

RF= Rainfall

PCALTL= Threshold for altitude correction

TTI= Threshold temperature interval

IN= Infiltration

EP= Potential evapotranspiration

EA= Actual evapotranspiration

EI= Evaporation from interception

SM= Soil moisture storage

FC= Maximum soil moisture storage

ALFA= Recession parameter

LP= Limit for potential evapotranspiration

BETA= Soil parameter

R= Recharge

CFLUX= Capillary transport

UZ= Storage in upper reservoir zone

LZ= Storage in lower reservoir zone

PERC= Percolation

K, K_4= Recession parameters

Q_0, Q_1= Runoff components

HQ= High flow parameter

KHQ= Recession at HQ

HQ_{uz}=UZ level at HQ

The general equation of HBV model water balance can be described as:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes] ------------------------- 2.1$$

Where:

P=precipitation, E=evapotranspiration, Q= runoff, SP= snow cover, SM= soil moisture, UZ=upper ground water zone, LZ=lower groundwater zone, lakes=lake volume and dt=time step. But, the routine for snow is not applicable for this study.

2.6.1 Precipitation accounting routine

To simulate rainfall-runoff processes the structure of HBV requires precipitation, air temperature and estimate of potential evapotranspiration. Precipitation calculation are made separately for each elevation/vegetation zone within a sub-basin.

$$RF = Pcorr * rfcf * P ----------------------------------- 2.2$$

If T > tt

Where, RF= rainfall

P=observed precipitation (mm)

T=observed temperature (^{0}C)

tt= threshold temperature (^{0}C)

rfcf= rainfall correction factor

pcorr= general precipitation correction factor

2.6.2 Soil moisture routine

The soil moisture routine is the main part controlling runoff formation. Three output components are generated in this routine, and these are direct runoff, indirect runoff and actual evapotranspiration. Each one of the sub-catchments has individual soil moisture accounting procedure and response function. Therefore, the runoff is generated independently for each of the sub-catchments.

Direct runoff: the volume of the soil moisture (SM, [mm]) in the catchment is computed with a soil moisture reservoir representing the unsaturated soil. It uses precipitation (P, [mm/day]) as input which is supplied by the precipitation accounting routine. As long as the maximum soil moisture storage (FC, [mm]) is not exceeded, the precipitation infiltrates into the soil moisture reservoir. Otherwise the precipitation becomes directly available for runoff DR, [mm/d]) as shown in equation 2.3.

$$DR = \max[(SM + P + FC),0] ------------------------------------ 2.3$$

Where, DR=direct runoff, SM= soil moisture, P=precipitation and FC=is soil moisture storage

From equation (2.2) the volume of infiltration water (IN, [mm/day]) is generated as shown in equation (2.4):

$$IN = P - DR -- 2.4$$

Indirect runoff: the infiltration water (IN) can be separated into two components; it replenishes the soil moisture state or it will seep through the soil layer, which is parameterized by R [mm/day]. This indirect runoff (R) through the soil layer is determined by the amount of infiltrating water (IN) and the soil moisture content (SM) through a power relationship with parameter BETA. This is shown in equation (2.5):

$$R = IN\left(\frac{SM}{FC}\right)^{BETA} -- 2.5$$

The relationship between parameters states that indirect discharge increase with increasing soil moisture content and that when no infiltration occurs, no indirect discharge is generated. The amount of water does not runoff indirectly is added to the soil moisture state.

Evapotranspiration: actual evapotranspiration **(**Ea, [mm/day]) which occurs at the soil moisture routine is related to the measured evapotranspiration (PET, [mm/day]), the soil moisture state and parameter value LP. This latter soil moisture value is a fraction between 0 and 1 denotes the limit where above the evapotranspiration reaches its potential value. This relation is shown in equation (2.6) and (2.7):

$$E_a = \frac{SM}{(LP * Fc)} * EP ------------------------------------ 2.6$$

With SM ≤ (LP*FC)

$$Ea = Ep ---------------------------------------2.7$$

With SM ≥ (LP*FC)

Where: Ea= actual evapotranspiration, LP= limit for potential evapotranspiration and EP=potential evapotranspiration.

Thus, the actual evapotranspiration is equal to the potential evapotranspiration if the actual evapotranspiration is above the specified threshold.

2.6.3 Quick runoff routine

The runoff generation routine is the response function which transforms excess water from the soil moisture zone (DR+R) to runoff. This response function is represented by an upper non-linear and a lower linear reservoir. These reservoirs represent respectively the rapid flow and slow flow. The quick runoff routine manages the upper non-linear reservoir. In this reservoir three components can be distinguished which are; percolation to the slow reservoir, capillary transport back to the soil moisture reservoir and quick runoff.

Percolation: the direct runoff (DR) and indirect runoff (R) together enter the quick runoff reservoir from which a specific amount percolates through to the underlying base flow runoff reservoir. Percolation (PERC, [mm/day]) only occurs when there is water accessible in the quick runoff reservoir.

Capillary rise: the second component within the quick runoff reservoir regards water returning to the soil moisture routine. This capillary flow (Cf, [mm/day]) depends on the amount of water stored in the soil moisture reservoir. The parameter CFLUX [mm/day], a maximum value for capillary flow, determines a limitation for the capillary flow. The capillary flow depends on the soil moisture deficit (FC-SM). When there is no soil moisture shortage, no capillary rise will occur. Otherwise, a fraction of the CFLUX will flow capillary upward. This is shown in equation (2.8):

$$C_f = CFLUX\left(\frac{F_C - SM}{F_C}\right) ---------------------------------2.8$$

Where: Cf= capillary flow and CFLUX is capillary rise coefficient

Quick runoff: when the yield from the soil moisture routine is higher than PERC and Cf allows, and water is available in the quick runoff reservoir, quick runoff (Qo, [mm/day]) is determined through equation (2.9):

$$Q = K_4 * UZ^{(1+alfa)} ------------------------------------2.9$$

Where: Q =direct runoff from upper reservoir, UZ [mm] is the storage in the quick runoff reservoir. ALFA a measure for the non-linearity of the reservoir and K_4 [day^{-1}] a recession coefficient. The recession coefficient is determined using ALFA and two additional parameters hq [mm/day] and khq [day^{-1}] representing respectively a high flow rate and a recession coefficient at a corresponding reservoir volume [mm]. This shown in equation (2.10):

$$k_4 = \frac{khq^{(1+alfa)}}{hq^{alfa}} ---------------------------------------2.10$$

Where: khq= recession coefficient in reservoir and hq is high flow rate in the reservoir.

Both additional parameters are approximated from observation data, but should be determined further during the calibration process.

2.6.4 Base flow routine

The base flow routine is the second part of response function which transforms excess water acquired from the quick runoff routine. It represents the flow of the catchment through Q_1 [mm/day]. This is represented by equation (2.11).

$$Q_1 = K_4 * LZ --2.11$$

Where: Q_1=lower reservoir outflow and LZ is lower reservoir storage. In which the recession coefficient K_4 [day^{-1}] is the only parameter to be determined, LZ [mm] represents the water level in the reservoir.

2.6.5 Transformation function

The total discharge Q= Q_0+Q_1, will be routed separately for each sub-basin through a transfer function in order to get a proper shape of the hydrograph. This transfer function is a simple filter technique with a triangular distribution of the weights. The generated runoff of one time step is distributed on the following days using one free parameter (MAXBAS). A value of one will distributed the runoff of one day over the same day. A higher value of MAXBAS will distributed the runoff of one day an over a larger period of time. As a result, this will lead to a delay and attenuation in the sub-catchment discharge.

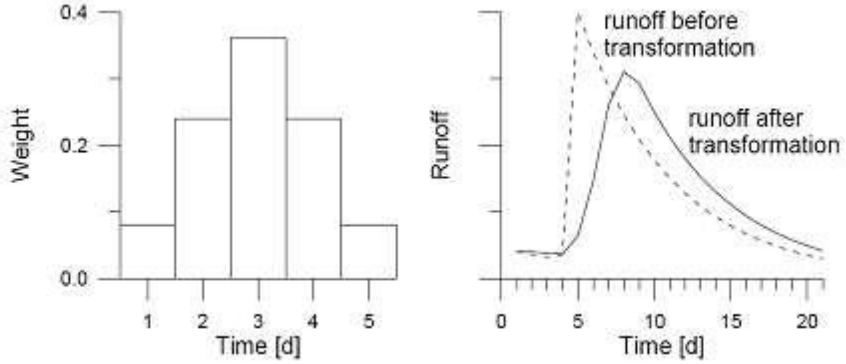


Figure 2. 3: Example of the transformation function with MAXBAS (IHMS, 2006)

2.6.6 Routing routine

With the transformation function, for each sub-catchment discharge runoff will be generated. In the routing routine HBV links the sub-catchments by adding the runoff from accompanying sub-catchments to the local runoff. Besides plain linkage of the sub-catchments, it is possible to delay and attenuate the water in the river channel by using the parameters LAG and DAMP. A modified version of the Muskingum equation is used for this computation (Shaw, 1994). In brief, this equation simulates the attenuation of the wave amplitude (concerning the parameter DAMP) and the travel time (concerning the parameter LAG) of the discharge through the sub-catchment. By the parameter LAG, the river channel will be subdivided into a number of segments. When this parameter is an integer, each segment will refer to a delay of one day. If DAMP has a value of zero, the outflow from a segment equals the inflow to the same segment during the preceding time step, so that the shape of the hydrograph is not changed. If DAMP is not zero, the shape will be changed, as the outflow from a segment will depend on the inflow during the same time step as well as the inflow and the outflow at the preceding time step. This is shown in equation (2.12).

$$Q_{Outi-1} * C_1 + Q_{Ini} * C_1 + Q_{in,(i-1)} * C_2 ---------------------------- 2.12$$

Where: I=the current model time step and i-1= the previous model time step. The coefficients C_1 and C2 are determined by the following equation:

$$C_1 = \frac{DAMP}{(1 + DAMP)} \text{------------------------------------} 2.13$$

$$C_2 = \frac{(1 - DAMP)}{(1 + DAMP)} \text{------------------------------------} 2.14$$

2.6.7 HBV model Application

The HBV approach has proved flexible and robust in solving water resource problems and applications now span over a broad range. The HBV model is today an Integrated Hydrological Modeling System, a modern, well-tested and operational tool that can be linked with Real Time Weather Information and Forecast systems.

The HBV model was initially intended for runoff simulation and hydrological forecasting. The number of applications grew to cover most rivers in Sweden where flood forecasting and reservoir operation is an issue. Today hydrological forecasting is probably still the most frequent type of application of the HBV model, both in Sweden and elsewhere. Research is still going on, in particular as concerns supplementary input from remote sensing and meteorological analysis techniques (Häggström *et al*, 1990).

Forecasting was the main task of the HBV model until the early 1980s. This was when realized a spillway design problem connected to the reservoirs of the Swedish hydropower system. New guidelines for hydrological design were developed and adopted in 1990, and all of a sudden there was a new role for the HBV model (Bergström *et al*, 1992, Lindström, 1992). A hydrological model of this type is a powerful tool for computation of hypothetical design floods, which have not yet occurred, but cannot be ruled out. A model for design flood simulation in a multiple-reservoir river system was developed. It is based on an iterative approach, where the most critical timing of flood generation processes is sought. This method is a present being implemented in connection to a hydrological re-assessment of all major Swedish dams(Norstedt *et al*, 1992).

The events in the 1980s triggered a debate on the impact of land use on flood risks. In particular clear cutting and forest drainage were suggested as aggravating floods. The HBV model, although not being fully physically based, was used as an analysis tool. It could, at least, give some crude estimates of potential consequences. It was concluded that the main problem was underestimation of natural variability's as concerns extremes and disharmony in infrastructure development, while land use probably has more limited impacts (Brandt *et al*, 1988).

It was with some hesitation that decided to try the HBV model for simulations of groundwater recharge. Nevertheless it could be shown that the storages of the response function of the HBV model could be used to describe at least the response of the unconfined aquifers of a catchment (Bergström, 1983). The model could not be used for the three dimensional flow of groundwater, but gave realistic recharge values.

Climate change due to human activities is one of the greatest scientific issues today. In spite of all uncertainties in regional climate outlooks, hydrological models are in use for water resources impact studies since the early 1990s. The HBV model is no exception (Vehvilainen, 1991).

A Nordic study on climate change and hydropower production was finalized in 1998 (Saelthun *et al, 1998)*. The work was based on regional climate scenarios and a modified HBV model.

In water resources modeling, reducing model complexity is the most important especially when data availability is poor. Hence, input data have to be kept as simple as possible. Despite its simplicity and scarcely gauged river basin, its simulation performance is commendable.

In the current study, a conceptual model based on the HBV model concepts is presented for hydrology educational purposes. The HBV model is selected mainly because of its conceptual approach in which the hydrologic processes are simplified to algebraic functions and thus, the required calculations can be easily conducted in an Excel spreadsheet format and in addition to that easily to see change in model parameters, and observe their effects on the predicted output and the model performance. Because of this reason HBV-96 model is selected rather than other rainfall-runoff model.

Generally, most of Ethiopian river watersheds are ungauged. Consequently, regionalization is the solution tool to solve this problem. Different researchers used it in different countries. For example used HBV-96 model to determine the runoff from ungauged catchments by transferring calibration model parameters of gauged catchments to ungauged catchments in middle and upper Awash river, Ethiopia (Gebeyehu, 2013). In the same way, developed the relationships between key model parameters and river basin characteristics to estimate the parameter values for the ungauged sub-basin using HBV-96 model in the Case of Blue Nile River Basin, Ethiopia(Wale, 2009). Performed regionalization in Lake Tana Basin to get optimized model parameters for gauged catchments (Perera, 2009) and used regional model method, spatial proximity, area ratio and default parameter sets method to transfer the optimized model parameters to ungauged catchments and he found that default parameter set and regional model is contributed the highest and lowest volume respectively. As well (Tamalew, 2015) performed determination of discharge for ungauged catchment using regionalization technique in Didessa Sub-Basin, Ethiopia. Performed model calibration in Lake Tana Basin, Ethiopia to get optimized parameters for gauged catchments and used the advantage of physical catchment characteristics similarity to transfer the gauged parameters to ungauged catchments. From the above result it can be conclude that the physical catchment similarity is considered as the most valuable for regionalization in poorly gauged river basins. Performed predicting discharge for ungauged catchments by estimating parameter through the method of regionalization in United Kingdom. (Deckers, 2006)

3. Materials and Methods

3.1 Description of study area

3.1.1 Location

Geba River, one of the tributaries of the Tekeze River, in the highlands of North Ethiopia, with dendritic drainage pattern as shown in Figure 3.1. It is located between $38^0$90'E and $39^0$48'E and between $13^0$18' N and $14^0$14'N. The Geba River originates from the Mugulat mountains (elevation: 3294 m.a.s.l) near Adigrat in the north and flows south and then westwards to join the river Tekeze at Chemey on its way to the Sudan.

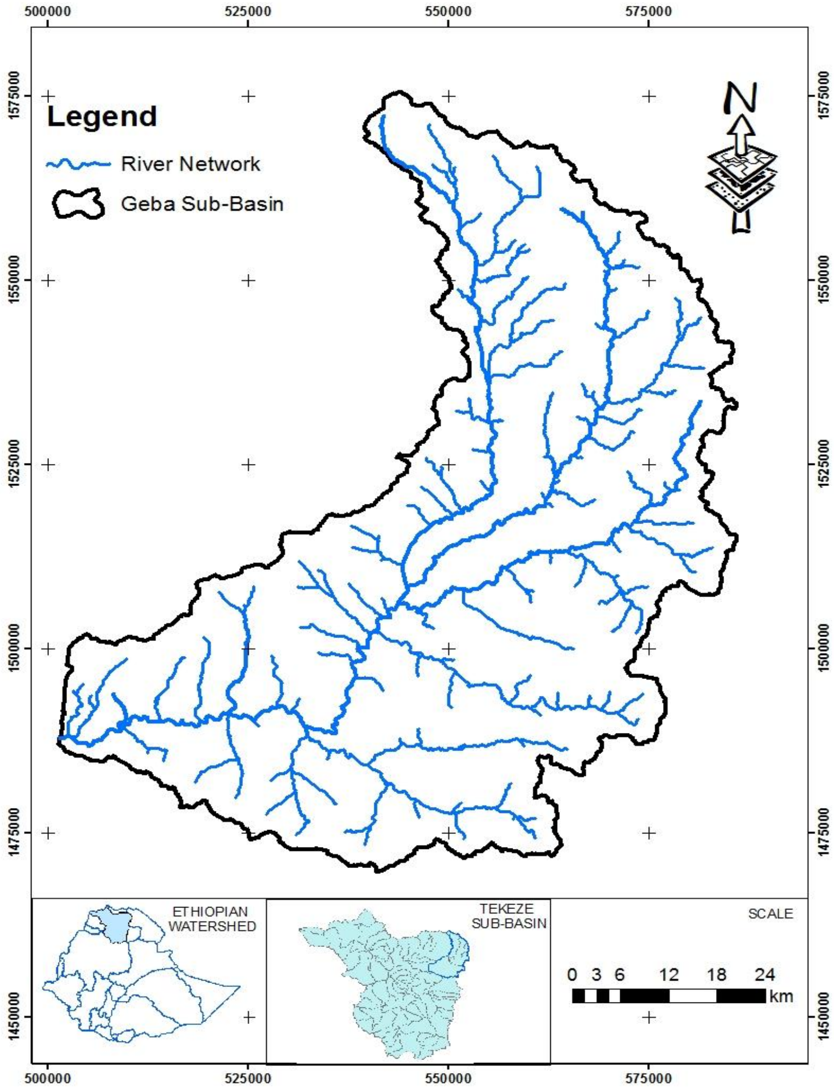


Figure 3.1: Location of study area

3.1.2 Climate

According to the definition given by the World Meteorological Organization (WMO), climate is defined as the synthesis of weather condition in a given area characterized by long-term statistics (mean, variance, probabilities of extremes,) of the meteorological elements in an area (NEDECO, 1998). The meteorological/ climatic elements include rainfall, temperature, wind, relative humidity, and sunshine hours. The conditions of some of climatic elements in the basin are described below.

3.1.2.1 Rainfall

The watershed receives two rainy seasons, the main rainy season (June to September) and the small rainy season (February to May). The mean annual rainfall ranges between 500 to 800 mm. Annual rainfall data obtained from selected stations show very pronounced annual and seasonal fluctuations. Moreover, the local rainfall pattern highly depends on the topography.

In the study area around 70% of the annual rainfall occurs between July and August (Figure 3.2). The rainfall distribution is bimodal at all stations, with a minor peak usually in March-April and with major peak in July-August.

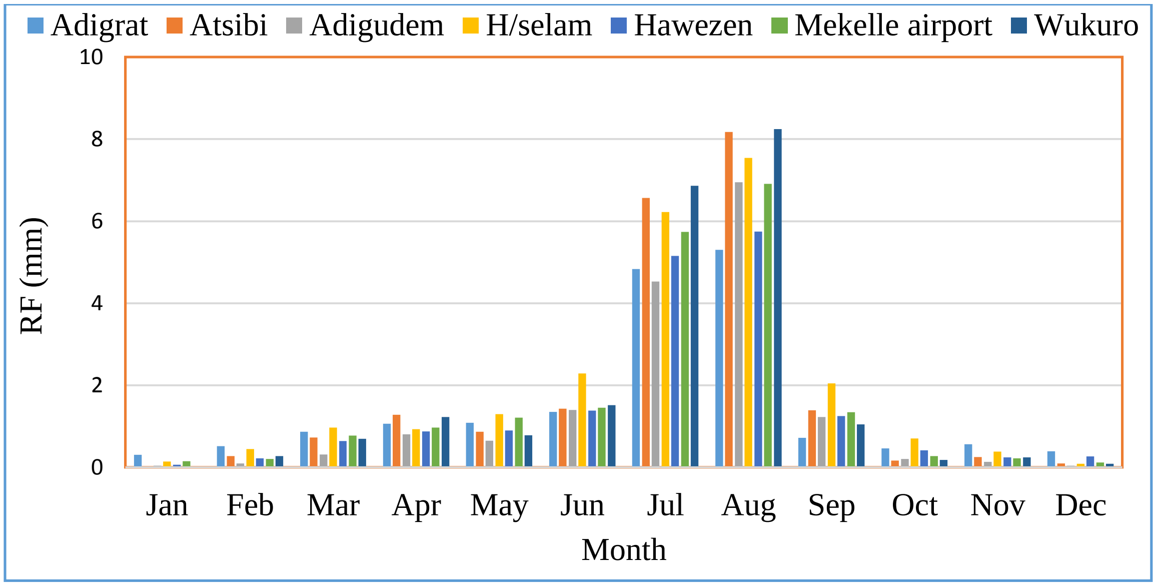


Figure 3.2: Average daily rainfall (mm) data series

3.1.2.2 Temperature

The National Meteorological Service Agency of Ethiopia divide the country based on temperature into four zones.

Table 3.1: General temperature zones

Temperature zones	Mean annual Temperature
Kolla I	$>25^0$c
Kolla II	$>20^0$c
Woina Dega	$>15^0$c
Dega	$<15^0$c

The study area is located in the kolla II zone; here hot season mean temperatures ranges from between 25^0c in the area close to Mekelle to about 22^0c on the high plateaus. The temperature of the coldest month average less than 6^0c on the high plateaus and reaches 11^0c near the Mekelle area. The highest mean monthly temperatures are reaches just prior to the onset of the rainy season in April and May. The approximate lapse rate (decrease of temperature with altitude) average 0.6^0c/100m (Gonfa, 1996).

3.1.2.3 Relative humidity

The highest relative humidity occurs when the rainfall is the highest, in the July and August the relative humidity in the early morning might reach up to 90%. The mean monthly relative humidity is only available for Mekelle airport station, the average humidity is highest in August and least in May. The humidity is highest in the morning (06:00) and lowest in the afternoon (15:00).

3.1.2.4 Wind speed

Wind direction during dry season in most parts of Ethiopia is generally from the east direction (easterly or south-easterly), changing to westerly or north-westerly during the rainy season. Winds are not very strong and velocity generally average 2.1 to 3.1 m/s with slight increase during the transition period between the dry and wet spell (WAPCOS, 2003).

3.1.2.5 Sunshine

The sunshine data are available for Mekelle airport weather station. As the major factor affecting the average daily hours of sunshine on the Basin is the cloud factor, with relatively little effect due to the seasonal movement of the earth. The sunshine hours average around 5.5 hours/ day in July and August and around 10 hours/day in December. Obviously the decrease in sunshine hours in July and August is due to persistent cloudiness during rain.

3.1.3 Physiographic

The topography of the basin is highly controlled by erosion features and geological structures. Sharp cliffs and steep slopes occurs along the major rivers. The northern and northeastern part of the basin are mountainous, with the eastern part comprising several upland plateau flanked by mountainous.

The slope gradients range from 0-74^0. Very steep slope gradients of 30^0 to $74^0$are recorded in the north and north east highland plateaus (Mugulat and Atsebi mountainous area, escarpment cliffs).

3.1.3.1 Land Use and Land Cover

The natural woodland vegetation in most of Tigray has been largely destroyed or severely modified by human activities (HTS, 1976).

The major land use and cover type of the Geba catchment used for this study are: Shrub land, cultivated land, grassland, bare land, natural forest, plantation, water body and wood land (Figure 3.3).

Based on the land cover classification scheme of the South Africa National Land-Cover Data based project (Thompson, 1999), the land cover categories for Geba catchment were defined as follows;

Cultivated land- areas of land prepared for growing rain fed or irrigated crops. This category includes areas currently under crop, fallow, and land under preparation.

Forest land- areas covered with a natural forest community with a closed, deep and complex canopy often consisting of several crown layers. Many species are ever green and their floor is incompletely covered with herbs, shrubs and grasses.

Bushed grassland- areas covered with scattered and/or patches of bushes and shrubs in combination of grasses.

Grass land- all areas of grassland with less than 10% tree and/or shrub canopy cover and greater than 0.1% total vegetation cover.

Water body- areas of (generally permanent) open water. The category includes natural and man-made water bodies, which are static or flowing, and fresh, brackish and salt water condition.

Bare land- non-vegetated areas, or areas very little vegetation cover (excluding agricultural fields with no crop cover), where the substrate or soil exposure is clearly apparent.

A majority of the catchments are dominated by cultivated land, shrub land, grassland and the next bare land. Natural forest, plantation, water body and wood land are very small proportion in all catchments, and they were not considered for further analysis.

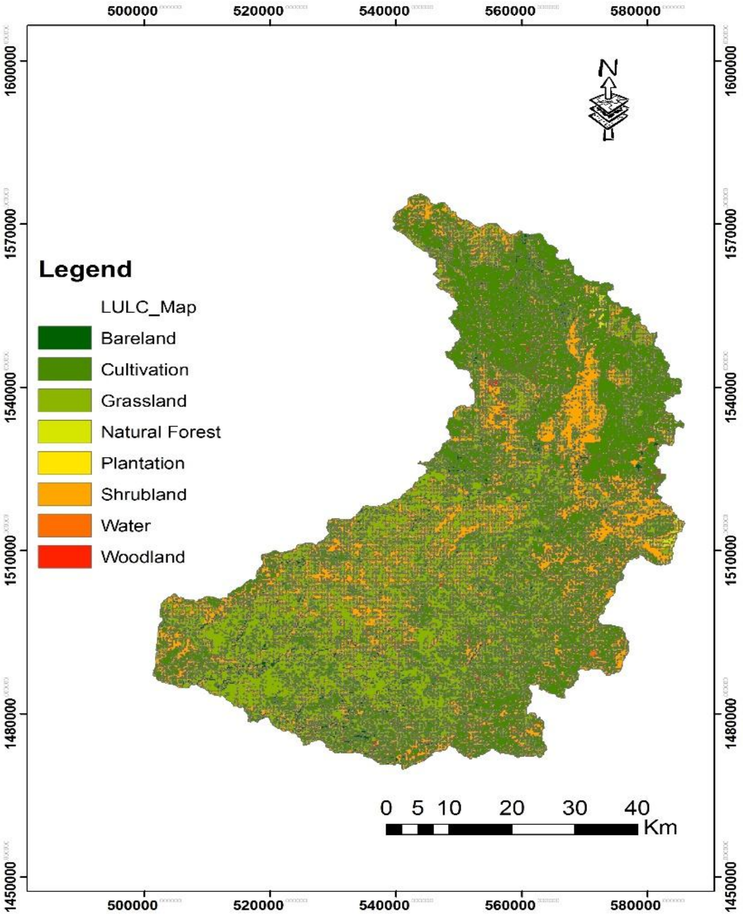


Figure 3.3: Land Cover and Use map of Geba Sub-Basin [source: MoWIE]

3.1.3.2 Geology

The geology of Geba sub-basin consists of a basement complex plateau (metamorphic rocks) having an upper sedimentary rock layer (sandstone, shale, limestone, and limestone-marl) with some doleritic intrusion, which is capped by basalt trap series (HTS, 1976). Alluvium occurs along narrow incised river valleys.

Table 3.2: Dominant geology in the Geba catchment based on the MU-IUC: Hydrology Project map (MU-IUC, 2007).

stations	BAS	DOL	GRA	LST	LSM	MET	SST	SHA
Suluh	7.6	0.0	4.8	23.1	4.1	20.1	39.2	1.0
Genfel	0.0	0.0	0.2	13.0	3.4	50.5	25.1	7.8
Agula	0.0	3.0	0.0	47.1	17.6	14.1	8.4	9.8
Geba Nr Mekelle	3.3	5.6	0.9	27.6	14.1	27.2	16.0	5.3

The legend of geology map were grouped as follow:

BAS: Basalt/Trap basalt; DOL: Dolerite; GRA: Granite; LST: Limestone (Limestone, Shale-Marl-Limestone, and Marl-Limestone); LSM: Limestone-Marl; MET: Metamorphic rock (Metavolcanic, Metalimestone, Metasediment, Metaconglomerate, Metagreywack); SST: Sandstone (Adigrat sandstone, Entich sandstone, Amaaradom sandstone), and SHA: Shale.

3.1.3.3 Soil type

Soil, land use and rainfall are the major physical catchment characteristics that governs runoff generation. The infiltration capacity of the soil depends on the porosity of the soil, which determines its storage capacity and affects the resistance of the water to flow into deep layers. Since the soil infiltration capacity depend on the soil texture, the highest infiltration rates are observed in sandy soil, this shows that surface runoff is higher in heavy clay and loamy which has low infiltration rate (SMEC, 2007). The soil map was collected from the MoWIE GIS department.

Lithic Leptosols; these are shallow soils, limited in depth by continuous hard rock, found dominantly in many mountainous parts of the Geba catchment, and are not suitable for crop production, but farmers use it for cultivation due to shortage of arable land

Cambisols; are moderately developed soils characterized by slight or moderate weathering of the parent material and by absence of appreciable quantities of illuviated clay, organic matter, aluminium or iron compounds. These soils are found in considerable parts of the Geba catchment. Vertic Cambisol is found in Suluh, Genfel and Agula sub-catchments and has vertic properties.

Vertisols; are churning, heavy clay soils with high proportion of swelling characteristics. This soil from deep wide cracks from the surface downward when they dry out. Vertisols are dominant in depression leveled to undulating topography of tropical, sub-tropical, humid and semi-arid to sub humid climates with an alternation of wet and dry seasons.

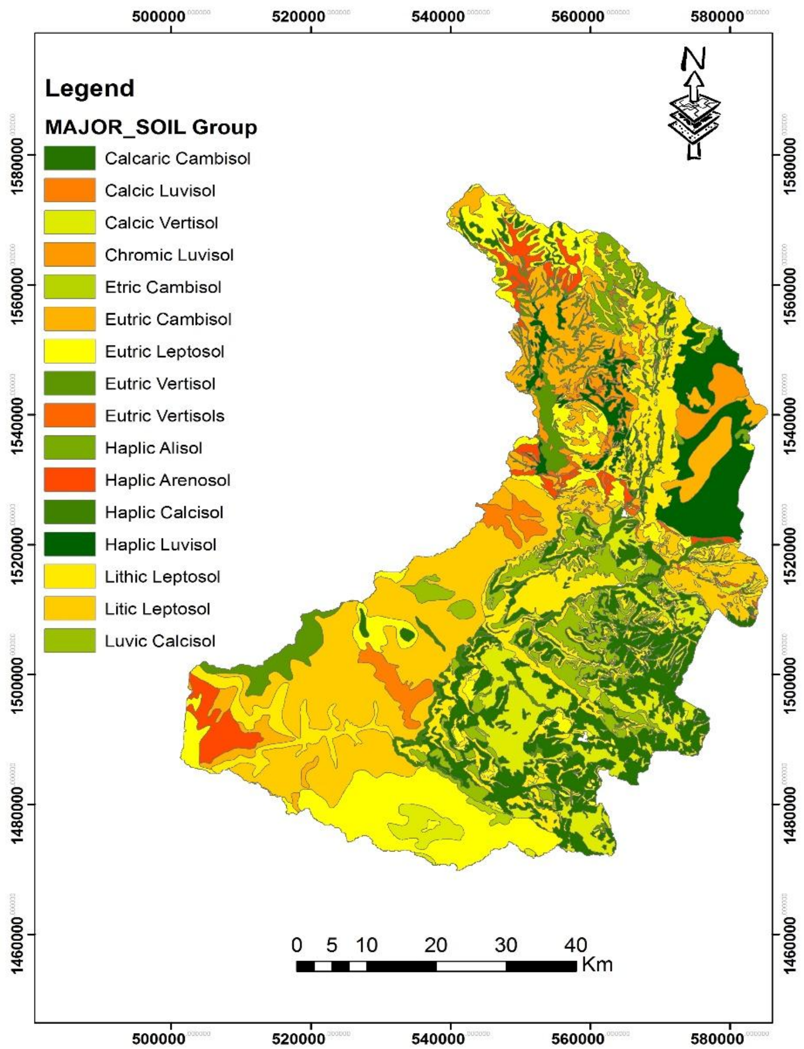


Figure 3.4: Major soil map of Geba sub-basin [source: MoWIE].

3.2 Data Collection and Processing

3.2.1 Data collection

According to the theories discussed in chapter two, three basic data sets are necessary for the modeling work. These are the Meteorological data (rainfall, temperature, and relative humidity and sunshine hours), the stream flow and catchment physiographic data.

The HBV model requires meteorological and hydrological input data in daily time step including rainfall, mean temperature, and daily flow data at the sub-basin outlet. Daily cumulative rainfall, mean maximum and minimum temperatures, data were compiled for all available stations in the sub-basins. Most of meteorological stations for which data collected were located inside the sub-basins and some are located around it. Record lengths of these stations vary from a few years to more than 30 years.

Taking into account the length of record, continuity of data, concurrent period of observation and the distribution of stations in the sub-basin, seven meteorological stations are selected for the study. The distribution of these stations within the sub-basin is not even. Hence, the Thiessen Polygon method was used to estimate the areal rainfall and minimize the error introduced by spatial variability.

3.2.1.1 Hydrological Data

Hydrological data were important data set in the research work. Other sets of data were all collected depending on the availability and suitability of data from the hydrological stations. The hydrological data made available comes from Ministries of Water, Irrigation and Electricity (MoWIE), Hydrology Department daily flow data have been collected.

Even though more than seven hydrometric stations are found in the sub-basin, only 4 gauging stations data were accessible from MoWIE Hydrology Department for this study. Summary of hydrological data is shown in Table 3.3.

Table 3.3: Summary of hydrological gauging stations

s.no	River name	Station name	Reference	Area[km^2]	x-coordinate	y-coordinate
1	Suluh	Nr.Hawzen	1996	420	554000.665	1545571.33
2	Agula	Nr.Agula	121013	456	561079.5	1511578.1
3	Genfel	Nr.Wukuro	121010	498	564851.168	1525688.48
4	Geba nr Mekelle	Nr.Mekelle	121004	526	541106.75	1503521.07

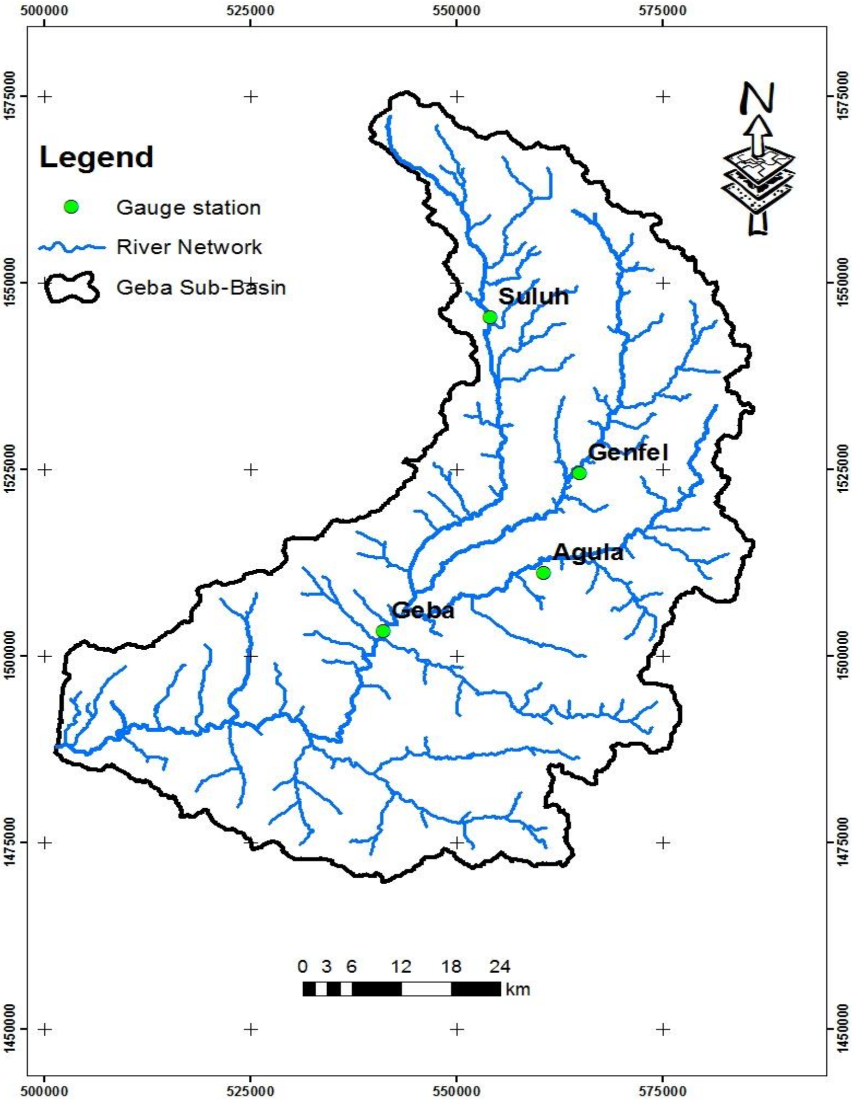


Figure 3.5: Geba sub-basin gauging stations

3.2.1.2 Meteorological Data

The second most important time series data necessary for this research is rainfall data. The source of raw meteorological data in Ethiopia is the National Meteorological Service Agency (NMSA). A request for daily rainfall data, in addition daily temperature, relative humidity and sunshine hour duration data was made to the agency. Following the approval of the agency's higher official, daily data including many more stations that are not exactly used in the model work were collected. Out of the entire available automatic recording stations those which are in or proximate to the catchments considered for the research work were selected. Accordingly a total seven rainfall stations were selected for use in the research work. The location of these rainfall stations are shown in Figure 3.6.

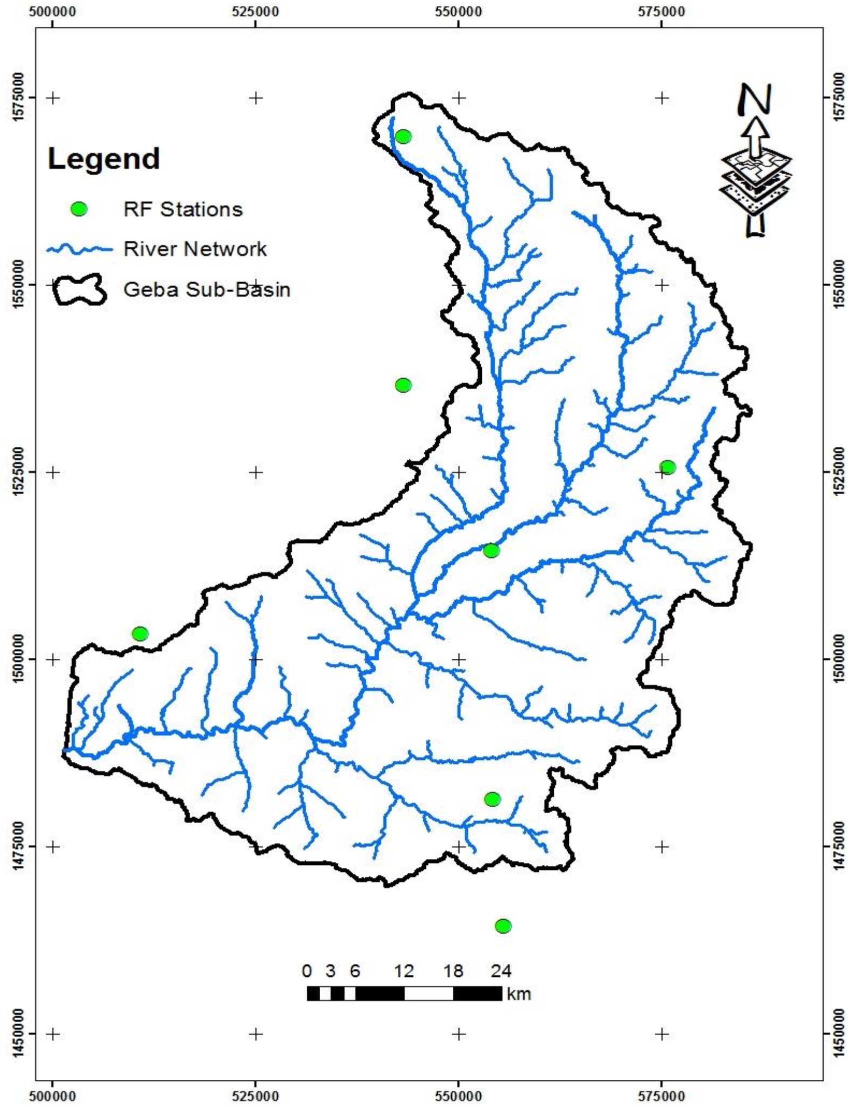


Figure 3.6: Rainfall station location

The rainfall records that obtained from NMSA cover the length of years from 1998 to 2014 depending on the available stream flow records particular to catchment being considered. The collected data stretched over these years to obtain adequate match between the rainfall events and the resulting stream flow records. A summary of the rainfall stations with elevation of record used in the thesis is given in Table 3.4.

According to NMSA, the meteorological parameters as monthly mean relative humidity (%) are taken every 3 hours at 06:00, 09:00, 12:00, 15:00 and 18:00 GMT. Maximum and minimum air temperature and sunshine hours are taken as an observed input data for the model works.

Table 3.4: Summary of the rainfall stations

s.no	Stations name	Latitude (Degree)	Longitude (Degree)	Elevations (m)
1	Mekelle air port	13.4	39.5	2257
2	H/selam	13.6	39.2	2618
3	Adigrat	14.3	39.4	2497
4	Atsibi	13.8	39.7	2729
5	Wukuro	13.8	39.6	1987
6	Hawezen	14	39.4	2242
7	Adigudem	13.2	39.5	2100

3.2.2 Data Processing

3.2.2.1 Rainfall data gap-filling

Missing data is common problem in hydrology. Before using the rainfall records of station, it is necessary to first check the data for continuity and consistency. The continuity of a record may be broken with missing data due to many reasons such as damage or fault in a rain gauge during a period. The missing data can be estimated by using the data of the neighboring stations. A number of methods have been proposed for estimate missing rainfall data (Richard, 1989). The stations average method is the simplest method. The normal-ratio and quadrant method provides a weighted mean, with the former basing the weights on the mean annual rainfall at each gauge and the latter having weights that depend on the distance between the gauges where recorded data are available and the point where a value is required.

The station average method for filling missing data is conceptually the same as the station average method for estimating a mean precipitation. This method may not be accurate when the total annual rainfall at any of the n region gauges differs from the annual rainfall at the point of interest by more than 10%. The normal-ratio method is conceptually simple; it differs from the stations-average method of that the average annual rainfall is used in deriving weights. If the total annual rainfall at any of the m region gauge differs from the annual rainfall at the point of interest by more than 10%, the normal-ratio method is preferable. Because this method is more advance than station average method and simple, so considered this method for filling missed rainfall data in this method. The general formula for computing P is

$$\overline{Pi} = \frac{Nx}{M}\left(\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + ... + \frac{P_7}{N_7}\right) ------------------------------ 3.1$$

Where: Nx=Average annual precipitation at the missing data.

N_1, N_2, N_3… N_7=Average annual precipitation at the adjacent site.

The selected and available rainfall data statistics are shown in the Table 3.3.

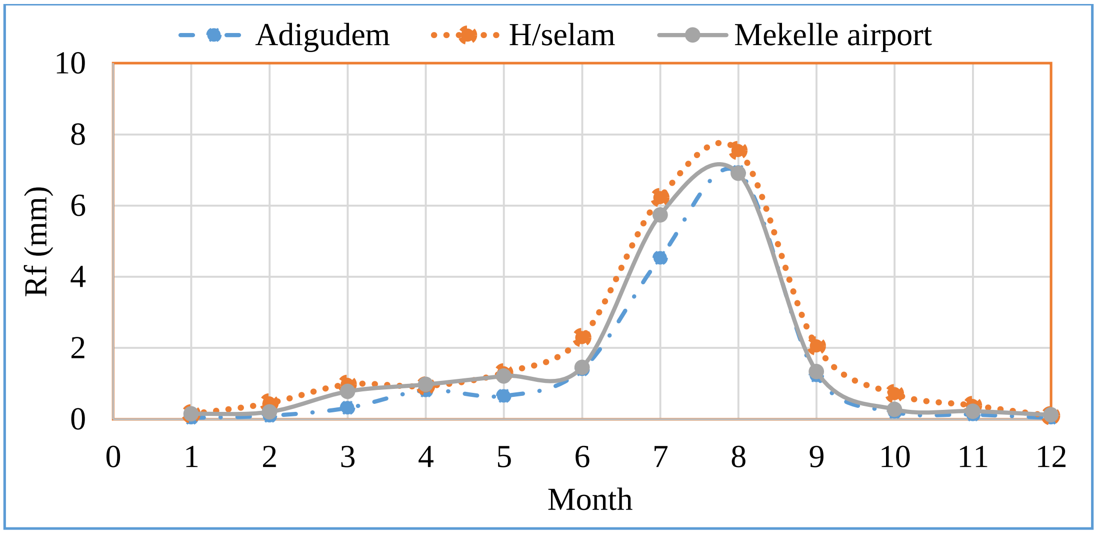
3.2.2.2 Homogeneity recording stations

In order to fill the missed rainfall data, and to select representative meteorological stations, checking homogeneity of group stations is essential. The homogeneity of the selected gauging stations monthly rainfall records have been carried out by non-dimensional zing using equation:

$$Pi = \frac{\overline{Pi}}{\overline{P}} * 100 ------------------------------------ 3.2$$

Where: - P_i=Non dimensional value of PP for the month i

$\overline{Pi}$ =Over years averaged monthly precipitation for the station i, $\overline{p}$ the over years average yearly precipitation of the station and plotted to compare the station included in the computation of area rainfall with each other as shown in Figure 3.7.



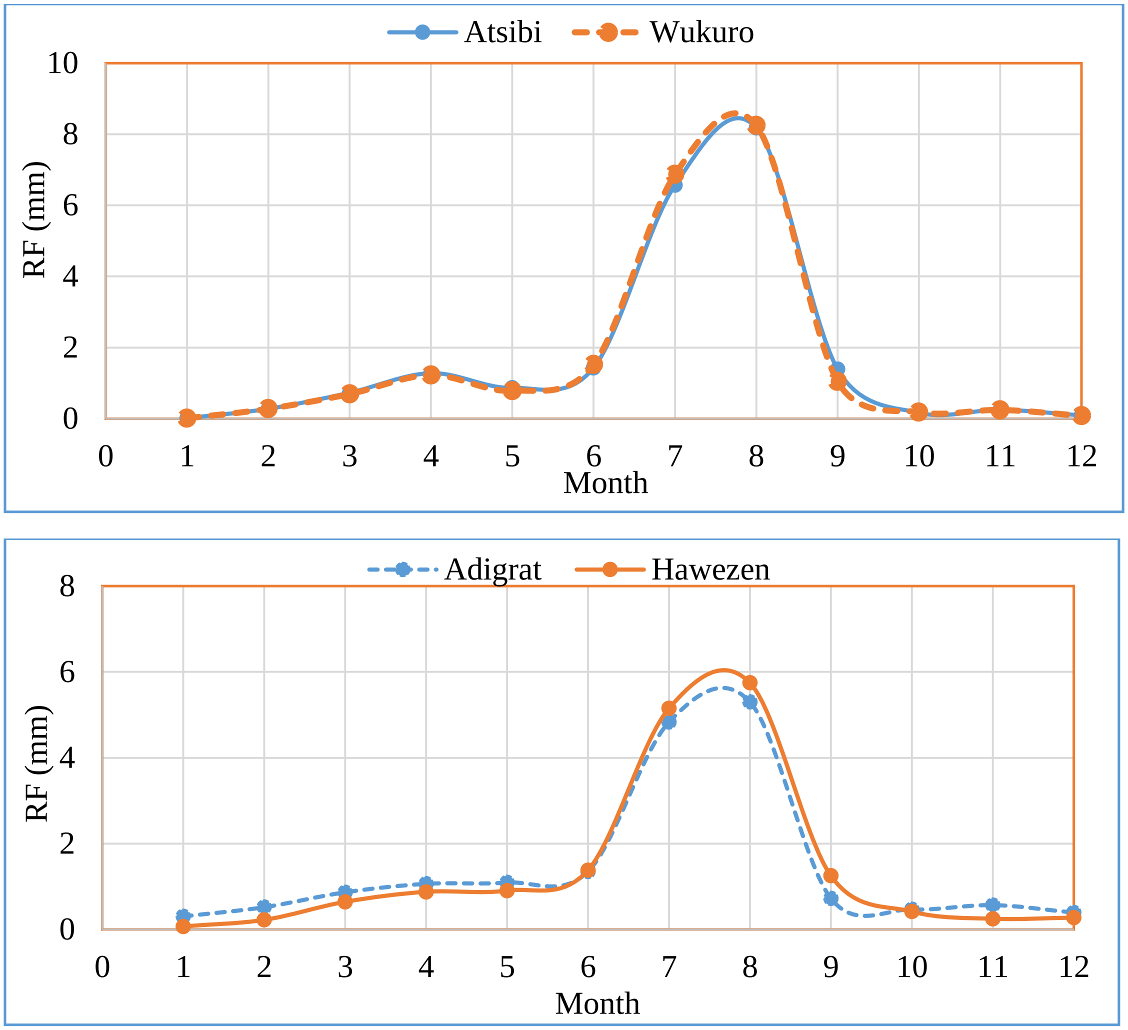


Figure 3.7: Homogeneity test for areal rainfall stations

3.2.2.3 Consistency of recording stations

If the conditions relevant to the recording of a rain gauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station. This inconsistency would be felt from the time the significant change took place. The checking for inconsistency of a record is done by double mass curve technique (Subramanya, 1998). The accumulated totals of the gauge in question are compared with the corresponding totals for a representative group of nearby gauge. If a decided change in the regime of the curve is observe it should be corrected. The below graphs showed all points set on or from almost the straight lines, which was plotted for checking of consistency of rainfall, all stations were consistence. Therefore, the stations did not need further adjustment. Figure 3.8 shows double mass curve graph analysis and the double mass curve for each rainfall stations were attached in Appendix B.

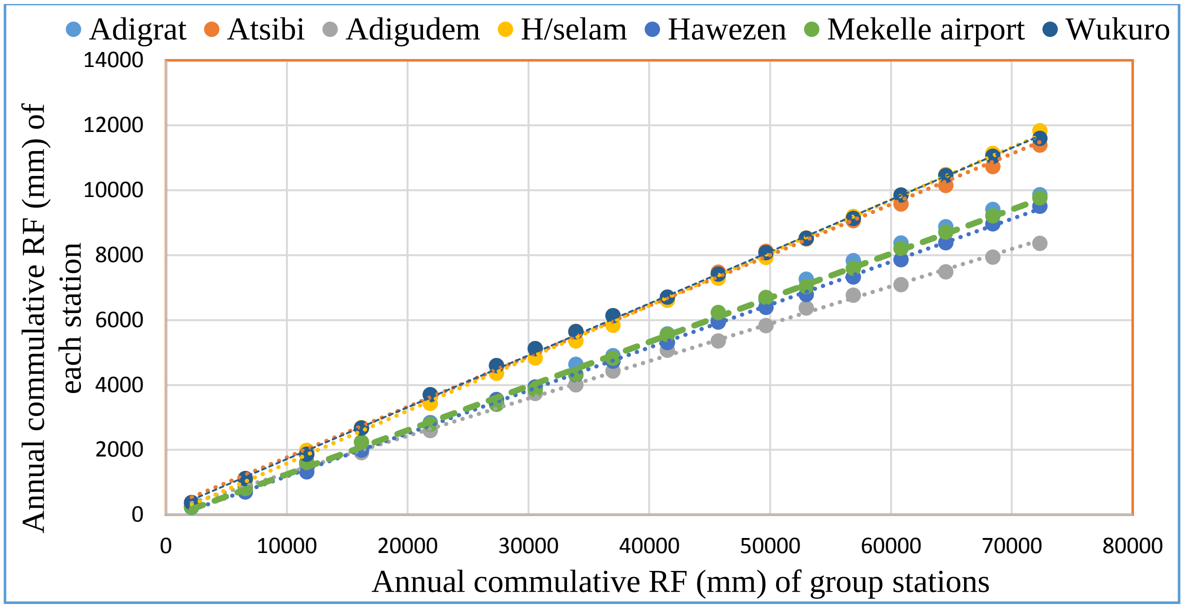


Figure 3.8: Double mass curve graph analysis for all the stations

3.2.2.4 Estimation of model input areal data

The areal input data HBV-96 model are rainfall, air temperature, and relative humidity and sunshine hours. This section presents the steps followed to calculate these areal data sets taking the rainfall data as an example and also summarizes the results obtained. A rain gauge records the rainfall at a single point. This point rainfall records has to be converted to areal rainfall. The average depth of precipitation over the area under the area of consideration is one of the most important parameter in hydrological analysis. The computation of average areal model input data may be done by the following methods:

1. Arithmetic average method: - when the rainfall is uniformly distributed over the area, the average rainfall may be taken as the arithmetic average of the recorded rainfall.
2. Thiessen polygon method: - rainfall varies in intensity and duration from place to place. Hence the rainfall recorded by each rain gauge station should be weighted according to the area it is assumed to represent.
3. Isohyetal method: - isohyets are a line joining places of equal rainfall intensities on a rainfall may of the basin. An isohytal map represents an accurate picture of the rainfall distribution over the basin. If the network rainfall stations within the storm area are sufficiently dense, the isohyetal map will give a reasonably accurate indication of the rainfall distribution zones.

The sub-catchments in the basin considered for this thesis work have one or more than one rainfall gauging stations within or in the vicinity of the boundary of their watershed. For the catchments having rainfall gauges more than one, theissen polygon method has been used to compute the areal rainfall. The method weights each gauge in direct proportion to the area it represents of the total basin. The area of influence of each gauge is obtained by constructing polygons determined by drawing perpendicular bisectors to line connecting the gauges by using Arc view GIS software. By taking two sub-catchments, the theissen gauge weights developed for sub-catchments with more than one rainfall gauging stations are presented in Figure 3.9.

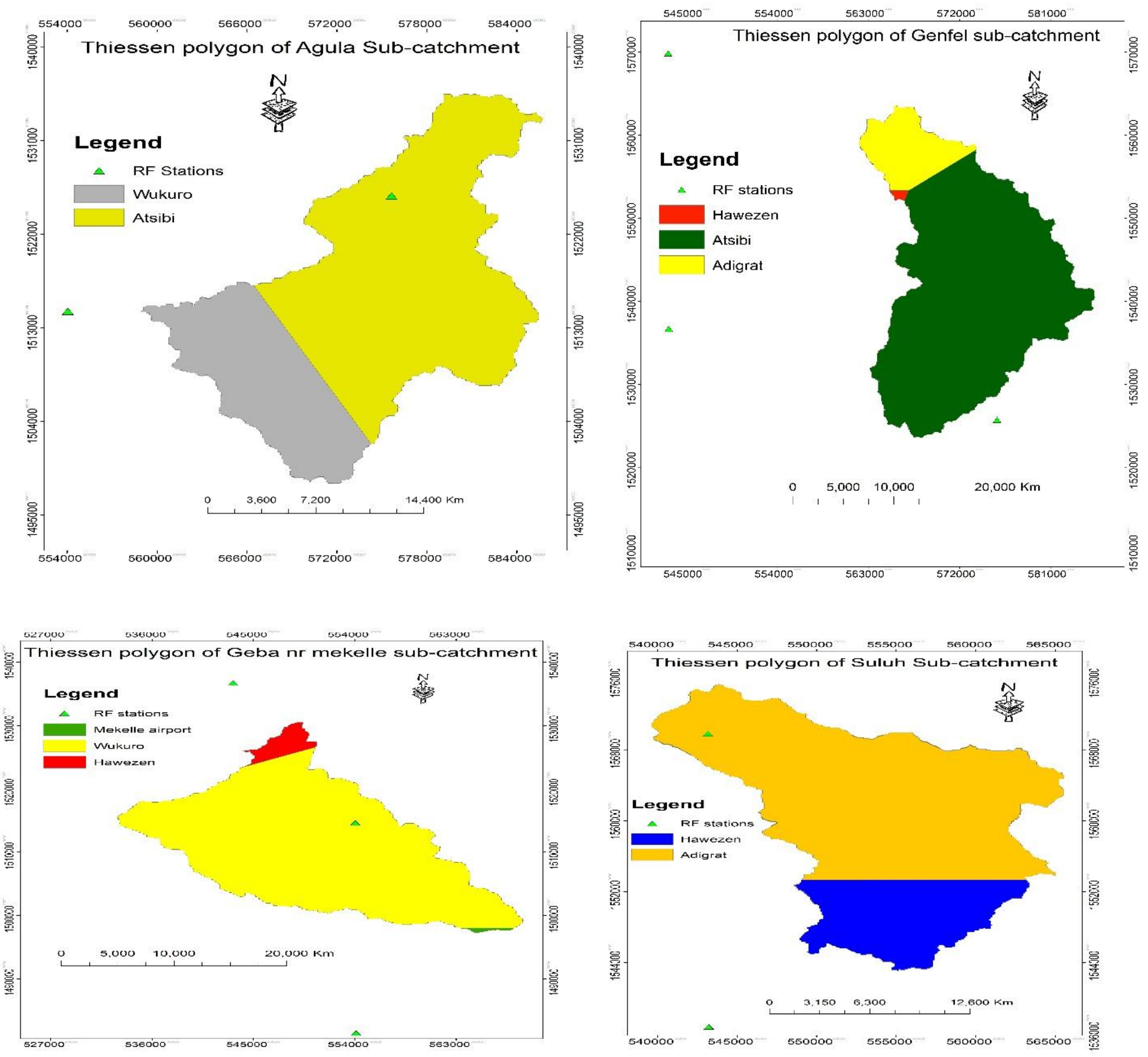


Figure 3.9: Thiessen polygon developed for gauged catchments

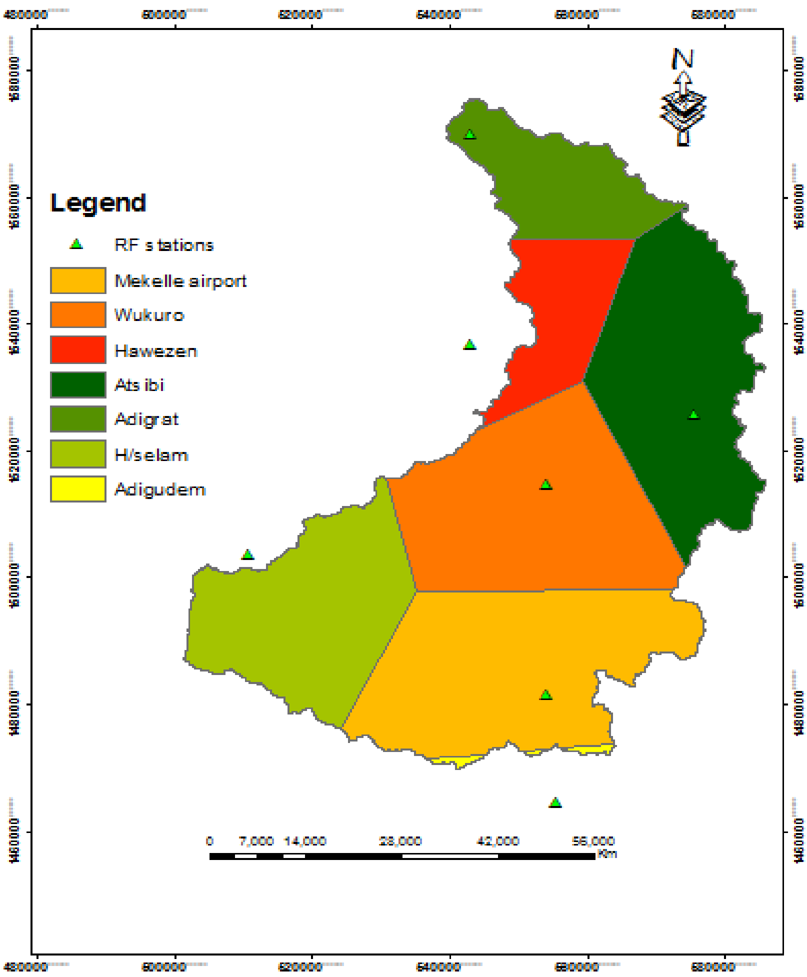


Figure 3.10: Thiessen polygon developed for Geba Sub basin

The general areal precipitation equation of Thiessen polygons method is as follow:

$$P_{Total} = \frac{A_1}{A_{Total}} * P_1 + \frac{A_2}{A_{Total}} * P_2 + \frac{A_3}{A_{Total}} * P_3 + \frac{A_4}{A_{Total}} * P_4 + - - - - - + \frac{A_7}{A_{Total}} * P_7 - - - - - - - - - 3.3$$

Where A=area, P=Precipitation and A_{Total}=the summation of area for seven meteorological stations

3.2.2.5 Potential Evapotranspiration

The other necessary input of the model is potential Evapotranspiration (PE). PE data is not found from the meteorological station. Hence there are number of methods to estimate potential evapotranspiration. The Penman-Monteith method is recommended, which is widely used as the standard method in hydrologic engineering applications to estimate PE estimation when the standard meteorological variables such as air temperature, relative humidity, sunshine hours and windy speed are available (Tufa, 2011). In this study one station has full meteorological data that is required by Pneman-Monteith method to calculate evapotranspiration. However, those data are not available in all stations in the study area. So, the remaining Potential evapotranspiration was calculated by using Hargreaves method, since most of the stations have maximum and minimum temperature in all stations.

The basic formula for calculating potential evapotranspiration by using Penman-Monteith is as shown below:

$$E_{to} = \frac{0.408(R_n - G) + Y\frac{900}{(T+273)}U(e_s - e_a)}{\Delta + Y(1+0.34U)} ----------------------- 3.4$$

Where:

E_{to}=reference evapotranspiration [mm day^{-1}]

R_n=net radiation flux [MJm^{-2} day^{-1}]

G= soil heat flux density [MJm^{-2} day^{-1}]

T= mean daily air temperature [^{0}C]

Y=psychometric constant [KPA ^{0}C^{-1}]

U=Wind speed measured at 2 m height [ms^{-1}]

e_s= saturation vapor pressure [kpa]

e_a=actual vapor pressure [kpa]

e_s-e_a=saturation vapor pressure deficit [kpa]

Δ=slope of the saturation vapor pressure curve [kpa]

3.2.3 Digital Elevation Model

The Digital Elevation Model (DEM) of 30 by 30 resolution from Shuttle Radar Topography Mission (SRTM) has been used to delineate the gauged and ungauged catchments to extract information about the topography of catchment and to analyze the drainage pattern of the stream network characteristics by using hydro-processing tool in SWAT and GIS software. A grid in which cell assigned the average elevation on the area represented by the cell.

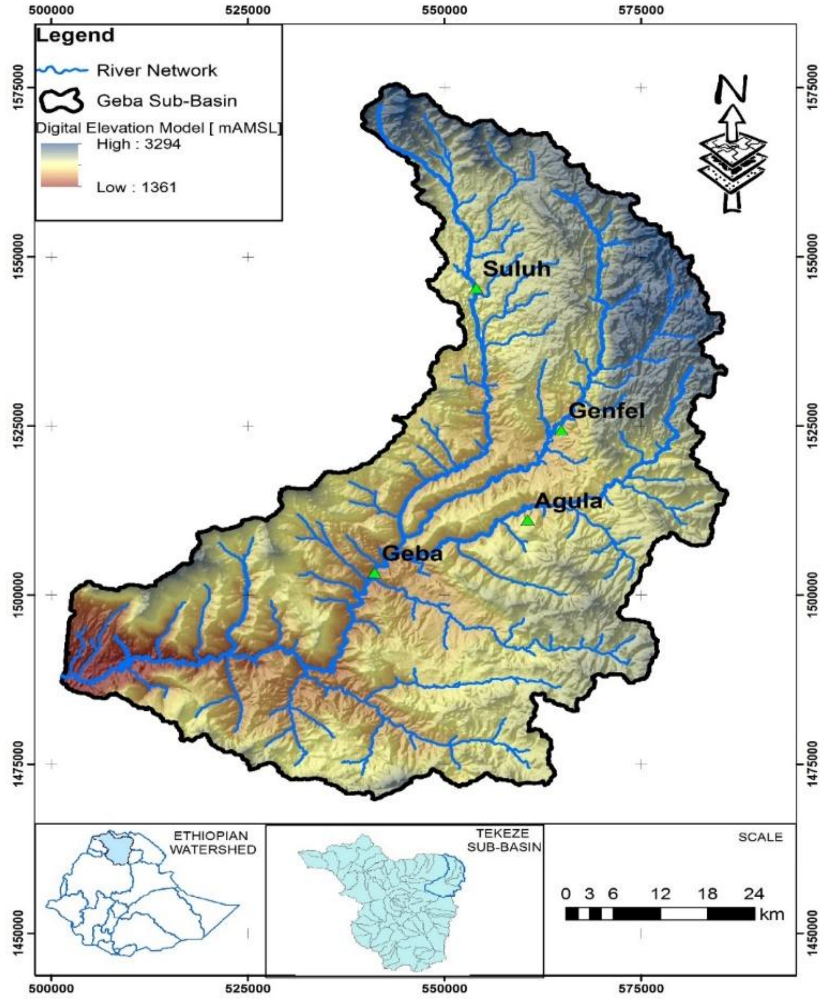


Figure 3.11: SRTM 30*30 DEM resolution Geba sub-catchment

3.2.4 Catchment delineation and selection of representative catchments

The result catchment delineation shows four gauged catchments are available. Even though in total there were seven gauged catchments, four gauged catchments were selected based on the availability of daily time series River flow data.

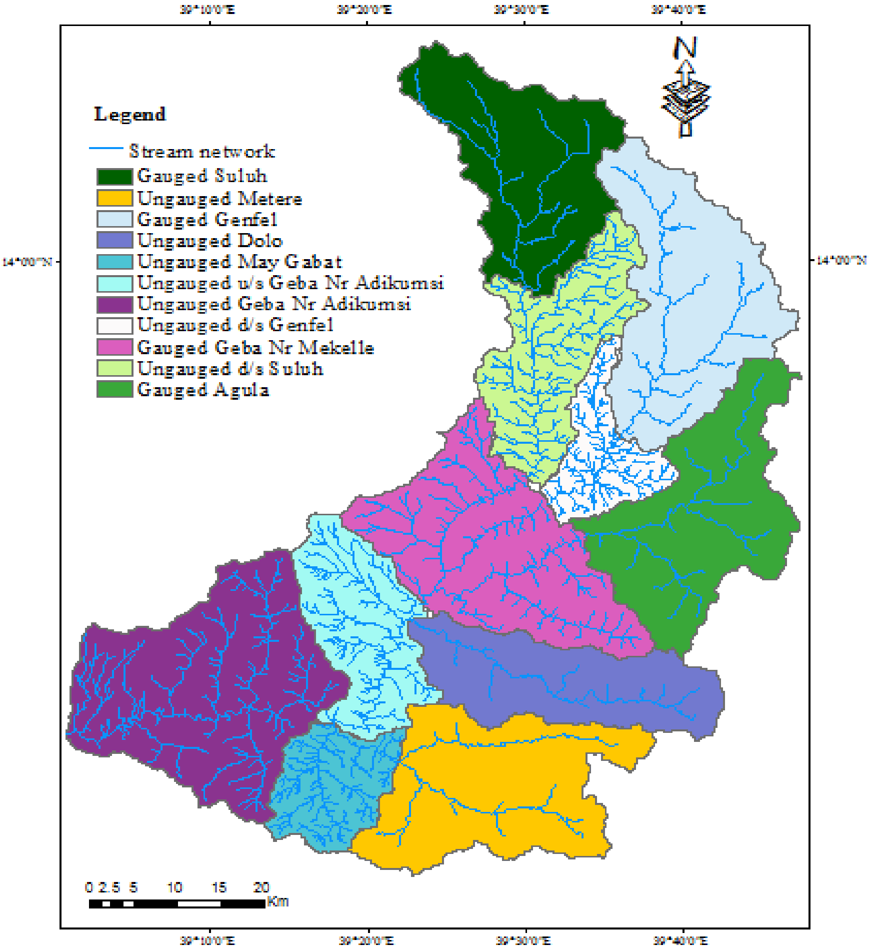


Figure 3.12: gauged and ungauged catchments of Geba sub-basin

Table 3.5: Major gauged and ungauged catchment delineated in Geba sub-basin.

Gauged catchments	Area (km^2)	Ungauged catchments	Area (km^2)
Geba nr Mekelle	525.95	D/s Suluh	324.18
Suluh	420.1	Geba nr Adikumsi	633.44
Agula	456.66	May Gabat	178
Genfel	497.62	Dolo	338.29
		Metere	462
		D/s Genfel	158.8
		U/s Geba nr Adikumsi	284

3.2.4.1 Selection of representative physical catchment characteristics

Runoff generation is governed by physical catchment characteristics (PCCs). In this study a SRTM 30 m*30 m resolution has been used to delineate catchment of the study area using SWAT and GIS software. Selected catchment characteristics were used to develop methods to estimate flow characteristics of ungauged catchments. A reasonable number of well gauged catchments with good quality data of climate, geography, physiographic, soil type, LULC and geology should be available to derive PCCs (Mazvimavi, 2003). However, prior to select of PCCs for regionalization, evaluation has to be done as there may be inter-dependency or inter-correlation between different PCCs. Therefore, a preliminary list of PCCs should be composed based on the available data and the physical meaning of the model parameters. Then, statistical analysis should be performed to identify the highly correlated PCCs. Table 3.6 shows selected PCCs used for this study.

Table 3.6: Selected Physical Catchments characteristics

Group	Parameters	Physical catchment characteristics	units
Geography and physiographic	Area	Catchment Area	Km^2
	LFP	Longest Flow Path	Km
	MDEM	DEM mean elevation	m
	HI	Hypsometric integral	%
	Av.slope	Average slope of catchment	-
	Bshape	Basin shape	-
	CI	Circularity index	-
	EL	Elongation ratio	-
	DD	Drainage density	m/Km^2
LULC	BL	Bare land	%
	Cultivated	Cultivated	%
	GL	Grass land	%
	Forest	Forest	%
	SL	Shrub land	%
	WL	Wood land	%
			%

Soil	LEP	Leptosols	%
	VER	Vertisols	%
	LUV	Luvisols	%
	CAB	Cambisol	%
	CAL	Calcisols	%
	ARE	Arenosol	%
Climate	SAAR	Standard annual average rainfall	mm
	MP wet	Mean precipitation wet season (June to September)	mm
	MP dry	Mean precipitation dry season (October to May)	mm
	PET	Mean annual evaporation	mm/day

Brief description of each group of the physical catchment characteristics is given below;

3.2.4.2 Geography and physiographic data

Catchment area: the area of each catchment is easily derived from the catchment size. The amount of water reaching the river from its catchment depends on the size of the area; it reflects the volume of water that can be generated from rainfall.

Longest flow path: the longest flow path is one of the outputs in catchment delineation processes. This indirectly an indication of time for water to reach the gauged station.

DEM mean: mean elevation is one of the frequently used PCCs obtained as an output processes of delineation of catchment using 30*30 resolution SRTM DEM. Mean elevation of each gauged and ungauged catchments were calculated to derive the regional equations.

Hypsometric integral: this catchment characteristics is generally described as the distribution of elevation throughout the catchment and simply calculated as;

$$HI = \frac{H_{mean} - H_{\min}}{H_{\max} - H_{\min}} \text{------------------------------------} 3.5$$

Where; H_{mean}=average altitude above sea level [m], H_{min}= minimum altitude above sea level [m] and H_{max}= is maximum altitude above sea level [m].

Average slope of the catchment: slope is one dominant factor that controls the water flow velocity where a high slope results a high velocity that reduce the travel time of water to reach the catchment outlet. It has been done by using Arc SWAT model.

Catchment shape: this catchment characteristic is commonly used as PCCs in regionalization studies. It is simply calculated as;

$$BShape = \frac{H_{\max} - H_{\min}}{\sqrt{A}} ------------------------------------ 3.6$$

Where**:** H_{max}= maximum altitude above sea level [m], H_{min}=minimum altitude above sea level [m] and A is area of the catchment [km^2].

When a high value is retrieved the catchment can be considered as a highly responsive catchment since a large difference between altitudes is present. Reversely, when a low value is retrieved, the catchment can be considered as a slow responding catchment.

Circularity index: the circularity index is calculated as the ratio of perimeter square to the catchment area. The equation is as follow;

$$CI = \frac{P^2}{A} ------------------------------------ 3.7$$

Where: P is perimeter of catchment [m] and A is area of catchment [m^2].

Elongation ratio: indicates how the slope of the basin deviates from a circle. It is an index to mark the shape of the drainage basin. It is defined as the ratio of length of longest drainage to diameter of a circle that has the same area as the basin.

$$EL = \frac{LL}{\sqrt{\frac{A}{\Pi} * 4}} ------------------------------------ 3.8$$

Where: LL and A are the length of longest length [m] and area [m^2] of the catchment respectively.

The circularity index and elongation ratio has important hydrological sequences because, in contrast to more circular catchments, precipitation delivered during a storm in highly elongated basins has to travel a wide range of distances to reach the basin outlet. The resulting delay in the arrival of a proportion of the storm flow consequently lead to a flattening of the storm hydrograph.

3.2.4.3 Land use land cover

In this study land use land cover map was collected from MoWIE, GIS department. It includes (Cultivate, Forest, Wood land, Grassland, shrub land and bare land). It is well known that deforestation causes changes in soil properties and infiltration rates, which ultimately affects the soil erosion processes and hydrological cycle of the catchment. The effect of changes in land use and plant cover are especially pronounced in mountain areas, since they are high-energy environments, which sediment transfer from the hill slopes to the channels is greatly facilitated.

3.2.4.4 Soil type

The soil map of the major soil groups of the catchment classified as per the FAO soil group was used for this study. This map was collected from MoWIE, GIS department.

3.2.4.5 Climate

Standard annual average rainfall: the most commonly used PCCs is the standard annual average rainfall (SAAR) with respect to the climate PCCs. For this characteristic the data are frequently available and calculated for each gauged and ungauged catchments annually.

Mean annual precipitation of wet and dry season: it is observed that there are two clear season for precipitation in the region, with high rainfall during June to September and low rainfall during October to May. Hence average daily rainfall in the wet and dry season was selected separately as climate PCCs. It was derived from meteorological data and calculated daily in each seasons for gauged and ungauged catchments.

Average annual evapotranspiration: the average annual evapotranspiration also has significant distributed over the catchment and varied from 1290 to 1965 mm/year. It was calculated annually for gauged and ungauged sub-catchments to determine mode parameters.

3.3 Methodology

3.3.1 Methods

The method followed to stream flow prediction for ungauged catchments in the study area was commenced by collection of data at secondary level. This research work makes use of a hydrological model and regionalization to simulate runoff from gauged and ungauged catchments of Geba sub-basins. The methods applied for this study include:

Review of previous studies in the Geba sub-basins, secondary data collection from institutions such as Ministry of Water Irrigation and Electricity, National Meteorological Agency, after collecting the necessary data for the research work, filling of missed data and quality controlling steps have been made. theissen polygon is drawn at different sub catchments to determine the areal model input data using Arc view GIS, Preparing DEM and delineating the catchment of the basin, preparing necessary input data in HBV-96 model format, Using both climate and river flow data, the hydrological processes in the Geba sub-basin shall be simulated. This is followed by model calibration and validation processes, finally, the relevant hydrological parameters were extracted from the validated model output to be used in the regionalization step.

The approach of regionalization is applied to estimate the flow of ungauged catchments. First, the HBV model is calibrated against the observed discharge to determine well performing parameter sets of gauged catchments. Next, a relationship is made between the model parameters (MPs) and physical catchment characteristics (PCCs) to be establish the regional model that serves to estimate model parameters for interest catchments. Then the HBV model is used to simulate the discharge for ungauged catchments.

3.3.2 Material Used

The materials used for this research are:-

Arc view GIS to obtain hydrological and physical parameters and information, SWAT model to delineate the sub-basins of the study area, HBV-96 model to simulate the different Sub-catchments, Microsoft excel spread sheet to undertake any statistical analysis in the course of the research.

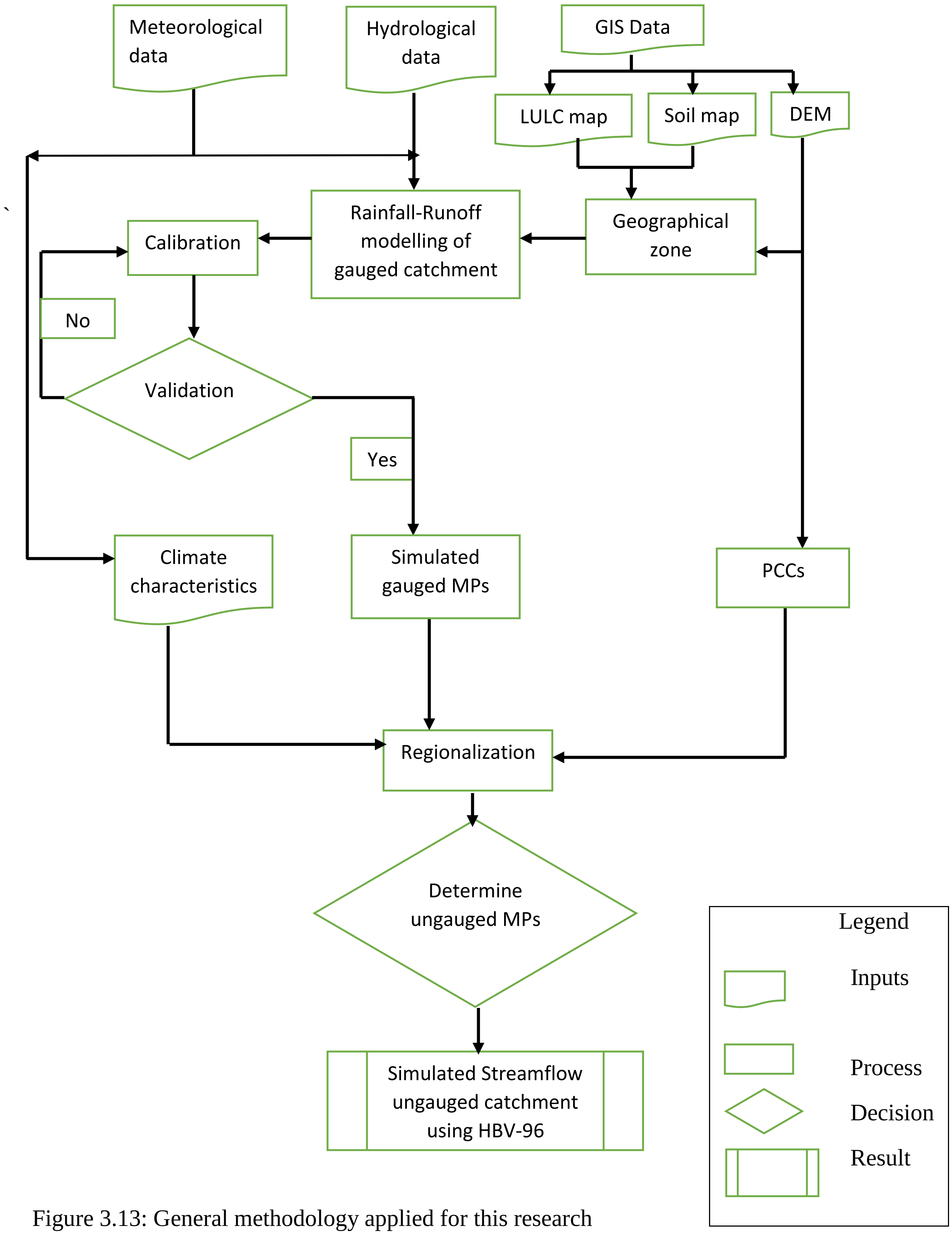


Figure 3.13: General methodology applied for this research

3.3.3 Model sensitivity analysis, calibration and validation

3.3.3.1 Model sensitivity analysis

The main idea of sensitivity analysis is to select the most effective model parameter for model calibration and validation. Sensitivity analysis will be applied manually by changing the value of one model parameter at a time (Aghakouchak *et al*, 2010).The effect of each model parameters will be analyzed based on objective functions (model performance) NSE and RVE visualization. Those model parameters having steep slope (having high variation between intervals in NSE and RVE) are considered as most sensitive while those having moderate to gentle slopes(having low variation between intervals in NSE and RVE) are considered as less sensitive.

3.3.3.2 Model calibration

Any hydrological model must be proven for its reliability, accuracy and predictive ability. At the initial run the model probably will not give satisfactory result as the input data do not reflect the real world with enough accuracy (Tesfaye, 2011). Some hydrological model requires adjustment of the model parameter values, hydrological influences and stresses in order to tune the model. The reliability of the model can be improved by calibration. The process of model calibration will be done either by manually or automatic calibration in order to identify the optimum model parameters set. In manual calibration, the user adjusts the parameters interactively in successive model simulations. As this approach mainly depends on the user's experience, only intelligent steps will be made through the parameter space that will be an advantage. Even if manual calibration is subjective; the parameter derived may be prone to be bias due to involvement of user's experience and the process is very time consuming and it does not have clear point at which the calibration process is completed. In this study, model calibration was performed manually by trial and error from 1998 to 2008 by changing one model parameter at a time until the model simulated stream flow match with observed stream flow.

In model calibration, the model parameters have to be adjusted until the observed natural system output and the simulation model output show an acceptable level of agreement. The goodness of fit is always evaluated through an objective function which is selected based on several criteria. These criteria should be selected properly to evaluate different aspects of the hydrograph. In this study the criteria that considered in selecting the objective function are as follows.

Relative Volume Error (RVE): It is define as variation between simulated and observed discharge as relative volume. This relative volume error can vary between ∞ and -∞ but performs best when a value of 0 is generated since no difference between simulated and observed discharge occurs. The relative volume error between +5% and -5% indicates that the model performed well while relative volume error between +5% and 10% or between -5% and 10% indicated that the model performs reasonably (Tamalew, 2015).

$$RVE = \left(\frac{\sum_{i=1}^{n} QSim,i - \sum_{i=1}^{n} Qobs,i}{\sum_{i=1}^{n} Qobs,i} \right) * 100 ----------------------------3.9$$

Where: RVE= average daily error between the predicted and observed flow (%), Qsimi =the simulated flow, Qobsi= the observed flow, i= the time step and n is the total number of time steps used during calibration.

Nash-Sutcliffe efficiency: The Nash-Sutcliffe efficiency (NSE) is used to evaluate the overall agreement of the shape of the simulated and observed hydrograph. NSE measures the efficiency of the model by relating the goodness of fit of the simulated data to the variance of the measured data. NSE can be defined according to the following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Qobs,i - Qsim,i)^2}{\sum_{i=1}^{n} \left(Qobs,i - \overline{Qobs}\right)^2} ---------------------------3.10$$

Where: NSE= the Nash-Sutcliffe coefficient, Qobsi= observed discharge, Qsimi=simulated discharge and $\overline{Qobs}$ is the observed average values. This objective function can vary between 1 and -∞ and performs best when a value of 1 is generated. Besides, due to frequent use of this objective function, it is known that when values between 0.60 and 0.80 are generated, the model performs reasonably well. Values between 0.80 and 0.90 indicate that the model performs very well and values between 0.90 and 1 indicate that the model performs extremely well (Deckers, 2006).

Correlation coefficient (coefficient of determination): i.e., r2, describes the proportion of the total variance in the observed data that can be explained by the model. It ranges from 0.0 (poor model) to 1.0 (perfect model) and is given by:

$$r^2 = \frac{\left[\sum_{i=1}^{n}\left(Qsim,i - \overline{Qsim}\right)\left(Qobs,i - \overline{Qobs}\right)\right]^2}{\sum_{i=1}^{n}\left(Qsim,i - \overline{Qsim}\right)^2 \sum_{i=1}^{n}\left(Qobs,i - \overline{Qobs}\right)^2} ----------------------3.11$$

Qsimi is the simulated value, Qobsi is the measured values, $\overline{\text{Qsim}}$ is the average simulated value and $\overline{\text{Qobs}}$ is the average measured value

3.3.3.3 Model validation

Calibrated model parameters can result in simulations that satisfy goodness-of fit criteria, but parameter values may not have any hydrological meaning. Values of model parameters will be a result of curve fitting. This is also reflected in having different sets of parameters values producing simulations which satisfy these criteria. It is necessary to test if parameter values reflect the underlying hydrological processes, and are not a result of curve fitting. Therefore, to conduct appropriate model validation results, it is necessary to carry out split sample test. Model validation in Geba sub-basin was carried out for six years (2009-2014) for testing of calibrated model results with independent data set without any further adjustment at different spatial and temporal scales. The split-sample test involves splitting the available time series into two parts. One part is used to calibrate the model, and the second part is used for testing (validating) if calibrated parameters can produce simulations which satisfy goodness-of-fit tests (Tesfaye, 2011).

3.3.4 Regionalization

All rainfall-runoff models currently in use merely are approximations of real world hydrological processes taking place at the catchment scale and none of them are able to completely describe these actual processes, which is also the case for the HBV model. However, in order to simulate the rainfall-runoff transformation processes, values for HBV model parameters have to be defined in some way. Since for the HBV model it is not possible to directly determine the model parameter values, these values are normally estimated through a model calibration process by trying to fit the model output with observed discharge data (Hundecha, 2004). However, not at every catchment well observed discharge data are available. Calibration of the model is therefore difficult and prediction of discharge regimes must be associated with some degree of uncertainty. Regionalization technique could be applied to reduce the parameter uncertainty in predicting discharge regimes in ungauged catchments. Several definitions of regionalization are used in the literature, but a generic definition as stated in (Bloschl *et al*, 1995) is used most often. Regionalization is the process of transferring information from comparable catchments to the catchment of interest.

The four regionalization methods that are used to predict discharge from ungauged catchments are described as follows;

Similarity of spatial proximity: Parameters of gauged catchments are transferred to the nearby ungauged catchment based on the assumption that catchments which are close to each other likely have a similar runoff regime since climate and catchment conditions often only vary smoothly in space. So the assumptions is made that catchments are highly comparable with respect to topographic and climatic properties. (Merz and Bloschl, 2004).

Area ratio method: Parameter set of gauged catchments are transferred to ungauged catchments of comparable area based on the assumption that catchment area was the dominant factor for controlling the volume of water that can be generated from the rainfall (Perera, 2009).

Sub-basin mean method: It represents the arithmetic mean of calibrated model parameters of gauged catchments to simulate the stream flow for ungauged catchments (Kim and Kalaurachchi, 2008).

Regional model: The regional model developed for gauged catchments is used to estimate model parameters of ungauged catchments link by respective PCCs and MPs (Kim and Kalaurachchi, 2008).

3.3.5 Model parameters selection

In order to determine the regional model, first model parameters have to be identified by calibrating the model against the observed discharge. The major causes of difficulty in identification of model parameters are over parameterization and selection of parameters in the calibration. With respect to the HBV model, several modification have been made to the model structure to reduce the amount of parameters (Lindström *et al*, 1997), even though (Merz and Bloschl, 2004) mentioned reduction of over-parameterization is a critical issue. However, many studies assess and conclude the HBV model is parsimonious enough. To establish relationship between PCCs all the parameters should not be used even though HBV model has more than 30 parameters. Such behavior will induce extra effort in establishing statistical relationship. Therefore, it is important to determine the most sensitive model parameters to be considered the processes of regionalization. In the HBV model structure these process are conceptualize by appointing appropriate model routines such as soil moisture routine which comprises the Horton overland flow and saturation overland flow, the quick runoff routine which comprises macro pore flow and perched subsurface flow and the base flow routing which comprises the unsaturated subsurface flow and groundwater flow.

All parameters pertaining in the model routine do not affect to the same degree the rainfall-runoff transformation processes. Therefore, most sensitive parameters have to be identified in model calibration and subsequently in regionalization. A number of studies used the HBV model approach and most experience was gained in demonstrating the most sensitive parameters.

Table 3.7: Selected model parameters and their priory range (SMHI, 2006) manual version 5.1.

Name	Description and units	Prior range	Default value
FC	Maximum soil moisture content [L]	100-1500	Use a value for a region
BETA	Parameter in soil routine [-]	1-4	1
LP	Limit for potential evapotranspiration [LT^{-1}]	< = 1	1
ALFA	Response box parameter [-]	0.5-1.1	0.9
K_4	Recession coefficient lower zone [T^{-1}]	0.001-0.1	0.01
Khq	Recession coefficient upper zone [T^{-1}]	0.005-0.2	0.09
PERC	Percolation from upper to lower [LT^{-1}]	0.01-6	0.5
CFLUX	Maximum value of capillary flow [LT^{-1}]	0-2	0.5

3.3.6 Establishing the regional model

In order to set up a regional model to predict the model parameters in ungauged catchments, a statistically significant relationship established between PCCs and calibrated MPs by using excel in data analysis. After determining the MPs through model calibration and selection of physical catchment characteristics, a method for establishing the relationship will be applied (Perera, 2009). With respect to regionalization two type of regression methods were applied.

A. Simple regression method

The relation between MP and PCCs will be determined based on a simple linear regression. This regression tries to fit two variables, one dependent and one independent variables. Most of the time, linear regression is expressed by correlation coefficient (Perera, 2009).

$Y' = \beta 0 + \beta 1 X 1$---3.12

B. Multiple regression method

It is used to select the independent variables (PCCs), which can efficiently determine the dependent variables (MPs). Dependent variables are whose value are to be determined while independent variables are those having fixed value or already determined. To select the best independent variables, stepwise multiple regression was used in excel data analysis, while to establish the regression equation, each independent variables should not be correlated ($r^2= 0$). The PCCs co linearity have been tested using coefficient of determination ($r^2 \geq 0.95$) and significance or p-values (≤ 0.05 for 95% confidence interval). Hence, the independent variables are forced to the model till the r^2 approaches to 1. The general regression equation is described as follows:

$Y' = \beta 0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$--3.13

Where: β_1, β_2, βn are regression coefficient, X_1, $X_2 \ldots Xn$, is independent variable (physical

Catchment characteristics), Y' is dependent variable (model parameters) and β_o is intercepting of Regression line. In statistical methods, the order in which the independent variables are entered into (or out of) the model is determined according to the strength of their correlation with the dependent variable. In multiple regression analysis, forward selection and backward elimination methods are available (Perera, 2009).

Forward selection: Starts with the predictor variable having the highest correlation with the criterion variable and continues adding variables so that the determination coefficient (R^2) is maximized at each step. A test of hypothesis is performed at each step and computation ends when all statistically significant predictor variables have been included (Richard, 1989).

Backward elimination: A second form of stepwise regression begins with an equation that includes all of the predictor variables in the analysis and sequentially deletes variables, with the predictor variable contributing the least explained variance being deleted first. This procedure is then repeated until only useful predictor variables remain in the model (Ibid).

A problem in this study was a limited number of available gauged catchments. In principle increasing the number of catchment will increase the reliability and the efficiency of the regional model (Tesfaye, 2011). In this study, gauged catchments with RVE in between +10% and -10% and NSE value greater than 0.67 and PCCs of gauged catchments were used to establish the regional model.

3.3.7 Estimation of PMs and estimation stream flow in ungauged catchments

After determining simple linear relationships between MPs and PCCs and optimizing by multiple regression analysis for several PCCs, plausibility from hydrological point of view and significance from statistical point of view are discussed. The objective is to only select relationships that are acceptable and statistically significant. The ensemble of selected relations makes up the so called regional model by which HBV-96 model parameter values for ungauged catchments are defined. The model parameters estimated by four regionalization methods in gauged catchments (Agula, Geba nr Mekelle, Genfel and Suluh) were transferred to ungauged catchments. At last, the model parameters estimated by the area ratio, regional model, sub-basin mean and spatial proximity regionalization methods in ungauged catchments were used to simulate stream flow for ungauged catchments by using daily rainfall, monthly evapotranspiration, daily mean temperature, geographical zones, elevation of station and outlet point of ungauged catchments as input data for HBV-96 model.

4. Result and Discussions

4.1 Modeling of gauged catchments

4.1.1 HBV-96 model input

Long-term average monthly potential evapotranspiration: Daily potential evapotranspiration was calculated based on seven meteorological stations (Mekelle airport, Wukuro, H/selam, Adigrat, Hawezen, Atsibi, and Adigudem) from 1998 to 2014 using Penman Monthie and Hargreaves equation located Geba sub-basin. The daily evapotranspiration is converted to long-term average monthly. As shown (Figure 4.1) potential evapotranspiration decrease on summer while increasing in dry season. The evapotranspiration of Atsibi station is smaller than Wukuro station. Because the elevation of Atsibi station (2729m) is greater than Wukuro (1987m) mean above sea level. This result indicates that evapotranspiration and elevation are inversely proportional.

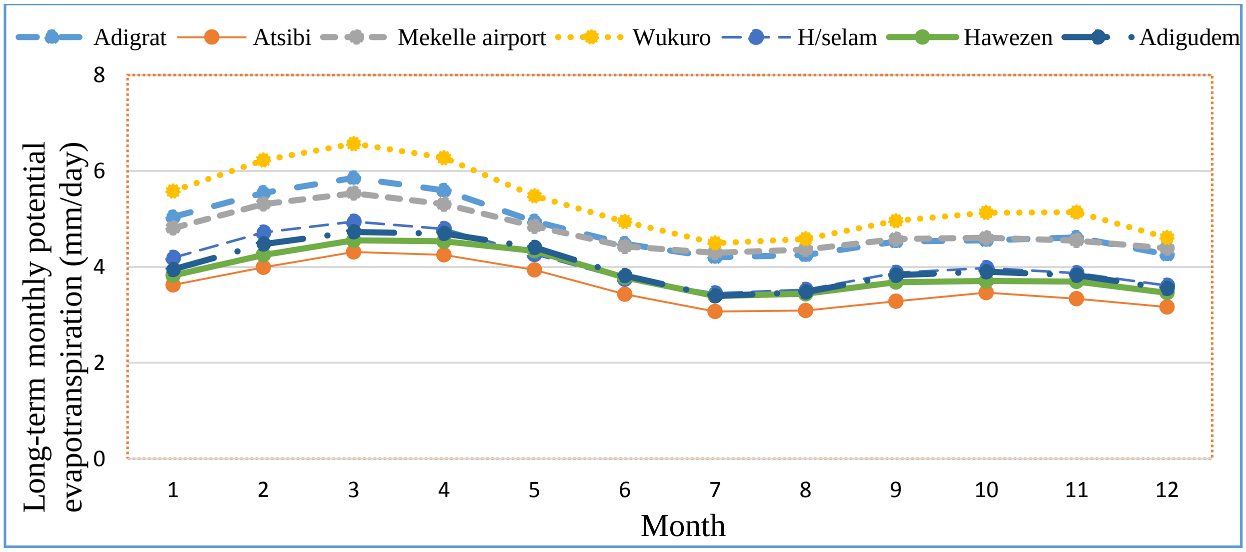


Figure 4.1: Long-term monthly average potential evapotranspiration (mm/day)

Rainfall: There are seven rainfall stations of which four of them are found inside the catchment and three of them are outside the catchment (see Figure 3.6) which is used to estimate areal rainfall station weights for gauged and ungauged catchments (Table 4.1 and Table 4.2) respectively in Geba sub-basin.

Table 4.1: Weights of rainfall stations for gauged catchments

	Rainfall stations						
Gauged catchments	Adigrat	Mekelle airport	Hawezen	H/selam	Wukuro	Atsibi	Adigudem
Agula					0.30	0.70	
Genfel	0.13		0.003			0.87	
Suluh	0.77		0.23				
Geba Nr.Mekelle		0.004	0.04		0.96		

Table 4.2: Weights of rainfall stations for ungauged catchments

	Rainfall stations						
Ungauged catchments	Adigrat	Mekelle airport	Hawezen	H/selam	Wukuro	Atsibi	Adigudem
D/s Suluh			0.66		0.21	0.13	
Geba nr Adikumsi				1			
Metere		0.97					0.03
D/s Genfel					0.48	0.52	
Dolo		0.83			0.17		
U/s GebanrAdikumsi		0.31		0.30	0.38		
May Gabat		0.89		0.11			

4.2 Model sensitivity analysis, calibration and validation

4.2.1 Sensitive analysis of model parameters

The sensitivity analysis of model parameters was performed based on the NSE and RVE using graphical plots for visualization in Agula, Genfel, Geba near Mekelle and Suluh sub-catchments. As a result shown in (Figure 4.2 and Appendix C) NSE value is tolerable within the range for the first 20% increment and decrement. The most sensitive model parameters are runoff coefficient (Beta), recession coefficient for upper zone reservoir (Khq), limit for potential evapotranspiration (LP) and field capacity (FC) while a measure for the nonlinearity of the reservoir (Alfa), capillary rise coefficient (Cflux), percolation (Perc) and recession coefficient (K4) are relatively less sensitive (see Figure 4.2). Similarly (Gebeyehu, 2013) found Beta, FC, LP and Perc as the most sensitive model parameters in Upper and middle Awash River Basin, Ethiopia and also (Perera, 2009) found FC, Beta and LP as sensitive model parameters in Tana sub-basin, Ethiopia. Such similarity in parameters dictate that the basins are dominated by surface flow than the groundwater.

As shown in equation 2.5 (in literature review), as Beta increases the soil moisture increases and the reverse is true in simulated stream flow volume. As clearly shown (Figure 4.2) when Beta value decrease from 60% to -60% the RVE becomes more positive. Hence, the peak flow is well represented with low value of Beta and the base flow will be less since much runoff is generated and less water will be stored during rainy seasons.

Field capacity (FC) has an effect on partitioning precipitation into soil moisture and runoff. When FC increased the soil storage will increases, hence the amount of water available for quick runoff generation is decreased. Figure 4.2 shows as field capacity increase the RVE become more negative showing that the volume of simulated runoff is decreasing but when it decreases RVE become more positive showing the volume of simulated runoff is increasing.

As LP increase the amount of water depleted as evaporation decreases and the volume of simulated stream flow will increases. This effect is clearly showing in (Figure 4.2) that shows as LP increase the RVE become increase (positive) and vice versa, showing that they are directly proportional to each other and has positive impact on simulated stream flow volume.

The recession coefficient for lower reservoir (K4) control the recession during low flow from the lower reservoir zone where as recession coefficient for upper zone reservoir (Khq) control the recession during peak flow from the upper reservoir zone with Alfa. RVE increase as Khq increase whereas no significance change when K4 and Alfa increases which indicates that less sensitive.

Perc and Cflux shows the percolation to lower zone reservoir and capillary rise coefficient from lower zone reservoir respectively. Perc will result in an increase in delayed runoff and decrease the peak flows, since it controls the flow from the upper zone reservoir to the lower zone reservoir storage. Figure 4.2 shows sensitivity analysis of Genfel sub-catchment using NSE and RVE graph and the remaining were attached in Appendix C.

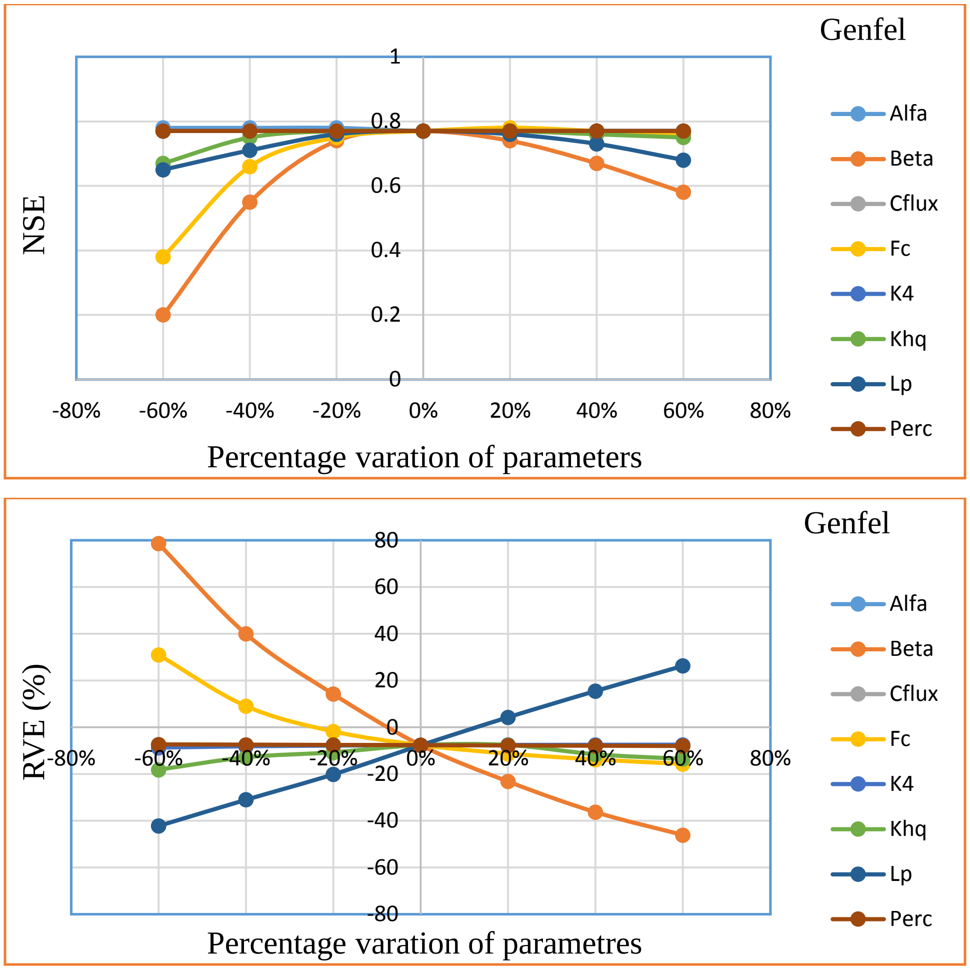


Figure 4.2: Sensitivity analysis results of Genfel

4.2.2 Results of HBV model calibration

In order to select an optimum parameter set, in this study manual calibration method was used. To evaluate the model performance visual inspection of hydrograph fits between the observed and the simulated stream flow with combination of the objective functions NSE and RVE are used and helps to assess whether the simulated and observed hydrographs fits well or not. From model calibration results shown in Table 4.3, the model performance of Agula, Geba near Mekelle, Suluh, and Genfel are satisfactory with NSE greater than 0.67 and RVE lies between +10% and -10%.

Table 4.3: Prior MP range and optimized MPs result

Prior model parameter range		Optimized model parameters			
MPs	Prior range	Agula	Geba nr Mekelle	Suluh	Genfel
Fc	100-1500	1500	1400	900	1500
BETA	1-4	1.81	1.14	1.4	1.23
LP	< =1	0.76	1	0.67	0.55
ALFA	0.5-1.1	1.1	0.51	0.5	0.54
K4	0.001-0.1	0.079	0.04	0.06	0.001
Khq	0.005-0.2	0.09	0.026	0.07	0.12
PERC	0.01-6	2.67	3.7	3.4	0.05
CFLUX	0-2	0.015	0.002	0.005	0.002
NSE		0.67	0.77	0.78	0.77
RVE (%)		9.78	-6.46	2.32	-7.66

Note: The prior model parameters range were taken from (SMHI, 2006) manual version 5.1 Accepted four sub-catchments daily observed and simulated flow hydrographs and scatter plot of Geba nr Mekelle catchment calibration 1998-2008 was presented in (Figure 4.3 and Figure 4.4) respectively and the remaining were attached in Appendix D.

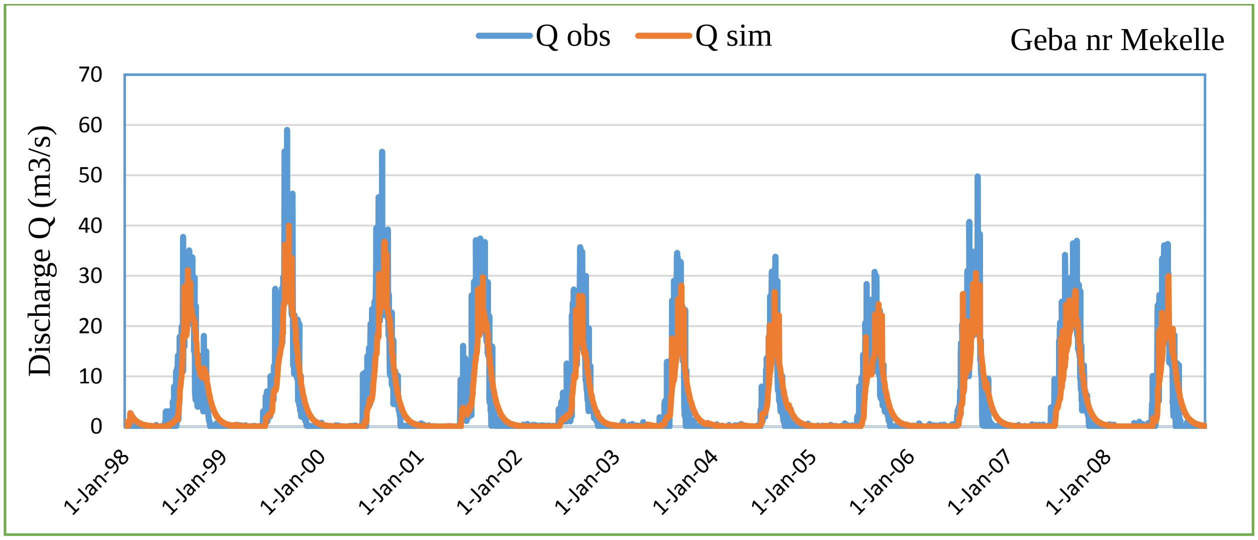


Figure 4.3: Graphical comparison of observed and simulated flow for calibration period

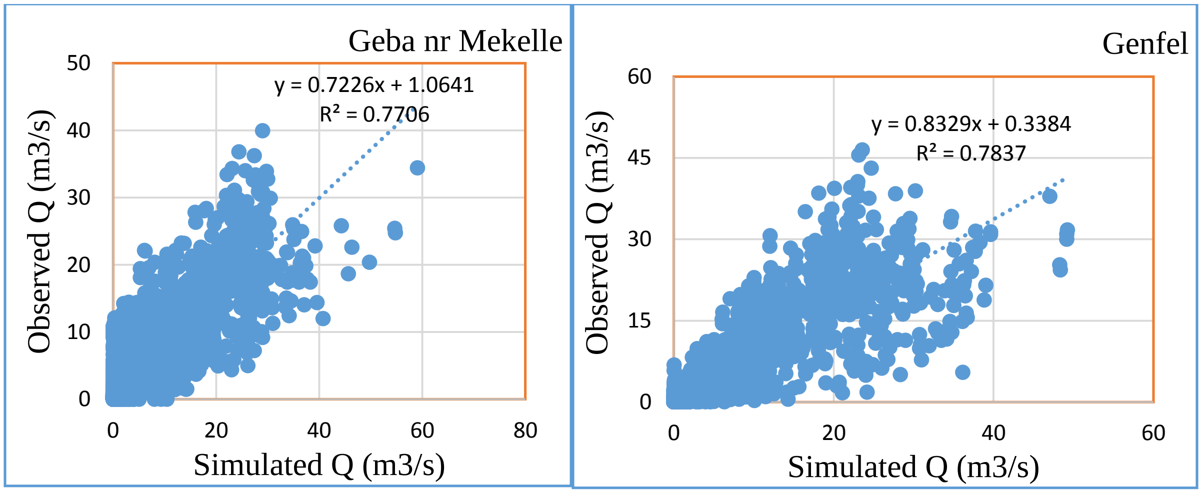


Figure 4.4: Scatter plot comparison of observed and simulated flow during calibration period

4.2.3 Model validation

If the calibration model parameter sets fail on the validation period the model is regarded unreliable and so not usable. The model must be recalibrated with a new set of model parameters followed by model valuation until it satisfies calibration targets in terms of objective function value. But, in this study the results show the model validation done for each catchment satisfy the objective function values of calibration period.

Table 4.4: Validation model parameter results of gauged catchments from (2009-2014).

Gauged Catchments	Optimized model parameters								Objective Functions	
	Fc	Beta	LP	Alfa	K_4	Khq	Perc	Cflux	NSE	RVE (%)
Agula	1500	1.81	0.76	1.1	0.079	0.09	2.67	0.015	0.83	-9.1
Geba nr Mekelle	1400	1.14	1	0.51	0.04	0.026	3.7	0.003	0.86	-8.21
Suluh	900	1.4	0.67	0.51	0.06	0.07	3.4	0.005	0.74	-9.44
Genfel	1500	1.23	0.55	0.54	0.001	0.12	0.05	0.002	0.78	-0.47

As shown (Table 4.4) the NSE performance of model validation of Agula, Geba near Mekelle, Genfel are increase their performance and decrease for Suluh catchment as compared to calibration result. The overall model validation shows good performance since NSE is greater than 0.74 and RVE lies between 10% and -10% (Table 4.4). The calibration and validated stream flow results showed a good agreement to the simulated and observed data since, the NSE greater than 0.74

which is well performance and RVE less than 10% or -10% for all of the catchments (see Figure 4.3 and 4.5). Therefore, these results of estimated stream flows indicate the HBV-96 model is good predictor of stream flow in Geba sub-basin. As shown in (Table 4.3 and 4.4) catchments that satisfy the objective functions for calibration also have good performance for validation test.

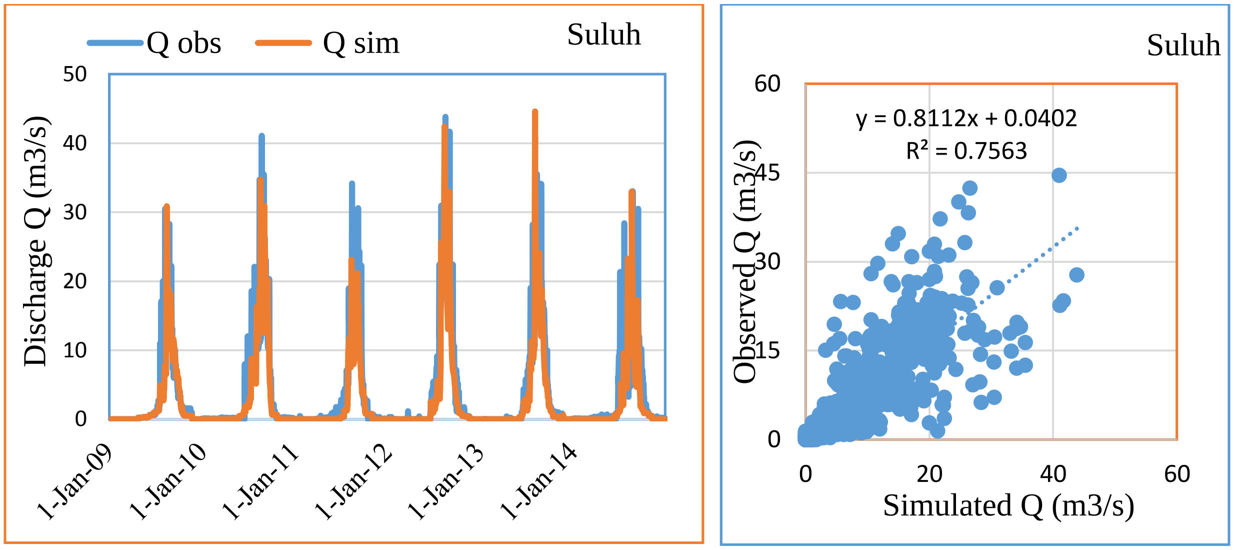


Figure 4.6: Graphical and Scatter plot comparison of observed and simulated flow during validation period

4.3 Result of regionalization

4.3.1 Catchment selection criteria for regionalization

Obviously, using larger number of catchments increase the reliability and efficiency of the regional model. Based on the results of calibration (Table 4.3) Agula, Geba near Mekelle, Suluh and Genfel catchments are selected for regionalization since the objective function of RVE between +10% or -10% and the NSE value greater than 0.67. Therefore, these catchments MPs were used for regionalization.

4.3.2 Relation of catchment characteristics and model parameters

The knowledge of the relation between HBV model parameters and PCCs allows us to understand and perhaps quantitatively predict how a change in physical properties of a catchment will affect its hydrological response. The optimized MPs (Table 4.3) and PCCs (Appendix F) of gauged catchments were used to determine the correlations. The corresponding correlation is statistically significant and the results are shown in (Table 4.5) in bold.

Table 4.5: Correlation value between MPs and PCCs for four selected catchments.

PCCs	FC	Beta	LP	Alfa	K_4	Khq	Perc	Cflux
MDEM	-0.17	-0.71	-0.59	-0.78	-0.87	0.39	-0.63	-0.79
Area	-0.30	0.85	0.18	0.69	**0.98**	-0.16	0.61	0.85
Ave.slope	-0.17	-0.42	-0.83	-0.55	-0.75	0.66	-0.75	-0.54
LFP	-0.25	-0.93	-0.18	-0.96	-0.82	-0.05	-0.30	**-0.98**
HI	-0.33	-0.67	0.74	-0.64	-0.05	-0.91	0.65	-0.61
DD	0.36	0.95	0.02	0.99	0.69	0.27	0.07	0.98
CI	-0.02	-0.84	0.66	-0.69	-0.38	-0.75	0.33	-0.76
ER	-0.15	**-0.94**	-0.20	-0.93	-0.87	0.05	-0.37	-0.97
Bshape	-0.12	-0.45	**-0.81**	-0.56	-0.79	0.65	-0.78	-0.56
Leptosols	0.05	0.82	0.14	0.90	**0.90**	0.02	0.38	0.98
Vertisols	0.47	-0.78	0.50	-0.49	-0.63	-0.41	-0.09	-0.68
Luvisols	**-0.89**	-0.34	0.31	-0.59	0.25	-0.66	0.71	-0.37
Cambisols	0.46	-0.52	-0.53	-0.38	-0.95	0.59	**-0.91**	-0.55
Calcisols	0.35	0.81	0.41	0.91	0.79	-0.14	0.40	**0.98**
Arenosols	0.38	-0.44	-0.65	-0.35	-0.91	0.69	-0.91	-0.49
Shrubland	-0.27	-0.28	0.92	-0.23	0.37	**-0.99**	**0.94**	-0.19
Cultivatin	-0.24	**-0.83**	-0.40	-0.89	-0.86	0.18	-0.47	-0.90
G.land	0.37	0.80	0.03	**0.99**	0.68	0.27	0.07	0.98
B.land	0.52	0.81	-0.26	0.95	0.40	0.56	-0.28	0.88
Forest	**-0.84**	-0.49	0.62	-0.59	0.18	-0.88	0.79	-0.46
W.land	0.22	-0.54	0.90	-0.30	-0.09	-0.84	0.49	-0.41
SAAR	0.01	-0.32	0.98	-0.17	0.25	-0.97	0.77	-0.20
MP dry	-0.31	-0.39	-0.84	-0.57	-0.66	0.62	-0.66	-0.52
MP wet	0.10	-0.02	**0.99**	0.14	0.48	-0.89	0.81	0.12
PET	0.81	-0.01	-0.32	0.26	-0.57	0.62	-0.83	0.02

4.3.3 Multiple linear regression

A set of generalized equation can be developed from watershed characteristics and their Rainfall-runoff model parameters for the construction of regional equations. The use of multiple PCCs will give better relation than the use of only one. The multiple linear regressions applied to establish regional model using optimized MPs and PCCs of gauged catchments in Microsoft EXEL, data analysis in stepwise regression method, entering one model parameter and all expected PCCs one by one. Therefore, relations between PCCs and MPs were assessed through multiple linear regression analysis. Depending up on the R^2 (≥ 0.99) and significance of p-value (≤ 0.05 for 95% confidence interval) the PCCs were selected to establish the regression equations. Each model parameters in relation with regression analysis is shown and discussed below.

Filled capacity (FC): It describes the maximum water holding capacity of the soil. The value of FC can be estimated based on soil type and the routing depth of the predominant vegetation and can further be refined in the calibration process (Hundecha and Bárdossy, 2004). In this study FC showed significance negative correlation with Luvisols and Forest and positive correlation with PET. The forward entry method was executed with Luvisols as the initial variable and the strength of relation improves 0.99 after adding Forest PCCs. Hence, the regression equation was established below.

Table 4.6: Statistical characteristics for the regression equation FC

$FC=\beta_0 + \beta_1 * Luvisols + \beta_2 * Forest$

Coefficient					95% confidence interval		Co-
		Std			Lower	Upper	Linearity
	β	Error	t-state	P-value	Bound	Bound	R^2
β_0	1484.500	3.854	436.982	0.001	1635.519	1733.480	0.999
β_1	258.625	4.885	52.941	0.012	196.553	320.697	
β_2	-43.694	0.499	-87.536	0.007	-50.036	-37.351	

BETA: The multiple regression showed that the empirical coefficient model parameter BETA has significant relation with Cultivation and taken as initial variable value for executing forward entry method. After adding Elongation ratio (ER) catchment characteristics R^2 increased to 0.99 and P-value is obtained as below and no another PCCs performs better than this. Hence, the co-linearity found here are feasible and the regression equation is developed as below.

Table 4.7: Statistical characteristics for the regression equation Beta

$Beta=\beta_0 + \beta_1 * ER + \beta_2 * Cultivation$

Coefficient	β	Std Error	t-state	P-value	95% confidence interval Lower Bound	95% confidence interval Upper Bound	Co-Linearity R^2
β_0	2.229	0.083	26.604	0.023	1.164	3.293	0.991
β_1	-3.764	0.640	-5.871	0.033	-11.908	4.380	
β_2	0.025	0.006	3.679	0.053	-0.061	0.111	

LP: It is the minimum moisture at which the full potential evaporation takes place from the soil water. At a soil moisture below LP, the actual evaporation reduces linearly to zero until the soil drains completely. In multiple regressions, LP has high co-linearity with MP wet and Basin shape with R^2 of 0.99 and P-value is as below. Thus regression equation was established using these two variables as below.

Table 4.8: Statistical characteristics for the regression equation LP

$LP=\beta_0 + \beta_1 * MP\ wet + \beta_2 * B.shape$

Coefficient	β	Std Error	t-state	P-value	95% confidence interval Lower Bound	95% confidence interval Upper Bound	Co-Linearity R^2
β_0	-1.398	0.185	-7.553	0.053	-3.751	0.954	0.998
β_1	0.470	0.027	17.440	0.036	0.127	0.812	
β_2	0.008	0.002	4.232	0.047	-0.016	0.032	

ALFA: In the response routine of HBV model, it is the measure of the non-linearity in the upper reservoir. In this study, ALFA has significant relation with Gras land catchment characteristics with R^2 of 0.992. The forward entry method was executed with Gras land as the initial variable. Therefore, this regression equation is accepted and the statistical characteristics are shown as below.

Table 4.9: Statistical characteristics for the regression equation ALFA

$Alfa=\beta_0 + \beta_1 * G.land$

Coefficient			95% confidence interval				Co-Linearity R^2
	β	Std Error	t-state	P-value	Lower Bound	Upper Bound	
β_0	0.277	0.028	9.831	0.01	0.156	0.398	0.992
β_1	0.016	0.001	16.307	0.003	0.012	0.020	

K_4: The regression equation showed that K_4 has high co-linearity with Leptosols and area with R^2 of 0.99 and P-value less than ≤ 0.05.The forward entry method was executed with Leptosols and area variables. But no PCCs can improve the co-linearity. So, the regression equation was developed using those variables as below.

Table 4.10: Statistical characteristics for the regression equation K4

$K4=\beta_0 + \beta_1 * Leptosols+ \beta_2 * Area$

Coefficient			95% confidence interval				Co-Linearity R^2
	β	Std Error	t-stat	P-value	Lower Bound	Upper Bound	
β_0	-0.197	0.025	-7.867	0.050	-0.517	0.121	0.998
β_1	0.001	5.040	10.399	0.051	0.000	0.001	
β_2	-0.002	0.000	-4.334	0.044	-0.007	0.003	

Khq: In this study Khq has significant relation with Shrub land catchment characteristics with statically strong relation of R^2 of 0.99 and by using this PCCs the Statistical was developed as below.

Table 4.11: Statistical characteristics for the regression equation Khq

$Khq=\beta_0 + \beta_1 * S.land$

Coefficient			95% confidence interval				Co-Linearity R^2
	β	Std Error	t-state	P-value	Lower Bound	Upper Bound	
β_0	0.215	0.004	48.547	0.000	0.196	0.234	0.998
β_1	-0.001	0.000	-32.233	0.000	-0.006	-0.004	

Percolation (Perc): In general, the water movement in soil governed by soil texture. The regression result also shows that Perco is best co-linearity with Cambisols and Shrub land with R^2 of 0.99. Therefore, the multiple regression result is accepted and its regression was developed below.

Table 4.12: Statistical characteristics for the regression equation Perc

$Perc=\beta_0 + \beta_1 * Cambisols + \beta_2 * S.land$

Coefficient					95% confidence interval		Co-Linearity
	β	Std Error	t-state	P-value	Lower Bound	Upper Bound	R^2
β_0	1.345	0.945	1.423	0.038	-10.670	13.362	0.992
β_1	0.127	0.026	4.790	0.013	-0.211	0.467	
β_2	-0.085	0.016	-5.191	0.012	-0.294	0.123	

Capillary Rise Coefficient (Cflux): It is a model parameter which used to correct water rise in the form of capillary through of water on soil matrix. In this study Cflux has significant correlation with Calcisols and LFP with R^2 of 0.99. Therefore, the multiple regression result is accepted and statistical characteristics are shown below.

Table 4.13: Statistical characteristics for the regression equation Cflux

$Cflux=\beta_0 + \beta_1 * Calcisols + \beta_2 * LFP$

Coefficient					95% confidence interval		Co-Linearity
	β	Std Error	t-state	P-value	Lower Bound	Upper Bound	R^2
β_0	0.045	0.002	16.053	0.039	0.009	0.081	0.999
β_1	-0.001	6.778	-7.348	0.053	-0.001	0.000	
β_2	-0.003	0.000	-15.755	0.040	-0.004	-0.001	

4.4 Determining Model Parameters and discharge for ungauged catchments

4.4.1 Determination of MPs for ungauged catchments

A total of seven ungauged catchments of the Geba sub-basin have been selected for detailed analysis in this study. Four regionalization methods were used to determine their parameters as depicted in the following subsequent sections. .

Regional model method: Each model parameters estimated by regional model derived using the equation of (Table 4.6-4.13). Table 4.14 shows the model parameters estimated by regional model.

Table 4.14: Model parameters estimated for ungauged catchments using regional model

Ungauged Catchments	Beta	LP	Alfa	K_4	Khq	Perc	FC	Cflux
Dolo	2.071	0.92	0.851	0.005	0.210	5.088	1484.5	0.068
Downstream of Genfel	2.295	1	0.850	0.048	0.230	3.045	1171.94	0.069
Downstream of Suluh	1.488	0.92	0.735	0.034	0.221	3.674	246.18	0.071
Geba nr Adikumsi	1.385	1	1.114	0.121	0.223	4.590	1423.33	0.079
May Gabat	1.346	1	1.118	0.044	0.216	2.942	1484.5	0.084
Metere	1.468	0.65	0.836	0.110	0.226	4.183	1484.5	0.066
U/s Geba nr Adikumsi	1.677	1	1.109	0.076	0.201	4.462	986.39	0.062

Spatial proximity method: The choice of catchments from which information is to be transferred is usually based catchment characteristics similarity measure; that is one tends to choose those catchments that are similar to the site of interest by calculating the correlation of each catchments. Similarity of catchment characteristics between gauged and ungauged catchments of Geba sub-basin are discussed below.

Table 4.15: Similarity of catchment characteristics between gauged and ungauged catchment

	Ungauged Catchments						
Gauged Catchments	d/s Suluh	d/s Genfel	u/s Geba nr Adikumsi	Dolo	Metere	Geba nr Adikumsi	May Gabat
Geography and physiographic catchment characteristics correlation (R^2)							
Agula	0.95	0.97	0.99	0.98	0.98	0.84	0.97
Suluh	0.98	0.97	0.94	0.99	0.99	0.82	0.97
Genfel	0.95	0.97	0.96	0.99	0.99	0.86	0.97
Geba nr Mekelle	0.97	0.94	0.98	0.87	0.89	0.99	0.95
Land cover catchment characteristics correlation (R^2)							
Agula	0.86	0.68	0.14	0.67	0.66	0.14	0.16
Suluh	0.92	0.69	0.05	0.76	0.80	0.12	0.22
Genfel	0.93	0.75	0.12	0.77	0.79	0.17	0.22
Geba nr Mekelle	0.49	0.74	0.91	0.67	0.61	0.99	0.91

Climate catchment characteristics correlation (R^2)

Agula	1	1	1	1	0.99	0.99	0.99
Suluh	1	0.99	0.99	0.99	1	0.97	0.99
Genfel	1	1	0.99	1	0.99	0.98	0.99
Geba nr Mekelle	0.99	1	0.99	0.99	1	0.98	0.99

Soil catchment characteristics correlation (R^2)

Agula	0.80	0.38	0.64	0.04	0.42	0.43	0.48
Suluh	0.87	0.34	0.18	0.31	0.66	0.21	0.13
Genfel	0.90	0.98	0.60	0.03	0.12	0.37	0.39
Geba nr Mekelle	0.23	0.82	0.86	0.01	0.35	0.68	0.79

The result of geography and physiographic characteristics estimated from 30 by 30 DEM shown in (Table 4.15) the correlation of ungauged basin downstream of Suluh has 0.95, 0.98, 0.95 and 0.97 with gauged catchments of, Agula, Suluh, Genfel and Geba nr Mekelle respectively. As the correlation result indicates ungauged D/s Suluh catchment obtained MPs from Suluh gauged catchment. Similarly the correlation of other catchments were shown in (Table 4.15).

Also the correlation result of land cover PCCs of Geba nr adikumsi has 0.14, 0.12, 0.17 and 0.99 with Agula, Suluh, Genfel and Geba nr Mekelle, catchments respectively. As the result shows Geba nr adikumsi and Geba nr Mekelle catchments have similarities in land cover PCCs. Similarity the correlation of others catchments were shown in (Table 4.15).

The correlation results in climate PCCs showed that Metere has correlation of 0.99, 1, 0.99 and 1 with, Agula, Suluh, Genfel and Geba nr Mekelle catchments respectively. Similarly the correlation of others catchments were showed in (Table 4.15).

The results in soil PCCs D/s Genfel has 0.38, 0.34, 0.98 and 0.82 correlation with Agula, Suluh, Genfel and Geba nr Mekelle catchments respectively. Similarly the correlation values of soil PCCs of others were shown in (Table 4.15).

Figure 4.7 shows the transfer of MPs from gauged catchments to ungauged catchments based on similarity of catchments characteristics (Table 4.15) in spatial proximity method.

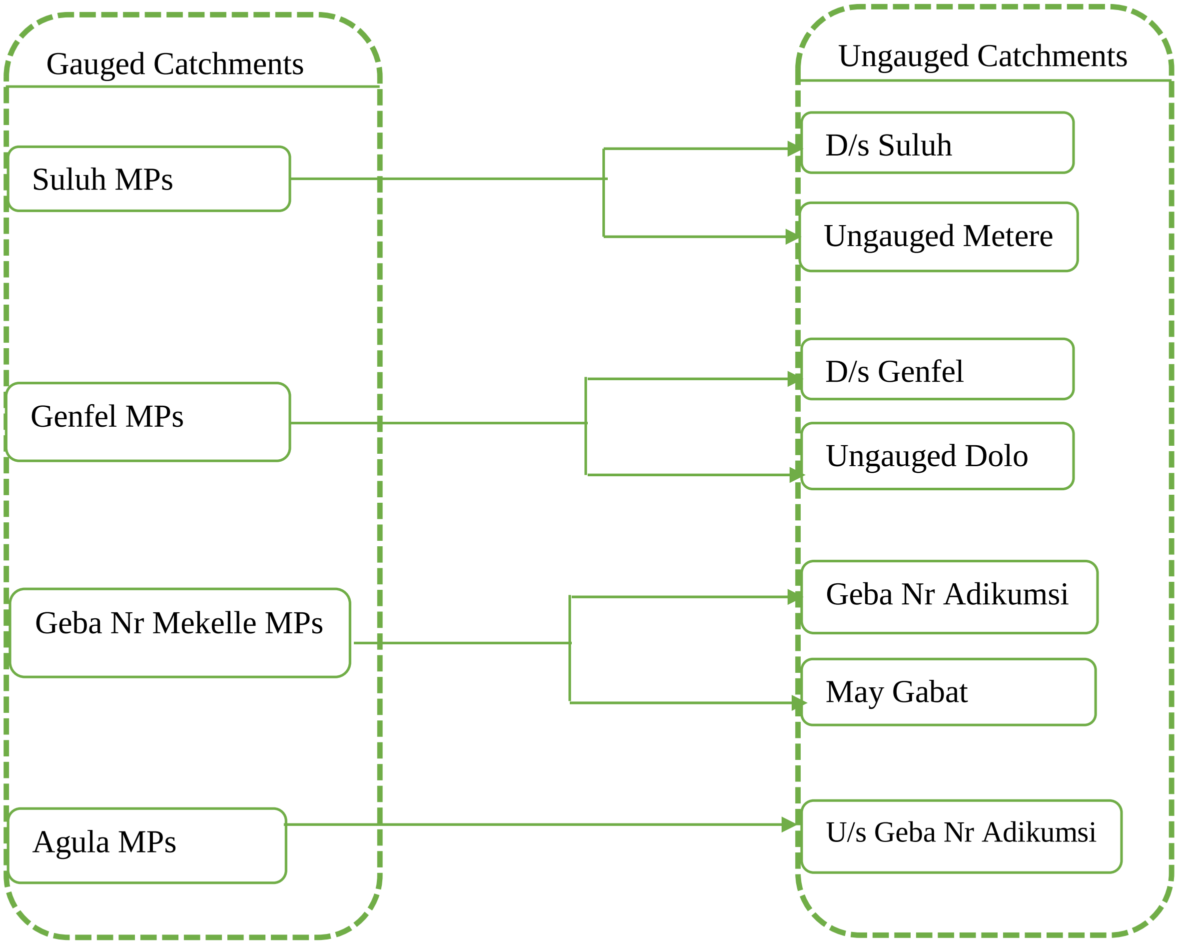


Figure 4.7: Model parameters transfer by spatial proximity method

Area ratio method: As shown (Figure 4.8) optimized model parameters of gauged catchments are directly transferred to ungauged catchments of comparable area based on the assumption that catchment area is the dominant factor for controlling the volume of water that can be generated from the rainfall. The gauged Genfel and Geba nr Mekelle MPs are transferred to D/s Genfel, U/s Geba nr Adikumsi and May Gabat of ungauged catchments in this study. Because the area ratio between gauged and ungauged catchments others are greater than 50%. Figure 4.8 shows model parameters transferred from simulated catchments to ungauged catchments based on area ratio method.

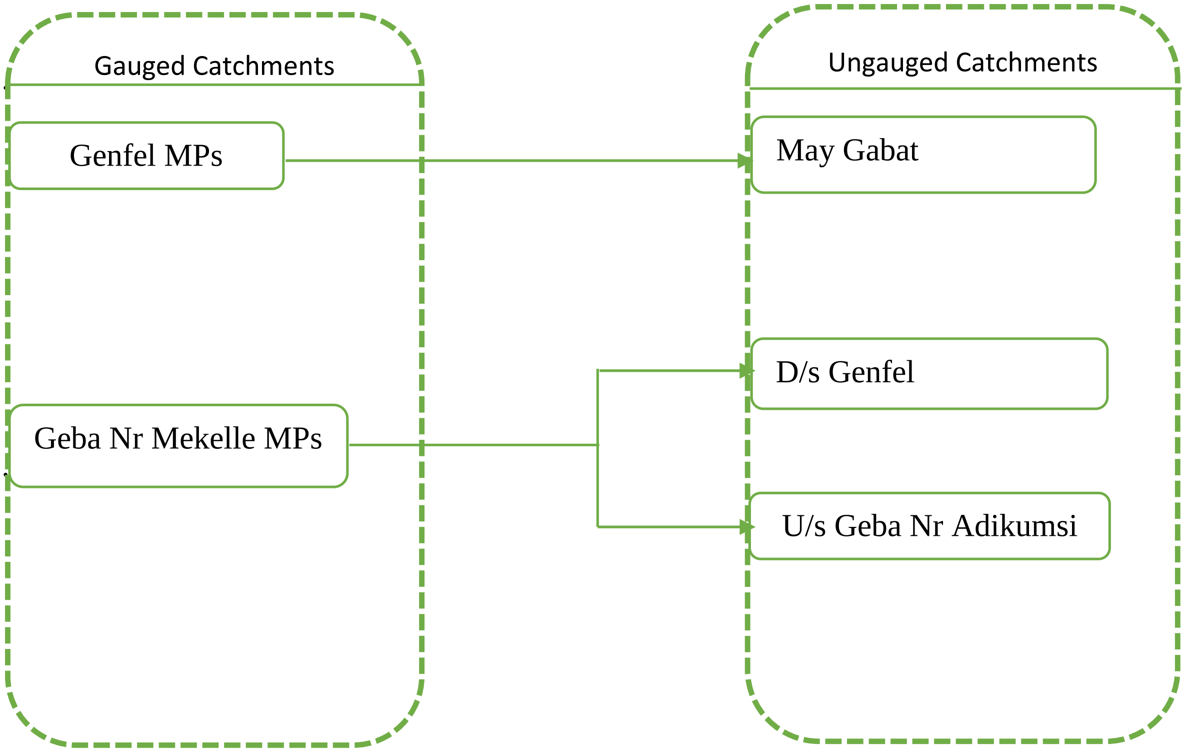


Figure 4.8: Model parameters transfer by area ratio method

Sub-basin mean method: The sub-basin mean represents the arithmetic mean (Kim and Kalaurachchi, 2008) of calibrated model parameter sets of four gauged catchments that satisfy the objective functions. The average value of gauged catchments (Agula, Genfel, Suluh and Geba nr Mekelle) model parameters were taken for each ungauged catchments to simulate the stream flow for ungauged catchments.

4.4.2 Simulation of discharge for ungauged catchments

Model parameters estimated from ungauged catchments were simulated by HBV-96 model. The result of daily stream flow from 1998 to 2014 years shows that runoff simulated by regional model (multiple regression method) (MR) contributes highest volume while in sub-basin mean method is the least due to the fact that it is simply transfer the average of optimized model parameters of gauged catchments to the ungauged catchments. (See Figure 4.9 and Appendix G).

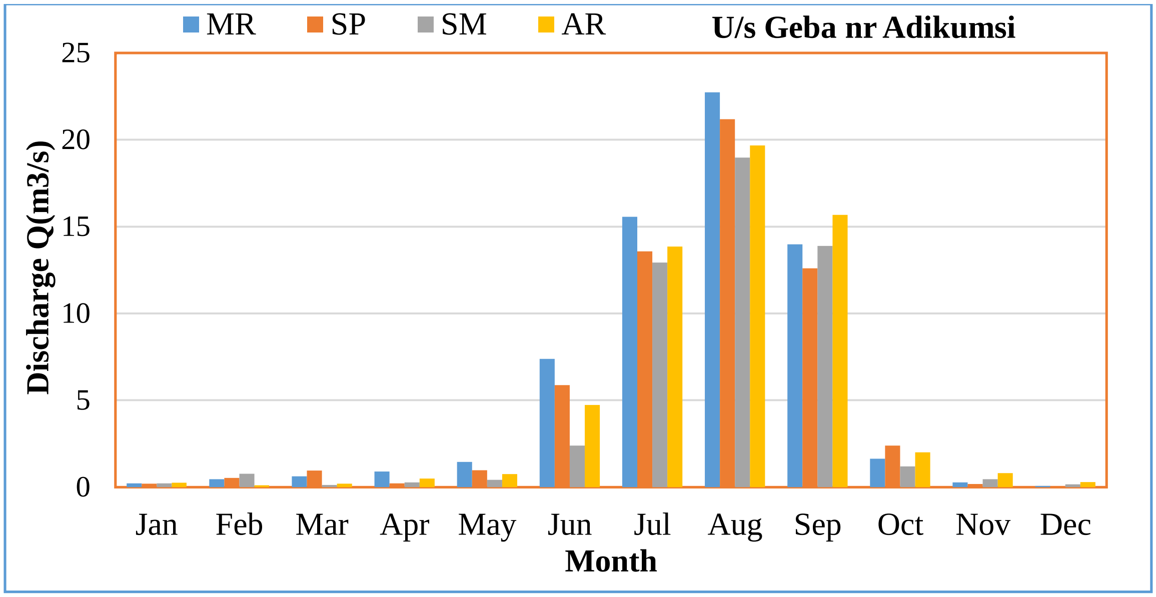


Figure 4.9: Comparison of daily runoff simulated for ungauged U/s Geba nr Adikumsi catchment

Note: MR is multiple regression method, SP is spatial proximity method, SM is sub-basin mean method and AR is area ratio method in U/s Geba nr Adikumsi catchment.

5. Conclusion and Recommendation

5.1 Conclusion

In this research, an attempt was made to determine model parameters required for estimating daily flow for gauged and ungauged catchments in Geba sub-basin. Also to develop regional model which would enable us to relate some of the model parameters to physical catchments characteristics using regression analysis. A relationship between gauged and ungauged catchments were also made using the methods of spatial proximity, area ratio and sub-basin mean. Thus based on the applied methodology and results obtained, the main conclusions of the thesis can be summarized as follow:

- In the Geba sub-basin, four gauged stations have been simulated with model performance NSE greater than 0.67 and RVE smaller than +10% or -10%.
- Sensitivity analysis of HBV-96 model parameters were carried out manually by trial and error. According to the sensitivity analysis, Beta, Khq, LP, and FC were more sensitive model parameters while $K_{4,}$ Cflux and Alfa are relatively less sensitive.
- The model was calibrated manually by changing one model parameter at a time using observed stream flow, mean temperature, evapotranspiration, geographical zones and rainfall as input from 1998 to 2008 and validation from 2009 to 2014 for gauged catchments.
- The developed regional model equations show values of correlation coefficient (R^2) greater than 0.98 and p-value less than or equal to 0.05 for all eight model parameters. Thus, the strength and overall significance of the multiple linear regression (regional model) equation is good or acceptable.
- Model parameters of ungauged catchments are estimated by regional model, spatial proximity, catchment area ratio and sub-basin mean method. From thus, area ratio method was less transferred model parameters to any ungauged catchments since the area ratio between gauged and ungauged catchments were greater than 50%.
- Model parameters estimated from ungauged catchments were simulated by HBV-96 model using four regionalization methods. As the result show the regional model contributes the highest stream flow volume followed by spatial proximity and area ratio method while the result of sub-basin mean is relatively the least.

5.2 Recommendation

- Future research in Geba sub-basin should focus on issues which can increase the reliability of estimation in ungauged basin. Since, in Geba sub-basin no more research work was done in the provisos time, so further research work is important. Climate change along with changes in land use and land cover due to human activities cause nonstationarity in stream flow time series which is generally overlooked by most regionalization methods that assume stationarity. Thus, estimating uncertainty in stream flow estimation/ prediction in ungauged basin using regionalization techniques remains a challenging research topic.
- In Tekeze sub-basin no more research work was done in the provisos time, so further research work is important in order to use water resources effectively.
- It is observed that the parameters Alfa and K_4 in this study do not show significant effect on the model performance. Thus, it can be kept as default value when applying the HBV-96 model to another regionalization studies.
- For this study, due to availability of limited reliable gauged stream flow data four gauged catchments that found within the Geba sub-basin were calibrated using HBV-96 model. However, to establish a best performing regional model for ungauged catchments a model parameter has to be calibrated for more gauged catchments. Therefore, for next study it is recommended to use more gauged catchments.
- In various cases rainfall in Ethiopia lead to a wide range of rainfall distribution in space and time. However, available rainfall stations were not well distributed to represent these rainfall events. As such the use of remote sensing data to estimate areal rainfall should be further explored.
- The result of this study can be used for the regional water allocation and planning purposes. As the derived parameters can be used to generate flow at ungauged catchments, it may also be used to assessment potential water development and planning of water projects at basin level.
- The importance of establishing hydrological feasible relationship between model parameters and PCCs should not be underrated and therefore these relationship should not be incorporated in the regional model in any case.
- A study of more advanced automatic model calibration technique is recommended.

References

Aghakouchak, A., Nakhjiri,N,Pradhan,N,R. 2010. An educational model for ensemble stream flow simulation and uncertainty analysis. Journal of Hydrology and Earth System Science Discussion.

Bergström, S., Harlin, J., & Lindström, G. 1992. Spillway design floods in Sweden. I: New guidelines. Hydrological Sciences Journal, 37, 5, 505 - 519.

Bergström, S., and Sandberg, G. 1983. Simulation of groundwater response by conceptual models - Three case studies. Nordic Hydrology, Vol. 14, No. 2.

Beven, K. J. 2012. Rainfall-runoff modelling : the primer.

Bloschl, G. S., M. 1995. Scale issues in hydrological modelling a review. Hydrological Processes, Vol. 9, 251-290.

Brandt, M., Bergström, S., Gardelin, M 1988. Modelling the effects of clearcutting on runoff - Examples from Central Sweden. Ambio, 17, 5: 307 - 313.

Brooks, K. N., Ffolliott, P.F., Gregersen, H.M., Debani, L.F. 2003. Hydrology and the Management of Watersheds. Iowa State Press, Ames, IA.

Chow, V. T., D.R., Maidment, L.W., Mays, 1988. Applied Hydrology. McGraw hill, New York.

Cunderllk, J. M. 2003. Assessement of water resource risk and vulnerability to changing climate conditions., university of western ontario.

Deckers. 2006. Predicting discharge at ungauged catchments: Parameter estimation through the method of regionalization. University of Twente.

Gebeyehu, H. 2013. Remote sensing and regionalization for integrated water resources modeling in upper and middle Awash River Basin,Ethiopia.

Gonfa, L. 1996. Climate classification of Ethiopia. Addis Ababa, Ethiopia.

Häggström, M., Lindström, G., Cobos, C., Martfnez, J., Merlos, L., Monzo, R.D., Castillo, G., Sirias, C., Miranda, D., Granados, J., A1faro, R., Robles, E., Rodrfguez, M. and Moscote, R., 1990. Application of the HBV model for flood forecasting in six Central American rivers. SMHI, Hydrology, No. 27, Norrköping.

HTS 1976. Tigray Rural Development Study, Annex 2: Water Resources. Vol. 1: Hydrology and Surface Water. Hunting Technical Services, Hemel Hempstead (G.B.), 213 pp.

Hundecha 2004. Modelling of the effect of land use change on the runoff generation of a river basin through parameter regionalization of a watershed model. Journal of hydrology 292, pp. 281-295.

Hundecha, Y. A. & Bárdossy, A. 2004. Modelling of the effect of land use change on the runoff . Journal of hydrology 292, pp. 281-295.

KIM, U. A. & Kalaurachchi, J. 2008. Aplecation of Parameter Estimation and Regionalization Methodologies to Ungauged Basin of The Upper Blue Nile Rive Basin, Ethiopia. Journal of Hydrology (Under review).

Kumar D. and Bhattacharjya, R. K. 2011. Distributed Rainfall Runoff Modeling, International Journal of Earth Sciences and Engineering, Volume 04, No.06, SPL, pp. 270-275.

Lenhart, E., N. Fohrer and Frede, H.G. 2002. Comparison of two different approaches of sensitivity analysis, Physics and Chemistry of the Earth 27 (2002), Elsevier Science, .

Lindström, G., Johansson, B., Persson, M., Gardeline, M., and Bergstrom, S., 1997. Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology, 201(1-4): 272-288.

Lindström, G., & Harlin, J. 1992. Spillway design floods in Sweden. II: Application and sensitivity analysis. Hydrological Sciences Journal, 37, 5, 521 - 539.

Mazvimavi, D. 2003. Estimation of Flow Characteristics of Ungauged Catchments: Case Study in Zimbabwe. ITC, Enschede

Merz, R., and Bloschl, G. 2004. Regionalization of catchment model parameters. Journal Hydrol.

MU-IUC 2007. Geological map of Geba catchment. Hydrogeology project of Mekelle University-Interuniversity co-operation, unpub. map, Mekelle , Ethiopia.

Nedeco 1998. Tekeze River Basin Integrated Development Master Plan Project, Vol 5 & 6. Ministry of water resources, Addis Ababa.

Norstedt, U., Brandesten, C.-O., Bergstrom, S., Harlin, J., and Lindströrn, G. 1992. Re-evaluation of hydrological dam safety in Sweden. International Water Power and Dam Construction, June.

Perera, B. 2009. Ungauged Catchment Hydrology;The case of Lake Tana Basin.

Richard, H. M. 1989. Hydrologic analisis and Design Englewood Cliffs. New Jersey.

Saelthun, N. R., Aittoniemi, P., Bergström, S., Einarsson, K., Jóhannesson, T., Lindström, G., Ohlsson, P-E. Thomsen, T., Vehviläinen, B. and Aamodt, K. O. 1998. Climate change impacts on runoff and hydropower in the Nordic countries. Final report from the project "Climate Change and Energy Production"Tema Nord 1988:552, Oslo.

Schultz, G. A. 1993. Hydrological Modeling based remote sensing information. Adv. Space Res., Vol.13, No.5.

Seibert, J. 1999. Regionalisation of parameters for a conceptual rainfall-runoff model. . Agricultural and forest meteorology.

Sivapalan, M., Takeuchi, K., Franks, S., Gupta, V. K., Karambiri, H., Lakshmi, V., Liang, X., Mcdonnell, J., Mendiondo, E., O‘ConnelL, P., Oki, T., Pomeroy, J., Schertzer, D., Uhlenbrook, S., and Zehe, E. 2003. IAHS decade on Predictions in Ungauged Basins (PUB), 2003-2012: Shaping an exciting future for the hydrological sciences, Hydrol. Sci. J.-J. Sci. Hydrol., 48(6), pp.857–880.

SMEC 2007. 'Hydrological study of the Tana-Beles sub-basin" part 1.

SMHI 2006. Integrated Hydrological Modelling System Features HBV,Manual version 5.1.

Subramanya, K. 1998. Engineering hydrology. 2nd edition. Tata McGrawhill.

Tamalew, C. 2015. determination of Discharge for Ungauged Catchments in Didessa Sub-Basin: The Case of Blue Nile River Basin, Ethiopia.

Tesfaye, B. 2011. Predicting Discharge at Ungauged Catchments Using Hydrological modeling (Case study: Omo-Gibe River Basin).

Thompson, M. W. 1999. South African National Land-Cover Database Project. Data Users Manual: Final Report (Phases 1, 2, and 3). CSIR Client Report ENV/P/C 98136.

TUFA, K. 2011. Performance comparison of conceptual rainfall-runoff models on Muger catchment (Abbay River Basin). MSc Thesis. Addis Ababa University, Ethiopia.

Vehvilainen, B., and Lohvansuu, J. 1991. The effects of climate change on discharges and snow cover in Finland. - Hydrological Sciences Journal, 36, 2, 4.

Wale, A. 2009. Ungauged catchment contributions to Lake Tana’s water balance. Hydrological Processes.

Wapcos, A. C. C. 2003. Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray and Water and Power Consultancy Services (India) Limited. Suluh Valley Integrated Rural, Agricultural and Water Resources Development Study. Identification and Reconnaissance Report. Mekelle, Ethiopia.

Appendices

Appendix A: Prepared annual mean input data for HBV model in Geba sub-basin

Appendix A1: Annual mean Rainfall (mm/day)

Year	Adigrat	Adigudem	Atsbi	H/selam	Hawezen	Mekelle air port	Wukuro
1997	1.912	1.777	2.339	2.113	1.339	1.489	2.339
1998	1.822	1.572	1.943	2.432	1.603	2.033	1.943
1999	0.921	1.305	1.765	1.899	1.559	2.003	1.765
2000	1.314	1.154	2.660	1.924	2.061	1.230	2.660
2001	1.819	2.978	2.811	2.043	2.406	1.722	2.811
2002	1.545	1.472	1.736	1.281	1.194	1.272	1.736
2003	1.496	1.338	1.367	1.580	1.063	1.434	1.367
2004	1.192	0.768	1.348	1.421	0.995	1.093	1.339
2005	1.348	1.129	1.365	2.323	1.223	1.741	1.365
2006	1.950	0.656	1.723	1.967	2.017	2.067	1.831
2007	1.885	0.932	2.536	1.774	1.426	1.681	2.056
2008	1.988	1.722	0.875	1.694	0.927	0.777	1.443
2009	1.046	1.173	1.288	1.494	1.293	1.123	0.986
2010	1.152	1.207	1.376	1.524	1.342	1.310	1.431
2011	1.546	0.758	1.242	1.824	1.478	1.715	2.021
2012	1.568	1.033	1.794	1.833	1.357	1.545	1.849
2013	1.475	1.291	1.490	1.881	1.762	1.436	1.745
2014	1.414	1.158	1.753	1.683	1.277	1.228	1.342

Appendix A2: Annual mean flow (m^3/s)

Year	Agula	Geba nr Mekelle	Genfel	Suluh
1997	0.423	3.817	3.943	0.798
1998	0.967	5.524	0.889	0.708
1999	1.217	3.384	3.481	0.523
2000	0.847	10.821	4.127	0.425
2001	1.173	3.610	3.691	0.413
2002	0.644	1.493	2.984	0.466
2003	0.721	2.206	3.263	0.121
2004	0.911	1.340	0.894	0.171
2005	0.699	2.241	0.594	0.245

2006	0.821	2.229	1.094	0.555
2007	1.424	2.400	1.395	0.454
2008	0.453	2.362	1.295	0.165
2009	0.355	3.382	1.205	0.241
2010	1.431	4.729	0.592	0.355
2011	1.226	3.242	1.724	0.465
2012	1.456	1.682	2.196	0.356
2013	1.262	2.317	1.925	0.481
2014	0.798	2.157	1.081	0.287

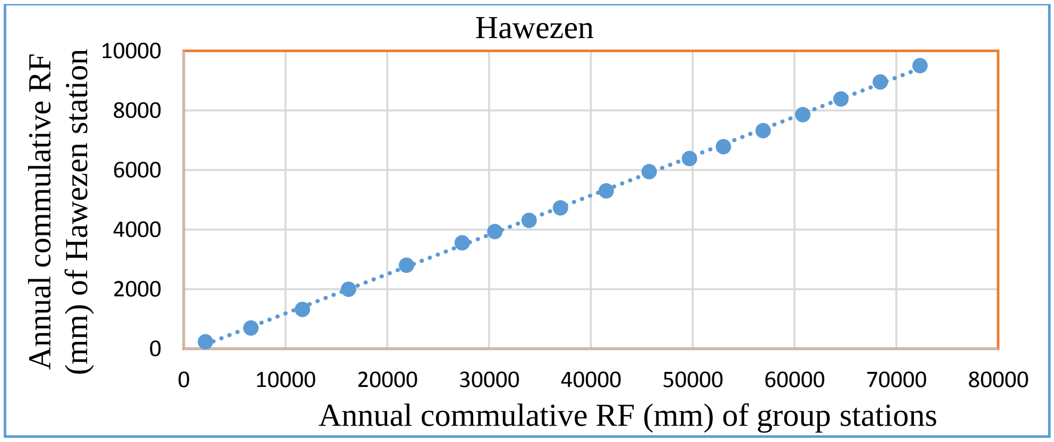
Appendix A3: Annual mean evapotranspiration (mm/year)

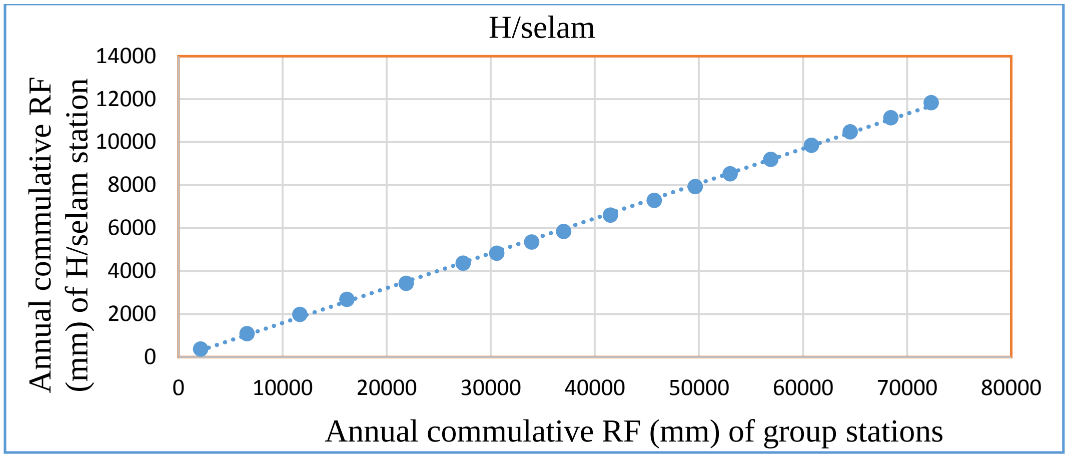
Year	Adigrat	Adigudem	Atsbi	H/selam	Hawezen	Mekelle air port	Wukuro
1997	1618.228	1696.384	1650.736	1419.200	1698.123	1504.886	1866.514
1998	1650.485	1747.314	1694.462	1419.131	1715.894	1467.726	1856.982
1999	1621.955	1714.165	1663.345	1417.637	1754.651	1517.447	1842.435
2000	1621.615	1733.598	1675.263	1428.689	1706.124	1498.416	1842.697
2001	1627.484	1730.211	1675.371	1414.040	1675.955	1432.004	1908.309
2002	1650.572	1757.430	1702.371	1416.101	1785.917	1551.934	1919.761
2003	1649.370	1745.416	1693.764	1427.251	1751.337	1510.100	1821.993
2004	1607.732	1705.143	1652.073	1413.080	1732.037	1535.703	1830.012
2005	1617.897	1708.707	1658.770	1404.159	1788.344	1498.256	1804.010
2006	1634.870	1722.191	1672.472	1363.939	1711.498	1409.218	1816.265
2007	1524.731	1672.761	1595.673	1385.007	1802.265	1441.481	1853.784
2008	1614.569	1718.489	1657.103	1327.779	1851.526	1448.592	1819.540
2009	1634.949	1752.317	1688.412	1376.236	1848.595	1491.388	1891.621
2010	1567.112	1743.682	1640.048	1328.592	1833.985	1331.927	1808.845
2011	1343.702	1572.281	1421.916	1330.076	1848.398	1378.404	1764.777
2012	1401.393	1628.933	1476.215	1372.563	1882.932	1421.732	1784.107
2013	1659.527	1210.576	1272.025	1360.696	1899.962	1290.434	1845.993
2014	1700.711	1353.484	1271.542	1408.258	1964.173	1418.920	1825.499

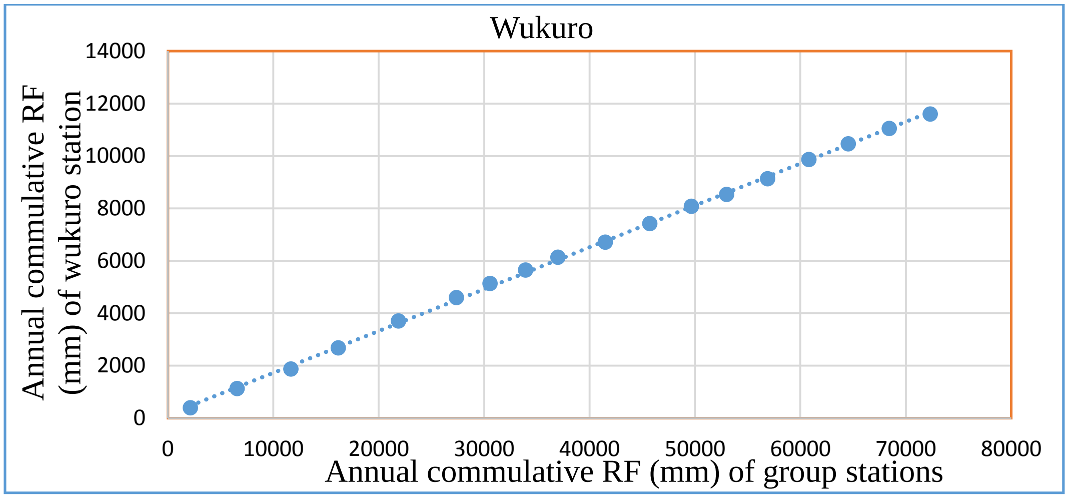
Appendix A4: Annual mean temperature (^{0}C)

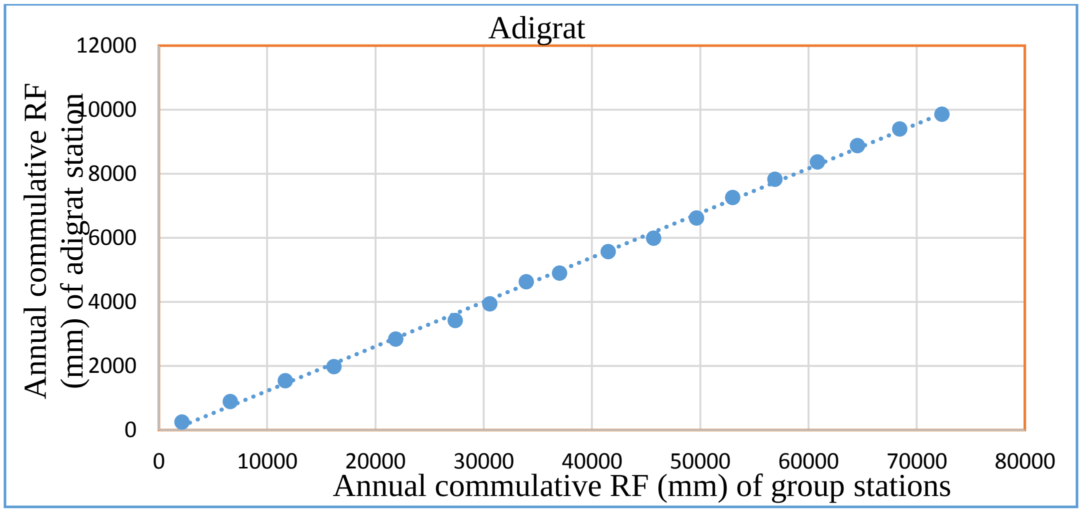
Year	Adigrat	Adigudem	Atsbi	H/selam	Hawezen	Mekelle air port	Wukuro
1997	17.849	19.963	18.947	16.426	18.839	18.230	19.642
1998	18.604	20.723	19.724	16.750	19.023	18.279	20.333
1999	18.121	20.096	19.139	16.241	18.385	17.778	19.476
2000	17.881	19.971	18.972	16.508	18.211	18.017	19.581
2001	18.320	20.407	19.407	16.437	18.459	18.074	19.203
2002	18.472	20.666	19.640	16.736	18.537	18.580	18.148
2003	18.563	20.637	19.654	16.777	18.522	18.312	20.108
2004	17.794	19.817	18.834	16.838	18.264	18.121	19.728
2005	18.023	20.019	19.056	16.637	17.865	17.989	19.869
2006	18.005	20.062	19.077	16.557	18.381	17.894	19.929
2007	16.009	19.303	17.754	16.815	18.971	18.105	19.474
2008	14.622	16.919	15.683	16.272	18.569	17.873	18.557
2009	18.614	20.956	19.655	16.963	19.524	18.246	20.192
2010	18.484	20.857	19.575	16.895	19.487	18.348	20.209
2011	17.629	20.885	19.103	16.550	19.500	18.149	20.255
2012	17.033	20.739	18.621	16.318	18.940	17.644	18.710
2013	18.232	21.850	19.865	16.663	18.972	17.855	19.365
2014	14.596	14.786	14.850	16.658	19.403	17.899	19.917

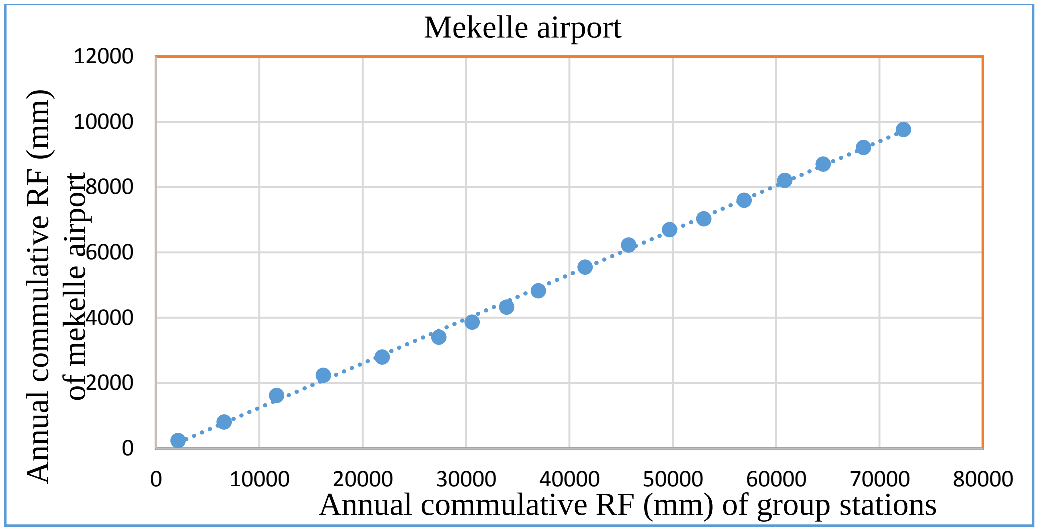
Appendix B: Double mass curve analysis of each rainfall stations

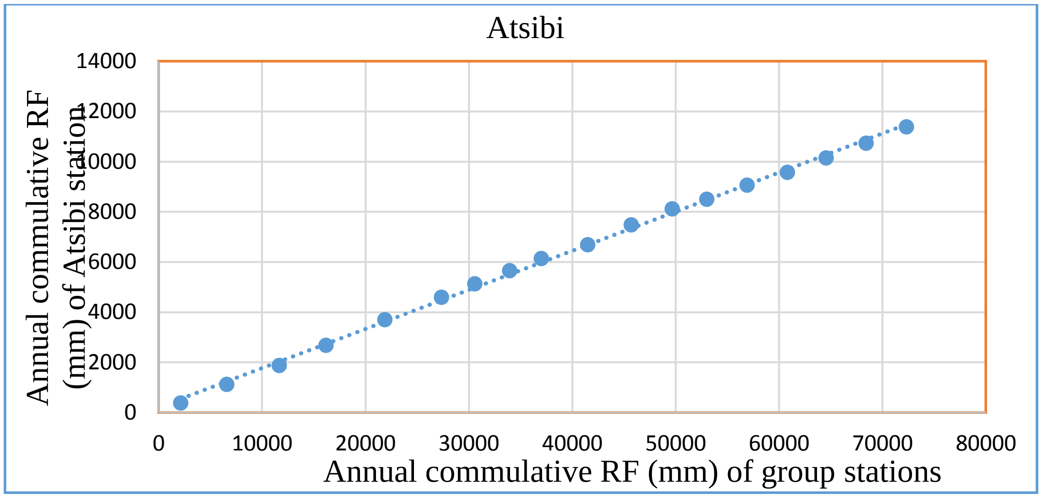


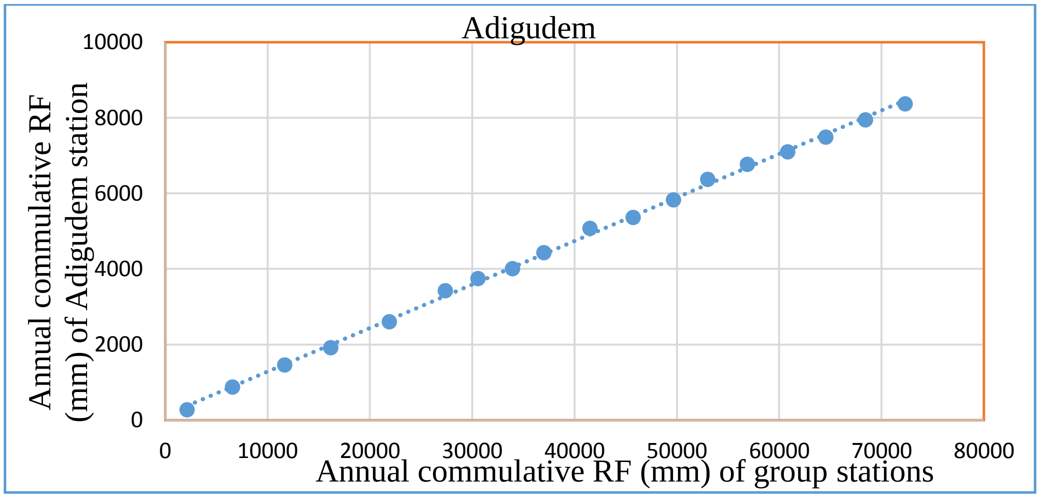

H/selam
Annual commulative RF (mm) of H/selam station
Annual commulative RF (mm) of group stations
14000
12000
10000
8000
6000
4000
2000
0
0
10000
20000
30000
40000
50000
60000
70000
80000


Wukuro
Annual commulative RF (mm) of wukuro station
Annual commulative RF (mm) of group stations
14000
12000
10000
8000
6000
4000
2000
0
0
10000
20000
30000
40000
50000
60000
70000
80000

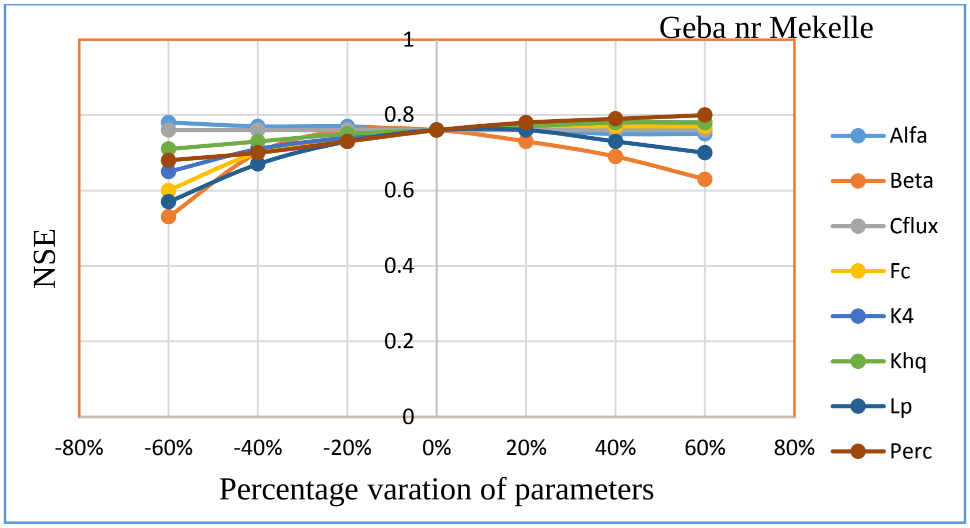

Adigrat
Annual commulative RF (mm) of adigrat station
Annual commulative RF (mm) of group stations
12000
10000
8000
6000
4000
2000
0
0
10000
20000
30000
40000
50000
60000
70000
80000

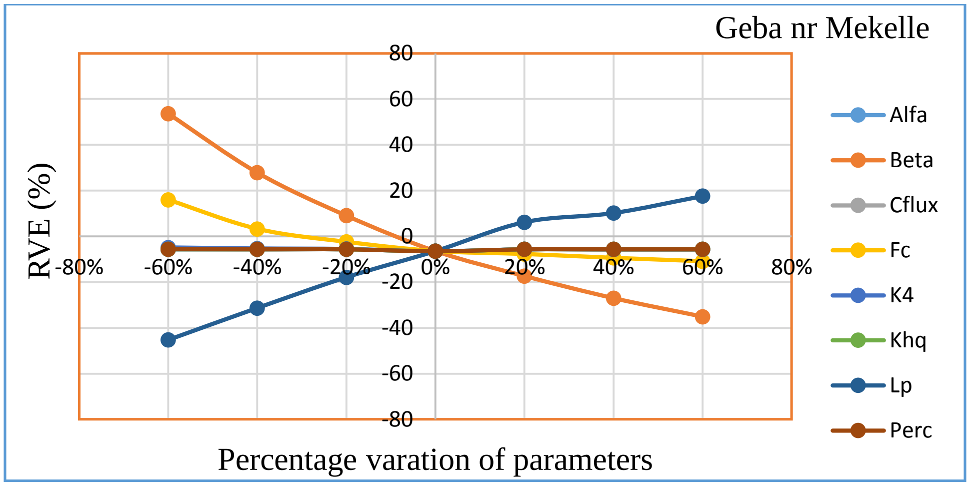

Mekelle airport
Annual commulative RF (mm) of mekelle airport
Annual commulative RF (mm) of group stations
0
2000
4000
6000
8000
10000
12000
0
10000
20000
30000
40000
50000
60000
70000
80000

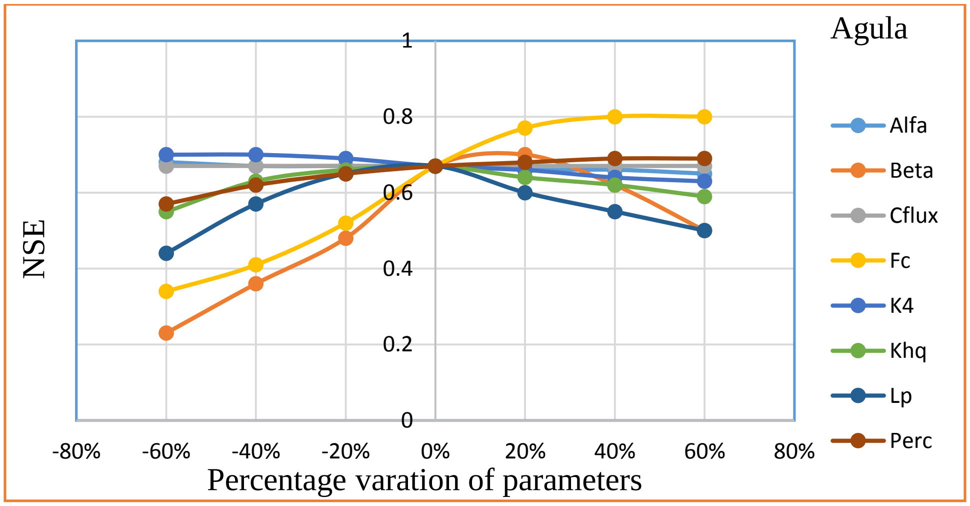

Atsibi
Annual commulative RF (mm) of Atsibi station
Annual commulative RF (mm) of group stations
0
2000
4000
6000
8000
10000
12000
14000
0
10000
20000
30000
40000
50000
60000
70000
80000

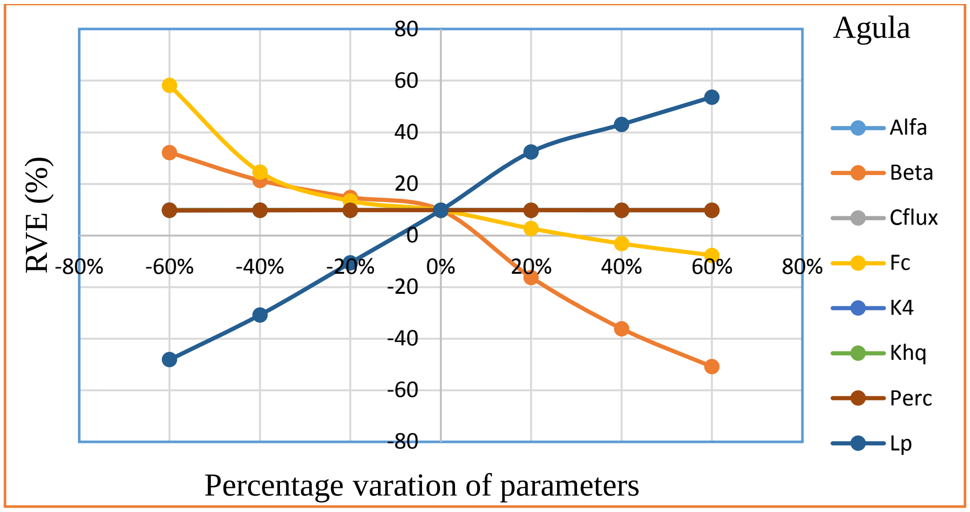

Adigudem
Annual commulative RF (mm) of Adigudem station
Annual commulative RF (mm) of group stations
0
2000
4000
6000
8000
10000
0
10000
20000
30000
40000
50000
60000
70000
80000

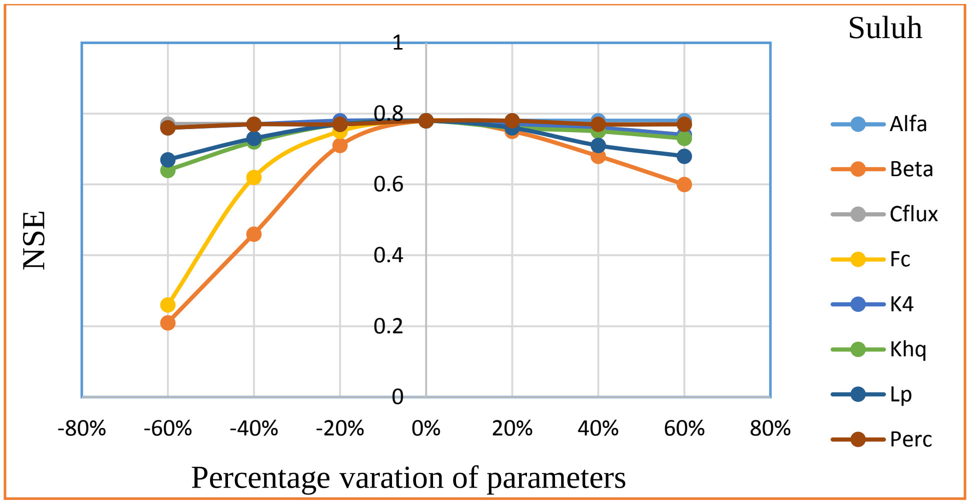
Appendix C: Sensitivity model parameter analysis of sub-catchments

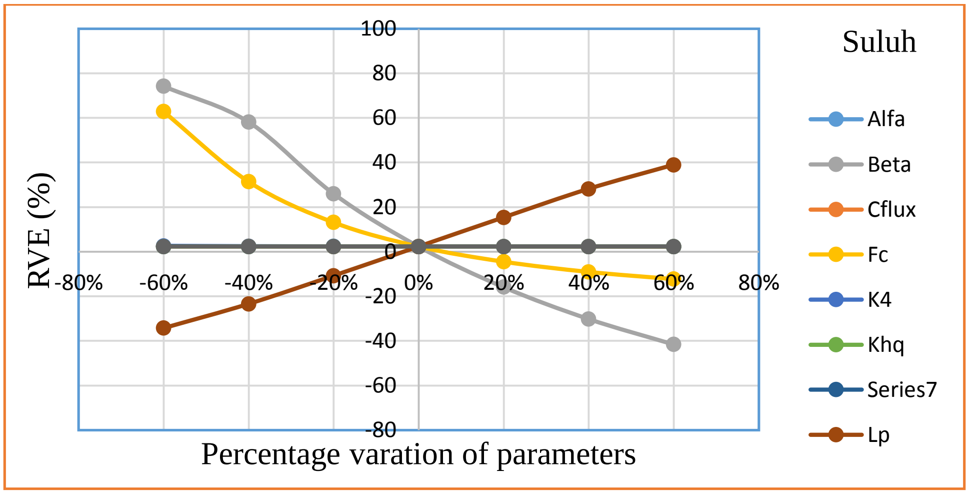




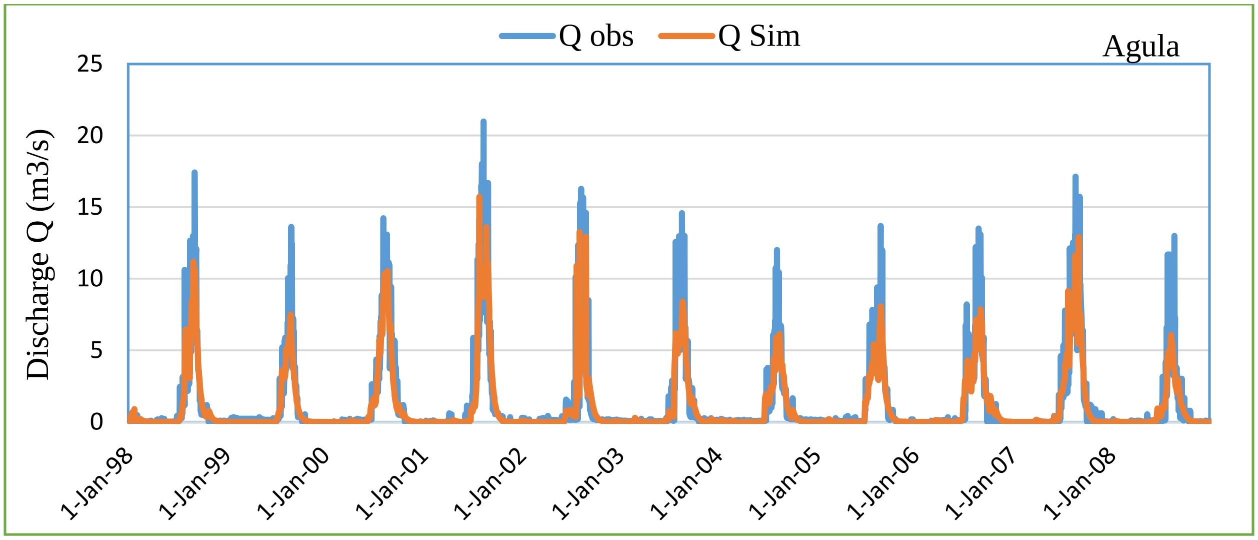


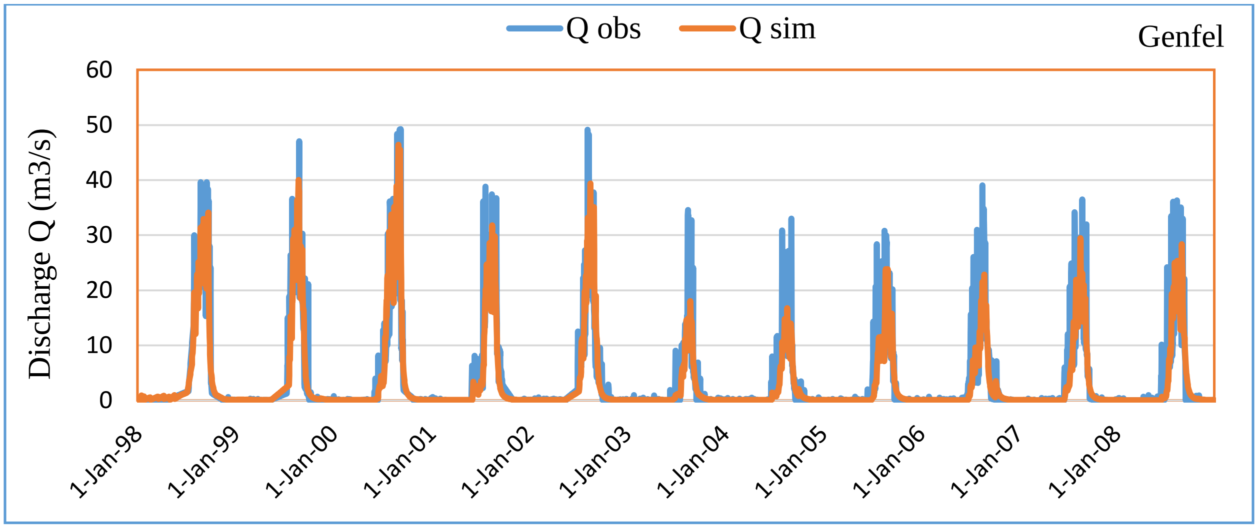

Agula
RVE (%)
80
60
40
20
0
-20
-40
-60
-80
-80%
-60%
-40%
-20%
0%
20%
40%
60%
80%
Alfa
Beta
Cflux
Fc
K4
Khq
Perc
Lp
Percentage varation of parameters


Suluh
NSE
1
0.8
0.6
0.4
0.2
0
-80%
-60%
-40%
-20%
0%
20%
40%
60%
80%
Alfa
Beta
Cflux
Fc
K4
Khq
Lp
Perc
Percentage varation of parameters


Suluh
RVE (%)
100
80
60
40
20
0
-20
-40
-60
-80
-80%
-60%
-40%
-20%
0%
20%
40%
60%
80%
Alfa
Beta
Cflux
Fc
K4
Khq
Series7
Lp
Percentage varation of parameters

Appendix D: Calibration and Validation graphical and Scatter plot of gauged catchment





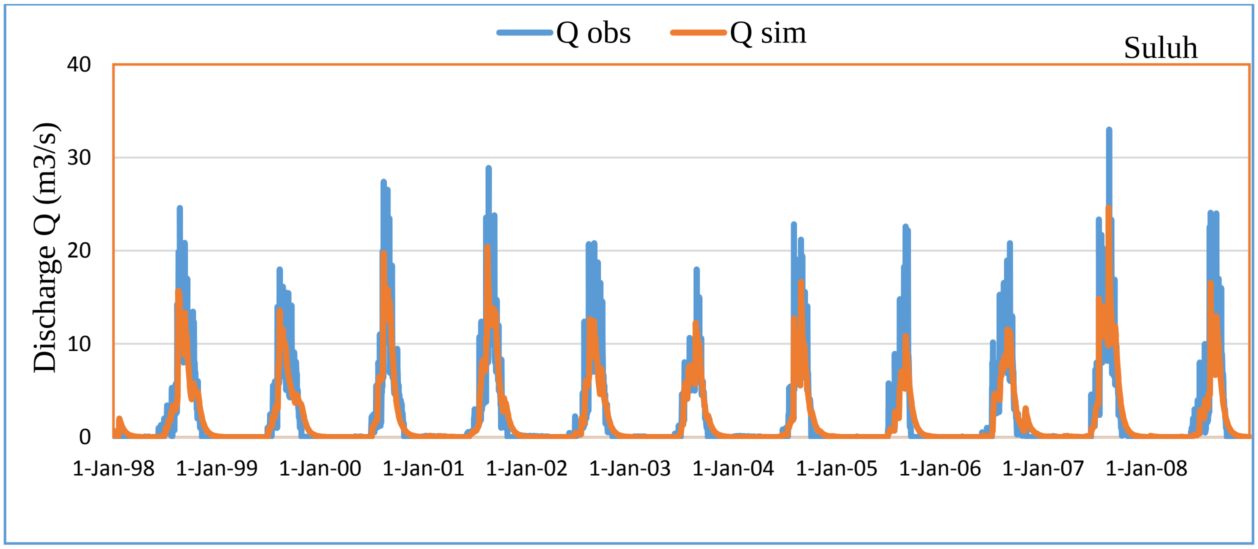


Figure 4.3: Graphical comparison of observed and simulated flow for calibration period

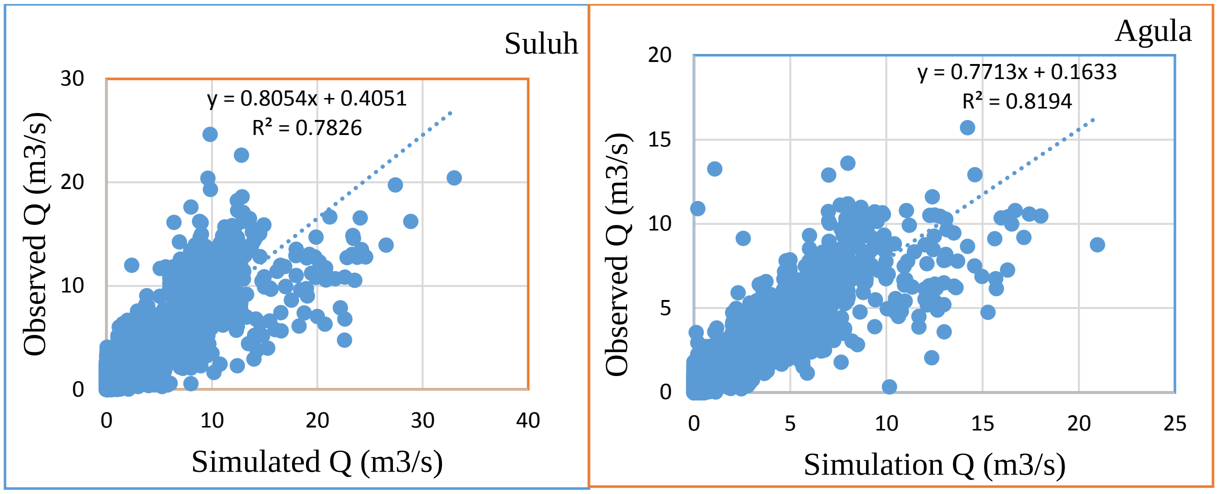
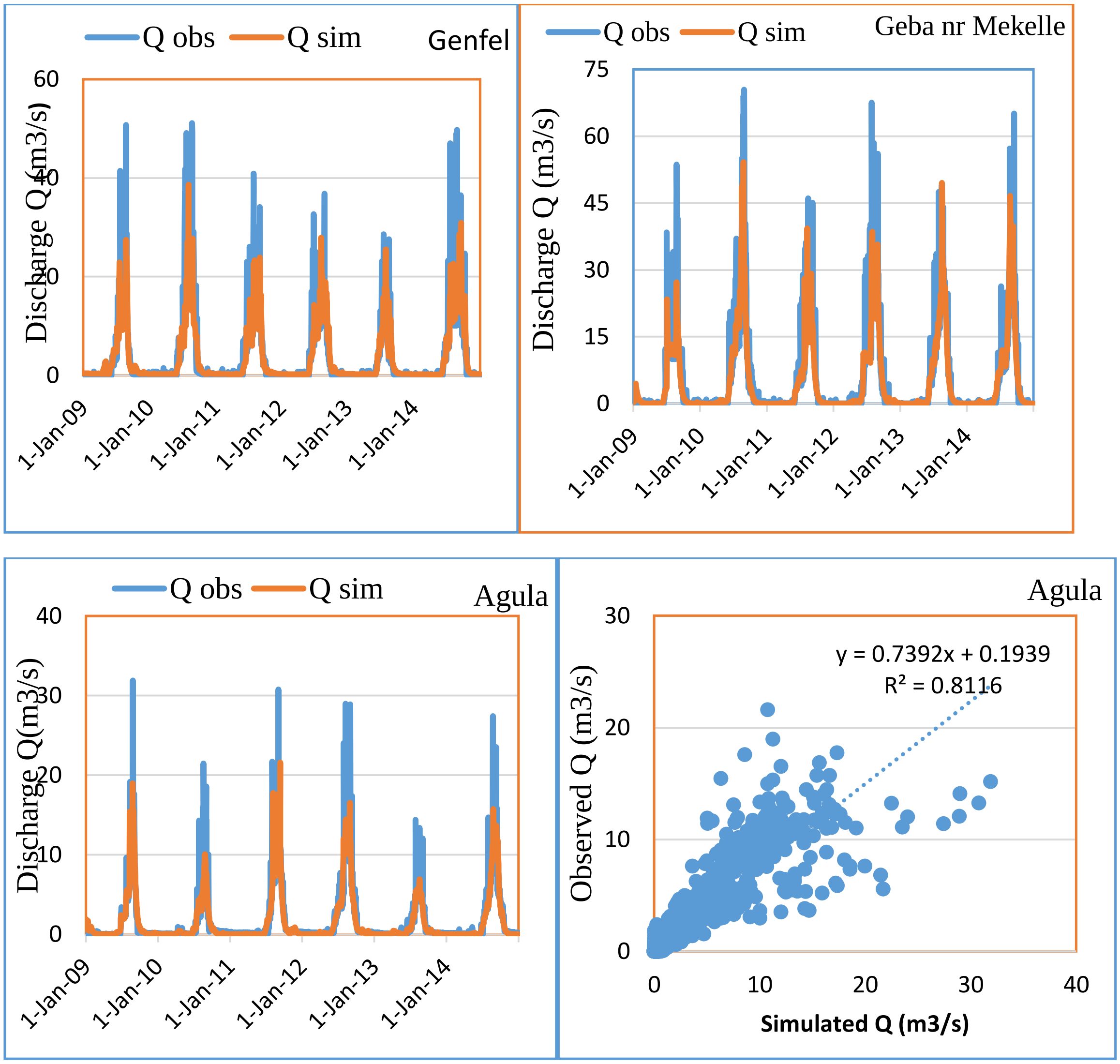


Figure 4.4: Scatter plot comparison of observed and simulated flow during calibration period



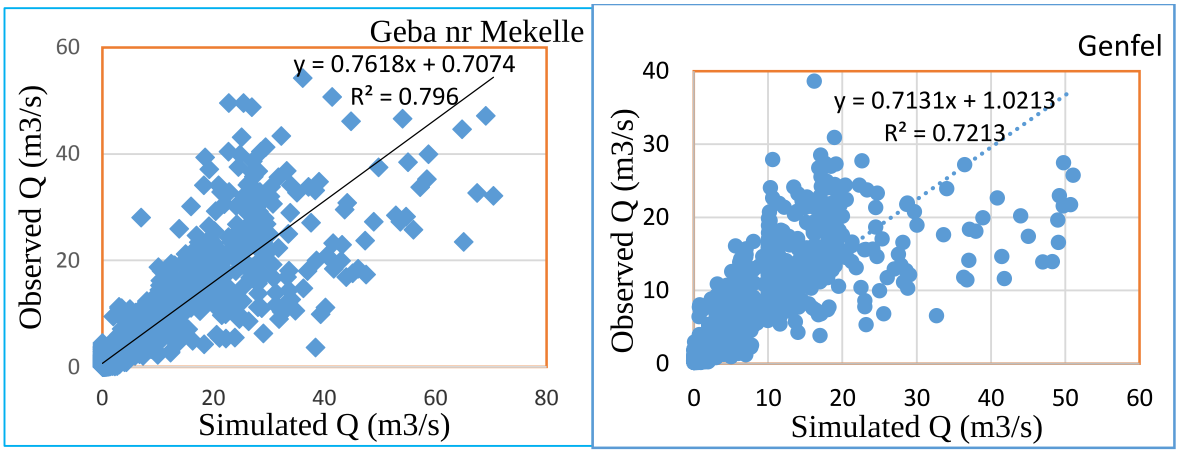


Figure 4.5: Validation graphical and scatter plot comparison of observed and simulated flow during validation period.

Appendix E: Physical catchment characteristics of gauged and ungauged Geba sub-basin.

PCCs	Area (km^2)	Ave. slope	LFP (km)	MDEM (m)	HI	DD (m/km^2)	CI	ER	Bshape (m/km^2)
Gauged catchments									
Geba nr mekelle	526	25.16	7.2	2206	0.5		46.4	0.28	39.8
Agula	457	25.5	15	2412	0.5		60.1	0.62	41.2
Genfel	498	28.6	14.7	2530	0.5		51.1	0.58	48.1
Suluh	420	31	16.8	2725	0.5		51.4	0.72	55.2
Ungauged catchments									
D/s Suluh	325	25.7	8	2316	0.5		69.1	0.39	47.1
D/s Genfel	159	27.2	4	2259	0.5		58.3	0.26	57.5
Geba nr Adik.	634	32.67	9.7	2085	0.5		37.3	0.34	57.5
Dolo	338	19.4	11	2204	0.5		50.8	0.53	50.4
Metere	462	26.3	13.5	2273	0.5		54.1	0.56	45
U/s Geba nr Adik.	284	25.56	5.7	2127	0.5		44.1	0.30	66
May Gabat	178	25.95	5.1	2110	0.5		35.2	0.34	75.6

PCCs	SAAR (mm)	MP dry (mm)	Leptosols (%)	Vertisols (%)	Luvisols (%)	Cambisols (%)	Calcisols (%)	Arenosols (%)

Gauged Catchments								
Geba nr meke.	576.2	0.35	51.22	3.99	4.92	16.14	23.73	0.00
Agula	643.2	0.36	31.71	12.1	21.55	21.1	9.29	0.98
Genfel	575.4	0.52	36.75	3.52	31.33	16.42	4.1	0.71
Suluh	544.6	0.58	27.12	8.79	4.41	39.76	0.00	11.52
Ungauged Catchments								
D/s Suluh	606.7	0.36	33.1	14.45	28.38	14.95	2.87	5.15
D/s Genfel	643.2	0.35	36.1	18.79	7.87	11.99	21.48	3.32
Geba nr Adik	662.9	0.57	59.75	8.8	1.43	6.98	0.00	9.03
Dolo	597.5	0.33	13.89	37.33	0.00	38.68	8.93	0.00
Metere	510.2	0.26	35.47	23.84	0.00	34.51	5.6	0.00
U/s Geba nr Adik.	619.3	0.41	67.44	0.32	11.35	11.45	9.42	0.00
May Gabat	604.2	0.47	80.27	11.4	0.00	2.74	5.52	0.00

PCCs	MP wet (mm)	PET (mm/year)	Shrub land (%)	Cultivation (%)	G.land (%)	B.land (%)	Forest (%)	W.land (%)
Gauged Catchments								
Geba nr meke.	3.89	1729.6	22.32	24.74	49.70	3.03	0.13	0.08
Agula	4.38	1718.5	32.95	49.82	13.03	0.94	2.54	0.68
Genfel	3.58	1697.4	25.54	55.22	15.67	1.13	2.26	0.04
Suluh	3.17	1747.1	16.40	66.88	14.86	1.75	0.02	0.06
Ungauged Catchments								
D/s Suluh	4.12	1778	23.85	52.10	27.70	0.74	0.00	1.67
D/s Genfel	4.38	1718.5	20.91	41.53	34.66	2.61	0.13	0.01
Geba nr Adik.	4.3	1389.6	20.70	21.42	52.46	5.01	0.01	0.42
Dolo	4.05	1645.9	17.46	45.77	34.73	1.09	0.00	0.51
Metere	3.58	1557.3	14.74	48.73	33.83	2.00	0.00	0.50
U/s Geba nr Adik.	4.13	1560.5	32.35	14.64	50.37	2.15	0.00	0.48
May Gabat	4.01	1421.2	10.65	28.92	52.12	7.89	0.00	0.36

Appendix F: Correlation of physical catchment characteristics

PCCs	MDEM (m)	Area (km^2)	Ave. Slope	LFP (km)	HI	DD (m/km^2)	CI	ER	Bshape (m/km^2)
MDEM	1								
Area	-0.82	1							
Ave.slope	0.94	-0.64	1						
LFP	0.90	-0.85	0.70	1					
HI	0.48	-0.80	0.16	0.77	1				
DD	-0.78	0.75	-0.54	-0.97	-0.82	1			
CI	0.22	-0.53	-0.13	0.61	0.94	-0.73	1		
ER	0.91	-0.90	0.71	0.99	0.79	-0.95	0.60	1	
Bshape	0.95	-0.69	1.00	0.72	0.21	-0.56	-0.10	0.74	1
SLD	-0.43	0.21	-0.68	0.01	0.89	-0.23	0.72	-0.04	-0.68
Cultivated	0.97	-0.84	0.84	0.97	0.25	-0.90	0.41	0.97	0.86
GLD	-0.78	0.74	-0.54	-0.97	-0.64	1.00	-0.73	-0.95	-0.56
BLD	-0.53	0.50	-0.26	-0.83	-0.84	0.94	-0.81	-0.78	-0.27
Forest	-0.04	0.05	-0.28	0.36	0.93	-0.56	0.72	0.28	-0.29
WLD	-0.20	-0.26	-0.52	0.21	0.84	-0.35	0.90	0.21	-0.48
Leptosol	-0.88	0.93	-0.66	-0.98	-0.43	0.94	-0.65	-0.99	-0.69
Vertisol	0.28	-0.75	-0.02	0.54	0.59	-0.56	0.86	0.59	0.04
Luvisol	0.07	0.17	-0.08	0.35	0.73	-0.52	0.45	0.25	-0.12
Cambisol	0.80	-0.89	0.77	0.62	-0.26	-0.43	0.10	0.69	0.81
Calcisol	-0.96	0.78	-0.84	-0.97	-0.27	0.91	-0.40	-0.96	-0.84
Arenosol	0.82	-0.83	0.84	0.59	-0.37	-0.39	-0.03	0.66	0.87
SAAR	-0.44	0.08	-0.72	0.00	0.86	-0.19	0.78	-0.03	-0.70
MP dry	0.92	-0.55	0.99	0.69	-0.27	-0.55	-0.16	0.69	0.98
MP wet	-0.70	0.32	-0.90	-0.32	0.67	0.12	0.55	-0.34	-0.88
PET	0.23	-0.51	0.29	0.00	-0.55	0.18	-0.18	0.10	0.34

PCCs	Leptosols (%)	Vertisols (%)	Luvisols (%)	Cambisols (%)	Calcisols (%)	Arenosols (%)	GLD (%)	SLD (%)	WLD (%)
Leptosol	1.00								
Vertisol	-0.67	1.00							
Luvisol	-0.19	-0.08	1.00						
Cambisol	-0.72	0.46	-0.52	1.00					
Calcisol	0.92	-0.33	-0.32	-0.64	1.00				
Arenosol	-0.67	0.32	-0.51	0.99	-0.65	1.00			
GLD	0.93	-0.56	-0.53	-0.43	0.91	-0.39	1.00		
SLD	0.02	0.37	0.66	-0.62	0.18	-0.72	-0.23	1.00	
WLD	-0.29	0.82	0.26	-0.13	0.04	-0.28	-0.35	0.82	1.00
Cultivation	-0.95	0.40	0.23	0.71	-0.99	0.71	-0.21	-0.90	-0.01
BLD	0.76	-0.50	-0.76	-0.10	0.74	-0.05	-0.53	0.94	-0.50
Forest	-0.26	0.26	0.92	-0.49	-0.24	-0.54	0.87	-0.56	0.61
SAAR	-0.02	0.56	0.45	-0.48	*0.23*	*-0.60*	*0.96*	*-0.19*	0.93
MP wet	0.28	0.37	0.30	-0.63	0.52	-0.74	0.90	0.13	0.83
MP dry	-0.62	-0.12	0.04	0.67	-0.84	0.75	-0.64	-0.55	-0.57
PET	-0.17	0.35	-0.93	0.77	0.01	0.74	-0.64	0.19	-0.12

PCCs	Cultivation (%)	Bare land (%)	Forest (%)	SAAR (%)	MP dry (%)	MP wet (%)	PET (%)
Cultivation	1.00						
Bare land	-0.71	1.00					
Forest	0.17	-0.81	1.00				
SAAR	-0.23	-0.45	0.74	1.00			
MP dry	0.83	-0.30	-0.20	-0.71	1.00		
MP wet	-0.53	-0.16	0.58	0.95	-0.90	1.00	
PET	0.10	0.47	-0.82	-0.40	0.15	-0.36	1.00

Appendix G: Daily simulated discharge for ungauged catchments