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SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

MASTERS OF SCIENCE PROGRAM IN HYDRAULIC ENGINEERING

RAINFALL RUNOFF MODELING USING HYDRAULIC ENGINEERING CENTER HYDROLOGIC MODELING SYSTEM FOR GILGEL GIBE CATCHMENT, OMO GIBE BASIN, ETHIOPIA

BY
SEWMEHON SISAY

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF JIMMA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN HYDRAULIC ENGINEERING

NOVEMBER, 2018

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ADVISOR: Dr.ing.TAMENE ADUGNA (PhD.)

CO-ADVISOR:Mr.TOLERA ABDISSA (MSc.)

NOVEMBER, 2018

JIMMA, ETHIOPIA

DECLARATION

I, Sewmehon sisay, declare that this thesis work entitled: "RAINFALL RUNOFF MODELING USING HYDRAULIC ENGINEERING CENTER HYDROLOGIC MODELING SYSTEM FOR GILGEL GIBE CATCHMENT, OMO GIBE BASIN, ETHIOPIA" is my own original work. It has not been submitted for similar or any other degree award in any other University. All the sources I have used or quoted have been indicated and acknowledge by complete reference.

_______________ _______________

Signature Date

APPROVAL SHEET

The undersigned certify that the thesis entitled: “RAINFALL RUNOFF MODELING USING HYDRAULIC ENGINEERING CENTER HYDROLOGIC MODELING SYSTEM FOR GILGEL GIBE CATCHMENT, OMO GIBE BASIN, ETHIOPIA” is the work of Sewmehon Sisay. It has been accepted and submitted for examination with my approval as university advisor in partial fulfillment of the requirements for Degree of Master of Science in Hydraulic Engineering.

Advisor: Dr.-Ing. Tamene Adugna	____________ Signature	____________ Date
Co -advisor: Mr.Tolera Abdissa	____________ Signature	____________ Date

As member of Board of Examiners of the MSc.Thesis Open Defense Examination, we certify that we have read, evaluated the thesis prepared by Sewmehon Sisay and examined the candidate. We recommend that the thesis could be accepted as fulfilling the thesis requirement for the Degree of Master of Science in Hydraulic Engineering.

____________ External Examiner	____________ Signature	____________ Date
____________ Internal Examiner	____________ Signature	____________ Date
____________ Chair person	____________ Signature	____________ Date

ABSTRACT

Runoff is one of the most important hydrologic variables used in most of water resources applications. This study was conducted on Gilgel Gibe catchment which is one of the sub-catchments of Omo-Gibe basin located in Ethiopia. The catchment runoff is highly varying spatially and temporally due to manmade and natural influence on the catchment. On the other side, the increase in human need on river flow has put pressure on the water resources of the catchment. These issues needs efficient water resources planning and management which depends on accurate information on runoff generated from the catchment. Therefore, the objective of this study was to develop rainfall-runoff modeling for Gilgel Gibe catchment using Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). The input data used for this study were Spatial and hydro-metrological data collected from different sources. HEC-GeoHMS and Geographic information system (GIS) were used to determine the spatial distribution of Curve Number (CN) in the catchment. The result indicates that 68.75% of the catchment has weighted CN value between 81 and 90, 22.92% between 69 and 80 and 4% greater than 90. The combined effects of agricultural land use and the low infiltration capacity of the soil has caused the CN value to be relatively high in most part of the catchment. The weighted CN value of the catchment was used as input data for HEC-HMS model Daily stream flow data from year 1985 to 2002 was used for model calibration. Sensitivity analysis was conducted to determine the most sensitive parameter that affects the model. The selected parameters that were checked for model sensitivity were canopy storage, surface storage, Muskingum (K) and Muskingum (x). The result indicates that the model was more sensitive to Muskingum (K) and Muskingum(x).The performance of the model was measured by Root Mean square Error (RMSE), Nash- Sutclif Efficiency (NSE) and correlation coefficient (R^2) during calibration and validation period. The values of RMSE, NSE and R^2 were 30.81 m^3/s, 0.727 and 0.865 respectively during model calibration. The difference in simulated and observed peak discharge was 39.5 m^3/s. This indicates that the peak discharge was well predicted. The calibrated model was validated with new set of daily observed stream flow data from year 2003 to 2013. The RMSE, NSE and R^2values were 13.6 m^3/s, 0.873 and 0.914 respectively. There was a difference of 79.305 m^3/s between the observed and simulated peak discharge during model validation. This indicates the peak discharge was slightly under predicted. The validated model was used to estimate the daily runoff from the year 1985 to 2017. Therefore, HEC-HMS model has performed well in simulating the Gilgel Gibe catchment runoff. The daily average runoff potential of the catchment was 83.121 m^3/s. The temporal variation of Land use/land cover was not considered for this study. Therefore, further study should be conducted by considering the effect of land use/land cover change on runoff potential of the catchment.

***Key words**: Calibration; Gilgel Gibe catchment; HEC-GeoHMS; HEC-HMS; Runoff; Validation.*

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ACRONYMS

`AMC	Antecedent Moisture Condition
DEM	Digital Elevation Model
EMA	Ethiopia Metrological Agency
ESRI	Environmental System Resarch Institute
FAO	Food and Agriculture Organization
GIS	Geographic Information System
HEC-GeoHMS	Hydrologic Engineering Center geospatial Hydrologic Modeling System
HEC-HMS	Hydrologic Engineering Centre Hydrologic Modeling System
HSG	Hydrologic Soil Group
HR	Hour
Kpa	Kilo pascal
LU/LC	Land Use/Land Cover
m.a.s.l	meter above sea level
MJ	Mega Jule
MW	Mega Watt
MoWIE	Ministry of Water,Irrigation and Electricity
NMAE	National Metrological Agency of Ethiopia
NSE	Nash and Sutcliffe Efficiency
Pct	Percent
R^2	Coefficient of determination
RMSE	Root Mean Square Error
SCS-CN	Soil Conservation Service- Curve Number
SMA	Soil Moisture Accounting
UH	Unit Hydrograph
USACE	United State Army Corps of Engineers

1. INTRODUCTION

1.1 Back ground

“The term “rainfall-runoff” explains what “runoff?”is generated from a given “rainfall” on a given “watershed”.” It is one of the most essential hydrologic variables used in most of the water resources application (Gobena, 2010). Runoff is related to all hydro-metrological and watershed variables directly or indirectly. Any surface area from which runoff resulting from rainfall is collected and drained trough common confluence point is called watershed. It is synonymous with drainage basin or catchment. The term “modeling” represents the mathematical representation and used at different stage of the hydrologic components to relate the rainfall and other hydrological parameters of the watershed with the parameter of the runoff characteristics (Tufa and Hailu, 2011).

Rainfall-runoff relation is a complex phenomenon to represent it in a mathematical form, because it involves many parameter either physical feature of the catchment or climatic parameter. In real world system, rainfall-runoff process is affected by every physical characteristics of the catchment. Understanding all the physical characteristics of the catchment is the most complex task. This is due to insufficient hydrological parameters or their questionable quality and reliability (Chaudari, 2014). Due to this, it becomes a major challenge to predict a catchment runoff response to rainfall event (McColl and Aggett, 2006). Therefore the determination of a definite relationship between rainfall and runoff for a watershed has still become one of the major challenges for hydrologists, Engineers, and agriculturists (Mishra and Singh 2003).

Rainfall–runoff model represents the relationship between rainfall and runoff of a catchment. The runoff in the channel or river system as a response to rainfall input data for the target catchment will be estimated by the model. Numerous rainfall–runoff models and software programs are available, and each of them has their own advantages and disadvantages (Ramly, 2016). It is difficult to measure all parameters that affect catchment runoff. Therefore, it is essential to choose a model with simple structure, minimum input data requirements and reasonable precision (Beven, 2001). HEC-HMS is one of the physically based hydrologic models that meet these criteria.

Gilgel Gibe catchment is one of the sub-catchments of Omo Gibe basin. Amenu et al.(2010) has studied real- time inflow forecasting for Gilgel Gibe reservoir located in Gilgel Gibe catchment by HVB model. But there are no other rainfall-runoff modeling conducted in the catchment. Moreover, the accuracy of HEC-HMS in runoff simulation is not yet checked for this catchment. Therefore, the main objective of this study is to develop rainfall-runoff relationship of Gilgel Gibe catchment by HEC-HMS.

1.2 Statement of the problem

Water resources are the most important renewable resources for continued existence and development of a society. Water crisis particularly caused by shortages, floods and diminishing water quality, among others, are escalating in all parts of the world. The growth of population has caused to increase domestic, agricultural and industrial water consumption (Sileshi, 2010).

According to Teklu et al. (2016), the Gilgel Gibe catchment runoff is highly varying temporally and spatially due to manmade and natural interference in the catchment. Therefore, proper exploitation of water resources requires to asses and manages these resources both spatially and temporally.

The Gilgel Gibe I hydropower plant with a capacity of 184 MW was constructed on Gilgel Gibe River which found in the southwest part of Ethiopia. Gilgel Gibe II hydropower plant is also constructed downstream of Gilgel Gibe I hydropower plant with a capacity of 420MW.The water released from Gilgel Gibe I is used to generate power in Gilgel Gibe II. They are constructed with the aim of expanding the electric power generation capacity of the country (Amenu et al., 2010).The power production and expansion of development activity in the catchment has pressure on the water resources of the catchment.

Therefore, to further strengthen the assessment, management and planning of water resources in Gilgel Gibe catchment, the need for developing rainfall runoff relationship using appropriate rainfall-runoff modeling tool is indisputable.

Water resource professionals need planning tools for the successful utilization and to maximize water management efficiency (Ramly, 2016). According to Easton et al. (2010), it is the state of the art to use hydrologic models for the planning process of different kinds of water resources development projects. Currently, a number of rainfalls-runoff models exist for generation of flow and establishing a rainfall-runoff relationship using different time steps. However, in areas where data are sparsely and scarcely available, the practical solution is to apply semi distributed physically based rainfall-runoff models like HEC-HMS with fewer parameters. The performance of HEC-HMS in runoff simulation must be checked by the catchment physical parameters. It is not yet checked for Gilgel Gibe catchment.

1.3 Objective of the study

1.3.1 General objective

The general objective of the study is to develop Rainfall-Runoff modeling for Gilgel Gibe catchment using HEC- HMS.

1.3.2 Specific objectives

1. To determine the spatial distribution of curve number;
2. To evaluate the performance of HEC-HMS model in runoff prediction and
3. To determine the daily catchment runoff potential.

1.4 Research questions

1. What is the spatial distribution of curve number in Gilgel Gibe catchment?
2. What is the performance of HEC-HMS in runoff simulation of Gilgel Gibe catchment?
3. What is the daily runoff potential of the catchment?

1.5 Scope of the study

This study was conducted on Gilgel Gibe catchment on southwest part of Ethiopia at Oromiya regional state in jimma zone. The study area covered seven weredas of the catchment. These are Jimma Asendabo,shebe,Limu Genet,Sekoru,Omo_Nada and Dedo. It has a drainage area of 4218.46 Km^2.The main objective of the study was modeling rainfall and runoff using HEC-HMS. Under this, CN determination, HEC-HMS model performance evaluation and identification of daily catchment runoff were performed to achieve the main objective.

Due to Limited time and cost, detail site investigation on moisture condition of the catchment will not be conducted for this study. Therefore, the average moisture condition of the catchment was considered during the determination spatial distribution of curve number in the catchment. Moreover, the initial parameters of the models were not obtained directly from the field. They were computed from the theoretical knowledge of these parameters. The performance of the model was not checked by all the model parameters. The selected model parameters were those that affect the selected that affect the selected loss model, base flow model and routing model.

1.6 Significance of the study

Modeling rainfall runoff in the catchment will be used for sustainable water resources management in the catchment. The study will also provide valuable information for planning future watershed management.

The evaluation of HEC-HMS model performance is used for future stream flow forecasting under LU/LC and climate change by the model. Moreover the model can be used for hydrological modeling and stream forecasting of other un-gauged catchment with similar physical characteristics.

2. LITERATURE REVIEW

2.1 Rainfall and Runoff relation ship

Rainfall is known as the main contributor to the generation of surface runoff. Therefore there is a significant and unique relationship between rainfall and surface runoff.

There are specific factors which have a direct bearing on the occurrence and volume of runoff. The most common factor is the soil type. The infiltration capacity is dependent on the porosity of a soil which determines the water storage capacity and affects the resistance of water to flow into deeper layers. Porosity differs from one soil type to the other. The highest infiltration capacities are observed in loose sandy soils while heavy clay or loamy soils have considerable smaller infiltration capacities (Subermaniya, 2008).

Another factor that can affect the runoff production is vegetation. An area which is densely covered with vegetation produces less runoff than bare ground while the amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage.

Slope also influence the generation of surface runoff. Steep slopes in the headwaters of drainage basins tend to generate more runoff than the lowland areas. On gentle slopes, water may temporarily pond and later infiltrate. But in mountain sides, water tends to move downward more rapidly. Soils tend to be thinner on steep slopes, limiting storage of water, and where bedrock is exposed little infiltration can occur. However, in some cases, accumulation of coarse sediment at the base of steep slopes soak up runoff from the cliffs above, turning into subsurface flow (Gautam et al., 2014).

Size of catchment may have an effect to the runoff generation in terms of the runoff efficiency (volume of runoff per unit area). The larger the size of the catchment, the larger is the time of concentration and the smaller the runoff efficiency (Chow et al., 1988).

2.2 Curve number

A curve number (CN) is an index developed by the Soil Conservation Service (SCS) now called the Natural Resource Conservation Service (NRCS), is used to estimate the amount of rainfall that infiltrates into the soil and the amount of surface runoff. It is first developed for agricultural watersheds and then it was consequently used in urban areas to represent the potential for storm water runoff within a drainage area (Mishra and Singh, 2004).

The CN for a drainage basin is estimated using a combination of land use, soil, and antecedent soil moisture condition (AMC). There are four hydrologic soil groups: A, B, C and D. Group A have high infiltration rates and group D have low infiltration rates (Berhanu et al., 2013).

The Soil Conservation Service Curve Number (SCS-CN) method is widely used for predicting direct runoff volume for a given rainfall event.The main reasons for its success is that it accounts for many of the factors affecting runoff generation including soil type, land use and treatment, surface condition, and antecedent moisture condition, incorporating them in a single CN parameter (Mishra and Singh, 2004).

A CN of 100 represents a limit condition for a perfectly impermeable basin with zero retention, where all the rainfall becomes runoff. A CN of zero conceptually represents the other extreme, with the basin trapping all the rainfall with no runoff regardless of the rainfall amount (Halwatura, 2013).

2.3 Hydrologic cycle

Water does not remain locked up in the oceans, icecaps, groundwater system or the atmosphere. Instead, water is constantly moving from one reservoir to another. This movement of water is called the hydrologic cycle. It consists of various unsteady processes occurring either in the atmosphere or beneath the earth's surface (Viessman et al., 2003).

The hydrologic processes by which water moves through the hydrologic cycle includes atmospheric movement of air masses, precipitation, evaporation, transpiration, infiltration, percolation, groundwater flow, surface runoff and streamflow (Baharudin,2007).Major components of the hydrologic cycle that have relation with run off generation,are discussed below.

2.3.1 Precipitation

Precipitation is water that reaches the earth from the atmosphere in the form of rainfall, snow, hail, frost and dew. Rainfall being the predominant forms of precipitation causing stream flow.

For a precipitation to form, there must be sufficient nuclei present to avoid condensation, weather condition must be good for the condensation of water vapor to takes place and the product of condensation must reach the earth (Subermaniya, 2008).

Precipitation as a function of time and space is highly variable. Systematic averaging methods such as thiessen polygon, isohyets and reciprocal distance methods have been developed to account for variations in space to obtain a representation of areal precipitation values from point observation (S.K Garg, 2005).

2.3.2 Interception

This is the process by which rain water is temporarily retained on leaves and stems of plants, roofs and other surfaces that are above the ground and are capable of holding water. In particular for rural catchments the interception of water by vegetation is of prime importance. According to Chow et al. (1988), the following items are needed to be considered to describe the interception process mathematically in the overall phenomenon these are: Storage on leaves and stems of plants, Evaporation of stored water and Dripping of water from leafs and stems.

2.3.3 Infiltration

Infiltration is the flow of water in to the ground through the soil surface. When water is applied at the surface of a soil, four major zones in the soil can be identified as follow.

Zone1 is the saturated zone at the top of the soil surface.

Zone2 is the transition zone.

Zone3 is the transmission zone where down ward motion of moisture takes place the moisture content in this zone is above field capacity but below saturated capacity.

Zone 4 is the wetting zone the soil moisture in this zone will be at near field capacity and moisture content decreases with depth.

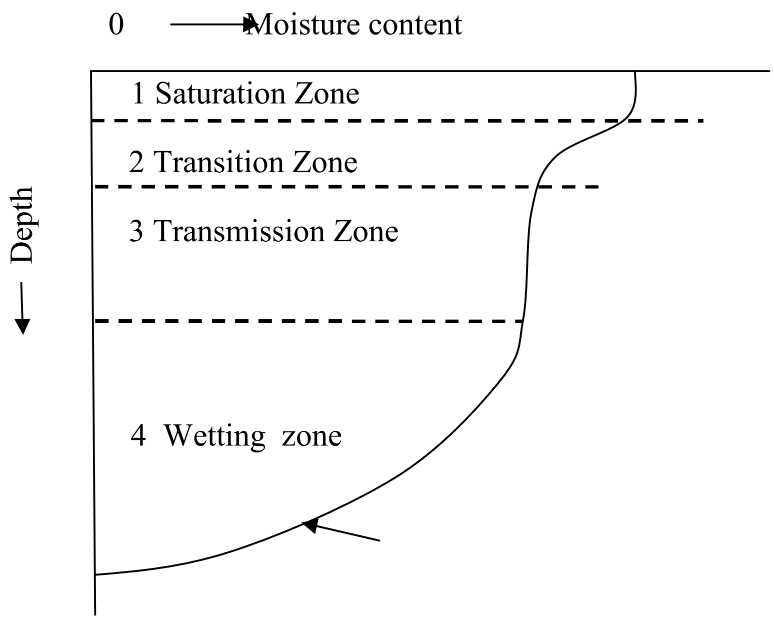

Figure 2. 1: Distribution of soil moisture in the infiltration process (source: Subermaniya, 2008)

The maximum rate at which a given soil at a given time can absorb water is known as infiltration capacity. It depends up on soil characteristics, vegetation cover, soil temperature and Current moisture content.

2.3.4 Evaporation and transpiration

The combined process of evaporation from the soil and transpiration from the plant is called evapotranspiration (S.K Garg, 2005). Catchment evaporation demand is generally defined as that evaporation which would occur if there were no deficiencies in the availability of moisture for evapotranspiration by that area's particular plant regime.

The amount of water that can theoretically evaporate (if water is not a limiting factor) is called Potential evaporation. The evaporation that takes place when water is a limiting factor is called actual evaporation. Similar nomenclature can be applied to evapotranspiration (Chow et al., 1988).

There are number of methods to estimate potential evapotranspiration. However, the methods vary based on climatic variables required for calculation. The temperature based method uses only temperature and sometimes day length while the radiation based method uses net radiation and air temperature. The modified FAO Penman_Monteith method considers more parameter.

2.3.5 Runoff

Runoff is the draining or flowing of precipitation from the catchment area through surface channel. It represents the output from a catchment in a given unit of time.

For a given precipitation, the evapotranspiration, initial loss, infiltration and detention storage requirement will have to be first satisfied before the commencement of runoff. When these are satisfied, the excess precipitation moves over the land surface to reach smaller channel. This portion of the runoff is called overland flow. Usually, the length and depth of overland flow is smaller and the flow is laminar regime (Baharudin, 2007).

Flow from several smaller channel join bigger channel and flow from this intern combine to form larger stream and so on till the flow reaches the catchment outlet. The flow traveling over the surface in the form of over land flow through channels as open channel flow reaches the catchment outlet is called surface runoff. Part of the precipitation that infiltrates and moves laterally through upper crest of the soil and returns to the surface at some location away from the point of entry in to the soil is called interflow. Another route for infiltrated water is to undergo deep percolation and reaches the ground storage in the soil. This part of runoff is called ground water flow.

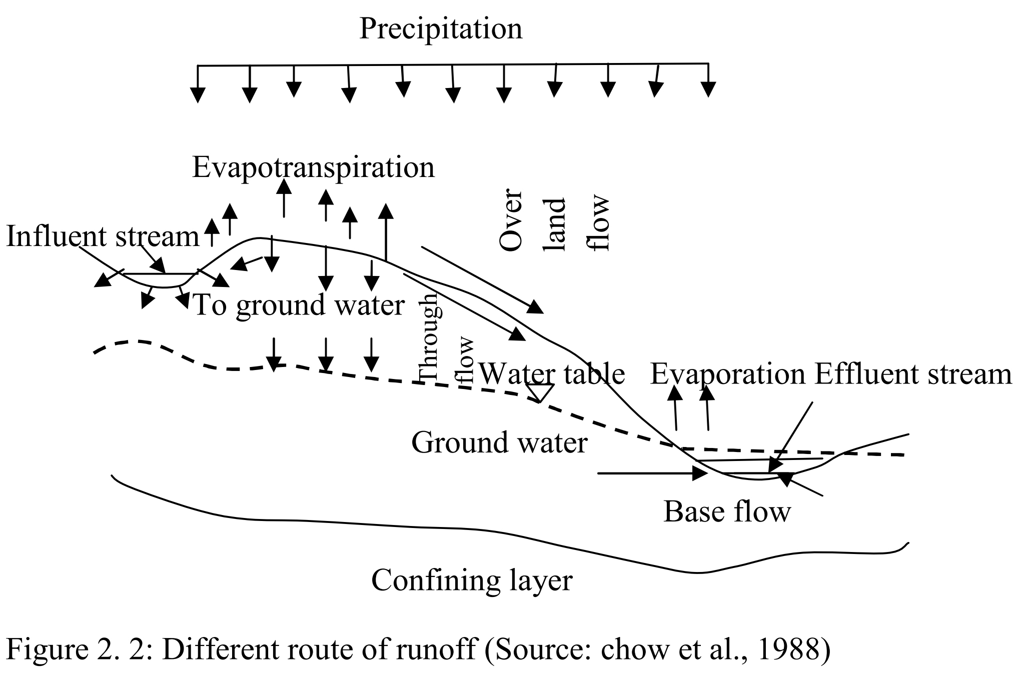

Figure 2. 2: Different route of runoff (Source: chow et al., 1988)

Based on the time delay between the precipitation and the runoff, the runoff is categorized in to two categories as (1) Direct runoff and (2) Base flow.

Direct runoff is part of runoff which enters the stream immediately after the rain fall. Base flow is the delayed flow that reaches a stream essentially as groundwater flow. Many times delayed interflow is also included under this category. In the annual hydrograph of a perennial stream the base flow easily recognized as the slowly decreasing flow of the stream in rainless periods (Subramanya, 2008).

2.4 Catchment water balance

According to Bolesław(2009), the water balance of a given catchment can be generalized by the equation:

$$I - O = \Delta S \qquad (2.1)$$

Where:

I = input to the catchment.

O = output from the catchment.

ΔS = change in storage in the catchment.

Rainfall, mist, fog, snowmelt, surface flow (run-on), sub-surface lateral flow, stream flow and groundwater inflow are input components to the catchment. Outputs from a catchment are generally considered to be stream/river flow, surface evaporation, transpiration, surface run-off, subsurface flow and groundwater movement. Storage of water can take place in soil, groundwater, lakes, rivers and in vegetation (Apgaua, 2015).

2.5 Hydrological models

According to the mathematics of the model, hydrological model can be divided in to deterministic and stochastic model.

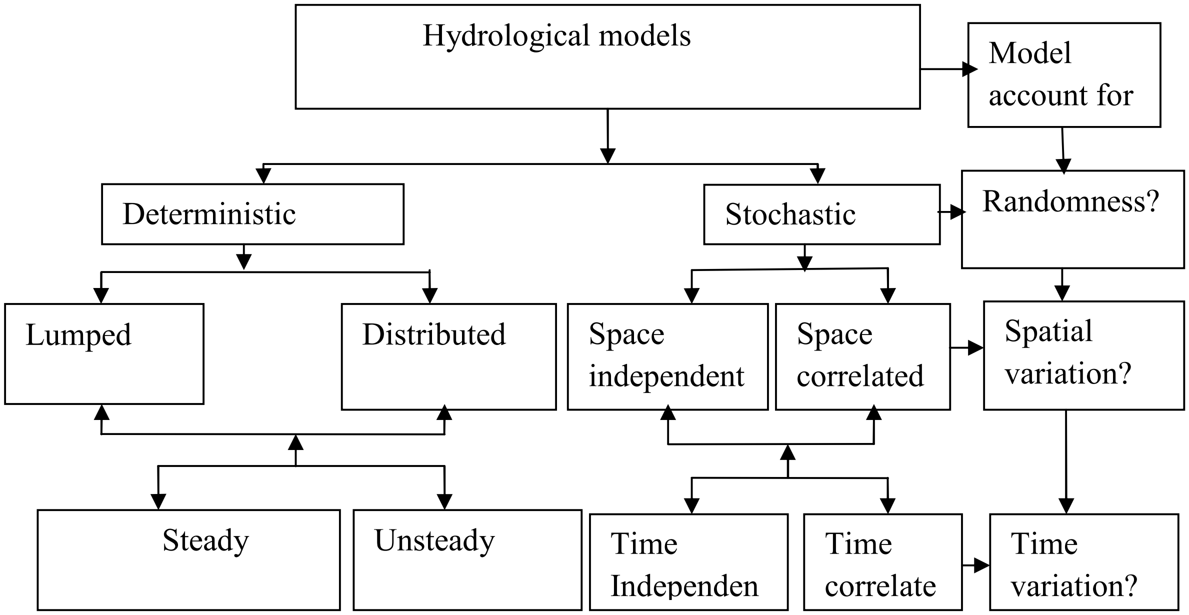

Figure 2. 3: Classification of hydrological models according to process description

2.5.1 Deterministic models

Deterministic models permit only one outcome from a simulation with one set of inputs and parameter values. There are three main groups of deterministic models (Lastoria, 2008).These are empirical models (black box), lumped conceptual models (grey box) and physically based distributed models (white box).

i. Empirical (black Box) models

They are empirical, involving mathematical equations that have been assessed from analysis of concurrent input and output time series.

ii. Lumped conceptual (grey box) models

Lumped models treat the catchment as a single unit with state variables that represent average values over the catchment area in the saturated zone. The model parameters cannot usually be assessed from field data alone, but they have to be obtained through the help of calibration.

These models are not applicable to event based processes and discharge is predicted at outlet only, but it is simple, requires minimal data and easy to use (Lastoria, 2008). Examples of lumped conceptual models are SCS-CN based models, IHACRES, WATBAL and etc.

iii. Distributed process description based(white box) models

Models of this type have the possibility of defining parameter values for every element in the solution mesh. They give detailed and potentially more correct description of the hydrological processes in the catchment than do the other model types. Recent examples of distributed process based models are MIKE11/SHE, WATFLOOD and etc.

iv. Semi- distributed model

In semi distributed models, parameters are partially allowed to vary in space by dividing the basin in to smaller sub-basins. According to Lastoria (2008), there are two types of semi-distributed models. These are kinematic wave theory models which are simplified version of surface flow equation of physically based model and probability distributed models.

In probability distributed models, spatial variation is accounted for by using probability distribution of input parameters across the basin structure. It is more physically based than lumped models and they are less demanding in input data than distributed models. Example: SWMM, HEC- HMS, TOPMODEL, HYDROTEL, SWAT and etc.

2.5.2 Stochastic time series models

Stochastic models allow for some randomness or uncertainty in the possible outcomes due to uncertainty in input variables, boundary conditions or model parameters. In this model, several synthetic series with identical statistical properties are generated. These generated sequences of data can then be used in the analysis of design variables and their uncertainties.

2.6 Hydrological model selection criteria

(Beven, 2001) has stated four criteria for selecting model structure as shown below.

1. Cosider models which are readily available and whose investment of time and money appeared meaningful.
2. Decide whether the model under consideration will produce the output needed to meet the objectives of a particular project.
3. Prepare a list of assumptions made by the model and check the assumptions likely to be limiting in terms of what is known about the response of the catchment.
4. Make a list of the inputs required by the model and decide whether all the information required by the model can provide within the time and cost constraints of the project.

Therefore, the semi-distributed physically based hydrological model (HEC-HMS) was selected based up on the above criteria to model the rainfall -runoff relationship of Gilgel Gibe catchment.

2.7 HEC-HMS model

HEC-HMS is the United States Army Corps of Engineers‟ hydrologic system computer program developed by the Hydrological Engineering Center (Feldman, 2000). It is numerical and semi -distributed conceptual hydrologic model. It includes large sets of method to simulate watershed, channel and water control structure behavior. Thus, predicting flow, stage and time.

HEC-HMS is designed for both continuous and event-based hydrologic modeling. It provides the user with several different options for modeling various components of the hydrologic cycle. Event-based modeling uses a smaller simulation time steps. This may be several hours to several days depending on watershed size. Continuous modeling has a much larger time window. It includes dry and wet periods, typically ranging from months to several years.

Evapotranspiration and groundwater seepage can typically be ignored for event based modeling, but they can be considered in continuous modeling because these are critical processes of soil drying (Scharffenberg and Fleming, 2010).

2.7.1 Limitations of HEC-HMS model

Every simulation system has limitations due to the choices made in the design and development of the software (Scharffenberg and Fleming, 2010).The limitations that arise in HEC-HMS program are due to two aspects of the design. These are simplified model formulation and simplified flow representation.

i. Model formulation

Simplifying the model formulation allows the program to complete simulations very quickly while producing accurate and precise results. However, it has brought the following major limitations on the program.

All of the mathematical models included in the program are deterministic. This means the boundary conditions, initial conditions and parameters of the models are assumed to be exactly known (Roy et al., 2013). This guarantees that every time a simulation is computed, it will yield exactly the same results as all previous times it was computed.

Deterministic models are sometimes compared to stochastic models where the same boundary conditions, initial conditions and parameters are represented with probabilistic distributions. According to USACE (2010), Plans are underway to develop a stochastic capability through the addition of a Monte Carlo analysis tool.

All of the mathematical models included in the program use constant parameter values, that is, they are assumed to be time stationary (Roy et al., 2013). During long periods of time, it is possible for parameters describing a watershed to change as the result of human or other processes at work in the watershed. These parameter trends are not included in a simulation at this version of HEC-HMS.

There is a limited capability to break a long simulation in to smaller segments and manually change parameters between segments. According to USACE (2010), Plans are underway to develop a variable parameter capability.

All of the mathematical models included in the program are uncoupled. For example, the program first computes evapo-transpiration and then computes infiltration (Halwatura, 2013). In the physical world, the amount of evapo-transpiration depends on the amount of soil water. The amount of infiltration also depends on the amount of soil water. However, evapo-transpiration removes water from the soil at the same time infiltration adds water to the soil. To solve the problem properly, the evapo- transpiration and infiltration processes should be simulated simultaneously. It can be done by developing mathematical equations that links both processes numerically.

This program does not currently include such coupling of the process models. Errors due to the use of uncoupled models are minimized as much as possible by using a small time interval for calculations (Scharffenberg and Fleming, 2010). According to USACE (2010), Preparations have been made to support the inclusion of coupled plant-surface-soil models; none have been added at this time.

ii. Flow representation

Even though simplifying the flow representation aids in keeping the compute process efficient and reduces duplication of capability in the HEC-HMS software suite, it has the following major limitations.

The design of the basin model only allows for dendritic stream networks (Scharffenberg and Fleming, 2010). The best way to visualize a dendritic network is to imagine a tree. The main tree trunk, branches and twigs correspond to the main River, tributaries and headwater streams in a watershed. The key idea is that a stream does not separate into two streams.

The basin model allows each hydrologic element to have only one downstream connection. Hence, it is not possible to split the outflow from an element into two different downstream elements. The diversion element provides a limited capability to remove some of the flow from a stream and divert it to a different location downstream in the network. Likewise, a reservoir element may have an auxiliary outlet. However, in general, branching or looping stream networks cannot be simulated with the program and will require a separate hydraulic model which can represent such networks (Majidi et al., 2012).

The design of the process for computing a simulation does not allow for backwater in the stream network. The compute process begins at headwater sub-basins and proceeds down through the network. Each element is computed for the entire simulation time window before proceeding to the next element. There is no iteration or looping between elements. Therefore, it is not possible for an upstream element to have knowledge of downstream flow conditions which is the essence of backwater effects.

There is a limited capability to represent backwater if it is fully contained within a reach element (Sok et al., 2016). However, in general, the presence of backwater within the stream network will require a separate hydraulic model.

2.7.2 Inter-connection of Arc GIS with HEC-HMS model

GIS is a system, usually computer based, for the input, storage, retrieval, analysis and display of interpreted geographic data. The database is typically composed of map-like spatial representations often called coverage or layers. These layers may involve a three dimensional matrix of time, location and attribute or activity. A GIS may include Digital line graph data, DEM, geographic names, land-use characterizations, land ownership, land cover, registered satellite and etc (Saleh et al., 2011). Various spatial data are pre-processed using ArcGIS which are used as input data for HEC-HMS model.

The power and speed of the program make it possible to represent watersheds with hundreds of hydrologic elements. Traditionally, these elements would be identified by inspecting a topographic map and manually identifying drainage boundaries direction matrix, ranked elevation matrix and flow accumulation matrix (Silva and Taylor, 1999). While this method is effective, it is prohibitively time consuming when the watershed will be represented with many elements.

GIS can use elevation data and geometric algorithms to perform the same task much more quickly. A GIS companion product was developed to aid in the creation of basin models for such projects. It is called the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS). It can be used to create basin and meteorological models for use with the program (Saleh et al., 2011).

2.8 HEC-GeoHMS model

The Geo-spatial Hydrologic Modeling Extension (HEC-GeoHMS) is a software package that can be used with the ArcGIS. It uses ArcGIS and Spatial Analyst to develop a number of hydrologic modeling inputs. It can be used to analyze digital terrain information. HEC-GeoHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. In addition to this, capabilities include the development of grid-based data for linear quasi- distributed runoff transformation, the HEC-HMS basin model and background map file. It helps to extract all necessary data to create the HEC-HMS project (Fleming and Doan, 2009).

HEC-GeoHMS uses the terrain pre-processing dataset for the drainage area upstream specified outlet to run the flow analysis (Ramley et al., 2016). It can be used to refine the sub-basin and stream delineations, extract physical characteristics of sub-basins and streams, estimate model parameters and prepare input files for HEC-HMS. The connectivity of ArcGIS, HEC-GeoHMS and HEC-HMS was summarized by Figure 2.4.

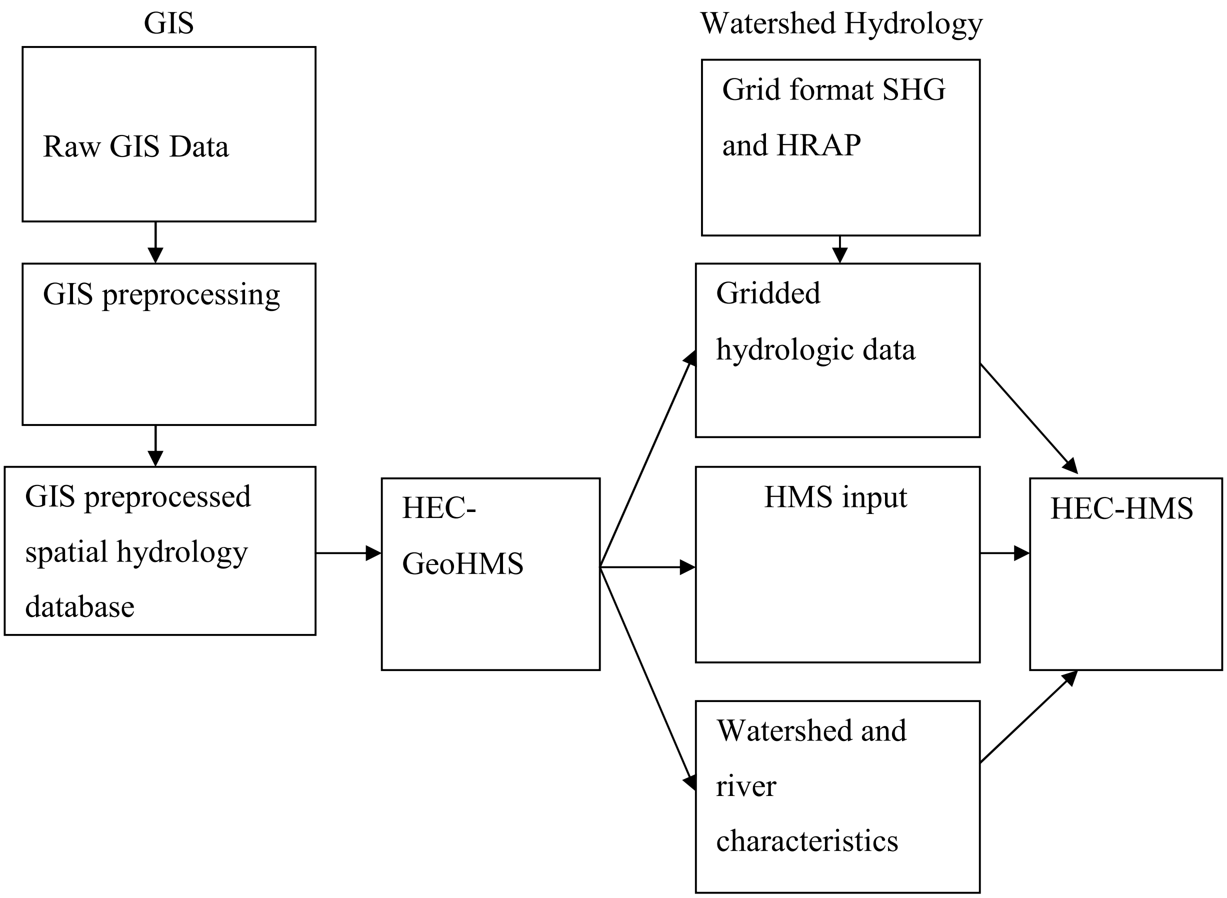

Figure 2. 4: Schematic diagram showing the connectivity of GIS, HEC-HMS and HEC-GeoHMS (Source: Fleming and Doan, 2009)

2.9 Previous studies

There is no rainfall-runoff modeling using HEC-HMS conducted on Omo Gibe basin (including Gilgel Gibe catchment). However there are little rainfall-runoff modeling that are conducted using HEC-HMS in Ethiopia. Some of them are described as follow.

Ayenew and Legesse (2008) developed rainfall- runoff model for sustainable water resources management on the gauged part of Gumara watershed. Simulation was done for a period of 5 year. The simulated peak discharge was 578.9 m^3/s. While, the observed discharge was 256.9 m^3/s which has a difference of 322 m^3/s.

Based on the result, the author has concluded that data scarcity (2001-2005) made calibration difficult to best fit the simulated model obtained using calibration and validation with observed value.

Gebre (2015) has used HEC-HMS with soil moisture accounting algorithm for runoff simulation of upper Nile river basin. The model was calibrated (from 1988-2000) and validated (from 2001-2005). The result obtained was satisfactory and accepted for simulation of runoff.

3. MATERIALS AND METHODS

3.1 Description of the study area

Gilgel Gibe catchment is one of the sub catchment of Omo Gibe basin which is one of the major river basins in Ethiopia. Geographically, the catchment lies between 7º19′ 07.15″ and 8º12′09.49″ North latitudes and 36º31′42.60″ and 37º25′16.05″ East longitudes. Figure 3.1 indicates the location of the study area in detail.

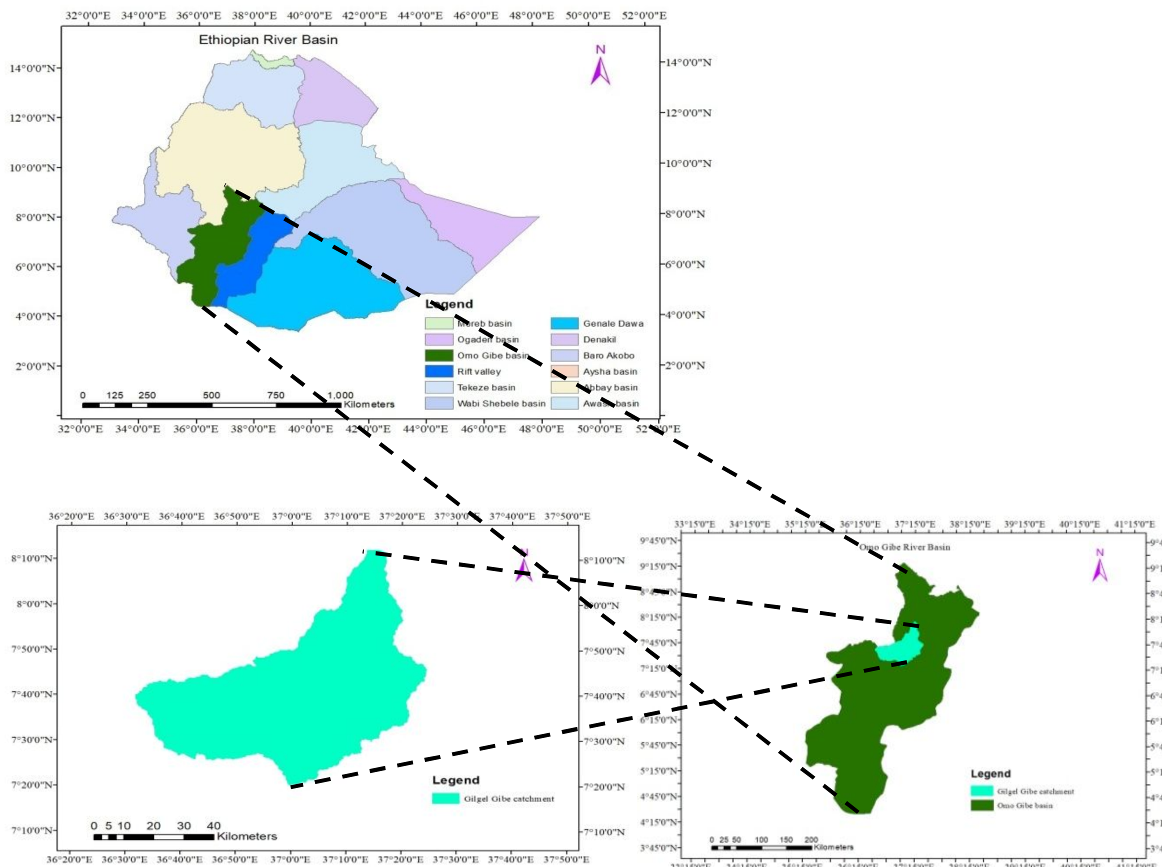

Figure 3. 1: Location map of the study area

The catchment is generally characterized by rough topography with upper platue that are cut by deep V-shaped valley in flank and flat river terraces around the river in the center of the catchment. It has an average elevation of about 1700 m a.m.s.l (Tesfay, 2017).

The catchment has a sub-humid warm to hot climate. It receives annual rainfall between 1300 mm-1800 mm and an average temperature of 19.2 °C.

According to FAO (1986), soil classification system, the study area has 7 major soil types. These are Chromic vertisols,Dystric fluvisols,Dystric nitisols,Eutric cambisols,Eutric fluvisols, Eutric nitisols and Orthic acrisols. In terms of coverage area, Eutric fluvisols is the dominant soil type .It covers 34% of the area. The minimum area of the catchment is covered by Eutric cambisols which occupy 0.065% of the study area.

Major types of LU/LC of the study area are agricultural, forestry, grass land, urban and water bodies. Almost all land has been taken into cultivation. Agriculture is the dominant land use of the area. Wheat, teff, barley, sorghum, faba bean, maize and coffee are the major types of crops which are grown in the study area. The total area covered by forest is only 15.5%. However, this is mainly bush vegetation which is extensively used by the farmers. Only the highest part of the study area is still covered by forest

3.2 Material used during the study

Major types of software used for this study were ArcGIS, HEC- GeoHMS, HEC-HMS and HEC-DSSVue. Additionally, Microsoft excel sheet, Rain bow and XlSTATE2018 were used.

ArcGIS version10.1, which is public domain software, was developed by ESRI. It was released in June 2012.This version was selected because it was compatible with HEC-GeoHMS version 10.1. It was used for spatial data analysis and terrain preprocessing.

HEC-GeoHMS version 10.1 was developed by HEC. HEC is an organization within the institute for water resources . It is the designated center of expertise for the USACE in the technical areas of hydrology, river hydraulics and sediment transport, hydrologic statistics and risk analysis and reservoir system analysis. This version was tested, verified and released by HEC in August, 2016. Newer versions of HEC-GeoHMS are available, but except HEC-GeoHMS 10.2, they are not supported by HEC. Therefore, HEC-GeoHMS version 10.1 was selected for this study. It was used for preparation of basin model and curve number generation.

HEC-HMS version 4.2 was used for rainfall-runoff simulation. It was developed by USACE and released in August, 2016. It is the recent version with several modifications to HEC-HMS version 4.1. Several new features have been added to the forecast alternatives to assist with setting initial conditions. A new probability distribution function has been added to the uncertainty analysis. Also new evaporation method has been added to the metrological model.

HEC-DSSvue version 2.0 is other major software used for this study. It was also developed by USACE and released in February, 2010. It is a java based visual utilities program that was used to plot, tabulate, edit and manipulate data in a HEC-DSS database file.

Additional software used during this study were Rain bow to test the homogeneity of rainfall data, Microsoft excel sheet for time series data analysis and XLSTATE2018 to fill the missing Hydro-metrological data.

3.3 Study design

Data input, process and analysis are the general procedures followed to achieve the objectives of this study. The overall frame work of the methodology followed throughout the study is shown in Figure 3.2.

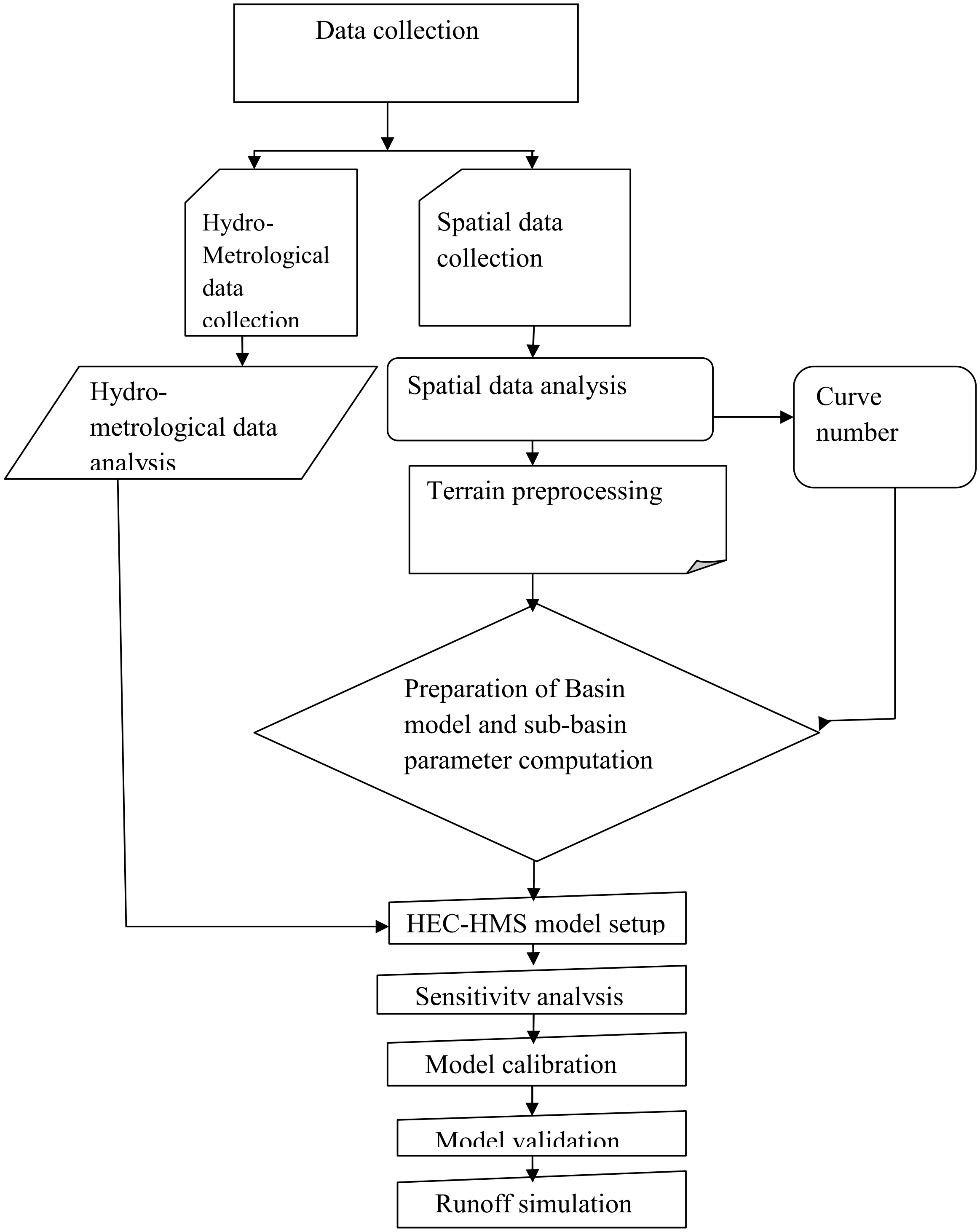

Figure 3. 2: Simplified representation of methodology flow chart

3.4 Data collection

Input data used for rainfall-runoff modeling and basin's water resources assessment can be categorized in to two. These are spatial data and physical data. Soil, LU/LC and DEM are categorized under spatial data, whereas metrological and hydrological data can be categorized under physical data (Atnafu and Niguse, 2015).

The HEC-HMS model requires metrological and hydrological input data at daily time step for daily runoff generation. The metrological data required for the study are minimum temperature, maximum temperature, precipitation, relative- humidity, wind speed and sunshine hours. Metrological data from 1985 to 2017 for 7 stations (Asendabo,Dedo,Jimma,Omo_Nada,Limu Genet and Sekoru) were collected from the NMAE .Metrological stations in and around the catchment were selected based on the number of missed data. A station having 85% of full recorded data were selected for this study. The spatial distribution of the selected metrological stations is shown in Figure 3.3.

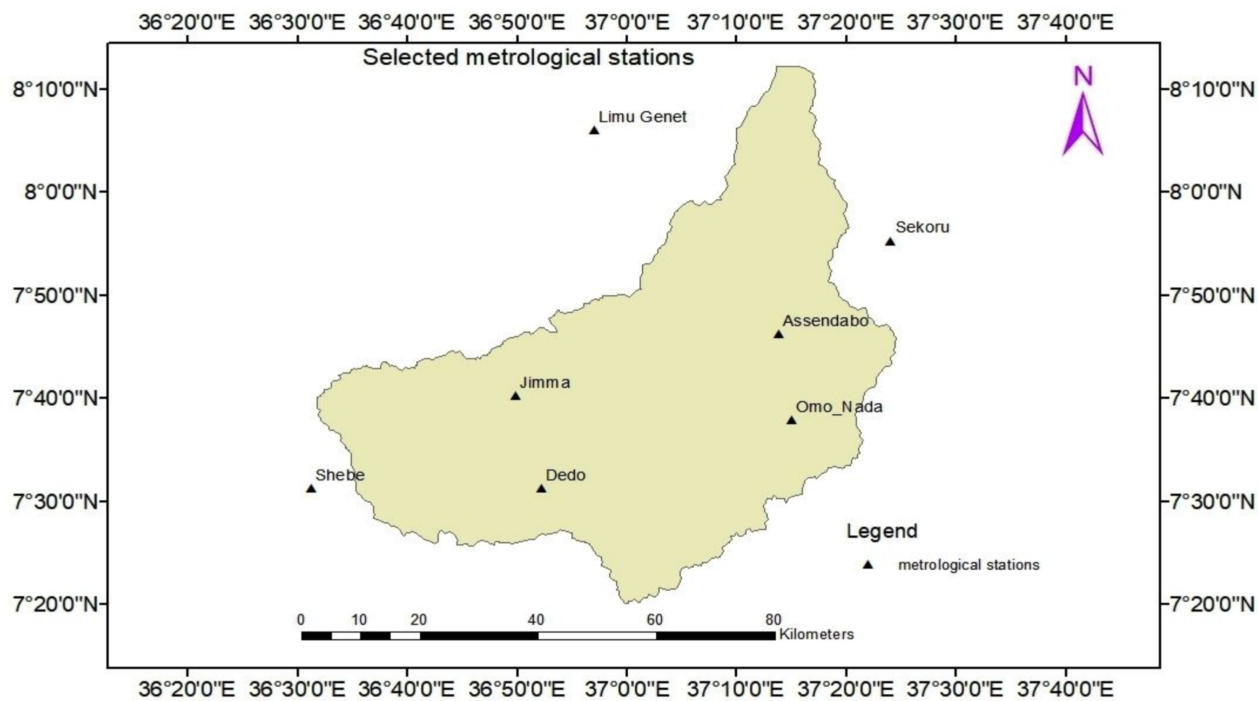

Figure 3. 3: Selected metrological stations

Table 3. 1: Summary information of the metrological stations

SNO.	Station name	Latitude (deg)	Longitude (deg)	Elevation(m)	Duration(year)	Missed data (%)
1	Sekoru	7.92	37.42	1928	1985-2017	12.5
2	Limu Genet	8.07	36.95	1766	1985-2017	7.8
3	Asendabo	7.75	37.22	1764	1985-2017	5.5
4	Jimma	7.7	36.82	1718	1985-2017	4.4
5	Dedo	7.52	36.87	2210	1985-2017	8.5
6	Omo_Nada	7.62	37.25	1838	1985-2017	10.65
7	Shebe	7.5	36.52	1813	1985-2017	13.5

The hydrological data used for this study is a daily streamflow for model calibration and validation. Daily streamflow data from 1990 to 2015 at Bidru Awana near Sekoru and from 1985 to 2015 for Gilgel Gibe near Asendabo was collected from the hydrology department of MOWIE.

A pixel size of 30 mx30 m DEM for the whole Omo Gibe basin was obtained from the GIS department of MOWIE. However, higher resolution DEM is preferred to study the hydrological response of a basin. Therefore, a DEM that has 12.5 m x12.5 m pixel size covering the entire study area was obtained from https://vertex.daac.asf.alaska.edu. Figure 3.4 indicates the DEM of the study area obtained from this site.

LU/LC data prepared in 2013 and Soil data for Omo Gibe basin was taken from EMA and GIS department of MOWIE respectively.

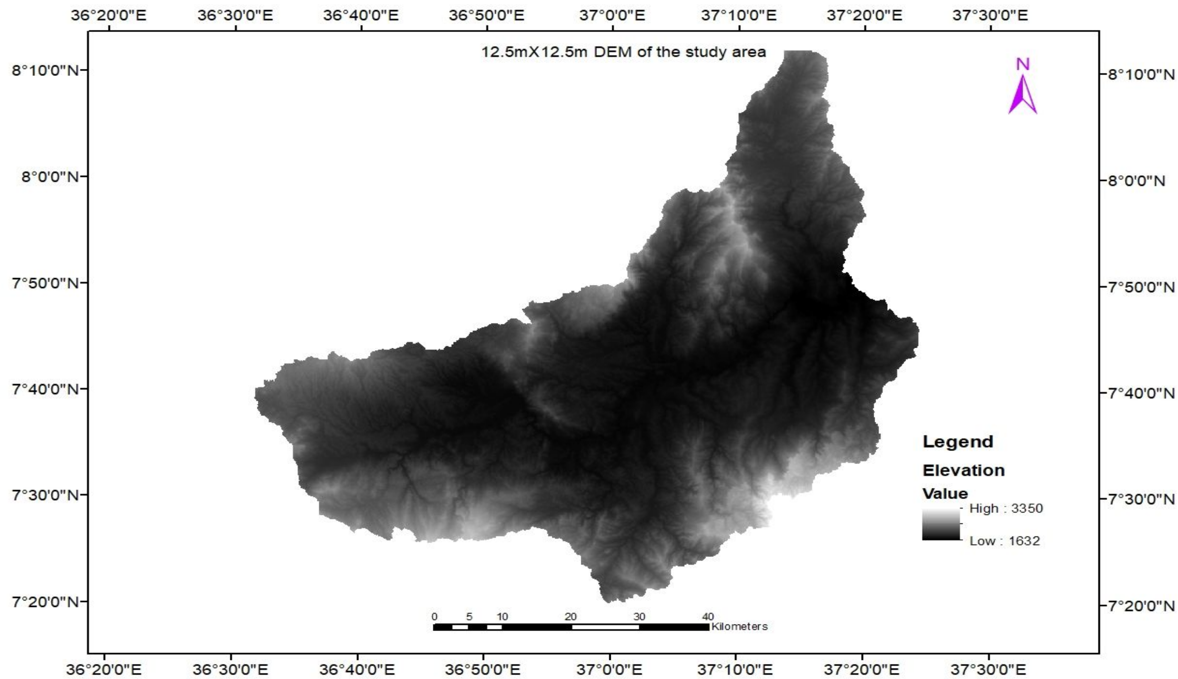

Figure 3. 4: DEM of the study area

3.5 Data analysis

3.5.1 Spatial data analysis

The study area's LU/LC was extracted from LU/LC of Omo Gibe basin. The study areas soil was also extracted from the soil data of Omo Gibe basin. Land surface slope of the catchment was computed (in degrees) using ArcGIS. To get insight on the variation of catchment responses owing to slope difference between the watersheds, slope of the catchment was reclassified to a gentle (0 – 9), steep (9 – 20) and excessive (> 20). The classification was based on Slope classes defined by Scott and Hofer (1995) (As cited in Tufa and Hailu, 2011). Slope analysis indicates that 52.3% of the catchment has gentle slope, 37.3% steep slope and 10.5% excessive slope.

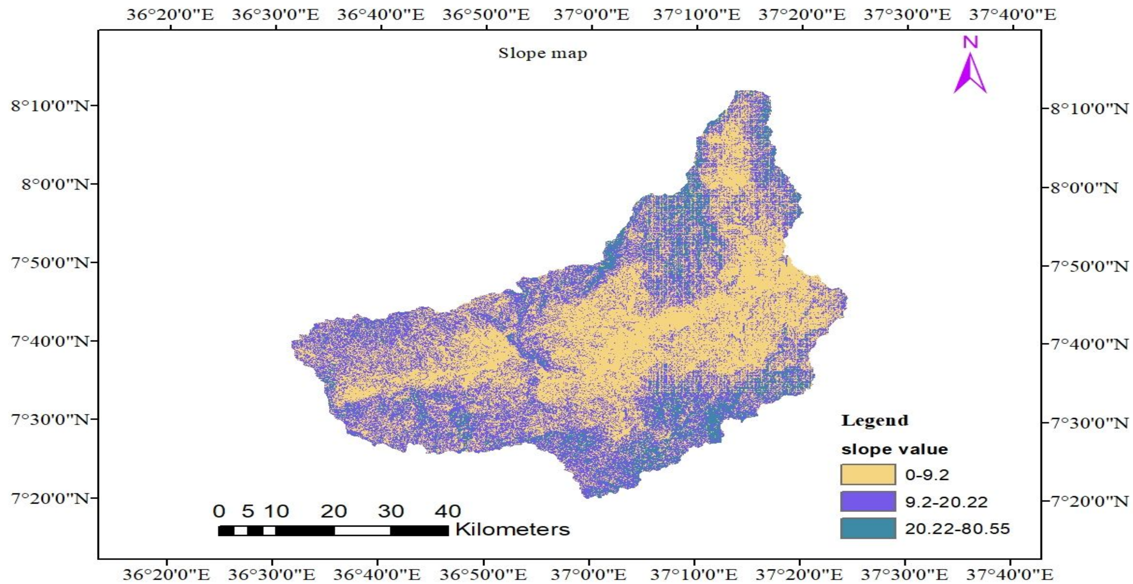

Figure 3. 5: Slope classes of Gilgel Gibe catchment

3.5.2 Metrological data analysis

3.5.2.1 Filling missing rainfall data

The continuity of the record may be broken with missing data due to failure of the observer to take reading at regular interval, vandalism of the recording gauges and instrumental failure. The rainfall data taken from the seven stations has missing data ranging from 4.4% to 13.5%. Therefore, it is required to estimate these missing records before undertaking further data analysis.

The arithmetic average, normal ratio and linear regression method was used to fill the missing rainfall data. When the average annual precipitation at the adjacent gauges differed from the average annual precipitation at the considered gauge by less than 10%, arithmetic average method was used. In this method, missing data is obtained by computing the arithmetic average of the rainfall data recorded nearest to the considered gauge (Dereje, 2015). Mathematically, arithmetic average method can be expressed as;

$$p_x = \frac{p_{1}+P_2+\cdots P_m}{M} \qquad \text{...3.1}$$

If the average annual rainfall at any of the adjacent gauges and the considered gauge is greater than 10% a normal ratio method was used. Mathematically, normal ratio method can be expressed as:

$$p_x = \frac{N_X}{M}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \cdots + \frac{P_m}{N_m}\right] \quad \text{...3.2}$$

Where:

N_1, N_2, N_3&N_m represent the average annual rainfall at station 1, 2, 3 & m respectively

P_1, P_2&P_m observed daily precipitation data for station 1, 2, 3 & m respectively

N_x represents the average annual rainfall at the missing station

P_x represents the required daily precipitation value at the missing station

M represents the number of station

The estimated data is considered as a combination of parameters with different weights from the surrounding gauges.

Linear regression is used for modeling relationship between scalar dependent variable denoted by Y and one independent parameter denoted by X. Model that depends on linearly on their unknown parameters are easier to fit than model that are linearly related to their parameter because the statistical parameters are easier to determine (Tesfaye and Chane,2011).

Mathematically, the correlation coefficient can be expressed as:

$$R^2 = \frac{a\sum Y + b(\sum XY) - \frac{1}{N}(\sum Y)(\sum Y)^2}{\sum Y^2 - \frac{1}{N}(\sum Y^2)} \quad \text{...3.3}$$

a Denotes the slope of the linear equation $Y = aX + b$ ...3.4

$$a = \frac{\sum Y - b\sum X}{N} \quad \text{...3.5}$$

b Denotes the y intercept of the above equation which is given by

$$b = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum Y^2)} \quad \text{...3.6}$$

X and Y denotes the two neighboring gauges having missed and observed daily rainfall

N denotes the number of observed daily rainfall from the two neighboring gauges

If the there is no observed rainfall data simultaneously at more than three stations and if the correlation coefficient (R^2) of the two station's rainfall data is greater than 0.7, linear regression method was used.

The computation of arithmetic average, normal ratio and linear regression was done using Microsoft excel sheet and XLSTAT.

3.5.2.2 Rain fall data test for record consistency

If the characteristic of the recorded data have not changed with time, it is called consistent record. However, if the characteristics of the recorded data vary with time, it is called inconsistent record. Inconsistency may occur due to change in observation procedures, exposure of the gauge and land use. Adjustment of measured data is important to obtain a consistent data. It involves the estimation of effect rather than missing value (Tufa and Hailu, 2011).

Double mass curve is one of widely accepted method. It is used to check the consistency of a long-term trend test of hydrological and metrological data. The method is based on the fact that a plot of two cumulative data having the same recorded period exhibits a straight line as long as the proportionality between the two remains unchanged (Atnafu and Niguse, 2015). Therefore, a double mass curve analysis was selected for this study to test the consistency and adjust an inconsistent data.

According to Tesfaye and Chane (2011), a double-mass curve is a graph of the cumulative rainfall at the rain gauge of interest versus the cumulative rainfall of one or more gauges in the region with similar hydro-meteorological occurrences. If a rainfall record is a consistent estimator of the hydro- meteorological occurrences over the period of record, the double-mass curve will have a constant slope. A change in the slope of the double mass curve indicates changes in the characteristics of the recorded values. Hence, the record needs to be adjusted with either the early or later period of record by changing the values. After that, the slope of the resulting double-mass curve will be straight line. The rainfall records of a given station x are adjusted by multiplying the recorded values of rainfall by the ratio of slopes of the straight lines before and after change in environment. Mathematically, it can be expressed as;

$$Y2 = \left(\frac{S2}{S1}\right) Y1 \quad \text{……3.7}$$

Where:

Y2 denotes the corrected precipitation at station x

Y1 denotes the original recorded precipitation at station x

S2 denotes the slope of double mass curve to be corrected

S1 denotes the original slope of double mass curve

Based on the result, rainfall data at station Jimma, Asendabo, Shebe and Sekoru were consistent with no break. Each of them have R^2 value of 0.999.However, it was relatively inconsistent at the remaining stations (Dedo,Omo_Nada and Limu Genet) with R^2 value of 0.986,0.992 and 0.994 respectively. By double mass curve analysis, R^2 value was adjusted to 0.999, 0.998 and 0.999 respectively.

Figure 3.6 shows the consistency test result for Jimma. The remaining stations consistency graph was attached in Appendix-1.

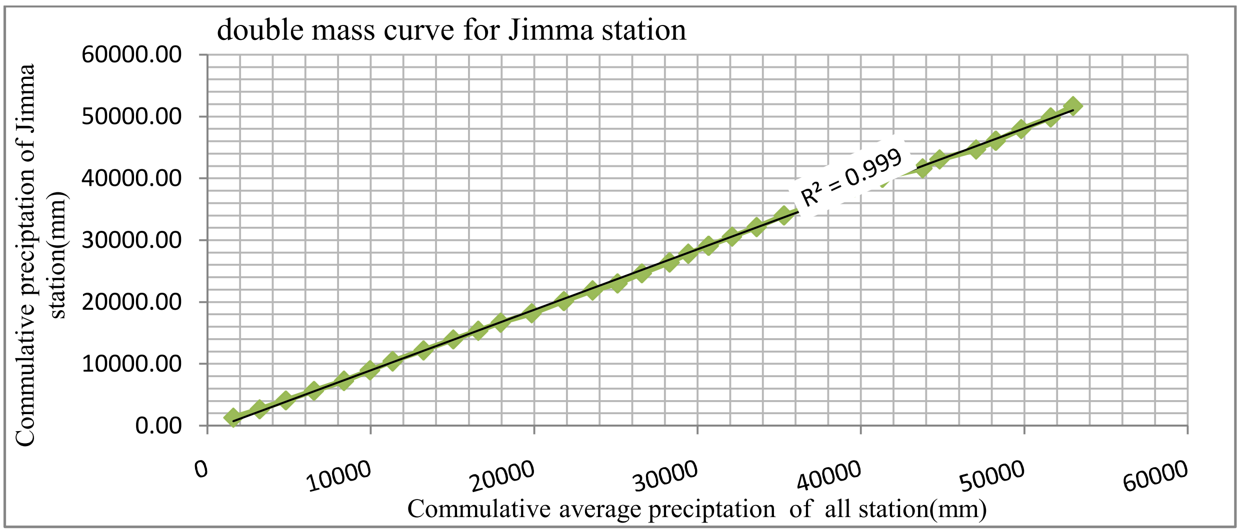

Figure 3. 6: Consistency test result graph for Jimma station

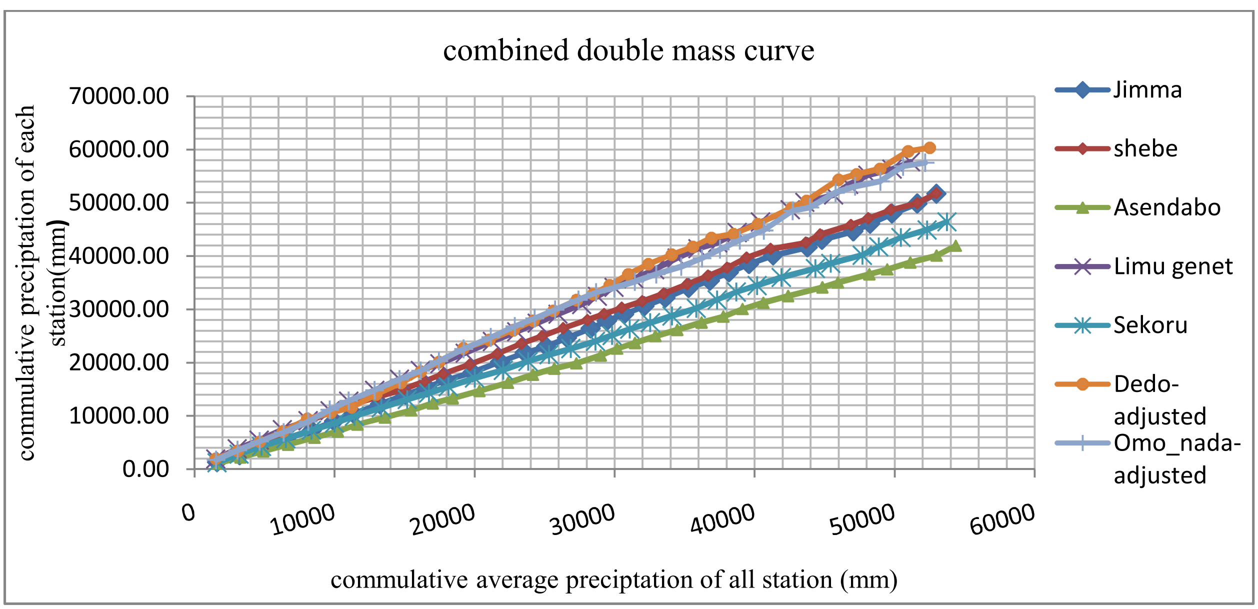

Figure 3. 7: Combined consistency test graph for all stations

3.5.2.3 Rain fall data outlier test

Outliers are data points that deviate from the trend of remaining data. This may be due instrumental and personal errors or due to extreme metrological events (Saleh et al., 2011).

When low outliers are definitely mistaken measurement, those outliers can be rejected and the problem will be converted in to one of missing data treatment. However, high outlier adjustment is generally considered a better procedure than excluding it from the sample except when a doubt exists that it is caused by measurement error (Ponce, 1989).

Keeping high outliers in the sample and treating them as an ordinary value seem to be a preferred approach because it is believed that they carry important information. On the other hand, keeping the high outliers may lead to over estimation of runoff. According to Saleh et al. (2011), an option that would combine keeping the information of higher outliers and showing consideration for effects of higher outliers would be to censor higher outliers. This can be done by replacing them by some threshold value that keeps their information so that the effect on the sample statics is reduced.

The Grubbs and Beck (1972) test was used to detect outliers. This method was selected due to its simplicity and reasonable precision. The Grubbs and Beck equation used to test higher and lower outlier is given by:

$$X_H = \overline{X} + K_N S \quad \ldots 3.8$$

$$X_L = \overline{X} - K_N S \quad \ldots 3.9$$

Where:

X_H is the higher outlier value

X_L is the lower outlier value

$\overline{X}$ is the mean of the logarithm of the sample

S is the standard deviation of the logarithm of the sample

K_N is critical deviate for sample size N. It is tabulated for various sample size and significance level (mostly 10% is used for outlier test). K_N value at 10% significance level was proposed by (Pilon et al., 1985) as:

$$K_N = -3.62201 + 6.28446N^{1/4} - 2.49835N^{1/2} + 0.491436N^{3/4} - 0.0379 \quad \ldots 3.10$$

According to this test, sample values greater than X_H were considered as high outliers while those less than $X_{L,}$ were considered as low outliers.

Based on the analysis, all precipitation data values were found within the limits of high and low outlier threshold values. The outlier test result graph for Jimma station was shown in Figure 3.8. The remaining stations outlier test graphs were attached in Appendix-3.

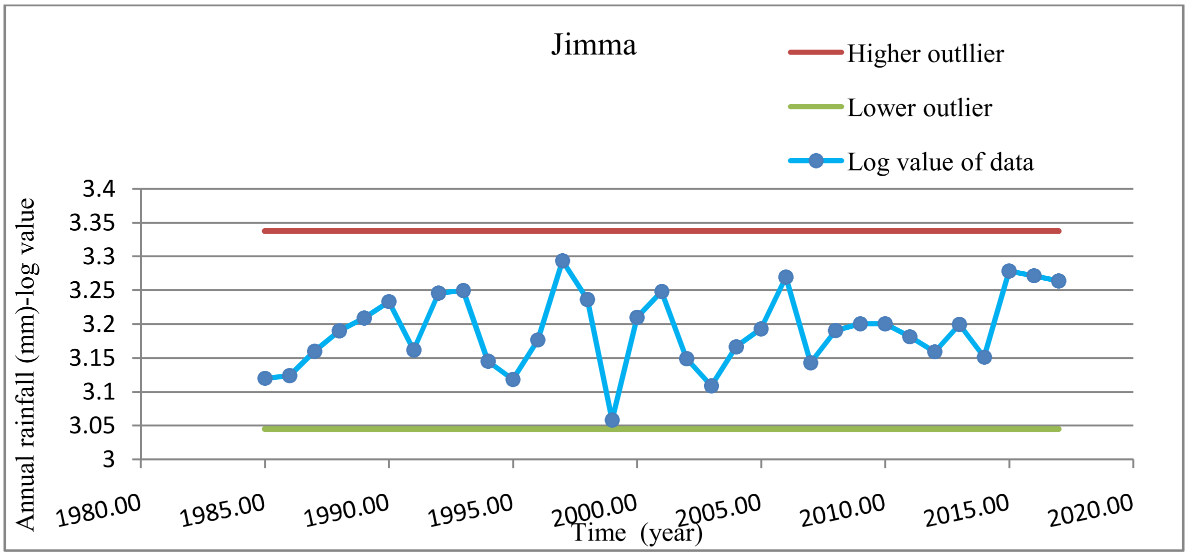

Figure 3. 8: Outlier test result graph

3.5.2.4 Rain fall data homogeneity test

Homogeneity test is necessary to detect the variability of the data. Homogeneity of a time series data indicates that the measurements of the data are taken at a time with the same instruments and environments. However, it is a hard task when dealing with rainfall data because there might be a certain error due to change in measurement and observational procedure, environment characteristics, and the location of measuring device.

There are various methods used for homogeneity, but the most preferred methods are, standard homogeneity test and measuring cumulative deviation from the mean. XLSTATE can be used for standard homogeneity test, while Rainbow software can be used to measure the cumulative deviation from the mean (Raes et al., 2006).

For this study, homogeneity of the rainfall data was checked using Rainbow software. This software is designed to carry out frequency analysis and to test the homogeneity of climatic and hydrological data. It tests the homogeneity of a given data set based on the cumulative deviation from its mean (Raes et al., 2006).

$S_k = \sum_{i=1}^{K}(X_i - \overline{X})$ K=1, 2, 3,.., n ……………………………………………...3.11

Where:

S_k is the cumulative deviation

K is the number of year

Xi is series of rainfall data

$\overline{X}$ is the mean of rainfall data

The initial value of Sk (for k=0) and the last value of Sk (for k=n) are equal to zero. When plotting the Sk's (also called a residual mass curve) changes in the mean are easily detected. For a record Xi above normal the Sk=i increases while for a record below normal, Sk=i decreases. For a homogenous record one may expect that the Sk's oscillate around zero since there is no regular pattern in the deviations of the Xi's from their average value X .

To test the homogeneity of the data set, the cumulative deviations are often rescaled. This is obtained by dividing the Sk's by the sample standard deviation value (s). By evaluating the maximum (Q) or the range (R) of the rescaled cumulative deviations from the mean, the homogeneity of the data of a time series can be tested. The equation can be expressed as:

$Q = \max\left[\frac{S_K}{s}\right]$…………………………………………………….................3.12

$R = \max\left(\frac{S_K}{s}\right) - \min\left(\frac{S_K}{s}\right)$…………………………………………………...3.13

Where;

Q denotes maximum cumulative deviation.

R denotes the range of cumulative deviation.

s denotes the sample standard deviation.

High values of Q or R are an indication that time series data is not from the same population and the fluctuations are not purely random.

The cumulative deviation versus time series graph of annual rainfall for all stations, were drawn using rainbow software. In this graph, the vertical-axis is rescaled and lines representing various probabilities with which the homogeneity of the data can be rejected were plotted. The rescaled Sk's fluctuated around zero although they were far off the lines where the homogeneity is rejected. Hence, the precipitation time series data were considered as homogeneous.

The homogeneity statistics menu for all station indicates that the cumulative deviation and maximum of cumulative deviation at 90%, 95% and 99% were not rejected. This also indicates the homogeneity of the precipitation time serious data.

Figure 3.9 shows the homogeneity test result for Jimma station's annual rainfall. The homogeneity test result for other station's annual rainfall was attached in Appendix -2.

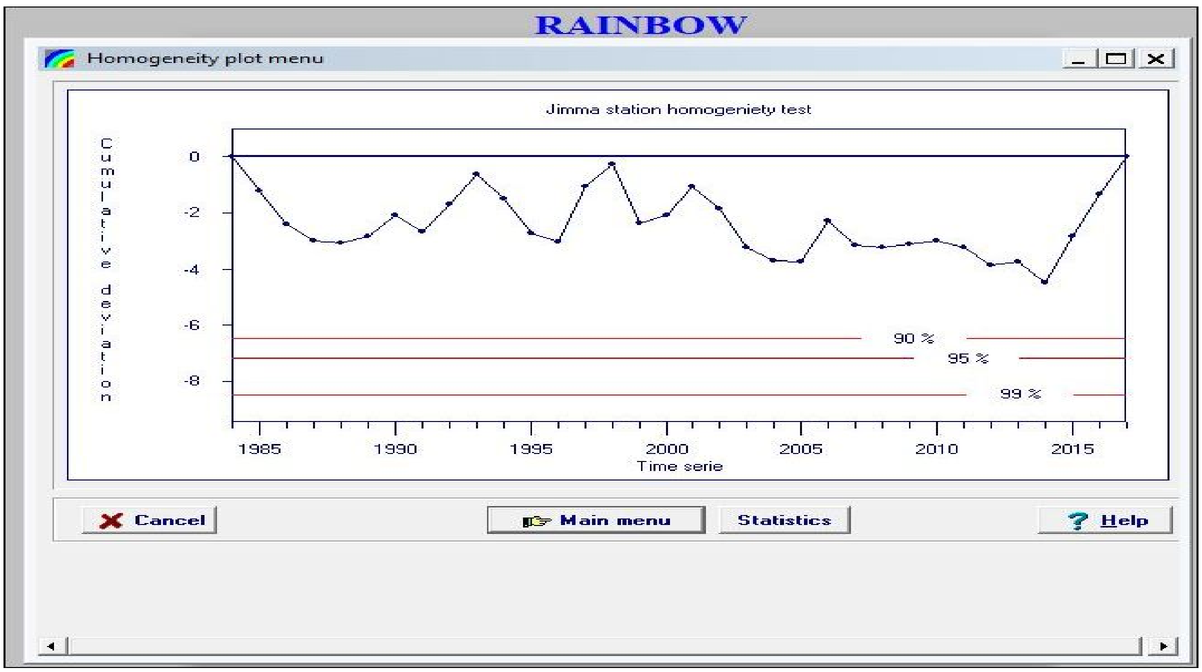

Figure 3. 9: Rescaled cumulative deviation from mean for annual rainfall of Jimma station

3.5.2.5 Conversion of point rainfall to areal rainfall

Rain gauge records rainfall at a single point. The average depth of rainfall over the area under the area of consideration is one of the most essential parameter in hydrological studies. HEC-HMS requires areal rainfall as an input data to convert it in to runoff (Feldman, 2000).

Various methods are available that are used to convert the point rainfall values in to an average value over a catchment. Among these, the most common methods are arithmetic mean, thiessen polygon and isohyetal method.

For catchments having rainfall gauges more than one rainfall-gauging station in vicinity of the boundary of the watershed, theissen polygon method is used to compute the areal rainfall.

In this method, stations out found of the catchment may also be used for assigning weights of marginal stations within the catchment (Ayenew and Legesse, 2008). The study area considered for this study has more than one rainfall-gauging station in the vicinity of the boundary of the watershed. Hence, the thiessen polygon method was selected. Table 3.2 shows the weight assigned for each rainfall gauge using this method.

Table 3. 2:Thiessen gauge weight developed for Gilgel Gibe catchment

SNO.	Rainfall stations	Area weight (km^2)	Gauge weight (%)
1	Jimma	825.5	19.57
2	Shebe	314.3	7.44
3	Asendabo	960.9	22.78
4	Omo_Nada	760.9	18.04
5	Dedo	895	21.22
6	Sekoru	346.52	8.22
7	Limu Genet	115.34	2.73
Total		4218.46	100

The area of influence of each gauge was obtained by constructing polygons determined by drawing perpendicular bisectors to lines connecting the gauges by using ArcGIS software. Each gauge was weighted in direct proportion to the polygon area. The individual weights were multiplied by the station observation to get the areal rainfall for each station.

A sub-basin that lies on a give polygon will take the areal rainfall of that polygon in direct proportional to the area of that sub-basin. The gauge weight for each sub-basin will be the ratio of area of the sub-basin that lies in the polygon and the area of the polygon. The sub-basin precipitation time series were obtained by multiplying the gauge weight by gauge precipitation for each sub-basin. Figure 3.10 represents the thiessen polygon developed for the catchment.

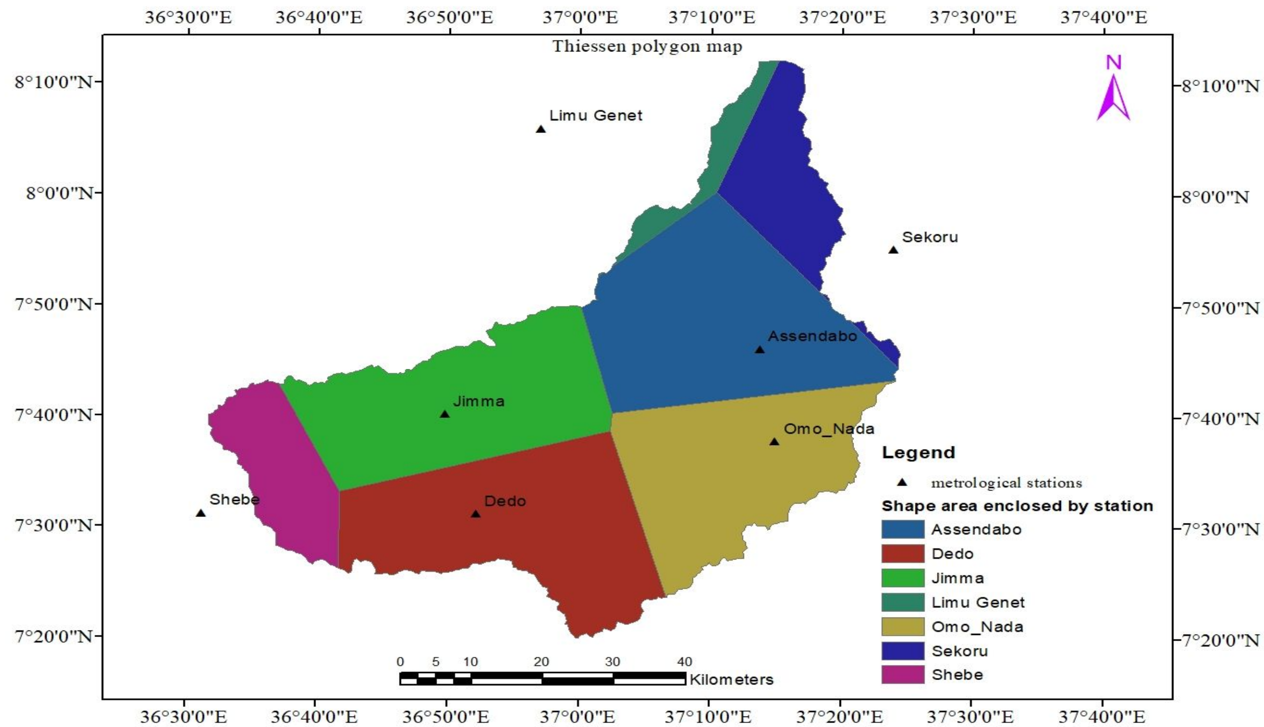

Figure 3. 10: Thiessen polygon developed for Gilgel Gibe catchment

3.6 CN generation

A runoff curve number for wide range of cover types and hydrologic soil groups are prepared by SCS (1985) in the form of charts and tables. Single curve number for single cover and soil type or weighed curve number for wide range of soil and cover type can be calculated manually. This can be done by using tables and charts. The traditional method of calculating the composite curve number from the readily available tables and curves is very tedious. In addition, this procedure leads to lesser accuracy. Therefore, for this study, curve number was generated by combining soil and cover type of Gilgel Gibe catchment using ArcGIS and HEC-GeoHMS

3.6.1 Hydrological soil group assignment

Originally, hydrologic soil group to soil series of the world were assigned by soil scientist based on their transmission rate of water, texture, structure and degree of swelling when saturated which have similar runoff response. Berhanu et al. (2013) has assigned the hydrological soil group for soil series of Ethiopia considering the published criteria.

For this study, the harmonized soil database by Nachtergaele et.al. (2010) was used to determine the percentage of clay, sand, silt and gravel for each soil types. Then hydrologic soil group were assigned based on the percentage of soil texture in each soil types of Gilgel Gibe catchment.

Due to lack of detail information on the moisture condition of the study area, the normal soil moisture condition was considered while estimating the curve number. The hydrologic group for each soil type is presented in Table 3.3.

Table 3. 3: HSG of Gilgel Gibe catchment

SNO.	Soil type	HSG	Area coverage (%)
1	Chromic vertisols	C	17.47
2	Dystric fluvisols	D	24.68
3	Dystric nitisols	A	18.76
4	Eutric cambisols	C	0.065
5	Eutric fluvisols	D	33.67
6	Eutric nitisols	B	0.29
7	Orthic acrisols	C	5.07

3.6.2 Curve number assignment for LU/LC of the study area

LU/LC of the study area was classified in to four based on the Anderson, (1976) LU/LC classification system. Curve number for a combination LU/LC and HSG of the study area were assigned referring Subermaniya (2008). This information was prepared by creating CN_lookup table (Table3.4). This table was added to the GIS working space.

Table 3. 4: Values of CN for different LU/LC and HSG combination

S.NO	LU/LC _type	Coverage area (%)	HSG			
			A	B	C	D
1	Water body	0.3	98	98	98	98
2	Forest	15.5	38	63	75	82
3	Agriculture	79.7	67	77	83	87
4	Urban	4.5	57	72	81	86

(Source: Subermaniya (2008).)

3.6.3 LU/LC and soil polygon union

By using the union tool in Arc tool box, the soil and LU/LC polygons were merged to form one polygon features that contains both soil and LU/LC information. Negative values that occur due to improper union or lack of union from the union table were removed. Then an empty field named "Soil Code" for storing soil groups was created to store HSG for each soil type. Because the attribute table of the soil and LU/LC layer union has no field for storing these data.

Four fields named "Pct A", "Pct B", "Pct C" and Pct D were created. One soil group was assigned to each polygon. Hence, a polygon with soil group "A" has Pct A = 100, Pct B = 0, Pct C = 0, and Pct D = 0. Similarly for a polygon with soil group D, only Pct D = 100 and the other three Pcts were zero. A field named "Land_Use" in the LU/LC_soil_union table which contains land use category information was created to link it to "CNLookUp". HEC-GeoHMS look for this information in Land Use field while it is stored in GRIDCODE field. The field name was added and equated it to GRIDCODE.

3.6.4 Generation of curve number

HEC-GeoHMS uses the merged spatial feature classes (land use and soil union) and the CNLookup_table to create the CN grid map. The CN for each LU/LC_soil_union polygon was generated using the utility tool of HEC-GeoHMS. The overall steps to create curve number grid was summarized in Figure 3.11.

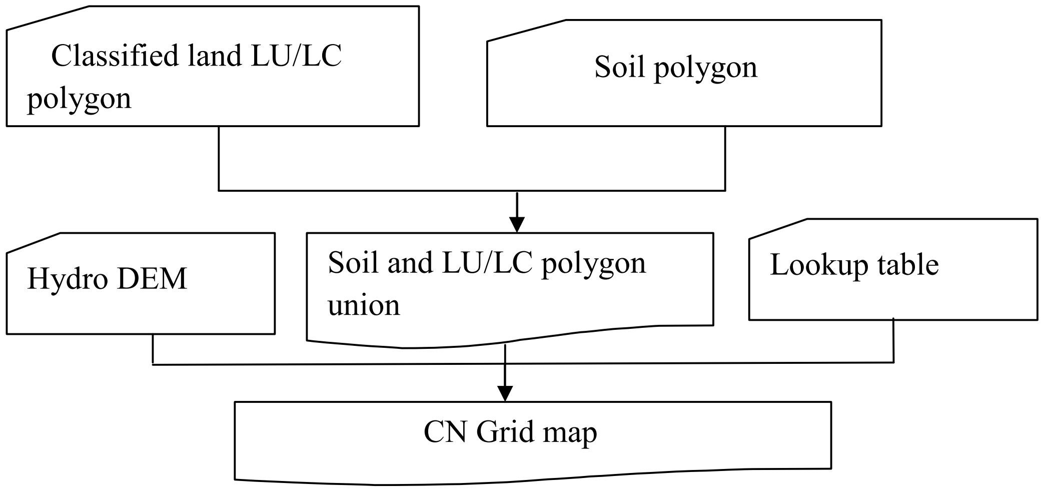

Figure 3. 11: Summarized procedure followed to Generate curve number

The curve number is one of the major parameter that was calculated from CN_grid raster file in the parameter estimation tool of HEC-GeoHMS. This tool calculates the weighted curve number for each sub-basin using the following formula.

$$CN = \frac{\left(\sum_{I=30}^{N}(CI)AI\right)}{A} \quad \text{........3.14}$$

Where:

CN denotes the weighted curve number.

CI denotes the curve number for the I^{th} polygon

AI denotes area with curve number CI

The calculated curve number was added to the sub-basin attribute table

3.7 Input data preparation for HEC-HMS basin model.

Input data for HEC-HMS basin model was prepared by two major processes. These are terrain preprocessing and hydrologic processing. Terrain preprocessing was done by Arc Hydro Tools. While, hydrologic processing was done by using HEC-GeoHMS tools.

3.7.1 Terrain preprocessing

Terrain preprocessing is delineation of watershed using existing DEM It must be competed in sequential order before any HEC-GeoHMS processing functions can be processed. The main steps are fill-sinks, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid delineation, Catchment polygon processing, and drainage line processing. They were performed using the HEC-GoeHMS user manual prepared by Fleming and Doan (2009).

The results or dataset in raster and vector format from terrain preprocessing were used for sub-basin and reach network delineation by HEC-GeoHMS. Drainage line feature is the final output of terrain preprocessing. Figure 3.12 shows the drainage line feature. The step by step results of terrain preprocessing was attached in Appendix-4.

Figure 3. 12: Terrain preprocessing results

3.7.2 Hydrologic processing

In hydrologic processing, HEC-HMS project setup on the HEC-GeoHMS main view toolbar menu was used to extract data that were used to develop the necessary information to create HEC-HMS project.

The approach for extraction involved specifying a control point at the downstream outlet which is the downstream boundary for HEC-HMS project. After defining the downstream outlet, all the terrain preprocessing data for the area was copied to the upstream of the outlet by HEC-GeoHMS. Then HEC-GeoHMS was used to process the sub-basin and stream delineations, extract physical characteristics of sub-basins and streams, estimate model parameters and prepare input files for HEC-HMS.

It involves basin processing, computation of stream and sub-basin characteristics, HMS basin schematics and legend, computation of lag-time for the sub-basins. Hydrologic processing was done following the procedures on HEC-GeoHMS user manual prepared by Fleming and doan (2009).

The SCS unit hydrograph method was used to calculate Lag time for each sub-basin. According to Mishra and Singh (2004), SCS unit hydrograph method of lag time calculation can be expressed as:

$$t_{lag} = \frac{l^{0.8}(s+1)^{0.7}}{1900y^{0.5}} \quad \text{..........} 3.15$$

Where:

t_{lag} denotes basin lag time measured in hours

l denotes length from sub-basin outlet to divide along longest drainage path in fit

y denotes sub-basin slope(%)

s is saturated moisture measured in inch expressed in terms of average curve number as

$$s(in) = \frac{1000}{CN} - 10 \quad \text{..........} 3.16$$

CN is average curve number for each sub-basin

Substituting equation 3.16 in to equation 3.15, lag time as a function of curve number can be expressed as:

$$t_{lag} = \frac{l^{0.8}(\frac{100}{CN}-9)^{0.7}}{1900y^{0.5}} \quad \text{..........} 3.17$$

Using equation 3.17, hydrologic parameter menu in HEC-GeoHMS has assigned lag time for each sub-basin. The calculated lag time was populated into the sub-basins attribute table. Figure 3.13 shows the final output of hydrologic processing.

Figure 3. 13: The study area sub-basin schematics

3.8 HEC-HMS model setup

HEC-HMS Model setup consists of four main model components. These are basin model, meteorological model, control specifications and input data (time series, paired data, and gridded data).

The Basin model contains the hydrologic element and their connectivity that represent the movement of water through the drainage system. The meteorological component is also the first computational element by means of which precipitation input is spatially and temporally distributed over the river basin. The control specification defines the time period and time step of the simulation run. Input data is required as parameter or boundary conditions in basin and meteorological models. Each components of the model used for this study were presented in detail as follow.

3.8.1 Basin model

Basin model contains the modeling components that describe infiltration, surface runoff, base flow, and channel routing. Gilgel Gibe catchment was divided in to 48 sub catchment using HEC-GeoHMS. Then, it was imported into HEC-HMS basin model. The hydrologic elements and their connectivity were shown in Figure 3.14.

Figure 3. 14 : Gilgel Gibe catchment basin model

The basin model consists of four major types of models for the major hydrological processes. It consists of loss model, transform model, base flow model and routing model.

3.8.1.1 Loss models

For this study, the SCS curve number loss model was selected. The major factors that affect runoff generation are soil type, land use and treatment, surface condition and antecedent moisture condition. All these factors are incorporated in a single CN parameter. In this method, the precipitation excess is a function of cumulative precipitation, soil type, land use/cover and antecedent moisture. Considering the initial loss and the potential maximum retention, the precipitation excess can be calculated. The maximum retention and the basin characteristics are related through the curve number by the following equation.

$$Q = \begin{cases} \frac{(P-I_a)^2}{(P-I_a+s)} & \text{for } p > I_a \\ 0 & \text{for } P < I_a \end{cases} \quad \ldots\ldots 3.18$$

Where:

P denotes the precipitation (mm)

S denotes the soil maximum retention (mm)

I_a denotes all loss before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation and infiltration.

To remove the necessity for an independent estimation of I_a , a linear relationship between I_a and S was suggested by Mishra and Singh, (2004) as:

$$I_a = s\lambda \ldots\ldots 3.19$$

Where:

λ is an initial abstraction ratio. The values of λ vary in the range of 0 to 0.3 and have been documented in a number of studies encompassing various geographic locations (Mishra and Singh, 2013). Through studies of many small agricultural catchments, I_a was found to be approximated by the following empirical equation.

$I_a = 0.2s$..3.20

By removing I_a as an independent parameter, a combination of S and P to produce a unique runoff amount can be approximated as:

$Q = \frac{(P-0.2S)^2}{(P+0.8S)}$..3.21

$S(mm) = \frac{25400}{CN} - 254$..3.22

Where:

CN denotes the curve number for each soil types of the sub-basin .Other variables were defined in Equation 3.18.

3.8.1.2 Transform model

For this study, SCS unit hydrograph was selected for modeling direct runoff. The appropriateness of the assumptions inherent in the model and their previous application was the main criteria to select this method.

The SCS unit hydrograph method defines a curvilinear unit hydrograph by first setting the percentage of unit runoff that occurs before the peak flow (USACE, 2000). A triangular unit hydrograph can then be fit the curvilinear unit hydrograph so that the total time base of the unit hydrograph can be calculated. The standard unit hydrograph is defined with 37.5% of runoff occurring before peak flow. The percentage of unit runoff that occurred was not uniform across all the sub-basin. The main reason was variation in flow length, ground slope and other properties of the watershed (Feldman, 2000).

3.8.1.3 Base flow models

Sub-basin element in HEC-HMS conceptually represents infiltration, surface runoff and subsurface processes interacting together. Subsurface calculations are performed by a base flow method.

Three alternative models of base flow are included in HEC-HMS program. These are constant monthly-varying value, linear reservoir and exponential recession (Halwatura et al., 2013). The constant monthly varying base flow method was selected for this study. It allows the specification of a constant base flow for each month of the year.

3.8.1.4 Routing models

For this study, Muskingum Routing Model was selected for flow routing in reach elements. This method was selected considering the availability of information for parameter estimation. The Muskingum routing method uses simple conservation of mass approach to route flow through the stream reach.

The Muskingum K is the travel time through the reach. The Muskingum x is the weight between inflow and outflow influence. It ranges from 0 to 0.5 when x=0, storage is only a function of discharge and when x=0.5, both inflow and outflow affects the storage.

The travel time of a flood wave passing through the reach (K) and the measure of degree of storage(x) need to be determined through calibration. This method is often used in channel routing. It is dependent primarily upon the number of integer steps for the routing, Muskingum K coefficient and Muskingum x coefficient. It uses a simple finite difference approximation of the storage continuity equation. Storage is modeled as the sum of prism storage and wedge storage. According to USACE (2000), storage is expressed as;

$$S_t = k0_t + kx(I_t - O_t) = K[xI_t + (1-x)O_t] \quad \text{......3.23}$$

Where:

k is the travel time of the flood wave through routing reach

S_t is the storage in the channel at time t

I_t is the inflow to the channel at time t

O_t is the outflow from the channel at time t

x is a weighting factor described above . The quantity on the right hand side is weighted discharge. Generally the routed out flow of a given reach is estimated by the following equation (Subermaniya, 2008).

$$O_t = \left(\frac{\Delta t - 2kx}{2k(1-k)+\Delta t}\right)I_t + \left(\frac{\Delta t - 2Kx}{2k(1-K)+\Delta t}\right)I_{t-1} + \left(\frac{2k(1-x)-\Delta t}{2k(1-K)+\Delta t}\right)O_{t-1} \quad \text{......3.24}$$

Where:

Δt denotes the time interval between each successive inflow. Other variables were defined in equation 3.23.

3.8.2 Meteorological models

Metrological models are used to prepare meteorological boundary conditions for sub-basins. The meteorological models were matched with the sub basins in the basin model using the name of sub-basins. It includes precipitation and evapotranspiration for continuous modeling (Feldman, 2000).

3.8.2.1 Precipitation

Precipitation is the driving factor for the watershed responses in the case of HEC-HMS model; in turn a major effort was made to compute the meteorological model to receive spatially and temporally distributed precipitation input data.

The distribution of precipitation over the river basin was specified using the gauge weight method. Using ArcGIS, thiessen polygons were constructed that used perpendicular bisectors to define the sub-basin that belongs to a given rain gauge. A sub-basin that lies on a give polygon will take the areal rainfall of that polygon in direct proportional to the area of that sub-basin.

The gauge weight for each sub-basin is the ratio of area of the sub-basin that lies in the polygon and the area of the polygon. The sub-basin precipitation time series data were obtained by multiplying the gauge weight by gauge precipitation for each sub-basin. Figure 3.16 shows how the precipitation data was divided between the sub-basins.

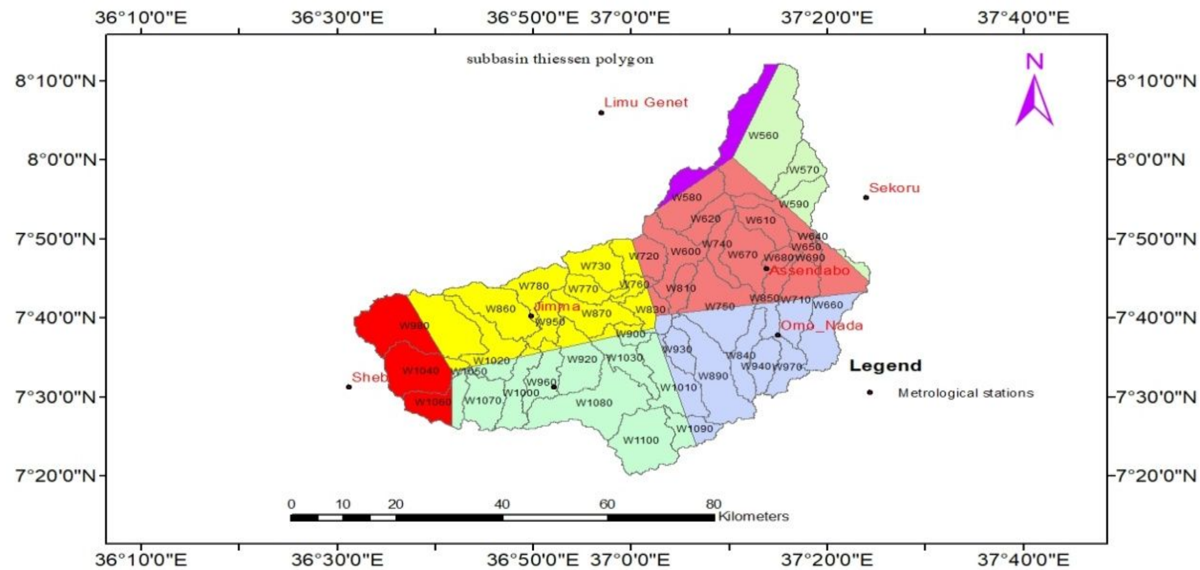

Figure 3. 15: Sub-basin thiessen polygon developed from metrological stations

3.8.2.2 Potential Evapotranspiration

The potential evapotranspiration for Gilgel Gibe catchment was computed by FAO Penman-Monteith method for Jimma station which has the required meteorological variables. This method will compute the potential evapotranspiration of an area using the following empirical formula.

$$ET_O = \frac{0.408(R_n - G) + \gamma\frac{900}{T+273}U_2}{\Delta + \gamma(1 + 0.34u_2)}(e_s - ea) \qquad \ldots 3.25$$

Where:

ET_O is the Reference Evapotranspiration (mm day-1)

R_n is the net radiation at the crop surface (MJ m-2 day-1)

G is the Soil heat flux density (MJ m-2 day-1)

T is the air temperature at 2m height (0C)

U_2 is the wind speed at 2m height (ms-1)

e_s is the saturation vapour pressure (kPa)

ea is the actual vapour pressure (kPa)

$e_s -$ ea is the saturation vapor pressure deficit (kPa)

Δ is slope vapour pressure curve (kPa0C-1)

Crop/plant coefficient for each crop/plant type was obtained from Allen et al (1998). The crop coefficient was used to take into account plant water use during the various portions of the plant life cycle. Each days of the first, second and third four months were considered as late, initial and mid stage of plant growth cycle. The maximum crop/plant coefficient was taken for the initial, mid and late stage of each plant growth cycle.

Each whether gauges of Jimma station and the crop coefficient gauge were connected to each sub-basin thorough the metrological model. The modified FAO penmanmontieth method calculates the actual evapotranspiration by multiplying the potential evapotranspiration and crop/plant coefficient (Allen et al., 1998).

3.8.3 Time serious data entry model

HEC-HMS model require time series weather data for runoff simulation. A time series of flow data, often called observed flow, is used for calibrating a model. Time series data are stored in a project as a gauge. The program separates different types of data with different gauge types. The gauges are part of the project and can be shared by multiple basins.

For this study, observed flow was added in time series data manager component as calibration and validation gauges. The earliest period of time series flow (01January1985-31 December 2002) was used for model calibration. While the recent period of time series flow (01January 2003-31 December 2013) was used for model validation.

Time series precipitation data for 6 stations, (Jimma,Shebe,Asendabo,Dedo,Omo-Nada,Limu Genet and Sekoru) was added by creating 6 precipitation gauges. This precipitation gauges were shared by 48 sub-basins. The remaining weather data and the crop/plant coefficient were added by creating weather data gauges and crop/plant coefficient gauge respectively.

3.8.4 Control specification model

Control specifications controls the starting time, ending time and the time interval of the simulation. They do not contain much parameter data.

Control specifications are created using a control specification manager in the components menu of the model. For this study, since the available data are daily, one day computation time interval was used during model calibration and validation.

3.8.5 Runoff simulation

Watershed and meteorology information is combined to simulate the runoff. Simulation run is the primary mode for performing simulations and forms the basis for additional analysis using optimization trials or analysis. Each run is composed of one basin model, one meteorological model and one control specification. Simulations runs were created using a wizard that can be accessed from "compute menu" or "run manager command" of the HEC-HMS model.

3.9 HEC-HMS model performance evaluation

3.9.1 HEC-HMS Model Performance evaluation criteria

The performance of a model must be evaluated whether it satisfies its objective or not. A criterion is therefore necessary to evaluate the performance of the model. In this study, Nash and Sutcliffe efficiency criteria, Root Mean square Error and coefficient of determination was used to evaluate the performance of HEC-HMS model.

i. Nash and Sutcliffe efficiency (NSE)

According to Nash (1970), the Nash and Sutcliffe coefficient (NSE) is a measure of efficiency that relates the goodness-of fit of the model to the variance of measured data. NSE can range from - ∞ to 1 and an efficiency of 1 indicates a perfect match between observed and simulated discharges. NSE is expressed mathematically as follows.

$$NSE = 1 - \frac{\sum_{i=1}^{n}[Q_{Oi} - Q_{Si}]^2}{\sum_{i=1}^{n}[Q_{Oi} - \overline{Q_O}]^2} \quad \text{......3.26}$$

Where:

Q_O denotes the observed flow

Q_S denotes the Simulated flow

$\overline{Q_O}$ denotes Average of the observed flow

i denotes the time step

n denotes the total number of time step used during calibration

NSE value between 0.9 and 1 indicate that the model performs very well while values between 0.6 and 0.8 indicate the model performs well (Yener et al.,2012). Moriasi et al (2007) categorized for monthly time steps of NSE values between 0.75 and 1 as very good and NSE-value between 0.65 and 0.75 good. According to Motovilov (1999), the NSE values can vary from 0 to 1, with 1 indicating a perfect fit of the data.

ii. Coefficient of Determination (R^2)

Coefficient of Determination (R^2) indicates the degree of co linearity between simulated and measured data. According to Saleh et al. (2011), R^2 describes the proportion of the variance in measured data explained by the model. The value ranges between 0 and 1, with higher values indicating less error variance and the ability of the model to perform the simulation well.R^2 has been widely used for model evaluation. Mathematically it is expressed as:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_{Si}-\overline{Q_s})(Q_{Oi}-\overline{Q_O})\right]^2}{\left[\sum_{i=1}^{n}(Q_{Si}-\overline{Q_s})\right]^2\left[\sum_{i=1}^{n}(Q_{oi}-\overline{Q_O})\right]^2} \quad \text{……3.27}$$

Where:

Qo denotes the observed flow

Qs denotes the Simulated flow

$\overline{Q_O}$ denotes the average of observed flow

$\overline{Q_s}$ denotes the average of simulated flow

n denotes the total number of time step used during calibration

iii. Root mean square error (RMSE)

The Root Mean Square Error (RMSE) (also called the root mean square deviation (RMSD) is a frequently used measure of the difference between runoff values predicted by the model and the observed value. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power (Moriasi et al., 2007).

Mathematically, RMSE is expressed as $RMSE = \sqrt{\frac{\sum_{1}^{n}(Q_{Oi}-Q_{ci})^2}{n}}$……..3.28

Where:

Q_O denotes the observed stream flow

Q_C denotes the simulated runoff

i and n denotes the time step and the total number of time step respectively

3.9.2 Sensitivity analysis

Sensitivity analysis was performed to determine a parameter which has greatest impact on runoff. Thus, at first the model was run with the model input values (the base data file), estimated by methods presented above and base output was collected. This was followed by varying each input parameter within prescribed range keeping the others constant and running the model. The output values were analyzed to determine their variations with respect to the base output set and this is a measure of the sensitivity.

3.9.3 HEC- HMS model calibration

Model calibration is a systematic process of adjusting model parameter values until model results match acceptably the observed data. In this study, two types of model calibration were used. These are manual and automatic calibration. Manual calibration relies on knowledge of basin physical properties of the catchment and expertise in hydrologic modeling.

Initial values of the parameters were entered adjusted by manual calibration. In the automated calibration, model parameters were iteratively adjusted to minimize the difference in observed and simulated value. The latest version of HEC-HMS (Version 4.2) model has optimization manager that allows automated model calibration. The iterative calibration procedure is outlined in Figure 3.16.

The quantitative measure of the goodness-of-fit between the computed flow result from the model and the observed flow is called objective function. An objective function measures the degree of variation between computed and observed hydrographs. It is equal to zero if the hydrographs are exactly identical values. Six different functions are provided by the model. Each of them measures the goodness-of-fit in different ways in the optimization manager

In this study, sum of squared residuals function (SSR) was selected due to the weight given for large error by the objective function. The key to automated parameter estimation is a search method for adjusting parameters to minimize the objective function value and find optimal parameter. Two search methods are available in HEC-HMS model. These are

i. Univariate gradient method (UG)

This method evaluates and adjusts one parameter at a time while holding other parameters constant.

ii. Nelder and Mead method (NM)

This method uses a downhill simplex to evaluate all parameters simultaneously and determine which parameter to adjust. The tolerance determines the change in the objective function value that will terminate the search. When the objective function changes less than the specified tolerance, the search will terminate.

If multiple parameters are adjusted simultaneously, it will be difficult to know the most sensitive parameter that affects the model. Hence, Univariate gradient method was selected for this study.

3.9.4 HEC- HMS model validation

Validation is testing the calibrated value without changing all the parameters that are used in calibration (Roy et al.,2013). It is adapting the model for the required catchment. The optimized parameters were used to validate HEC-HMS model for Gilgel Gibe catchment.

4. RESULT AND DISCUSSION

4.1 Soil_LU/LC polygon CN value

The Soil and the reclassified LU/LC layer of the catchment were combined using ArcGIS. The curve number for each soil_LU/LC polygon union was generated using HEC-GeoHMS. More than two soil_LU/LC polygon was created for one sub-basin. Therefore, more than two CN values were generated for each polygon. Soil_LU/LC polygons found in the same LU/LC type have similar CN value.

Soil data analysis indicates that 33.67% of the study area has Eutric fluvisols. This soil type belongs to HSG D. Soil types that lie in this group are characterized by very slow infiltration rates and high runoff potential.

Figure 4.1 represents the HSG distribution on the catchment. For each soil type, the HSG is represented by different colors. The Figure indicates that the major portion of the area is sheltered by the color that represents HSG D. This indicates that major part of the study area has HSG D.

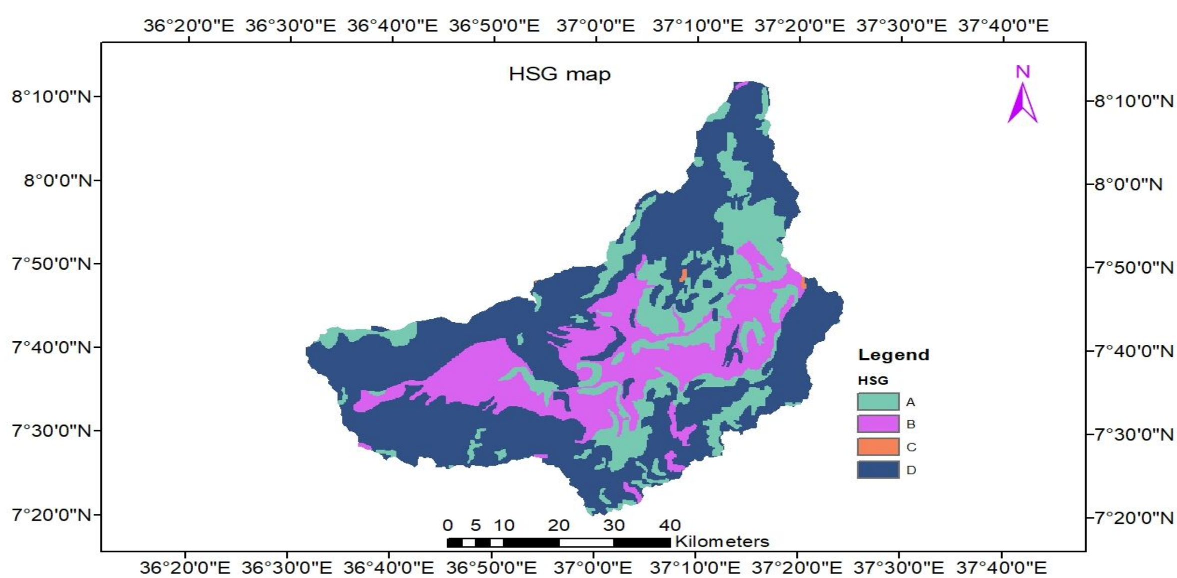

Figure 4. 1: HSG map of the study area

The dominant LU/LC of the area was agricultural land which has high runoff potential compared with forest. Forest has high infiltration capacity and low runoff potential. Therefore, an area covered by forest has low CN value, because an area having high infiltration capacity has low CN value. Figure 4.2 represents the HSG distribution along the LU/LC of the catchment. The Figure indicates that major part of the study area, which is occupied by agricultural land use, has HSG D.

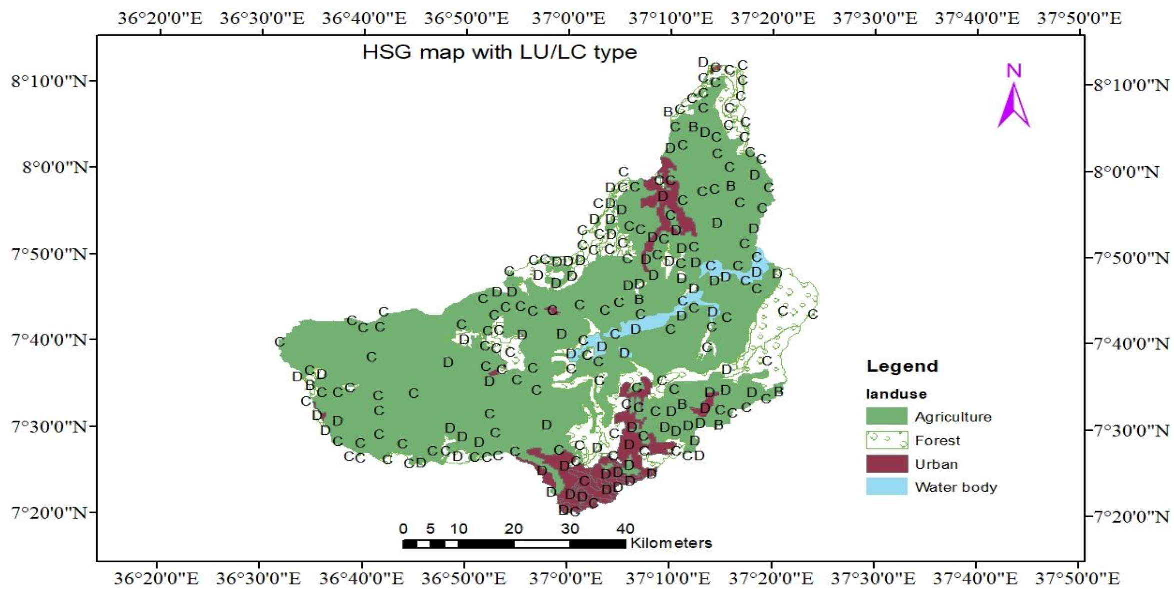

Figure 4. 2: CN distribution based on LU/LC

The combined effects of majority of the area covered by agricultural land and the existence of soil type having high runoff potential has caused to generated high CN value in most part of the catchment. Figure 4.3 indicates that the highest and lowest CN was generated by an area covered by water body and forest part of the catchment respectively.

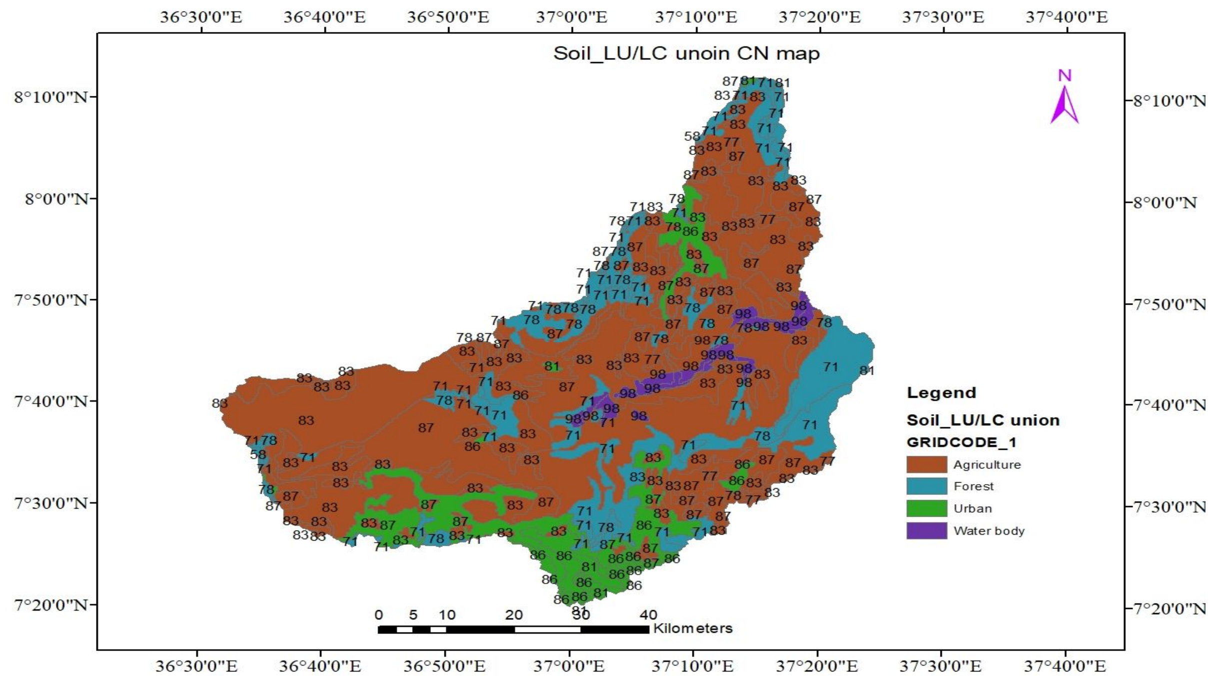

Figure 4. 3 : CN distribution based on LU/LC of the catchment

Generated minimum and maximum values of CN were 71 and 98 respectively. Theoretically, the maximum value of CN is 100 and the minimum value of CN is 30. Therefore, the generated CN is found within this range. The minimum and maximum value of CN for each LU/LC was summarized in Table 4.1.

Table 4. 1: Ranges of CN value for each LU/LC type

Sno	LU/LC type	CN value	
		Minimum	Maximum
1	Agriculture	83	87
2	Forest	71	78
3	Urban	81	87
4	Water body	98	98

Figure 4.4 shows the spatial distribution of CN in raster form with respect to soil and LU/LC type. The green color indicates the forest area with low CN value. The red color indicates the water body with high CN value.

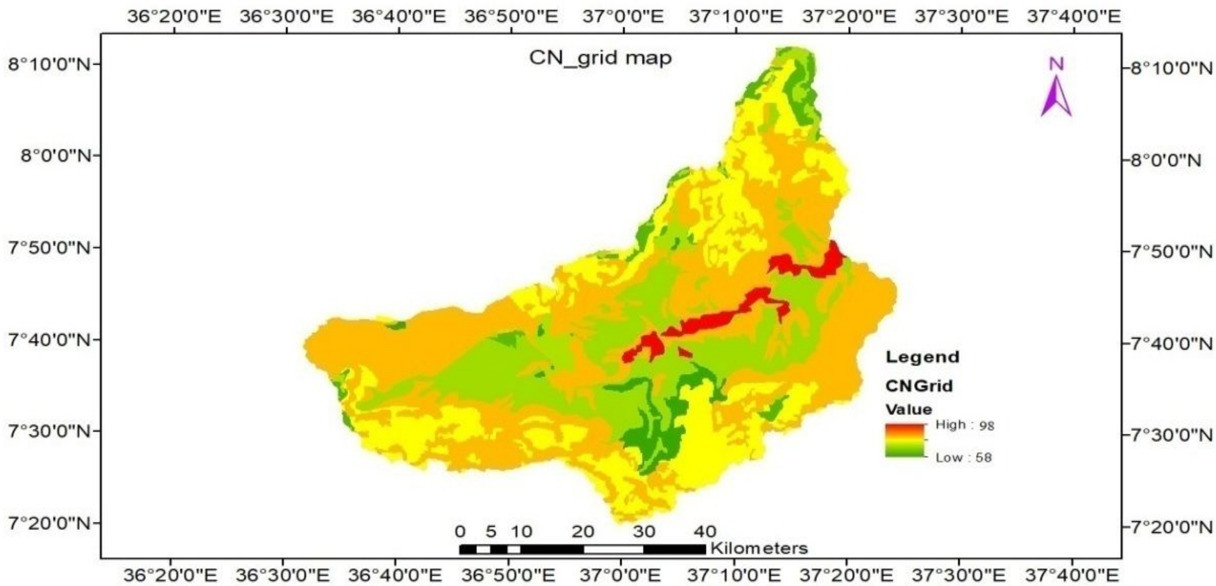

Figure 4. 4: CN grid map of Gilgel Gibe catchment

4.2 Sub-basin weighted CN value

The average weighted curve number for each sub-basin was computed based on equation 3.14 using sub-basin parameter estimation tool of HEC-GeoHMS. The result indicates that 68.75% of the study area has weighted CN value between 81 and 90, 22.92% between 69 and 80 and 4% greater than 90. The maximum and minimum values of weighted CN were 95 and 69 respectively.

These values show that Gilgel Gibe catchment generates more runoff for a given rainfall in areas having greater CN values. Because by increasing the value of CN in a specific area, the amount of runoff will be increased. The extracted sub-basin parameters, including curve number, were attached in Appendix-6. The value of CN for each sub-basin, was shown in Table 4.2.

Table 4. 2: Generated sub-basin curve number

Sub-basin Name	Sub-basin_CN	Subbasin name	Sub-basin_CN
W560	82	W840	69
W570	85	W850	70
W580	83	W860	83
W590	79	W870	81
W600	81	W890	81
W610	74	W900	85
W620	83	W920	82
W630	95	W930	77
W640	93	W940	82
W650	91	W950	80
W660	87	W960	83
W670	88	W970	85
W680	87	W980	86
W690	93	W1000	84
W710	82	W1010	75
W720	82	W1020	81
W730	85	W1030	78
W740	85	W1040	83
W750	85	W1050	81
W760	80	W1060	83
W770	80	W1070	85
W780	85	W1080	83
W810	77	W1090	82
W830	84	W1100	83

4.3 HEC-HMS model performance evaluation result

4.3.1 Sensitivity of model parameters

Sensitivity analysis was conducted to determine the most sensitive parameter that affects runoff simulation. The objective was to minimize the number of parameters that was estimated by optimization. In this study, canopy storage, surface storage, Muskingum K and x, were parameters checked for runoff sensitivity.

Muskingum K is a wave travel time which was computed from stream length and channel velocity. From the theoretical background, the minimum velocity of water passing through a natural channel without erosion and sediment deposition is 2.5 m/s. Therefore, minimum channel velocity of 2.5 m/s was assumed for the first trial by considering the channel as natural.

The length of river for each sub-basin was computed using HEC-GeoHMS. The minimum length of river was 70.72 m. Therefore, the minimum initial value of Muskingum K was 0.008 hr. Similarly, the maximum river length was 34083.7 m. Hence the maximum initial value of Muskingum K was 3.8 hr. Other sub-basins' initial value of Muskingum K were computed in the same way. The boundary of storage coefficient is between 0 and 0.5. Therefore, the average value of 0.25 was assumed initially.

Canopy storage is a function of cover type of the study area. The initial storage was assumed 0. The computed weighted average value of maximum canopy storage was 0.8 mm. Surface storage is a function of land use type and surface slope. The maximum computed surface storage was 12 mm and the initial value of surface storage was assumed 0.

The initial values of these parameters were entered in to HEC-HMS manually. Initially, the simulation was done with model input values and the output was collected. Then simulation was run by varying each of the above parameter within prescribed range keeping the other constant. The output values were analyzed to determine their variations with respect to the base output set. The result indicates that runoff was sensitive to Muskingum K and x, but it was more sensitive to Muskingum K than x.

4.3.2 Model calibration result

The temporal variation of model parameters will be considered in a good manner as the number of sample increases. As a result, long period of observed flow will be preferred for model calibration. Therefore, the major portion of the data was used for model calibration Model calibration period should have both dry and wet extremes. The average annual observed flow should also be similar to the average annual observed flow of the whole period. Considering this fact, 18 years of data (01 January 1985-31 December 2002) with a time interval of 1 day was used for calibration. The selection of simulation time interval both for model calibration and model validation was based on the time interval of available data.

The most sensitive parameters used for model calibration were Muskingum K and x. At first, runoff was simulated from these initial parameters. The first result indicates that there was large difference between the observed and simulated runoff hydrograph.

The model performance during calibration period was measured using three statistical tests of error functions. These are NSE, R^2 and RMSE. The initial values of NSE, R^2 and RMSE were 0.05, 0.43 and 93.73 m^3/s. Therefore, parameters were optimized using optimization tools available in HEC-HMS model.

Manual parameter adjustment was used in addition to parameter estimation using optimization in order to obtain more accurate result. Optimization was conducted from initial Muskingum K and x estimates and adjusted them until the simulated flow matches with the observed stream flow as closely as possible. The objective sensitivity toward Muskingum K and x has changed from-1.5% up to 1.5% at each optimization trial. The trial was terminated when the difference in observed and simulated runoff hydrograph was minimized.

From the result, the minimum and maximum optimized values of Muskingum K were 0.082 hr and 3.9 hr respectively. The minimum and maximum optimized values of storage coefficient(x) were 0.25 and 0.39 respectively. The final optimized values of Muskingum K and x for all reaches were attached in Appendix 7.

At the end of optimization trial, the difference in observed and simulated runoff hydrograph was reduced as shown in Figure 4.5**.** The red and blue line represents the simulated and observed runoff hydrograph respectively. The graph indicates that there was minimum difference between the two hydrograph throughout the calibration period.

The direct HEC-HMS calibration result which is not analyzed by Microsoft excel sheet was attached in Appendix-7. The values of NSE, RMSE, the observed peak discharge, simulated peak discharge and the time of peak during calibration are also attached in Appendix-7.

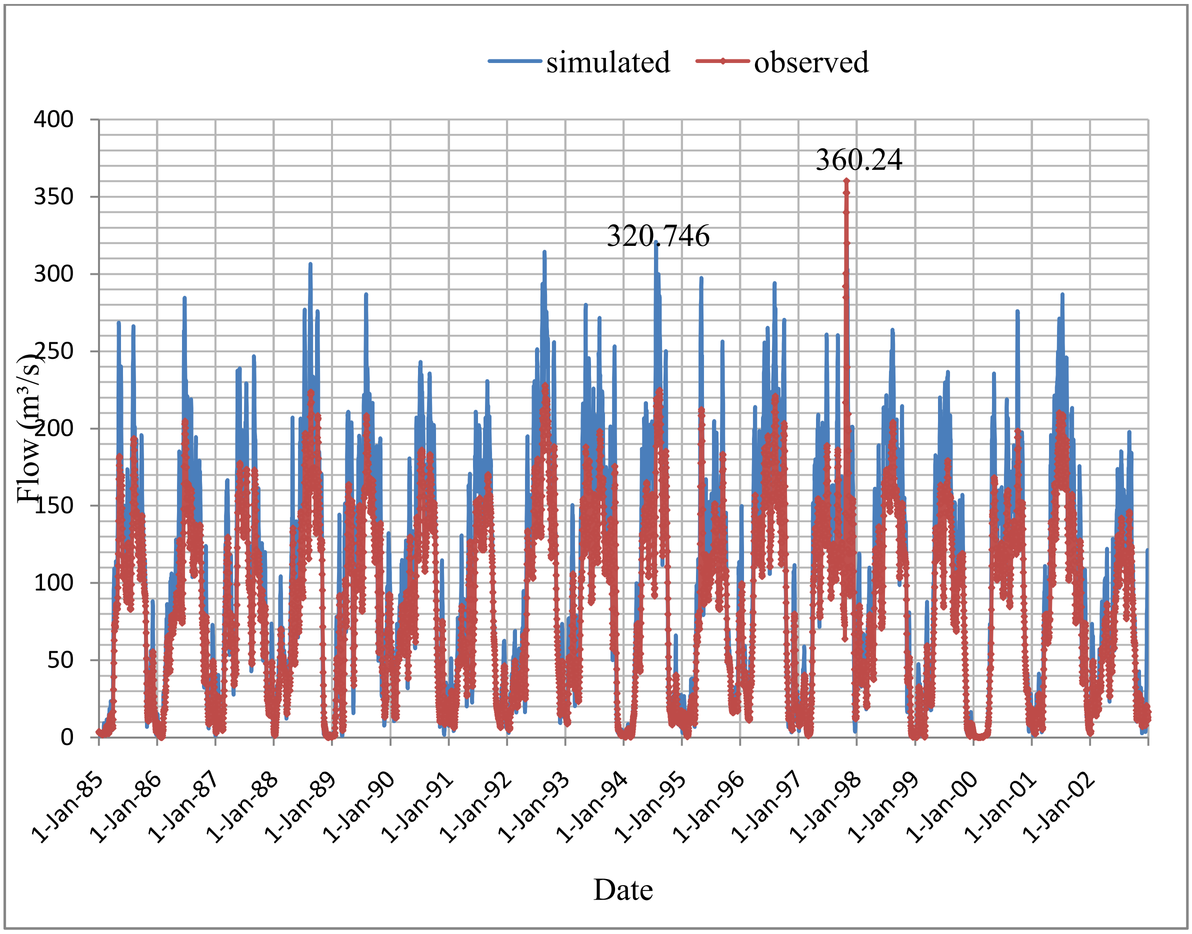

Figure 4. 5: Calibration result of daily simulated and observed runoff hydrograph

The finial values of NSE, R^2 and RMSE were 0.727, 0.865 and 30.809 m^3/s respectively. The values of the statistical test of error functions indicate that there is a good agreement between the simulated and observed runoff hydrograph.

The simulated and the observed peak discharges were 320.746 m^3/s and 360.240 m^3/s respectively. This indicates the peak discharge was well predicted during model calibration. Figure 4.6 shows the co linearity between the observed and simulated runoff hydrograph during model calibration.

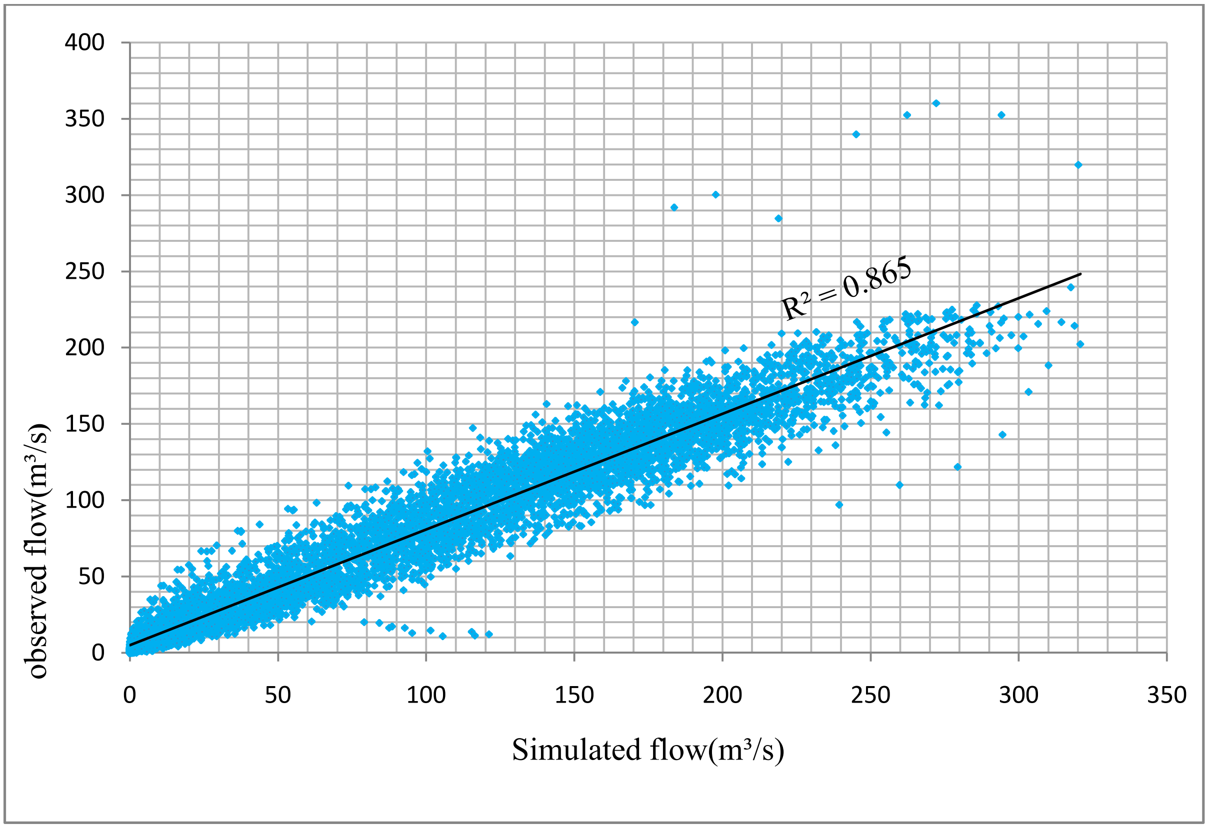

Figure 4. 6: R^2 Value for simulated and observed daily runoff hydrograph during calibration

4.3.3 Model validation result

It is better to validate the calibrated model for any future use. During model validation, the simulated runoff should be compared with the observed runoff using the same criteria that was used for model calibration. The values of parameters obtained from model calibrations are directly used to validate the model.

For this study, the recent observed flow data from 01 January 2003 to 31 December 2013 was used for model validation. The validation period was selected considering the availability of recorded data in addition to the recentness of the sample. 95% of the data were recorded and 5% of the data were missing. The missing flow data was filled using different techniques that were mentioned in the methodology part of this document.

The optimized parameters during model calibration were used to simulate the daily catchment runoff for during model validation. The simulated value of peak discharge was 190.195 m^3/s.Wereas, the observed value of peak discharge was 269.5 m^3/s. Hence, there was a difference of 79.305 m^3/s between the observed and simulated peak discharge. This indicates the peak discharge was slightly under predicted by the model. Figure 4.7 shows the daily simulated and observed runoff hydrograph. The Figure indicates that there is little difference between the simulated and observed runoff hydrograph. The unprocessed output from HEC-HMS was attached in Appendix-7.

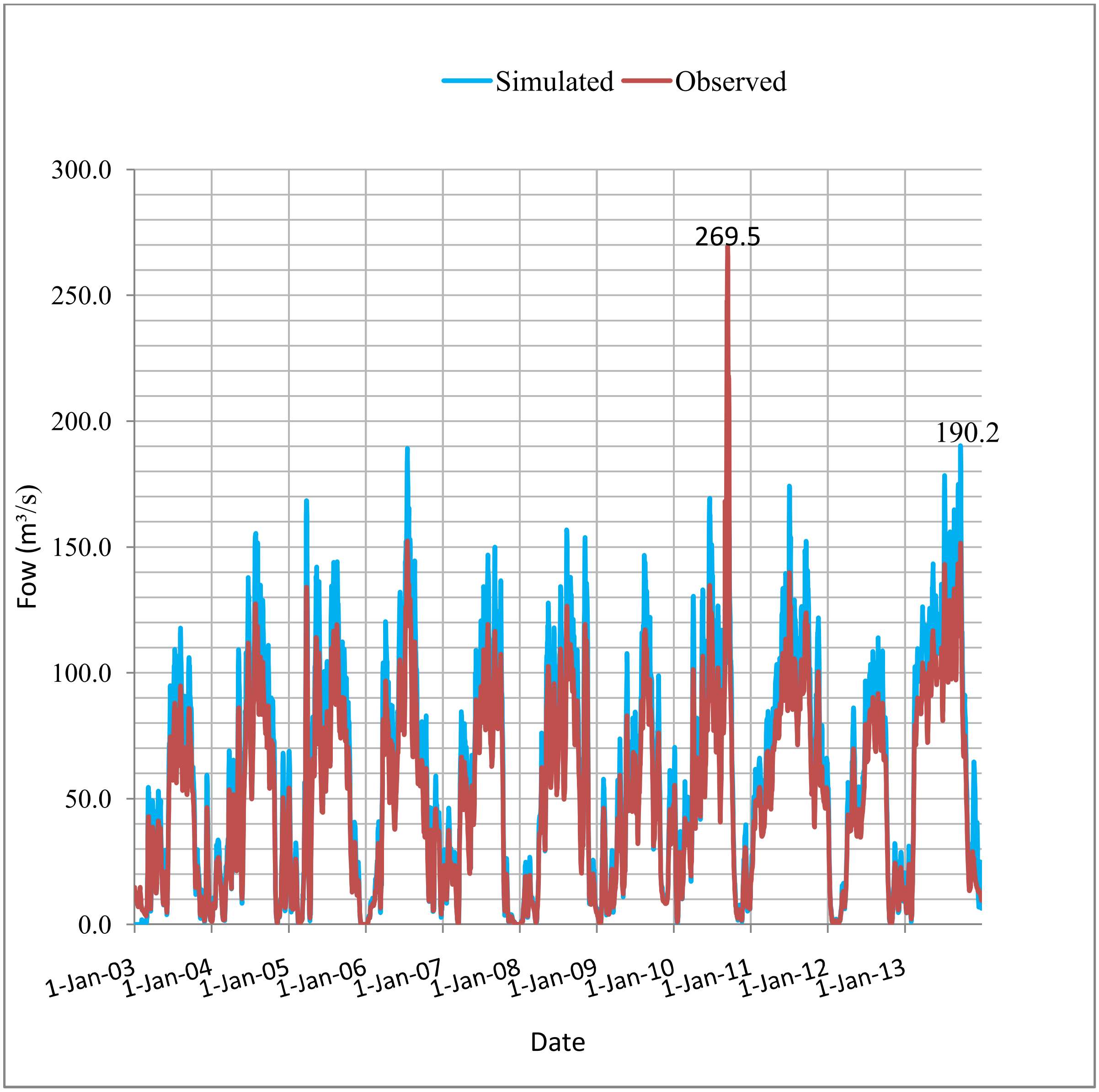

Figure 4. 7: Validation result of daily simulated and observed runoff hydrograph

The daily simulated and observed runoff hydrograph were compared by using the same statistical error functions used in model calibration. The values of NSE,R^2 and RMSE were better than those obtained during model calibration. The computed values of NSE,R^2 and RMSE were 0.873,0.914 and 13.6 m^3/s respectively.

Thus the statistical tests of error functions justify the soundness of HEC-HMS model for runoff simulation of Gilgel Gibe catchment. Figure 4.8 shows the co linearity between the observed and simulated flow runoff. The value of R^2 indicates that there is strong co linearity between observed and simulated runoff during model validation.

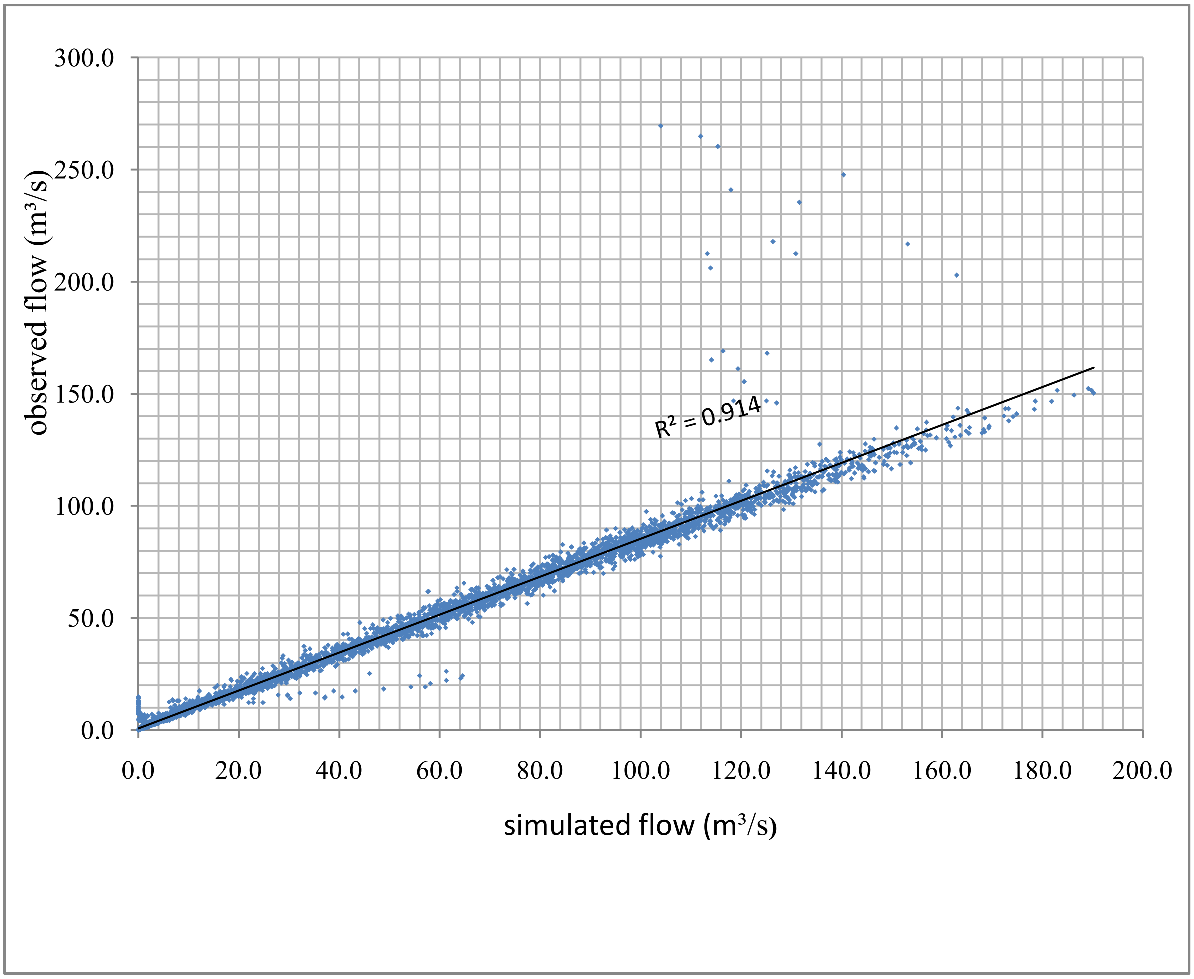

Figure 4. 8: R^2 Value for simulated and observed daily runoff hydrograph during validation

4.4 Daily catchment runoff potential

The objectives to checking the performance of any runoff hydrological models are to estimate the catchment runoff yield at daily, monthly or yearly basis. Determining the quantity of runoff from a catchment is critical in designing hydraulic structure including storm sewer, ditches, culverts, dams, weir and detention basins at the outlet of the catchment.

The daily catchment runoff was generated after HEC-HMS model calibration and validation from 01 January 1985 to 31 December 2017.

The maximum peak discharge for different hydrologic elements such as watershed, reach, junction and outlet was computed using the validated HEC-HMS model. The result indicates that the maximum simulated value of runoff was 320.746 m^3/s. The minimum simulated runoff was 0 m^3/s. The average value of daily catchment runoff was 83.121 m^3/s

The trend of simulated runoff throughout the simulation period was presented in Figure 4.9. The Figure indicates the general decrease in catchment runoff potential starting from 12 July 2011 to 31 December 2017. Site observation at different time and the different year of LU/LC information obtained from different source, indicated that there is rapid change in LU/LC change of the study area which brought significance effect on runoff.

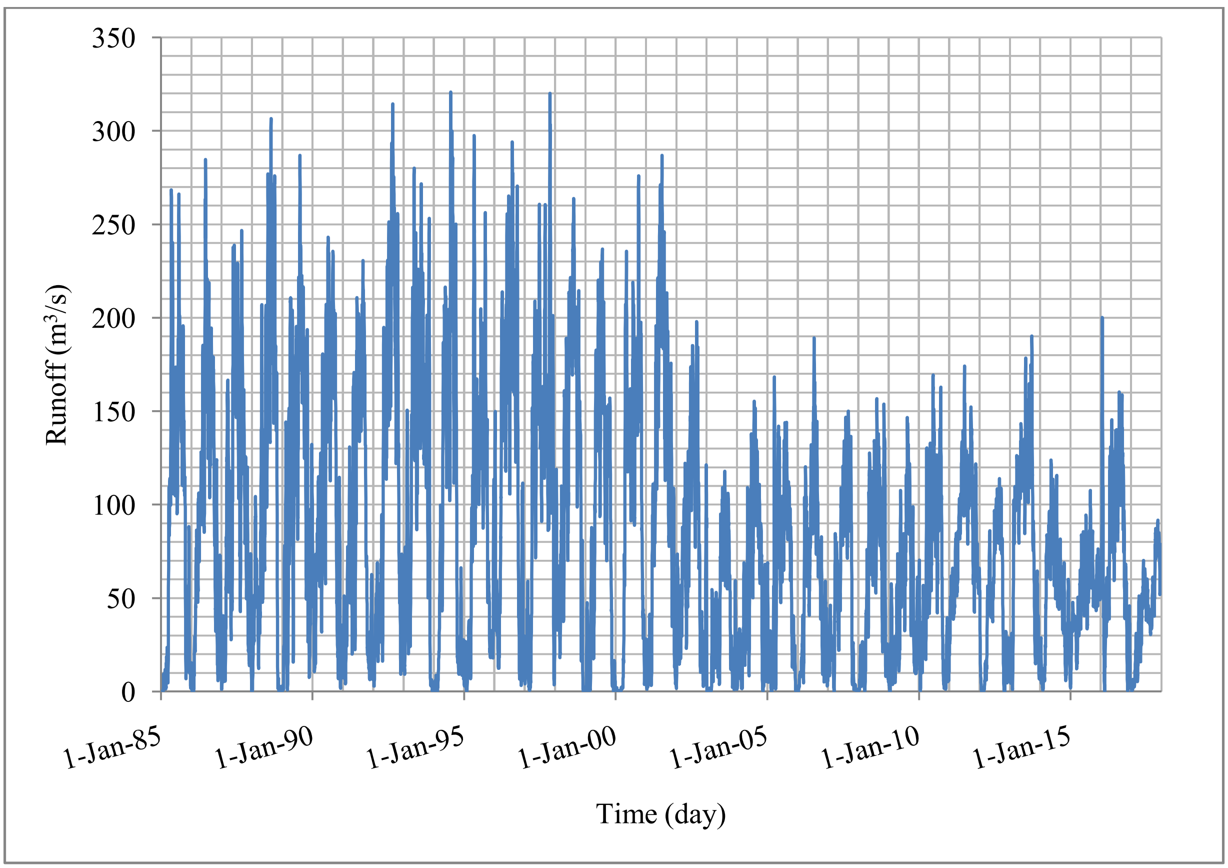

Figure 4. 9: Daily Catchment runoff

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Curve number was generated by the combination of soil and recent LU/LC of the catchment using ArcGIS and HEC-GeoHMS. Major part of the study area is covered by soil having HSG D. More over agriculture is the dominant land use type in the study area. Due to these, high curve number was generated in most part of the study area which has the potential to generate the greatest amount of runoff with little infiltration rate.

Sensitivity analysis was conducted for canopy storage, surface storage, Muskingum K and Muskingum x. The analysis shows that Muskingum K Muskingum x were more sensitive parameters.

The Statistical test of error functions like NSE,R^2 and RMSE were used to check the model performance in both calibration and validation period. The results are satisfactory and acceptable. The high value of NSE,R^2 and RMSE in validation indicates the existence of good agreement between the simulated and observed runoff. Thus the study indicates that the calibrated model performs well in simulating Gilgel Gibe catchment runoff.

5.2 Recommendation

The normal AMC was considered to determine the spatial distribution of curve number due to lack of detail information on the moisture condition of Gilgel Gibe catchment. Therefore, further study should be conducted considering the detail moisture condition of the catchment.

The HEC-HMS model performance for the study area should be checked by selecting a different combination direct runoff losses, base flow and routing method other than the methods considered in this study. Then it can be used for runoff estimation of other catchment or at a basin level with similar physical characteristics of the study area.

Future design and construction of any hydraulic structure should consider the generated maximum and average daily catchment runoff. Effective watershed management strategies should be implemented to minimize the effect of man-made activities and natural phenomena on daily catchment runoff.

The LU/LC of the catchment may not remains constant for a long period. Therefore Future study should consider the effects of dynamic change in major categories of LU/LC on curve number and runoff.

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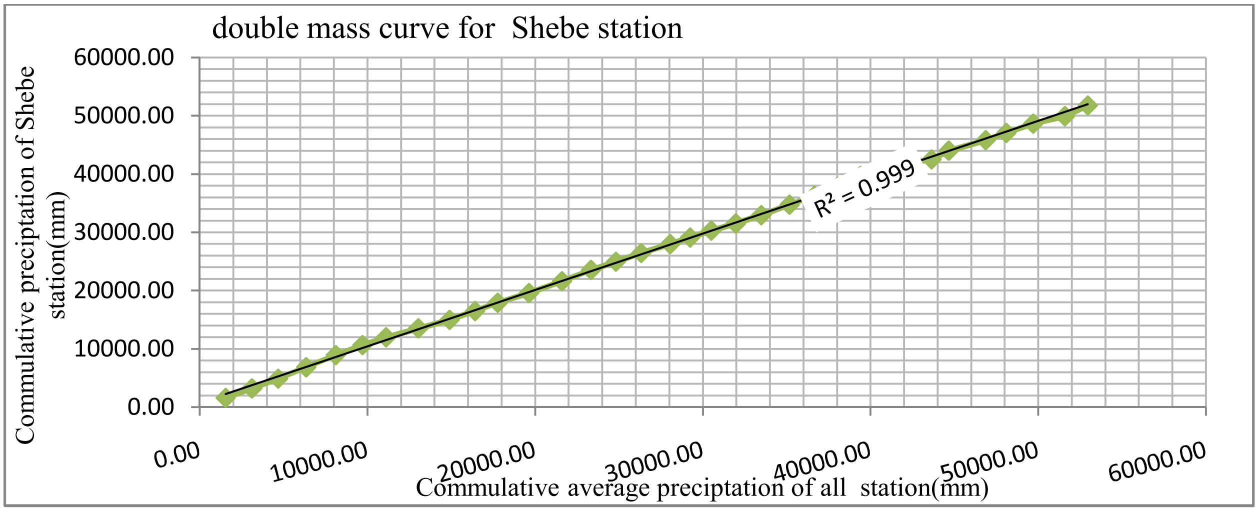
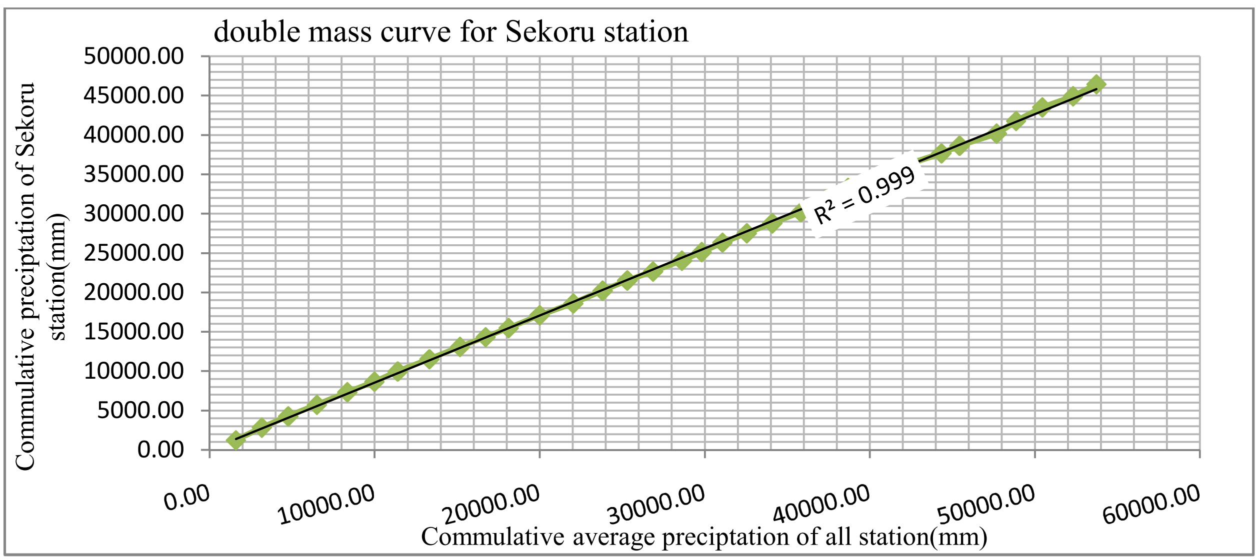
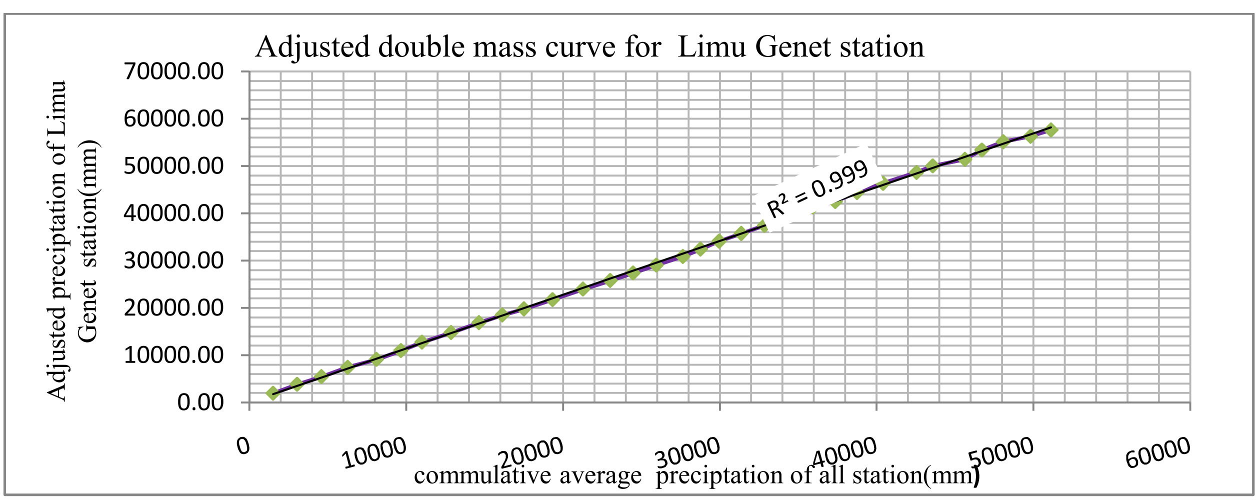
APPENDIXES

Appendix -1: Consistency test result







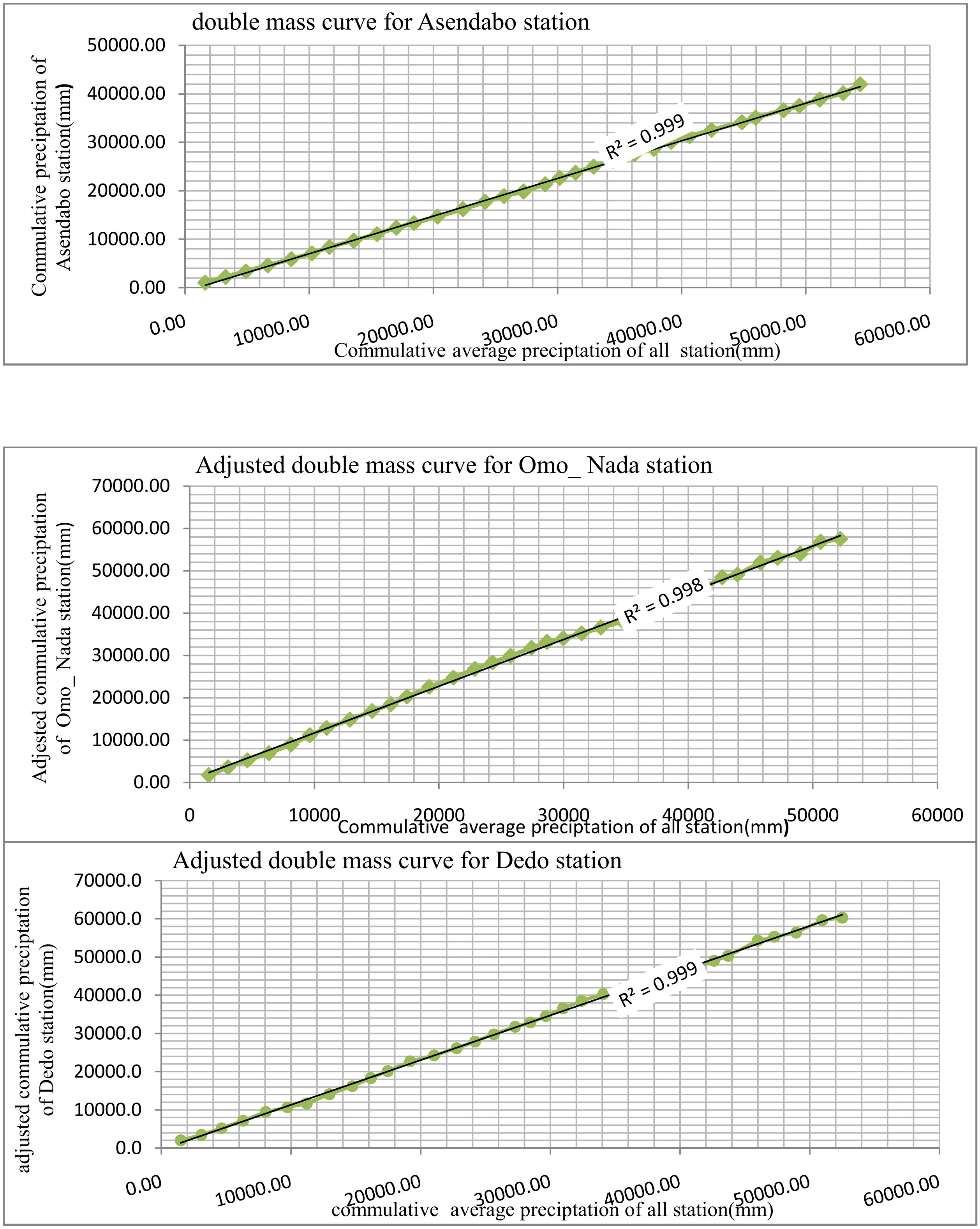
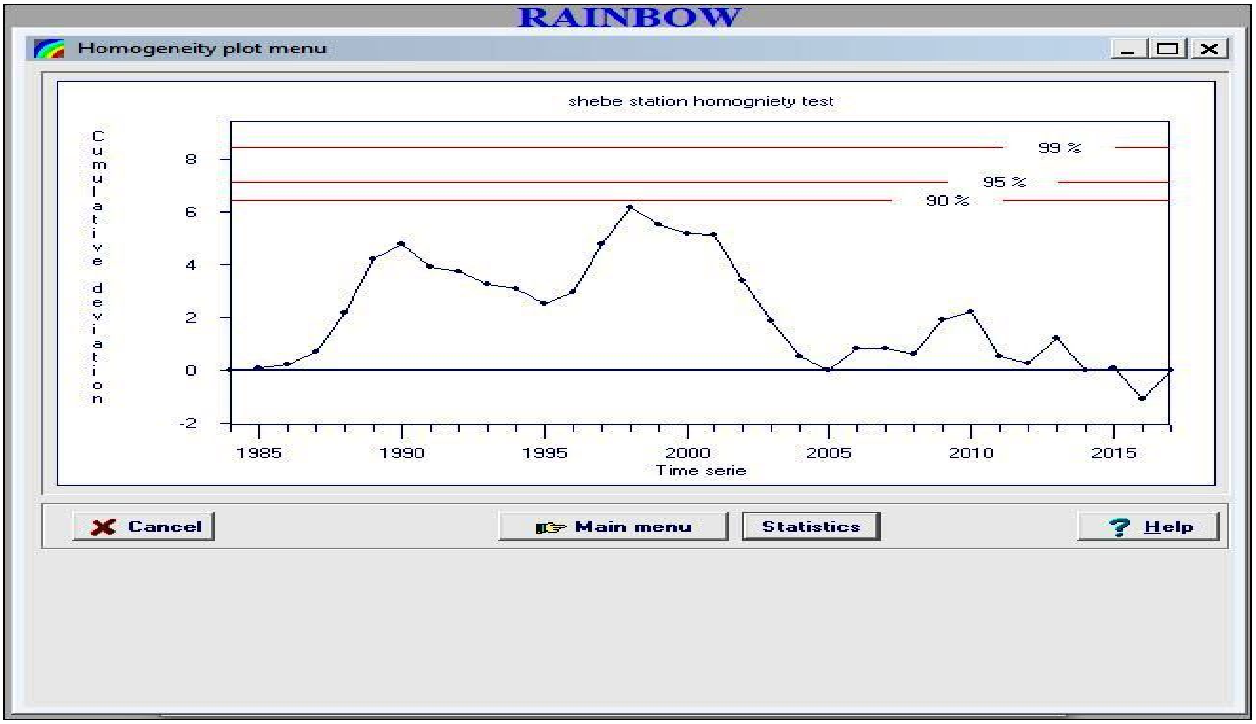
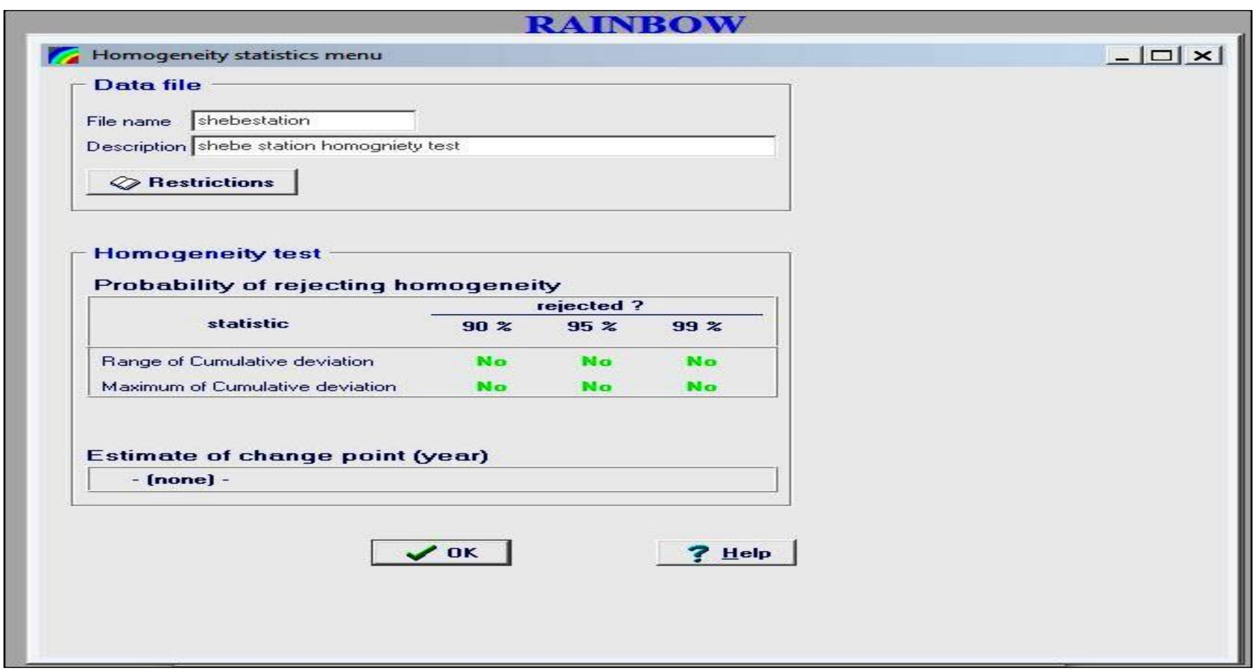
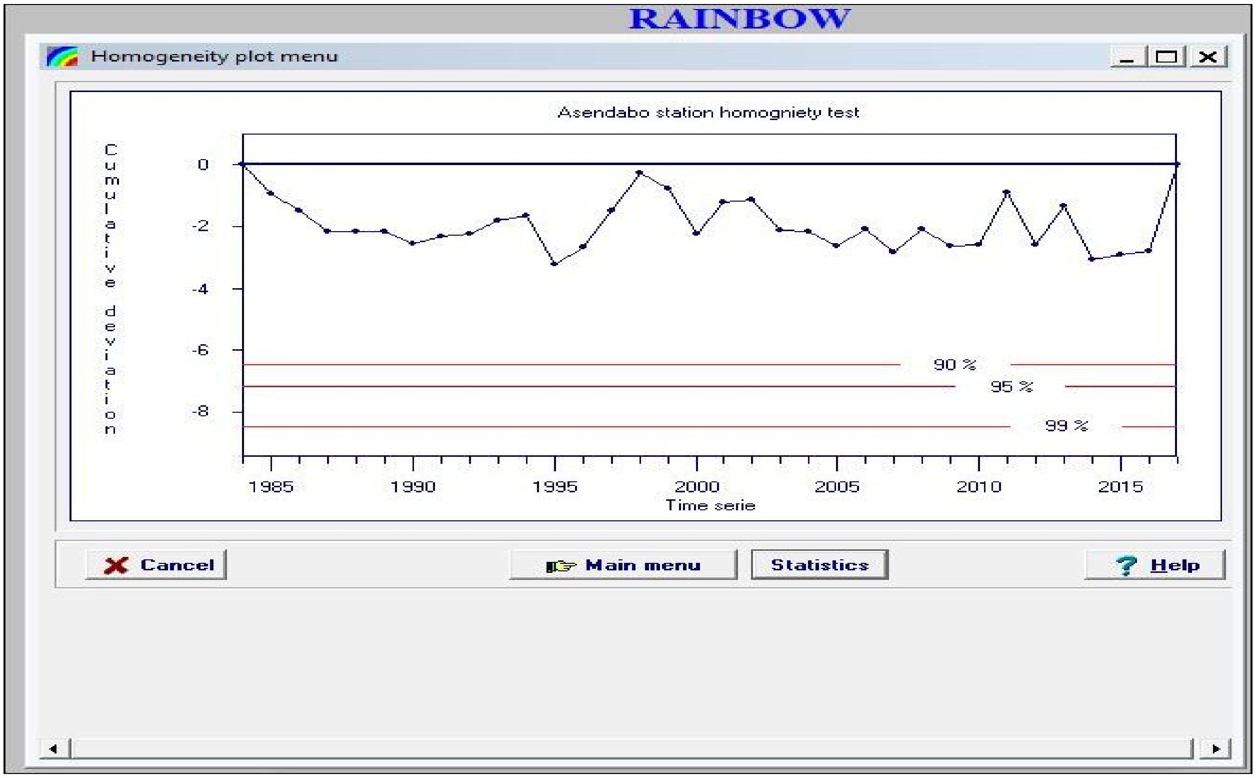


Figure 1.1: Precipitation data consistency test graph

Appendix- 2: Homogeneity test



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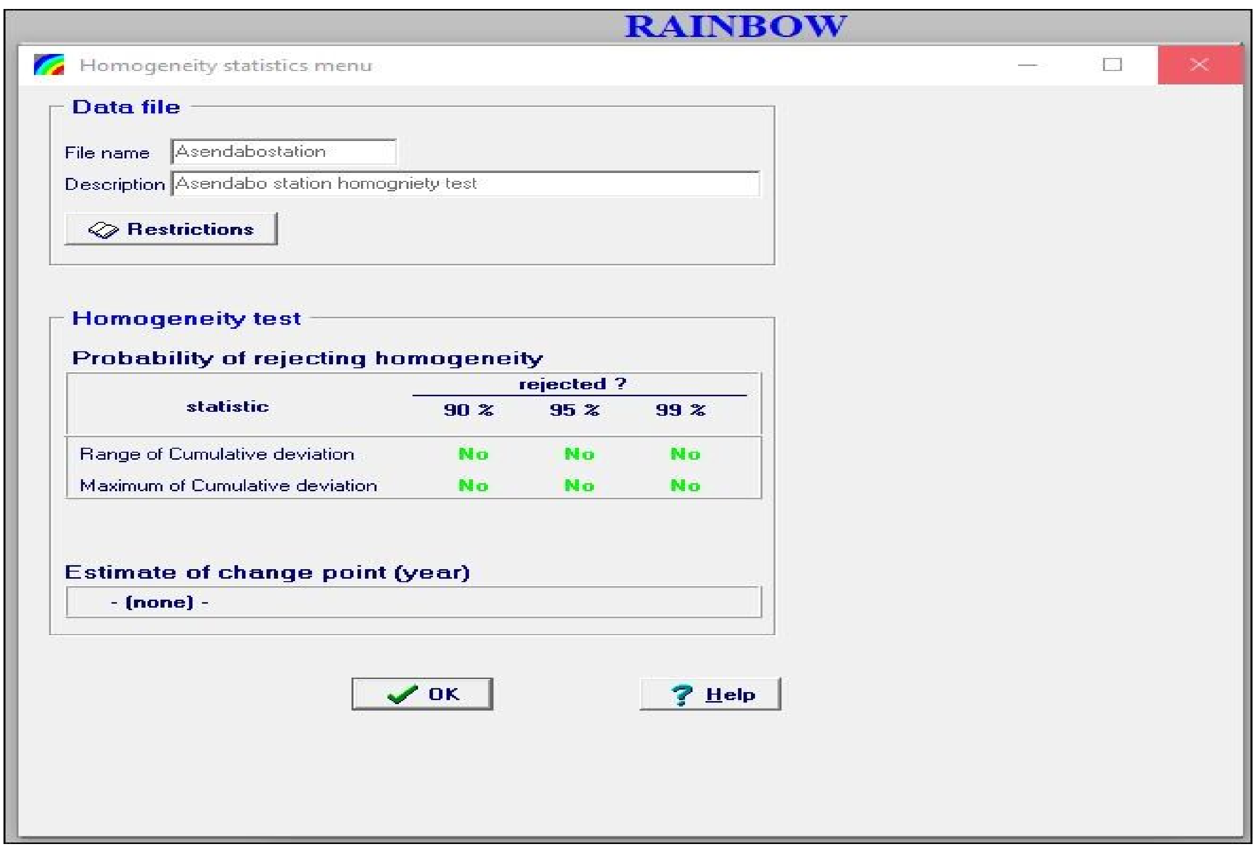
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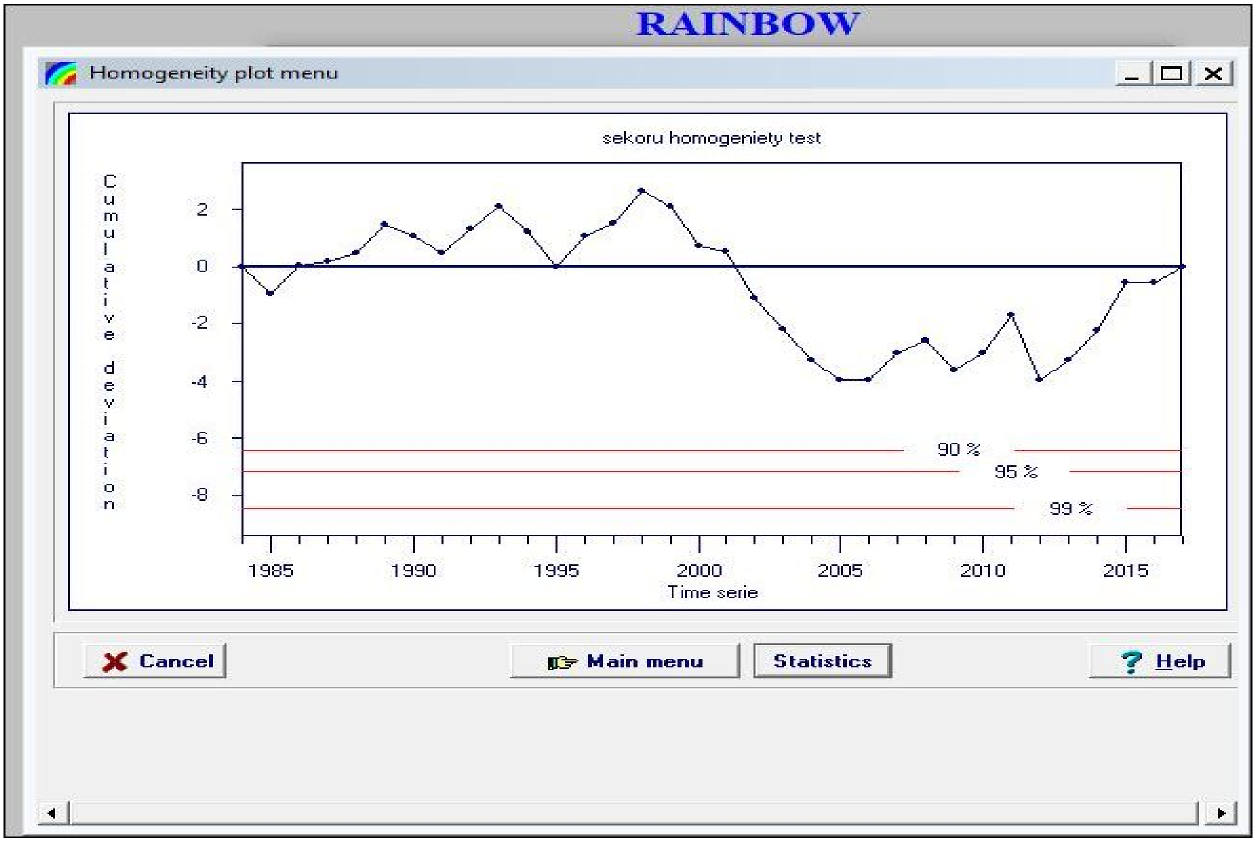
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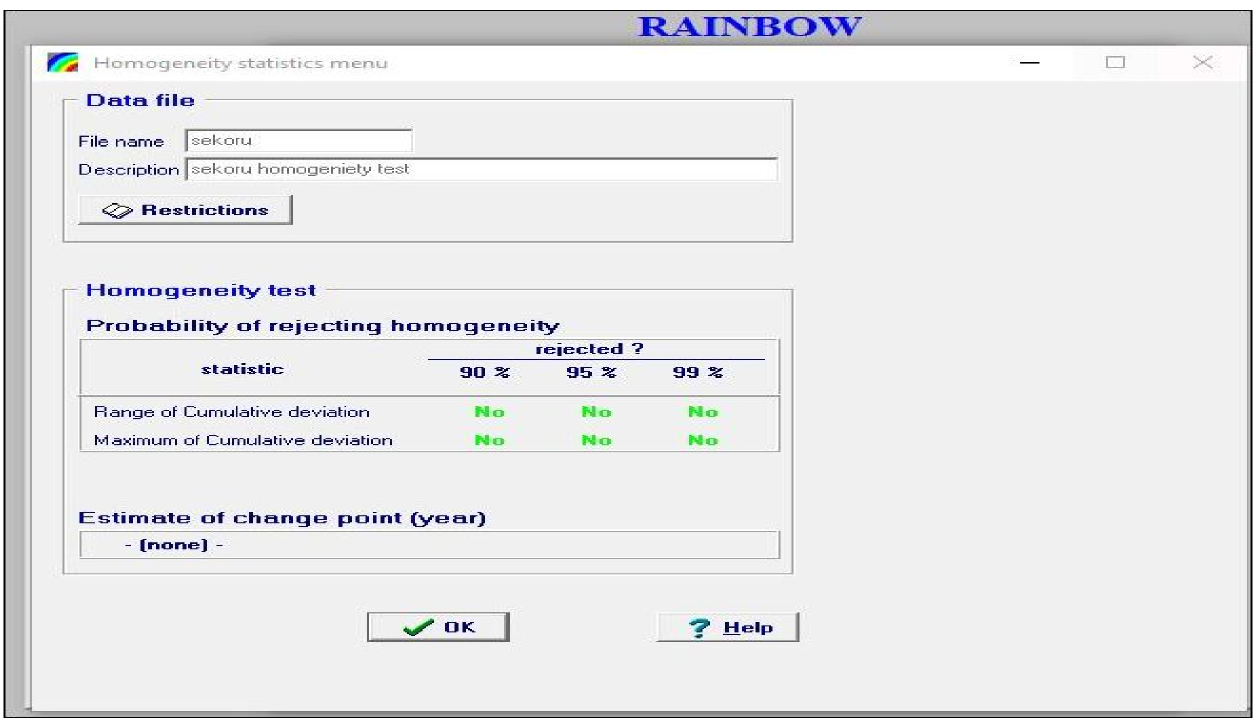
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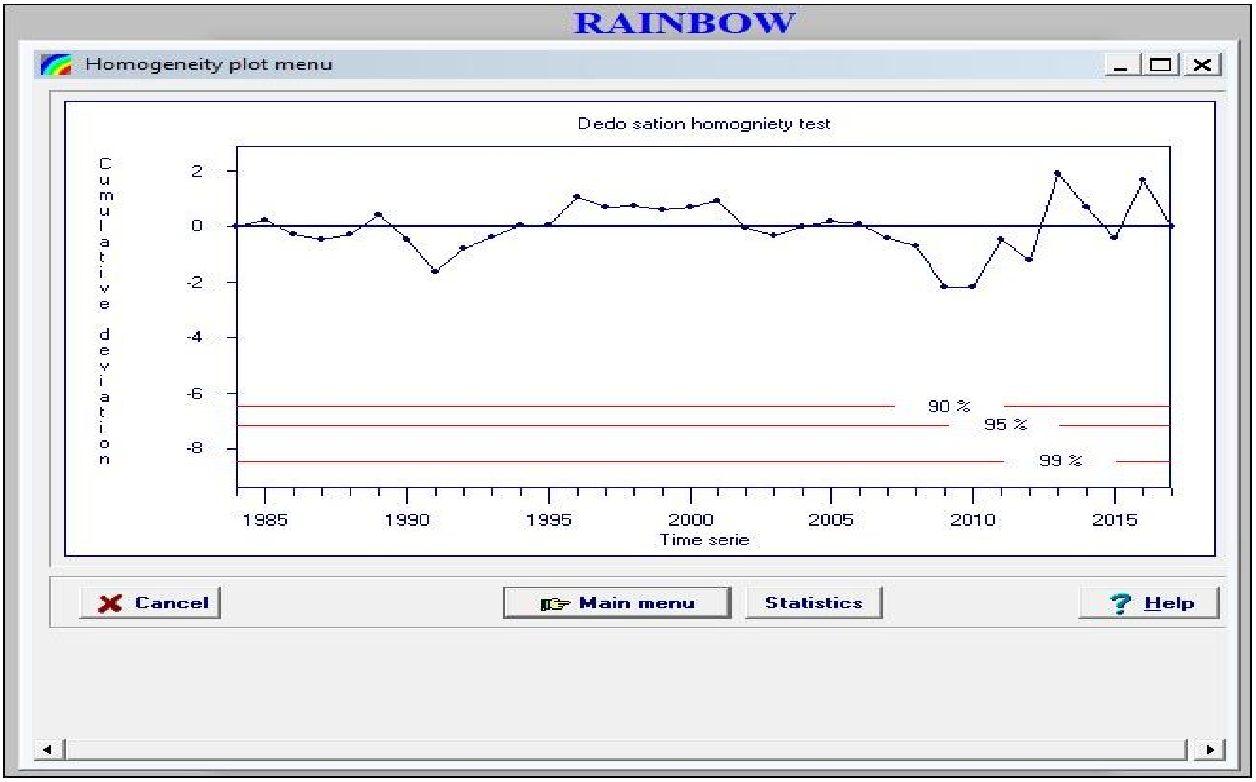
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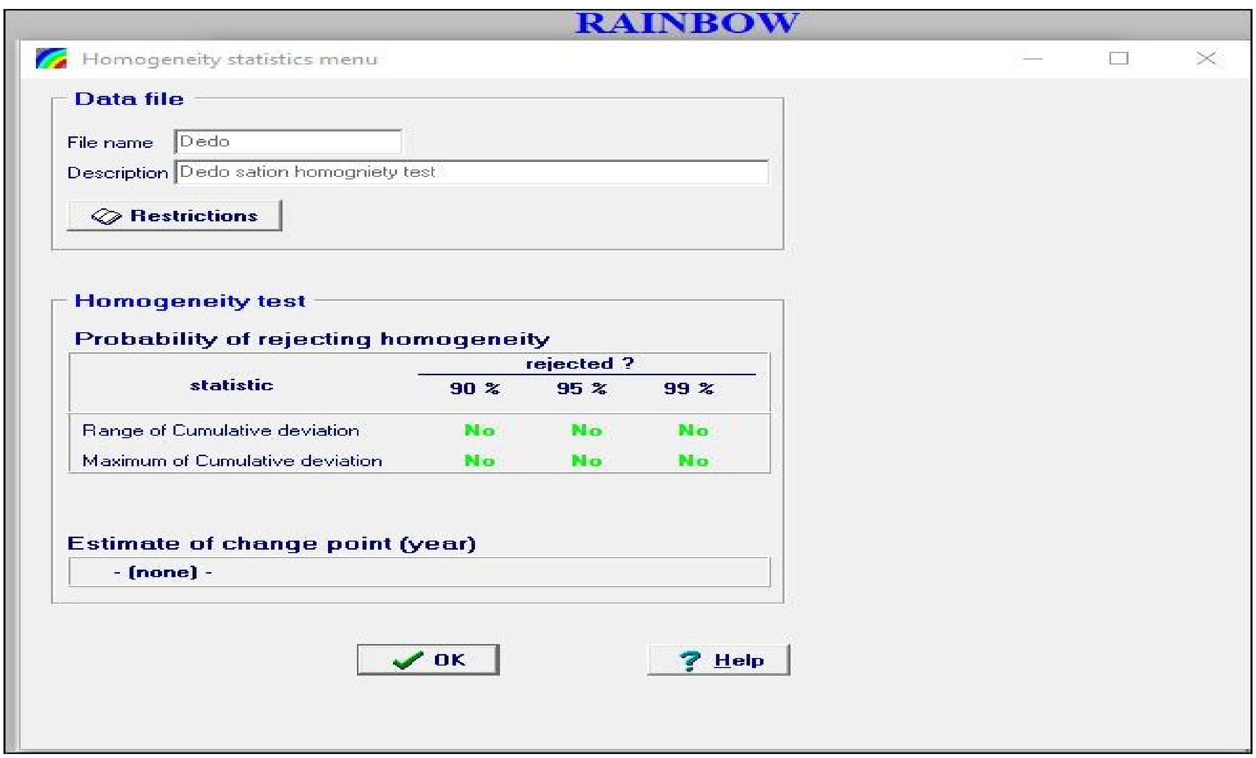
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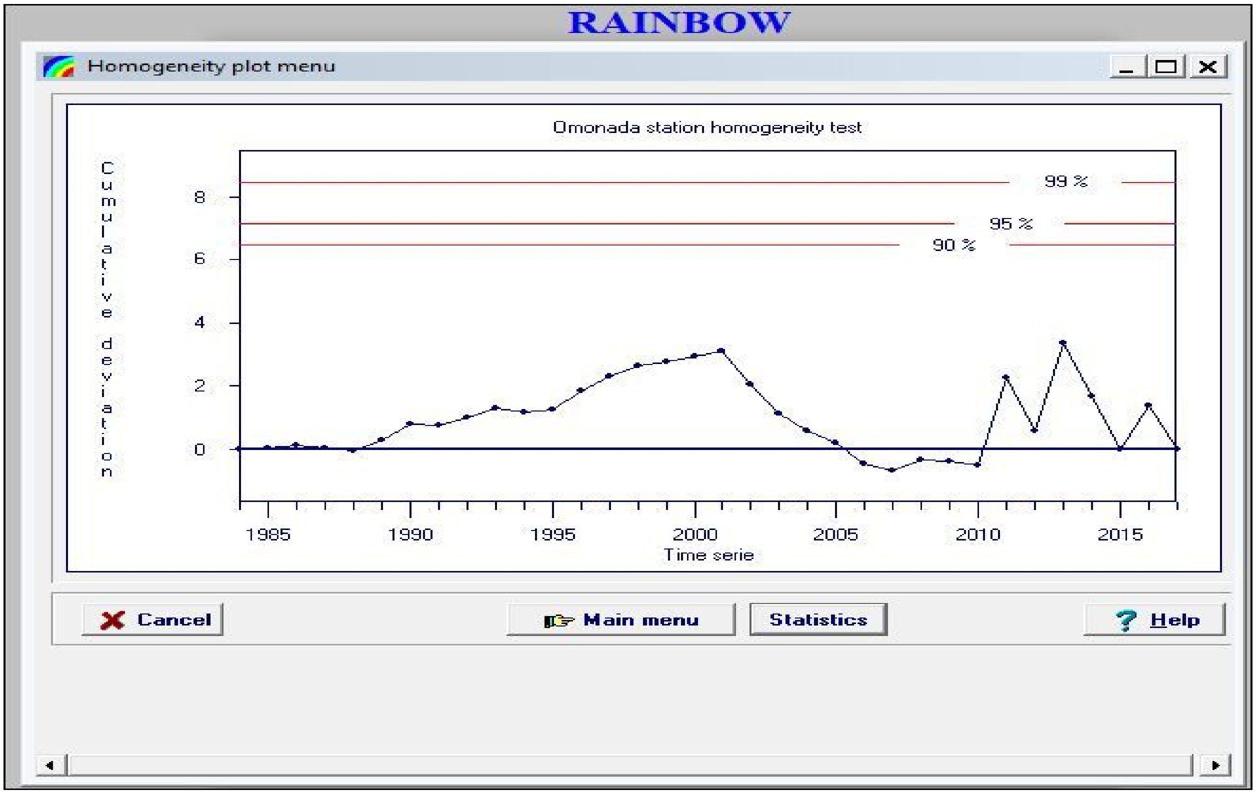
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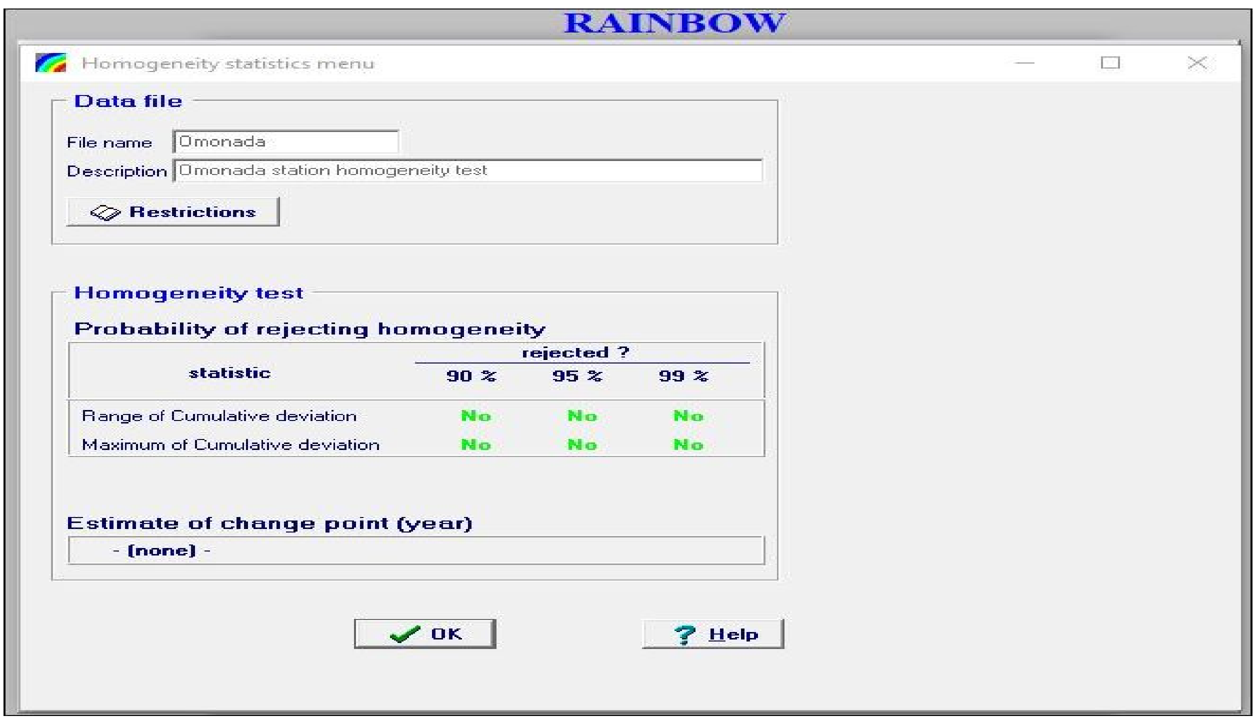
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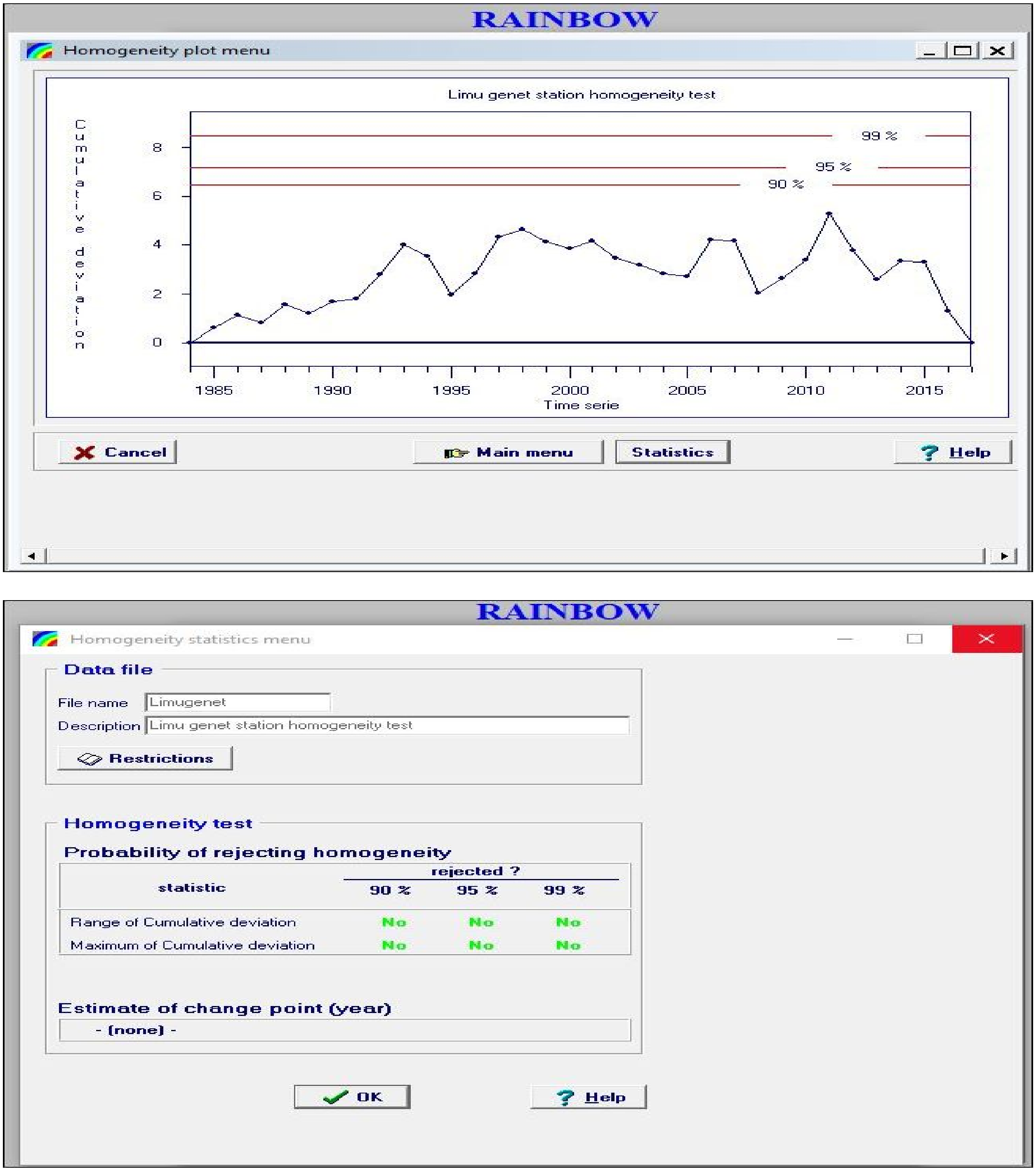
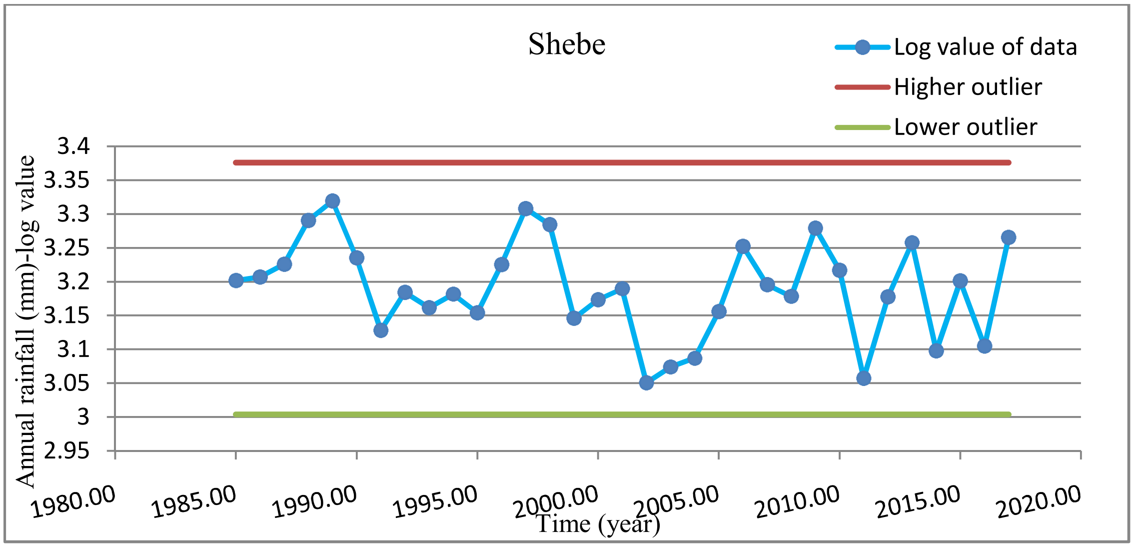
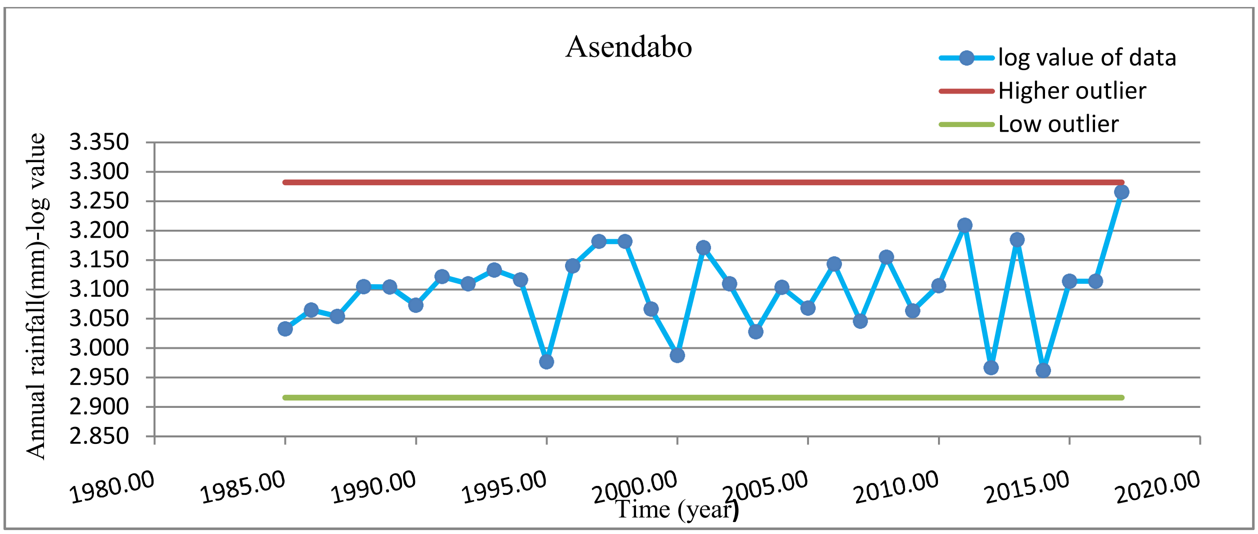
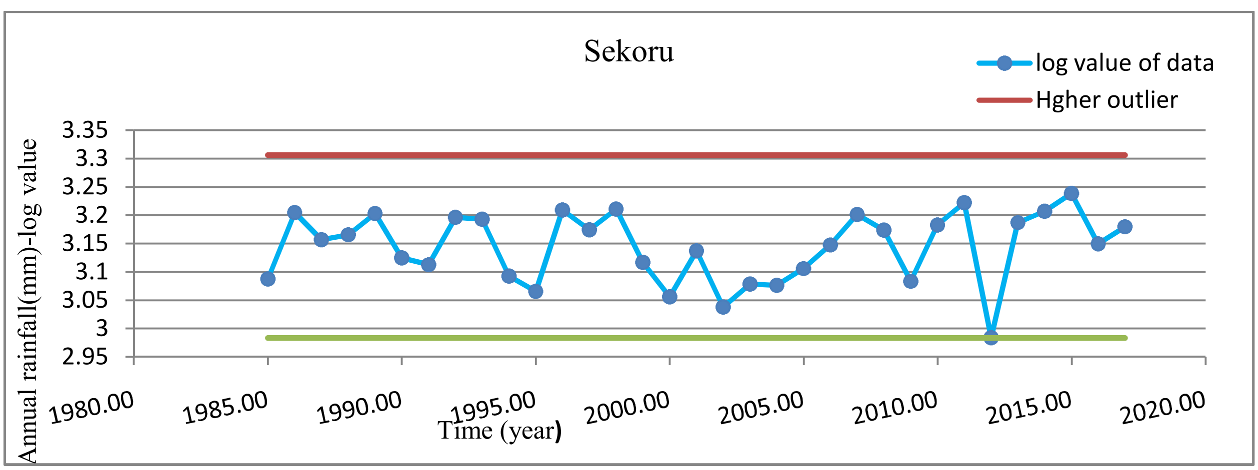


Figure 2.1: Precipitation homogeneity test report

Appendix- 3: Outlier test result







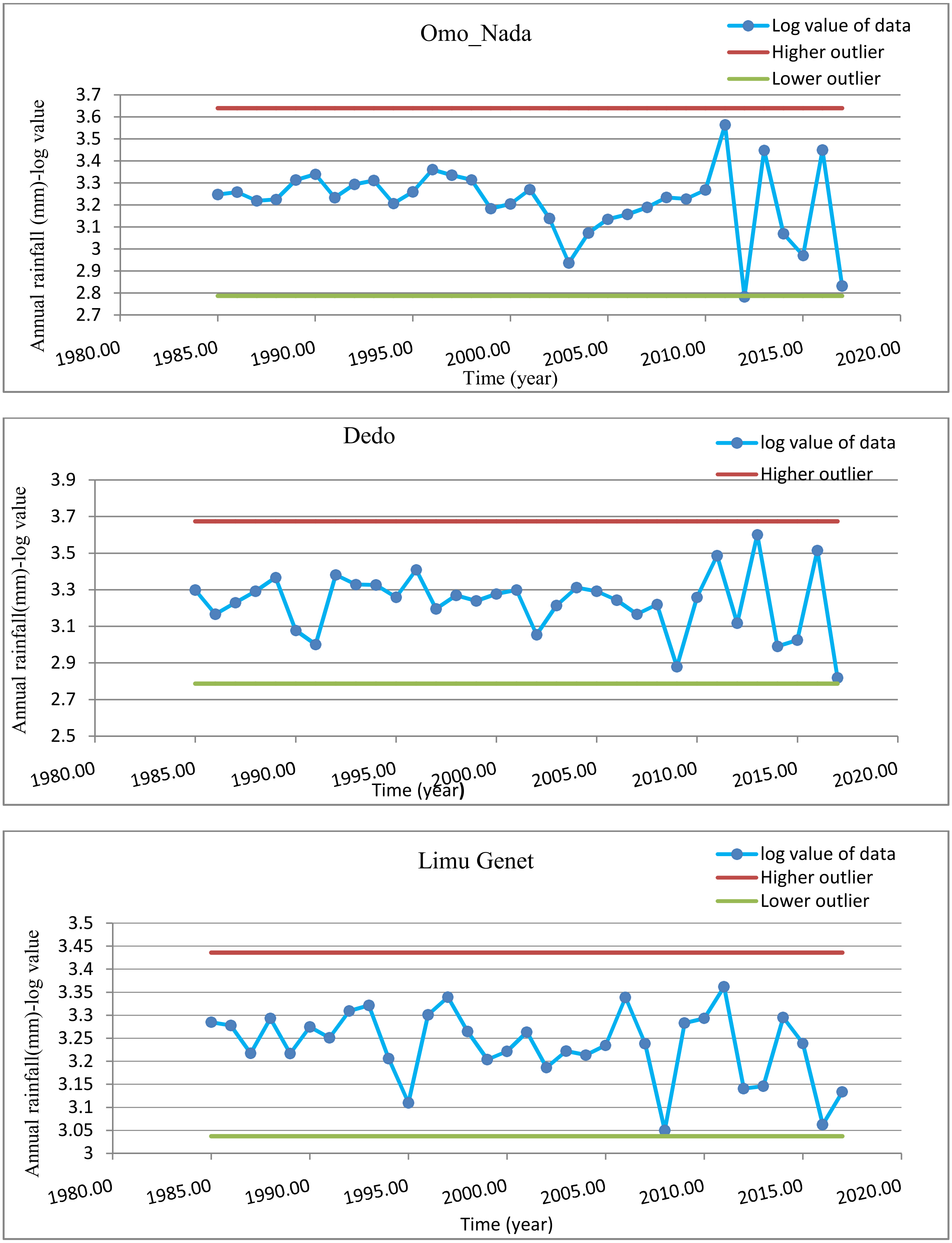


Figure 3.1: Precipitation outlier test graph

Appendix-4: Terrain preprocessing Results

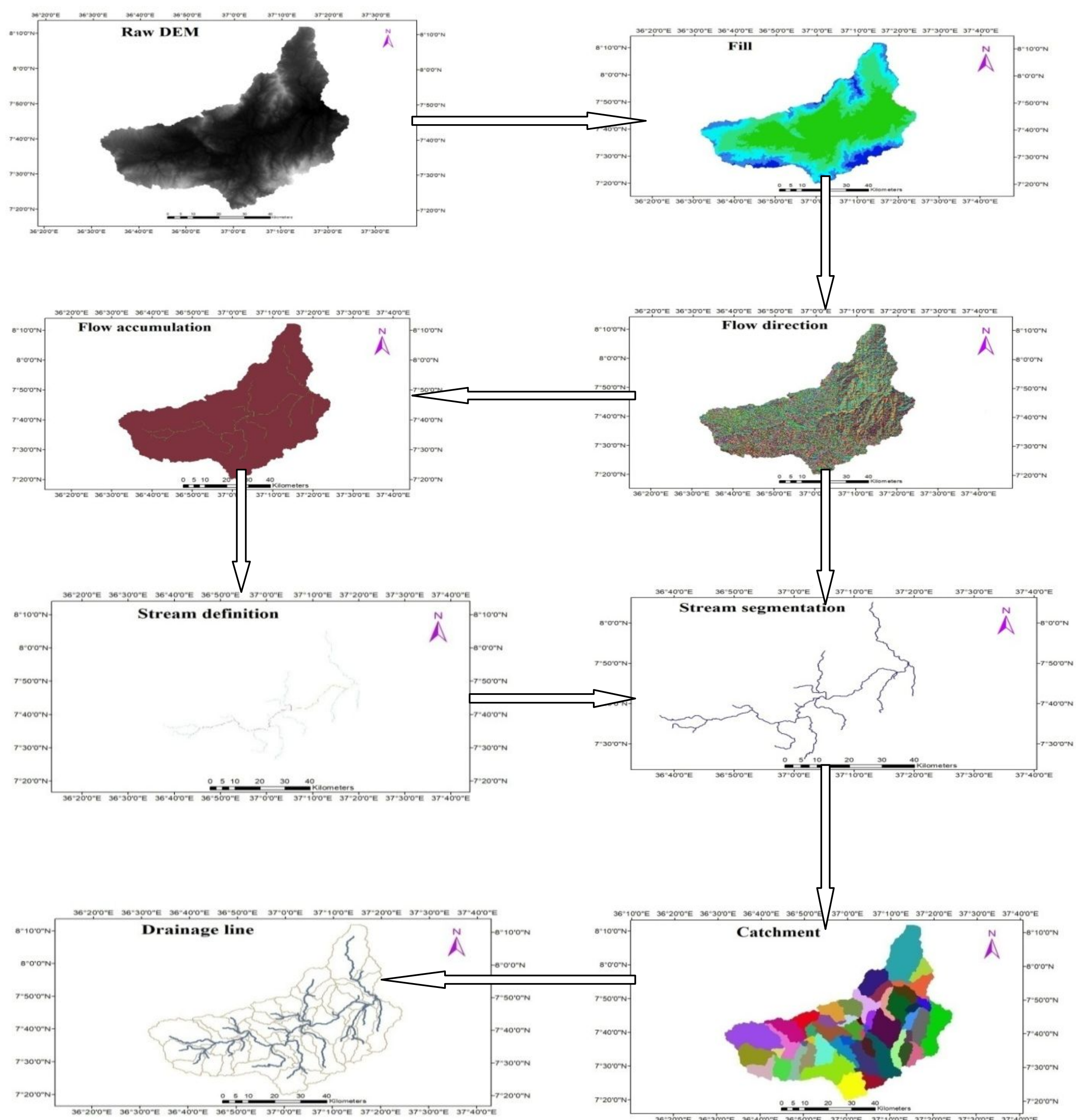


Figure 4.1: The order and results of Terrain preprocessing

Appendix-5: Stream and sub-basin characteristics

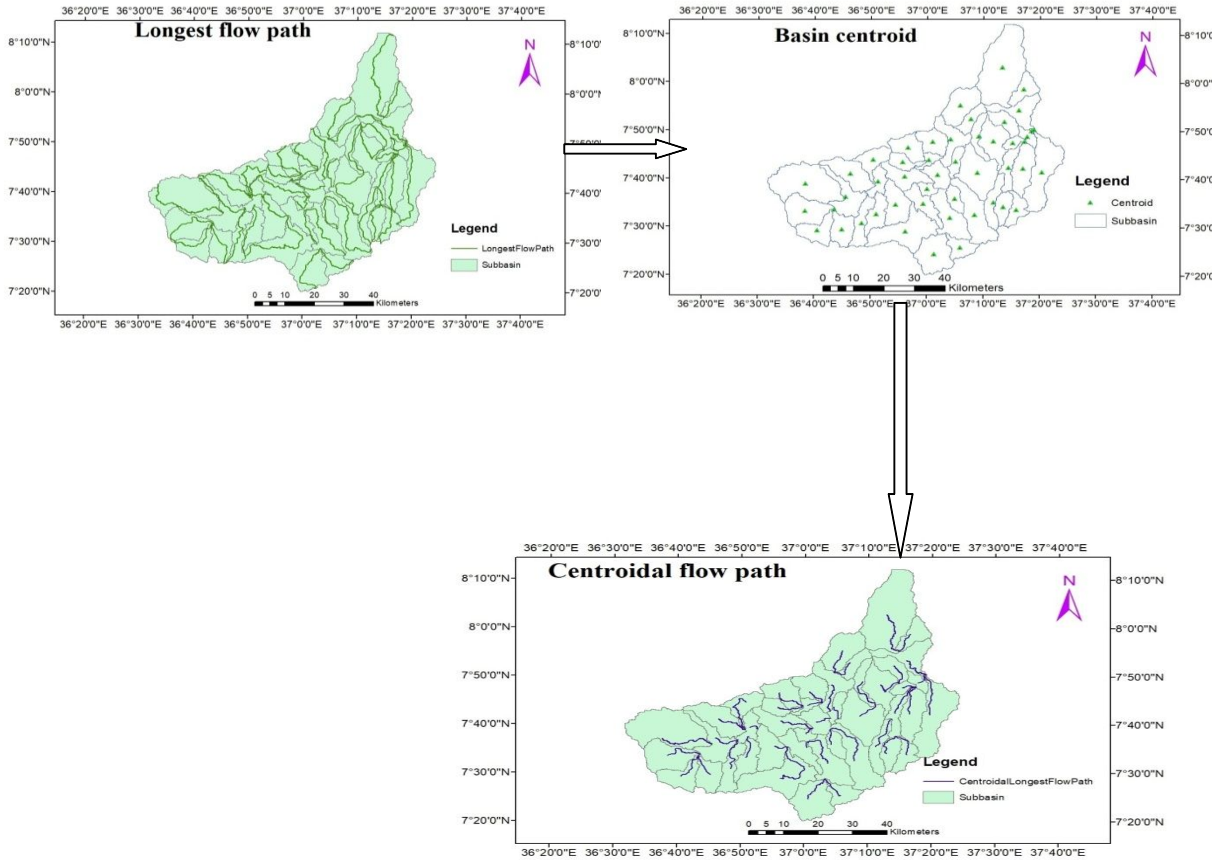


Figure 5.1: The step by step results of computed stream and sub-basin characteristics

Appendix-6:Sub-basin parameters computed from raster

Table 6.1:Sub-basin curve number and lag time

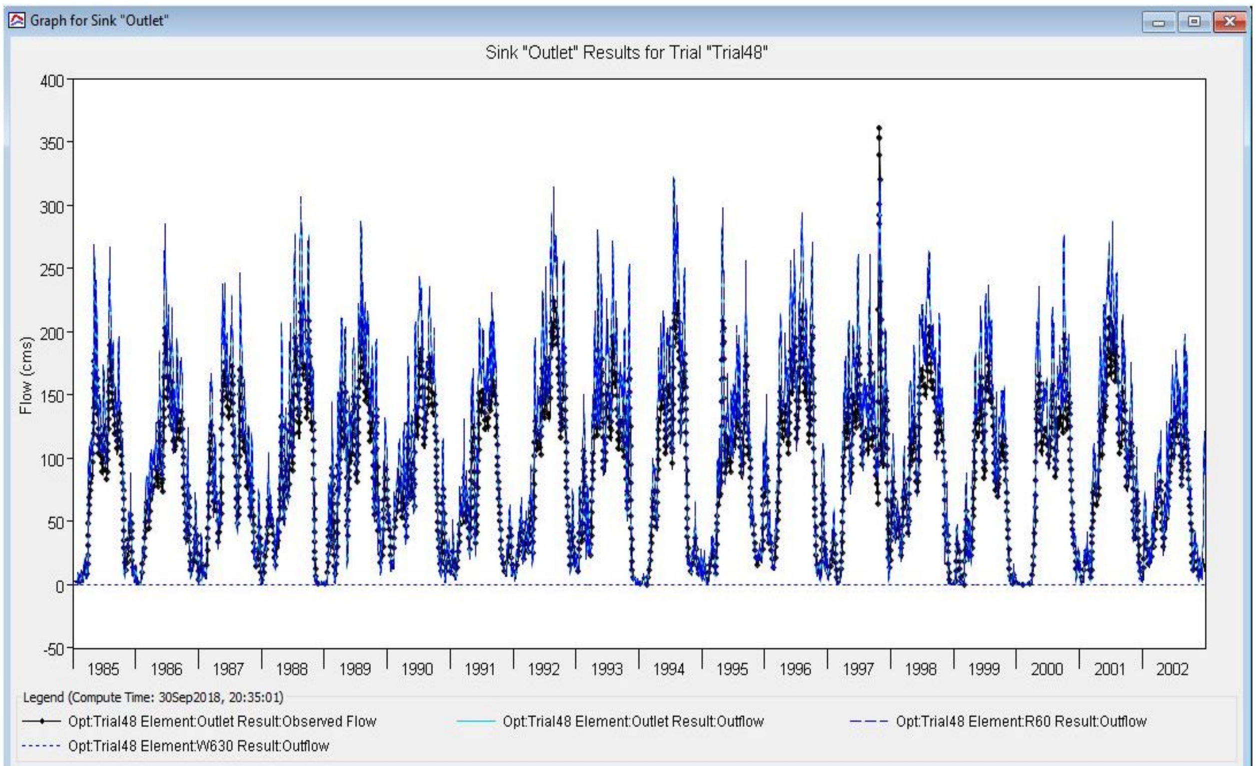
Wshed_Name	Shape_Area	Basin_Slope	Basin_CN	Basin_Lag
W560	347733437.5	21.125542	81.574402	3.468667
W570	62568125	21.907413	84.834061	1.516656
W580	122466250	28.777464	82.577721	1.64825
W590	96483593.75	16.069016	78.535995	2.345967
W600	91710937.5	20.223581	80.666267	2.455178
W610	57752031.25	15.36028	73.749527	1.868763
W620	48522187.5	26.220324	83.072296	1.502634
W630	187968.75	4.525491	95.021985	0.13328
W640	1872812.5	9.911265	92.529282	0.259228
W650	27498906.25	7.486984	90.543945	1.564436
W660	198890781.25	17.695585	86.694008	3.040822
W670	113277187.5	15.234669	87.466537	1.920986
W680	23046718.75	6.912478	86.825928	1.612828
W690	41718.75	4.271139	93.142255	0.174585
W710	109347187.5	11.209563	81.91581	3.17515
W720	77842031.25	21.080519	81.57299	1.692951
W730	82229375	20.509357	85.084061	1.645162
W740	51034687.5	24.713053	85.585831	1.786069
W750	173484843.75	10.72725	84.751144	3.331133
W760	24289531.25	9.254013	79.918564	2.137354
W770	46455468.75	17.312618	85.499893	1.616785
W780	73477812.5	17.897833	84.48951	2.283574
W810	37107968.75	11.431067	76.67971	1.623193
W830	64099062.5	8.27481	84.322342	1.910119
W840	70085781.25	22.420198	69.030739	2.362885
W850	59375468.75	9.634913	69.917702	3.676119
W860	118764687.5	15.810243	83.218269	2.561107
W870	90248125	15.446485	80.827919	2.664773
W890	160370625	25.954609	81.381126	3.062233
W900	25051718.75	9.502767	84.936684	1.595254
W920	108312500	16.765203	81.477951	1.900422
W930	42366093.75	14.925918	76.557602	2.191902
W940	54042343.75	26.180174	82.377953	1.593789
W950	47307031.25	12.011582	79.62133	1.954281
W960	72055312.5	17.202929	82.533592	2.230194
W970	56265312.5	28.919916	84.89872	1.566868
W980	264382187.5	19.264534	85.816025	2.808972
W1000	75040312.5	22.990515	83.859787	2.22469
W1010	126536250	17.235811	75.45137	3.589273
W1020	105834843.75	15.675241	81.079697	2.685199
W1030	77177968.75	12.152565	78.320786	2.339661
W1040	131892656.25	18.332573	83.213326	2.276292
W1050	765937.5	33.041012	81.498161	0.20356
W1060	85907500	21.016518	83.876755	1.790246
W1070	80877968.75	23.523123	85.031418	1.489235
W1080	202677656.25	21.262751	82.936211	3.465063
W1090	58958281.25	32.941086	82.351074	1.432829
W1100	140602031.25	25.795055	82.783928	2.032422

Appendix-7: HEC-HMS model calibration and validation results

Table 7.1: Initial and optimized values of Muskingum K and x

Reach	Element	Unit	Initial value	optimized value
R100	Muskingum - K	HR	1.5	1.7
R110	Muskingum - K	HR	0.008	0.082
R120	Muskingum - K	HR	2.5	2.7
R160	Muskingum - K	HR	2.6	2.6
R180	Muskingum - K	HR	2.5	2.7
R190	Muskingum - K	HR	2.7	2.7
R210	Muskingum - K	HR	2.5	2.6
R220	Muskingum - K	HR	2.5	2.8
R230	Muskingum - K	HR	3.5	3.1
R240	Muskingum - K	HR	2.8	2.8
R270	Muskingum - K	HR	2.5	2.5
R290	Muskingum - K	HR	2.3	2.3
R310	Muskingum - K	HR	2.5	2.5
R330	Muskingum - K	HR	3.0	3.0
R340	Muskingum - K	HR	2.2	2.3
R360	Muskingum - K	HR	2.1	2.2
R40	Muskingum - K	HR	3.3	3.3
R420	Muskingum - K	HR	2.3	2.4
R430	Muskingum - K	HR	2.3	2.3
R440	Muskingum - K	HR	2.0	2.0
R470	Muskingum - K	HR	3.78	3.9
R510	Muskingum - K	HR	2.5	2.4
R380	Muskingum - K	HR	2.4	2.5
R60	Muskingum - K	HR	2.81	2.76
R70	Muskingum - K	HR	3.1	3.2
R90	Muskingum - K	HR	2.9	3.0
R100	Muskingum - x		0.25	0.39
R110	Muskingum - x		0.25	0.39
R120	Muskingum - x		0.25	0.39
R160	Muskingum - x		0.25	0.39
R180	Muskingum - x		0.25	0.39
R190	Muskingum - x		0.25	0.39
R210	Muskingum - x		0.25	0.39
R220	Muskingum - x		0.25	0.39
R220	Muskingum - x		0.25	0.39
R230	Muskingum - x		0.25	0.39
R240	Muskingum - x		0.25	0.39
R270	Muskingum - x		0.25	0.39
R290	Muskingum - x		0.25	0.39
R310	Muskingum - x		0.25	0.39
R330	Muskingum - x		0.25	0.39
R340	Muskingum - x		0.25	0.39
R360	Muskingum - x		0.25	0.39

R380	Muskingum - x		0.25	0.39
R390	Muskingum - x		0.25	0.39
R40	Muskingum - x		0.25	0.39
R420	Muskingum - x		0.25	0.39
R430	Muskingum - x		0.25	0.39
R440	Muskingum - x		0.25	0.39
R470	Muskingum - x		0.25	0.39
R380	Muskingum - x		0.25	0.39
R510	Muskingum - x		0.25	0.39
R60	Muskingum - x		0.25	0.39
R70	Muskingum - x		0.25	0.39



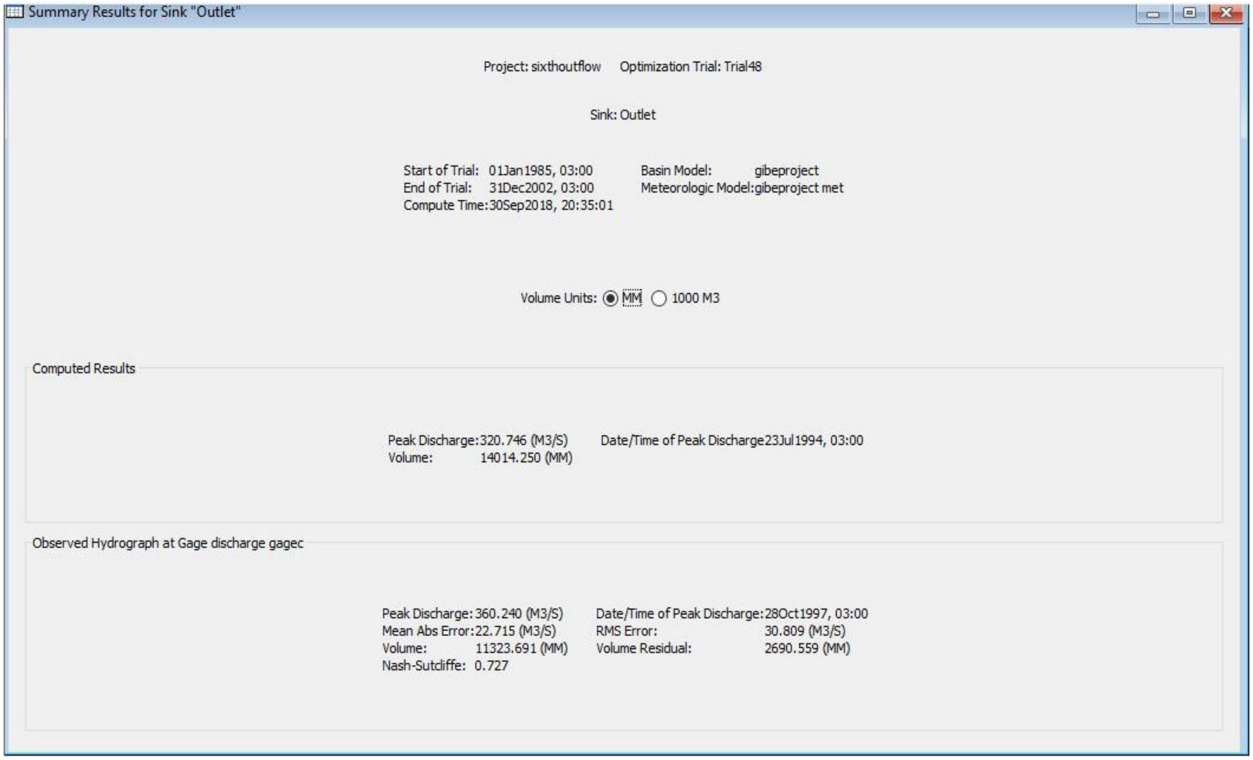


Figure 7.1 : Calibration result daily runoff and and observed stream flow hydrograph

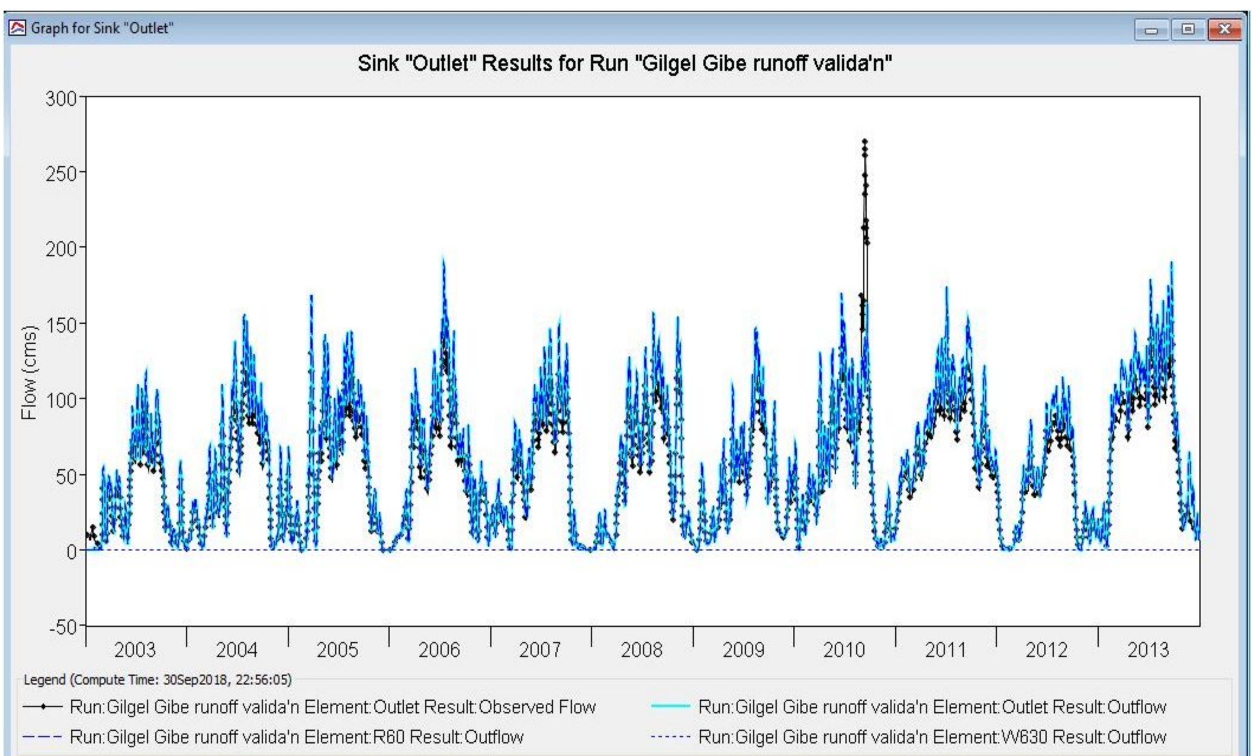


Figure 7.2: Validation result daily runoff and and observed stream flow hydrograph

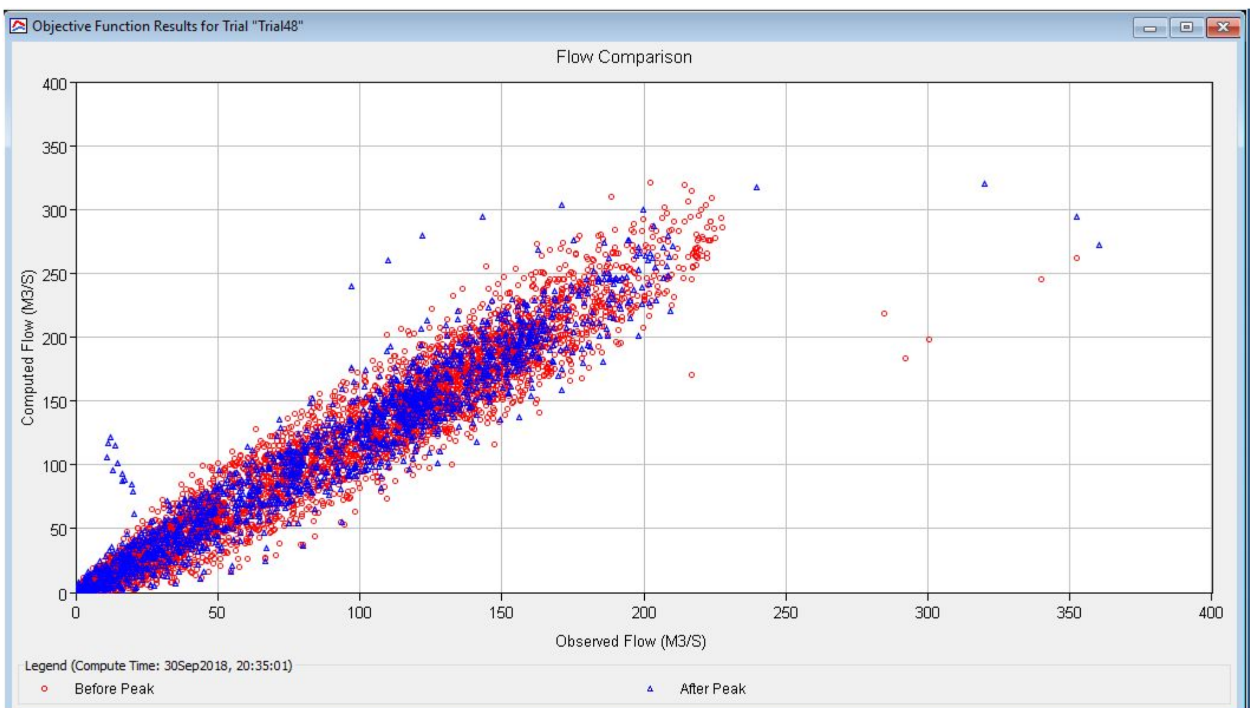


Figure 7.3: Observed and simulated flow comparison during model calibration

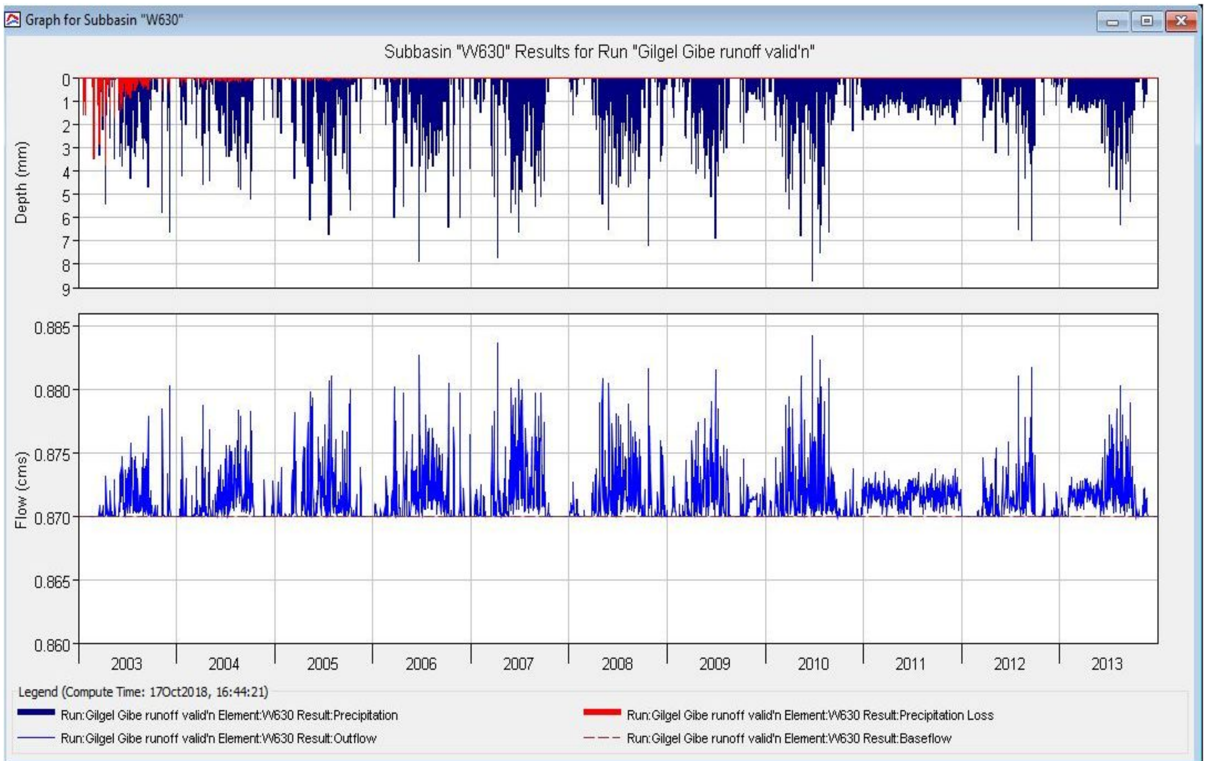


Figure 7.4: Graph showing runoff as a result of precipitation for sub-basin 630 (near the outlet)

ANNEXES

Annex- 1: SCS –CN for different LU/LC and hydrologic soil group

Table 1.1: Runoff curve number for urban area[1]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area[2]	A	B	C	D
Fully developed urban areas					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acre	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c					

[1] Average runoff condition, and $I_a = 0.2S$.
[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.
[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
[4] Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4, based on the degree of development (imperviousness area percentage) and the CN's for the newly graded pervious areas.

(Source: chow et al., 1988)

Table 1.2: Runoff curve number for cultivated agricultural land[1]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment[2]	Hydrologic condition[3]	A	B	C	D
Fallow	Bare soil	–	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C & T)	Poor	66	74	80	82
		Good	62	71	78	81
	C & T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	838
	C & T	Poor	61	72	79	82
		Good	59	70	78	81
	C & T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C & T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and Ia = 0.2S.
[2] *Crop residue cover* applies only if residue is on at least 5% of the surface throughout the year.
[3] Hydrologic condition is based on combination of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes in rotations, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.
Good: Factors impair infiltration and tend to increase runoff.
Poor: Factors encourage average and better than average infiltration and tend to decrease runoff.

(Source: chow et al., 1988)

Table 1.3: Runoff curve number for other agricultural area[1]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Hydrologic condition	A	B	C	D
Pasture, grassland, or range – continuous forage for graving.[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow – continuous grass, protected from grazing and generally mowed for hay.	–	30	58	71	78
Brush – brush-weed mixture with brush the major element.[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[4]	48	65	73
Woods – grass combination (orchard or tree farm).[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods.[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30[4]	55	70	77
Farmsteads – buildings, lanes, driveways, and surrounding lots.	–	59	74	82	86

[1] Average runoff condition, and $I_a = 0.2S$.

[2] *Poor:* <50% ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: >75% ground cover and lightly or only occasionally grazed.

[3] *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

[4] Actual curve number is less than 30; use CN=30 for runoff computations.

[5] CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

(Source: chow et al., 1988)

Table 1.4: Runoff curve number for arid and semi arid range land [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition[2]	A[3]	B	C	D
Herbaceous – mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen – mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper – pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub – major plants include saltbrush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

[1] Average runoff condition, and $I_a = 0.2S$.
[2] *Poor:* <30% ground cover (litter, grass, and brush overstory).
Fair: 30 to 70% ground cover.
Good: >70% ground cover.
[3] Curve numbers for group A have been developed only for desert shrub.

(Source: chow et al., 1988)

Table 1.5: Hydrologic soil group and properties

Hydrologic Soil Group	Soil Group Characteristics
A	Soils having high infiltration rates, even when thoroughly wetted and consisting chiefly of deep, well to excessively-drained sands or gravels. These soils have a high rate of water transmission.
B	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D	Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

(Source: chow et al., 1988)

Annex- 2: Calibration parameter constraints and HEC-HMS model output

Table 2.1: Ranges of parameter for model calibration

Model	Parameter	Minimum	Maximum
Initial and constant-rate loss	Initial loss	0 mm	500 mm
	Constant loss rate	0 mm/hr	300 mm/hr
SCS loss	Initial abstraction	0 mm	500 mm
	Curve number	1	100
Green and Ampt loss	Moisture deficit	0	1
	Hydraulic conductivity	0 mm/mm	250 mm/mm
	Wetting front suction	0 mm	1000 mm
Deficit and constant-rate loss	Initial deficit	0 mm	500 mm
	Maximum deficit	0 mm	500 mm
	Deficit recovery factor	0.1	5
Clark's UH	Time of concentration	0.1 hr	500 hr
	Storage coefficient	0 hr	150 hr
Snyder's UH	Lag	0.1 hr	500 hr
	C_p	0.1	1.0
Kinematic wave	Lag	0.1 min	30000 min
Baseflow	Manning's *n*	0	1
	Initial baseflow	0 m^3/s	100000 m^3/s
	Recession factor	0.000011	-
Muskingum routing	K	0.1 hr	150 hr
	X	0	0.5
	Number of steps	1	100
Kinematic wave routing	N-value factor	0.01	10
Lag routing	Lag	0 min	30000 min

(Source: USACE, 2010)