JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRNMENTAL ENGINEERING

CHAIR OF HYDROLOGY AND HYDRAULIC ENGINEERING

MASTERS OF SCIENCE PROGRAM IN HYDRAULIC ENGINEERING

SIMULATION OF RAINFALL-RUNOFF PROCESS USING HEC-HMS MODEL FOR MEKI RIVER WATERSHED, RIFT VALLEY RIVER BASIN, ETHIOPIA

BY: JERJERA ULU

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

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ADVISOR: Dr. ZEINU AHMED (PhD)

CO- ADVISOR: Mr. WANA GEYISA (MSc.)

DECLARATION

I, the undersigned, declare that this thesis work is my own original work and that it has not been presented and will not be presented by me to any other University for similar or any other degree award.

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Student Signature Date

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

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Mr. Wana Geyisa (MSc.) ____________________ ____________________
Co-Advisor Signature Date

APPROVAL

The undersigned certify that the thesis entitled: **Simulation of Rainfall Runoff Process Using HEC-HMS Model for Meki River Watershed, Rift Valley River Basin, Ethiopia** is the original work of Jerjera Ulu and we hereby recommend for the acceptance by school of Post Graduate Studies of Jimma University in partial fulfillment of the requirement for Degree of Master of Science in Hydraulic Engineering.

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As members of the Examining Board of the final MSc. open defense, we certify that we have read and evaluated the thesis prepared by: Mr. Jerjera Ulu entitled; **Simulation of Rainfall-Runoff Process Using HEC-HMS Model for Meki River Watershed, Rift Valley River Basin, Ethiopia**. We recommend that it be accepted as fulfilling the thesis requirement for the degree of Master of Science in Hydraulic Engineering.

________________________ ____________________ _________________

Name of Chair Person Signature Date

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Name of External Examiner Signature Date

____________________ ____________________ ________________

Name of Internal Examiner Signature Date

DEDICATION

This work is dedicated to my family, friends and for all whose loved me. Special dedication goes to my wife, brother, mother and father.

ABSTRACT

Understanding the complex relationship between rainfall and runoff processes is judicious for proper estimation of runoff generated at outlet point. The stream flow of Meki river watershed is always fluctuating from season to season and this causes flooding problem on surrounding agricultural land. Estimating the amount of flood is very important to take appropriate action to mitigate its impacts. Hence, the aim of this study is to model stream flow and forecast flood of Meki river watershed using Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). The data used for this thesis were soil, Land Use Land Cover (LULC), Digital Elevation Model (DEM) 30 m x 30 m resolution, 31 years (1987-2017) daily rainfall and 24 years (1987-2010) daily stream flow data. Daily rainfall data was collected from Ethiopian Meteorological Agency whereas DEM, soil and daily stream flow data were collected from Ethiopian Ministry of Water Resources, Irrigation and Electricity and LULC data was collected from Ethiopian Mapping Agency. The missed rainfall data was filled using station average and normal ratio method while the missed stream flow data was filled using linear regression method. The HEC-HMS input parameters were generated using Hydrologic Engineering Center Geospatial Hydrologic Modeling System (HEC-GeoHMS). The Gage weight meteorological method was selected to assign the areal rainfall computed by Isohyetal method to each sub-basin. The Soil Conservation Service Curve Number, Soil Conservation Service Unit Hydrograph, monthly constant base flow and Muskingum method were employed for loss computation, excess rainfall computation, base flow modeling and flood routing respectively. The model was calibrated and validated with stream flow data of 18 years (1987-2004) and 6 years (2005-2010) respectively. Nash-Sutcliffe Error (NSE), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2) were used to evaluate efficiency of the model, giving values of 0.832, 0.50, and 0.91 and 0.804, 0.40, and 0.89 during calibration and validation respectively. This indicates very good performance rating of the model. Flood prediction was conducted using 24 hour rainfall depth of 2, 10, 25, 50 and 100 years return period and found to be 133.21, 178.1, 239.7, 313.2 and 346.19 m^3/s respectively. Hence, these predicted values will help further researchers to prepare flood inundation map and take appropriate actions to control flood for this study area.

Key Words: *HEC-HMS, Meki River, Peak Flow, Rainfall-Runoff Simulation*

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LIST OF ACRONOMIES AND ABBREVIATIONS

CN	Curve number
ERA	Ethiopian Road Authority
ESRI	Environmental System Research Institute
DEM	Digital Elevation Model
GCS	Geographic Coordinate System
HEC-GeoHMS	Hydrologic Engineering Centre-Geospatial Hydrologic Modelin System
HEC-HMS	Hydrologic Engineering Centre-Hydrologic Modeling System
HSG	Hydrologic Soil Group
IDF	Intensity Duration Curve
ITCZ	Inter Tropical Convergence Zone
MM	Mili Metre
MoWR	Minstry of Water Resource
MoWRIE	Minsrty of Water Resource,Irrigation and Electricty
NRCS	Natural Resources Conservation Service
PEPF	Percentage Error in Peak Flow
PEV	Percentage Error in Volume
SCS	Soil Conservation Service
SMA	Soil Moisture Accounting
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
UH	Unit Hydrograph
USACE	United States Army Corps Of Engineers
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WMO	World Meteorological Organization

1. INTRODUCTION

1.1 Background

An adequate knowledge of runoff within a given catchment is very important for the planning and designing of many water resources development and related projects. An actual estimation of runoff volume and peaks is also important for planning different interventions in integrated watershed management and many flood protection projects (Oleyiblo, 2010). The activities relation to estimation of runoff volumes and flood peaks can be simplified by adopting model, understanding rainfall partitioning and principal factors triggering runoff (Zhang *et al.*, 2014).

Various factors influence the amount of runoff generated from rainfall (Baharudin, 2012). The commonly known factors are intensity and duration of rainfall, soil types, Antecedent Moisture Condition (AMC), Topography (slope of watershed) and Land Use Land Cover (LULC) of study area (Subramanya, 2008). Rainfall is the main source of surface runoff generation. Hence, there is unique relationship between rainfall and runoff generate. High rainfall will generate high runoff and vice versa. Flood is one of the harmful natural disasters that occurs in various area of the world. Flooding problem may occur when river channel cannot accommodate the runoff thus over banking of river channel and inundate normally dry area temporarily or permanently over the area (WMO, 2008). Similarly, Carlos (2002) stated that, flooding occurs due to unusual heavy rainfall which generates flood beyond the channel capacity. Flooding results in damage to human life and deterioration of environment (Semu, 2007).

The rainfall- runoff simulation is very important in various activities of water resources development and management such as flood control and its management, irrigation scheduling, design of irrigation and drainage works, design of hydraulic structures, and hydro-power generation etc. Simulation is often used as a tool for a wide range of tasks, such as the modeling of flood events, the monitoring of water levels during different water conditions or the prediction of floods (Panigrahi and Paul, 2014).

In watershed with ungagged stream flow data, generating stream flow at the outlet of watershed on basis of perceived precipitation is vital for water resource managing, design of hydraulic structure (Panigrahi and Paul, 2014). Generating river discharges from rainfall has stimulated the imagination and ingenuity (cleverness) of engineers for many years, and more recently has been the inspiration of many research workers (Kossuth and Bercher, 2011).

The situation in Ethiopia is problematic, as there are few hydrological gauging stations with few years recorded stream flow data. Most of Ethiopian watershed have no hydrological gauging stations (Gebeyehu, 2013). In Meki River watershed there is only one stream flow gauging station which is found at the exit of Meki River to Lake Ziway.

As number of population increase the interest of expanding agricultural land increase in upstream and middle part of the study area (Legesse, 2010a). Hence, using irrigation water as supplementary to rain fed is important. To do this, construction of hydraulic structure is needed. However, to properly design hydraulic structure, the recorded hydrological data is very important. Hence, routing discharge along the river through simulation from rainfall data is essential for this study area.

Detailed hydrological studies regarding watershed especially in real life situation is challenged due to the lack of sufficient data on one hand and complexity of hydrological systems on the other hand (Azmat *et al.*, 2016). These challenges resulted to the inevitable use of rainfall runoff models. This means that the complexity of real systems enforce to use hydrological models for prediction of flood amount from rainfall depth of different return periods(Jain *et al.*, 2013). To solve this problems, many computer-based hydrological models such as Soil Water & Assessment Tool (SWAT), Water Erosion Prediction Project (WEPP) Model Hydraulic Engineering Center-Hydrologic Modeling System (HEC-HMS), Topography based hydrological model (TOPMODEL) have been developed (Skhakhfa, 2016).

The type of the modelling approach normally depends on the purposes, data availability, and ease of use (Beven, 2012). Obtaining all parameters affecting runoff is too difficult (Safapoor *et al*., 2004). Thus it is mandatory selecting a model with simple structure, minimum input data requirements and reasonable precision (Beven and Majid, 2012). HEC-HMS model is one of the hydrological models which meet these criteria and has been widely used in different studies (Rostami *et al.*, 2011). Because of its ability in the simulation of runoff both in short and long time events, ease to use, and use of common methods, HEC-HMS has become very popular and been adopted in many hydrological studies to simulate runoff volume and for estimating flood peaks, irrespective of the size of the catchment (Halwatura and Najim, 2013). HEC-HMS is hydrological modelling software developed by the US Army Corps of Engineers Hydrologic Engineering Centre (HEC), which is designed to simulate the precipitation runoff processes within a wide range of geographic areas, such as large river basins and small urban or natural watersheds (Halwatura and Najim, 2013).

Hence, the study is intended to use Hydraulic Engineering Center Hydrologic Modeling System (HEC-HMS) to model the stream flow and forecast flood of different return periods for Meki river watershed.

1.2 Statements of the Problems

Ethiopia is easily vulnerable to flood due to its topography. For instance Rift Valley River basin is prone to flood due to highland system bounding it in both directions (PDPPA, 2006). Meki river watershed is one of Rift valley river sub-basin which is affected by flood generated from highland area of Gurage Mountains which found in the upper part of the study area and further affects downstream area like lake Ziway and its surrounding (Ayenew and Legese, 2007).

Ethiopian rainy season is highly concentrated between June to September (Sanyal, 2005). Intense rainfall in highland areas during this rainy season cause inundation of agricultural land close to any stretch of river courses (Getahun, 2015). Meki River watershed is one of Rift Valley River sub-basin which is frequently inundated by flood due to intense and prolonged rain fall occurs from June to September (Hawi, 2007).

In most developing countries like Ethiopia, there are usually no plenty of recorded stream flow data. In Meki River watershed, there is no recorded stream flow data at the outlet of each sub-basin except stream flow gauging station at the exit of Meki River to Lake Ziway. However, the more elaborate and expensive stream flow measurements are often required by design engineers for the assessment of water resources management. Decision support tools can help in better development to solve this challenge is the use of suitable hydrologic models for the efficient management of watersheds and ecosystems (Yener *et al.*, 2012).

Hence, this thesis applied Hydraulic Engineering Center Hydrologic Modeling System (HEC-HMS) to model stream flow and forecast flood at different return periods for Meki river watershed.

1.3 Objective of the Study

1.3.1 General Objective of the study

The main objective of this study is to model the stream flow and forecast flood of Meki River watershed using Hydraulic Engineering Center Hydrological Modeling System (HEC-HMS).

1.3.2 Specific Objectives of the study

The specific objectives of this study are:

1. To develop watershed parameters.
2. To conduct HEC-HMS model performance for this study area.
3. To predict flood at different return periods.

1.4 Research Question

1. Is it possible to develop watershed parameters?
2. Is HEC-HMS model applicable for Meki River watershed?
3. How much peak flood will be generated at different return period?

1.5 Scope of the Study

This thesis focused on rainfall runoff simulation due to hydrological response of rainfall events through employing the past thirty-one years meteorological data of six metrological stations of Meki River watershed that comprise 2240 square kilometer (Km^2). Moreover, it predict flood at different return period using rainfall depth of 24hour.

1.6 Significance of the Study

This thesis can provide detail information regarding with characteristics of study area, amount of flood at different return periods that helps for flood control, management, decision making, and design of drainage works. Moreover, it can helps researchers as reference for developing flood mapping and mitigation measures for Meki River watershed.

2. LITERATURE REVIEW

2.1 Hydrologic Cycle and Its Components

The movement of water in different phases through the atmosphere to the Earth and back to the atmosphere is called hydrological cycle (Lastoria, 2011). There are nine major physical processes involved water cycle which forms the water movement (Mohammad *et al.*, 2014). The nine processes involved in hydrological cycle are evaporation, condensation, precipitation, interception, infiltration, percolation, transpiration, runoff and storage (Baharudin, 2012). The basic characteristic of hydrological cycle is that it has no starting and ending point. Rainfall and runoff are the most visible components of hydrologic cycles.

When all forms of water particles fall from the atmosphere to ground, it is called rainfall. The rainfall can flow over the land, penetrate into the soil, get into stream channels and also absorbed by plants. Interception interrupts the movement of water going to the streams. When the precipitation contact with soil, the water move through the soil layer which is known as infiltration (Lastoria, 2011). When heavy rainfall occurs over an area for short time or prolonged period of time surface runoff which beyond river holding capacity will be generated that leads flooding problems.

2.1.1 Rainfall and Runoff Relationship

Various factors influence the amount of runoff generated from rainfall (Baharudin, 2012). The commonly known factors are intensity and duration of rainfall, soil types, Antecedent Moisture Condition (AMC), Topography (slope of watershed) and Land Use Land Cover (LULC) of study area. The longer and intensified rainfall produce high runoff.

Different soil types have different infiltration capacity for instance infiltration capacity is high in sandy soil thus runoff generation is low whereas runoff increases in heavy soil like clay and silty soil where infiltration capacity of these soils are low. Similarly, in area which is densely covered by vegetation runoff rate is low than the area covered by bare land. Moreover, the steep slop increases downward movement of water thus decrease infiltration which in turn contribute increment of runoff (Subramanya, 2008). Rainfall is the main source of surface runoff generation. Hence, there is unique relationship between rainfall and runoff generate. High rainfall will generate high runoff and vice versa.

2.2 Flood

Flood is an excessive overflowing or irruption of great body of water over land area which is normally not submerged (WMO, 2011). According to Pathak *et a*l. (2017), flood is an unusual extremely increase of river depth due to rainfall or melting of snow.

The amount of flood generated from watershed highly depends upon the rainfall amount, rainfall intensity, watershed characteristics, Land Use Land Cover, soil moisture conditions and topography (Pathak *et al*., 2017). The low magnitude and intensity of rainfall results low generation of flood. If the watershed highly covered by vegetation, the rate of infiltration increases which decrease surface runoff. Moreover, the steepest topography increase the velocity of surface runoff (Pathak *et a*l., 2017).

2.2.1 Types of flood

Based on its occurrence flood have different types like flash, river, urban and coastal flood (Wright, 2014). Flash flood is caused by heavy rainfall within a short period or prolonged time. River flood occurs due to heavy rainfall long lasting which causes water depth to rise over the banks of the river while urban flood occurs when heavy rainfall exceeds the capacity of sewer systems and drainage canals. Moreover, the coastal flood is the inundation of coastal area due to combination of high tides, increased precipitation and strong winds. However, flash and river flood are common in Ethiopia (Getahun, 2015).

2.2.2 Flood prediction

The prediction of flood amount is very important for planning and design of water resource projects and flood plain management because any design of hydraulic structures depend on the frequency and magnitude of peak flood (Bedassa, 2016). According to Subramanya (2008), hydrologic systems are impacted by extreme events such as severe storms, floods and droughts. Flood prediction is used to determine the magnitude of extreme events to their probability of distribution (Ashraful *et al.*, 2018). The magnitude of an extreme event is inversely proportional to its frequency of occurrence. Very severe events occurs less frequently than moderate events (Subramanya, 2008).

Over or under-estimation of design flood results in losses like a waste of resources, and infrastructural damage. Investigation in design flood estimation is on the decline and there is a large gap between design flood and practice (Arnaud *et al*., 2017). Hence, it is important to conduct flood frequency analysis to relate magnitude of extremely event to its probability of occurrence.

2.2.3 Flood estimation techniques

The magnitude of flood occurred can be estimated from stream flow events by statistical distribution functions which are empirical or simulated from design storm events using rainfall runoff model (Kumar and Chatterjee, 2011; Vivekananda, 2015). The comparison of results obtained from rainfall and stream flow events is necessary for accuracy. There are a number of statistical distributions in hydrology which are used to analyze the probability of occurrence of a flood at different return periods (Subramanya, 2008).

The Probability Distribution Functions (PDF) are continuous mathematical expressions that determine the probability occupancy of a particular event. If a prediction is to be based on a set of hydrologic data, then the probability distribution that best fits the set of data may expected to give the best estimates (Subramanya, 2008).

2.3 Goodness of Fit Test

Goodness of Fit (GOF) test measures the compatibility of a random sample with a theoretical probability distribution function. A common approach is the daily maximum stream flow data of each year is determined and the statistical distributions are fitted to these time series data (Schendel and Thongwichian, 2017). These data are used to make frequency distributions for various discharges as a function of their recurrence interval or exceedance probability (Schendel and Thongwichian, 2017).

2.3.1 Easy Fit Software

Easy Fit software is a data analyzer and simulation software which allows to fit probabilistic distributions to given data samples, simulate them, choose the best fitting probability distribution and implement the results of analysis to take better decisions (Pakgohar, 2014). It is too tedious and time consuming to determine the best fit probability distribution functions to given sample data manually. Hence, using Easy fit software simplifies to identify the best fitted probability distribution to given data within short time.

The output of easy fit would include graphs related to raw input data, distribution or improved fitting parameters, graphs of fitted distribution, additional graphs and tables which help to determine best fitted probability distribution functions (Mehrannia, 2014).

It determines the best fitted distribution function based on Goodness of Fit (GOF) tests like Kolmogorov-Smirnov, Anderson-Darling and Chi-Square test (Alem, 2018). Kolmogorov-Smirnov (KS) and Chi-Square are widely used goodness of fit tests. These tests depend on the deviation of the sample distribution function from the specified continuous hypothetical distribution function by providing a comparison of a fitted distribution with the empirical cumulative distribution function (Kalkidan, 2015).

2.4 Hydrologic Models

Hydrologic models are mathematical descriptions of components of hydrologic cycle and developed for many different reasons. However, hydrologic models are in general designed to understand the hydrologic processes in watershed, how changes in the watershed and for hydrologic prediction (Ismail *et al*., 2018).

Whenever data is not available, hydrological modeling are important to establish baseline characteristics and determine long term impacts which are difficult to calculate (Lenhart *et al.,* 2002). A modeler should understand the hydrological process and then simulate this process at a desired spatial and temporal resolution (Devos *et al*., 2006). Hydrologic models can be used to estimate the design flood hydrograph in addition to the magnitude of the design flood peak (Kalita, 2011).

2.4.1 Classification of Hydrologic Models

Based on their principles, hydrologic models can be classified in to three such as lumped, semi-distributed and distributed model (Cunderlik and Simonovic, 2004 ; Thinh, 2010).

2.4.1.1 Lumped models:

Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet without explicitly accounting for the response of individual sub basins (Lastoria, 2008). These models are not usually applicable to event scale processing (Cunderlik and Simonovic, 2004). If the interest is primary in the discharge prediction only, then these models can provide just as good simulations as complex physically based models (Geographica and Comenianae, 2010).

2.4.1.2 Semi-distributed Models

Parameters of semi-distributed models are partially allowed to vary in space by dividing the basin into number of smaller sub basins (Orellana *et al*., 2008). There are two main types of semi-distributed models are kinematic wave theory models such as HEC-HMS and probability distributed models such as TOPMODEL. The kinematic wave models are simplified versions of the surface and subsurface flow equations of physically based hydrologic models (Feyen, 2002). Semi distributed model is a conceptual and physical based model which has been developed to bridge the gap between the lumped and distributed model and it has more advantages than other models with respect to time of calculation, less number of parameters, comparatively low calibration needs and have high efficiency of model (Gautam, 2016).

2.4.1.3 Distributed models

Models in which the spatial distribution of rainfall and watersheds characteristics are fully taken into account are known as distributed hydrological models (Saghafian *et al*., 2010). Parameters of distributed models are fully allowed to vary in space at resolution chosen by the user. Parameters of these models spatially vary at a given resolution and require considerably more input data often unavailable than semi-distributed models and they have direct physical interpretation (Pechlivanidis *et al*., 2011). Generally, these models require large amount of inputs (Cunderlik and Simonovic, 2004).

2.4.2 Hydrological Model Selection

There are many criterias which can be used for choosing hydrologic model. The selection criteria always project dependent since every project has its own specific requirements. Furthermore, some criterias are user dependent such as the personal preference for Graphical User Interface (GUI), computer operating system and output needed. Hence, choosing hydrologic model for particular application is one of the challenges for model user. Sok and

Oeurng (2016) stated that, selecting the best and appropriate model is essential in any research work and it depends on objective of the hydrological prediction in the basin. According to Cunderlik and Simonovic (2004) the criteria for choosing the most suitable model depends mainly on the output needed, availability of input data, financial and simplicity of the model to use.

2.4.3 Rainfall-Runoff Modeling

The term rainfall runoff shows what runoff is generated from given rainfall of the watershed. Rainfall runoff model represents the relationship between rainfall and runoff. Rainfall runoff modeling is the process of transforming rainfall into a flood hydrograph and translation of that hydrograph throughout a watershed or any other hydrologic system (hydraulics). It describes the interactions between rainfall and surface runoff from the watershed.

The process of rainfall runoff modeling is too difficult due to its susceptibility to various parameters (Taheri *et al*., 2012). However, the development of advanced rainfall runoff computing software have simplified the complexity of modeling real world system (Rathod *et al*., 2015). Therefore, it is possible to understand and represent a world complex real systems. Nayak *et al*. (2013) stated that, rainfall-runoff modeling extensively helps to predict flood.

Runoff processes are approximated either physically or mathematically where the relationship between system state, input and output are represented (Rathod *et al*., 2015). Runoff modeling is the simplified representations of real systems (Moradkhani, 2009). Accurate representation of actual processes is of paramount significance in predicting flood extent and depth, especially explaining transient characteristics of river flow in the model (Moradkhani, 2009). Determining the variation of flow characteristics in spatial and temporal resolution enables to design flood evacuation plan quite efficiently (Ramesh, 2017).

2.4.4 Model Description

2.4.4.1 HEC-GeoHMS

The Hydrologic Engineering Center Geospatial Hydrologic Modeling Systems (HEC-GeoHMS) is a public domain extension to ESRI's ArcGIS software and the spatial analyst extension. It is used for preparing input parameters for HEC-HMS hydrological model (Fleming and Doan, 2013). It helps to visualize the spatial information, extract watershed physical characteristics like Curve Number, Basin Lag and Time of concentration from Digital Elevation Model and delineate sub-basins and streams to develop hydrologic parameters as well as generate inputs to hydrologic models (Fleming and Doan, 2013).

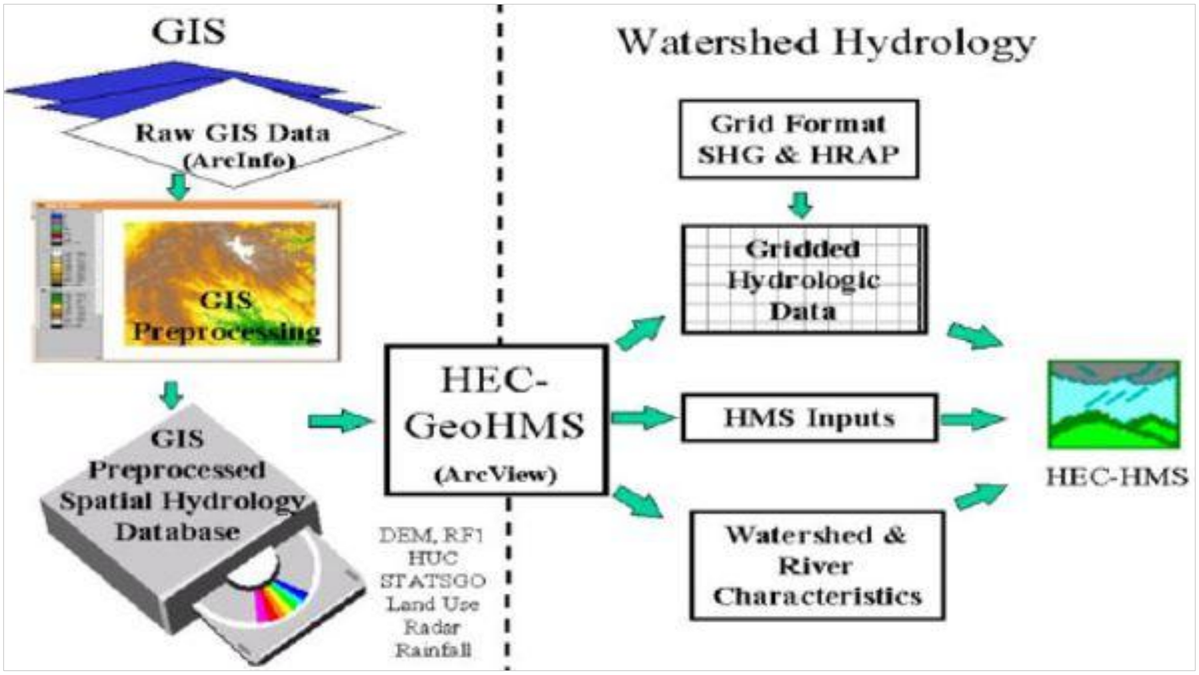


Figure 2.1: Overview of GIS, HEC-GeoHMS and HEC-HMS (Fleming and Doan, 2013).

2.4.4.2 HEC-HMS Model

Hydraulic Engineering Center Hydrologic Modeling System (HEC-HMS) is an open source computer software developed by U.S. Army Corps of Engineering´s Hydrologic Engineering Center that helps in simulating the hydrologic cycle of a watershed by describing its physical and meteorological properties. Scharffenberger *et al*. (2010) stated that, HEC-HMS model is semi-distributed hydrologic model developed to simulate hydrologic response of watershed based on hydro-meteorological data. The program uses separate model to represent each component of the runoff process like model to compute runoff volume, model of direct runoff, base flow and channel flow as well as alternative models to account for the cumulative losses (Fleming and Brauer, 2016).

In HEC-HMS model, interception, evaporation and infiltration processes in the watershed are determined from loss components while runoff is computed as the pure surface runoff using transform component (Yusop *et al*., 2007). HEC-HMS has become very popular and been adopted in many hydrological studies because of its ability to simulate runoff both in short and longtime events, its simplicity to operate (Najim, 2013). Davis (2015) stated that, the hydrographs simulated by HEC-HMS model are used for studying water availability, flow forecasting and flood damage reduction.

2.5 HEC-HMS Processing

HEC-HMS model comprise four components which help for simulation of hydrologic response to rainfall in a watershed. These components are basin models, meteorological models, control specifications, and time series data. Basin model has three parts such as infiltration loss modeling, excess rainfall modeling and flood route modeling. Meteorological model manager is used to store input material such as metrological data required for simulation purpose. The control specification define the time period (starting and ending date) and time step of simulation run (USACE, 2010b).

2.5.1 Rainfall loss modeling

Interception, infiltration, storage, evaporation and transpiration are collectively considered as loss in HEC-HMS program. For computation of these loss, HEC-HMS uses separate option like Initial and Constant Rate, Soil Conservation Service Curve Number, Green-Ampt, Deficit and Constant, Soil Moisture Accounting and Gridded Soil Moisture Accounting method. The user can choose suitable combination of models depending on the availability of data, purpose of modeling and the required spatial and temporal scale (Ismail *et al.,* 2018).

Gridded Loss Methods and Soil Moisture Accounting Loss Methods are not preferred for the simulation studies because they require many parameters. Among the remaining loss methods, the Soil Conservation Service Curve Number (SCS-CN) method is selected for the event based simulation studies. SCS-CN method is one of empirical methods that is widely and globally used by hydrologists, water project planners and water engineering and has been suggested and supported by the department of agriculture natural resources conservation service of USA. The SCS-CN method is simple and practical because it requires few input parameters like Curve Number, initial abstraction, and lag time (Feldman, 2005). It has been used for various watersheds in different countries by many research studies for water resource management, runoff estimation for storm event and prediction of peak discharge for different return periods (Suvendu and Biswaranjan, 2013). Shabanlou (2014) conducted study titled Flood Hydrograph Calculation Using Different Methods in the Karun River watershed using the SCS-CN method with HEC-HMS hydrological model, and the simulated flood hydrograph were close to observed hydrograph of the basin. Nasir and Alipur (2014) stated that, SCS-CN method is a versatile and widely used approach for quick runoff estimation and also relatively easy to use with minimum data and give adequate results. It is the most popular method for computing surface runoff (Burges *et al.*, 2001).

The key parameter of the SCS-CN model is the Curve Number (CN) which depends on LULC, Hydrological Soil Group (HSG) and Antecedent Moisture Condition (AMC) (Deaksjoman, 2014). One of limitation of this method is its sensitivity to the choice of CN.

2.5.2 Excess rainfall modeling

Modeling excess rainfall is the transformation of excess rainfall into runoff at a given outlet. There are various options in HEC-HMS to compute excess rainfall. These are Snyder’s Unit Hydrographs model, Soil Conservation Service Unit Hydrograph model, Clark’s model, Modified Clark’s model. Nezhad (2001) simulated the Hydro Climate in rivers of Khoram Abad-Kashkan in Lorestan province using HEC-HMS model by Soil Conservation Service-Unit Hydrograph method to determine direct runoff and found very small error. Arekhi (2012) used Soil Conservation Service Unit Hydrograph method to model runoff for Kan watershed in Iran and obtained precise results.

2.5.3 Flood Routing Model

Flood routing is a mathematical method used to estimate the generated flood hydrograph as it travels to downstream area (Tewolde and Smithers, 2006). Song *et al*. (2011) stated that, hydrologic and hydraulic routing are the basic method used for flood routing in natural channels. The hydrologic and hydraulic routing follow principle of storage continuity equation and both continuity and momentum equation respectively (Narulkar, 2002).

The routing models available in HEC-HMS include Lag, Muskingum, Modified pulls, Kinematic Wave and Muskingum Cunge. Each of these models compute downstream hydrograph, given an upstream hydrograph as boundary condition. The hydrographs from the upper sub-basin would be combined with the lower sub-basin at the watershed outlet. Routing parameters should be determined to compute Lag time and attenuation on the upper basin hydrographs before adding them to the lower hydrograph. The parameters which describe the reach determine the relationship between the upstream and downstream hydrograph (Feldman, 2005).

The Muskingum model is frequently used for flood routing in natural channels and uses hydrologic routing principle (Chang, 2009). This model uses a simple finite difference approximation of the storage continuity equation.

The Muskingum method has different parameters like flood wave traveling time Muskingum-k, and weighting factor Muskingum-x and number of sub reaches (n) which need to be specified. Muskingum-k is essentially a flood wave travel time through the reach and it ranges from 0.016-150. Muskingum-x is the weighting factor between inflow and outflow influence, and ranges from 0 to 0.5.

The number of sub reaches affects attenuation where one sub reach gives more attenuation and increasing the number of sub reaches decreases the attenuation (Rathod, and Manekar, 2015).

2.6 Previous Studies by HEC-HMS Model

Bitew *et al*. (2019), applied HEC-HMS Model for Flow Simulation in the Lake Tana Basin in Case of Gilgel Abay Catchment, Upper Blue Nile Basin, Ethiopia. The result showed that, the model is appropriate for hydrological simulations in the Gilgel Abay Catchment. Yibeltal (2010) conducted Rainfall-Runoff Modelling using HEC-HMS model for Sustainable Water Resources Management on Gumara Watershed, Ethiopia. The result indicated that satisfactory for simulation of rainfall-runoff modeling. Davis (2015) stated that, the hydrographs simulated by HEC-HMS model are used for studying water availability, flow forecasting, and flood damage reduction. Melesse and Zelelew (2016) stated that, the results of model simulation were location specific, in that different combinations of a model set containing loss methods, runoff transform methods and base flow separation techniques were found to respond variably. Sardoii *et al.* (2012), studied the calibration of loss estimation methods for simulation of surface runoff on Amirkabir Dam Watershed Iran showed that HEC-HMS model can give more acceptable results than other models. Bizuneh (2014) studied Modeling the Effect of Climate and Land Use Change on the Water Resources in Suluh River Basin, Northern Ethiopia and found that hec-hms model can efficiently model climate and land use change for Suluh river basin. Sampth *et al*. (2015) conducted runoff simulation in Tropical Region of Deduru Oya River Basin in Sri Lanka using HEC-HMS model and indicated that HEC-HMS model is efficiency to simulate runoff. Bashar and Zaki, (2016) studied Continuous Based Hydrologic Simulation of the Blue Nile using HEC-HMS model. From the finding they stated that, HEC-HMS model produced good result on simulation of stream flow for Blue Nile. Ihimekpen *et al*. (2018) conducted Modelling of Rainfall-Runoff Relations for Sustainable Water Resources Management in Ethiopia Watershed using HEC-HMS. The result of study indicates that hec-hms model can perform well in modeling rainfall-runoff for Ethiopian watershed. Asnake (2018), conducted Flood Modeling and Mapping of Lower Omo Gibe River Basin, Ethiopia. The result indicates that very good performance of the HEC-HMS model for this study area. Zelelew and Langon (2019), conducted study on Selection of appropriate loss methods in HEC-HMS model and determination of the derived values of the sensitive parameters for un-gauged catchments in Northern Ethiopia and from the result of finding the concluded that HEC-HMS can efficiently perform in simulation of watershed parameters. Melesse and Zelelew (2018) studied that, Applicability of a spatially semi-distributed hydrological model HEC-HMS for watershed scale runoff estimation in Upper Blue Nile, Northwest Ethiopia. The result of model calibration and validation indicates the model can estimate runoff very well. Dereje and Yerosan (2019), conducted assessment of failure on drainage structures along the Ethiopian national railway line of Sebeta-Mieso (case study of Akaki river crossing drainage structure) and they concluded that, HEC-HMS modeled design discharge appropriately.

3. MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location

The Meki river watershed is situated in the northern part of Rift Valley River Basin. It originated from Gurage Mountains and ends to Lake Ziway. Geographically the study area is bounded within the limits of 7^0 59’ 32” to 8^0 27’ 23” N latitude and 38^0 14’ 48” to 38^0 49” 35” E longitude and covers a total area of about $2240Km^2$.

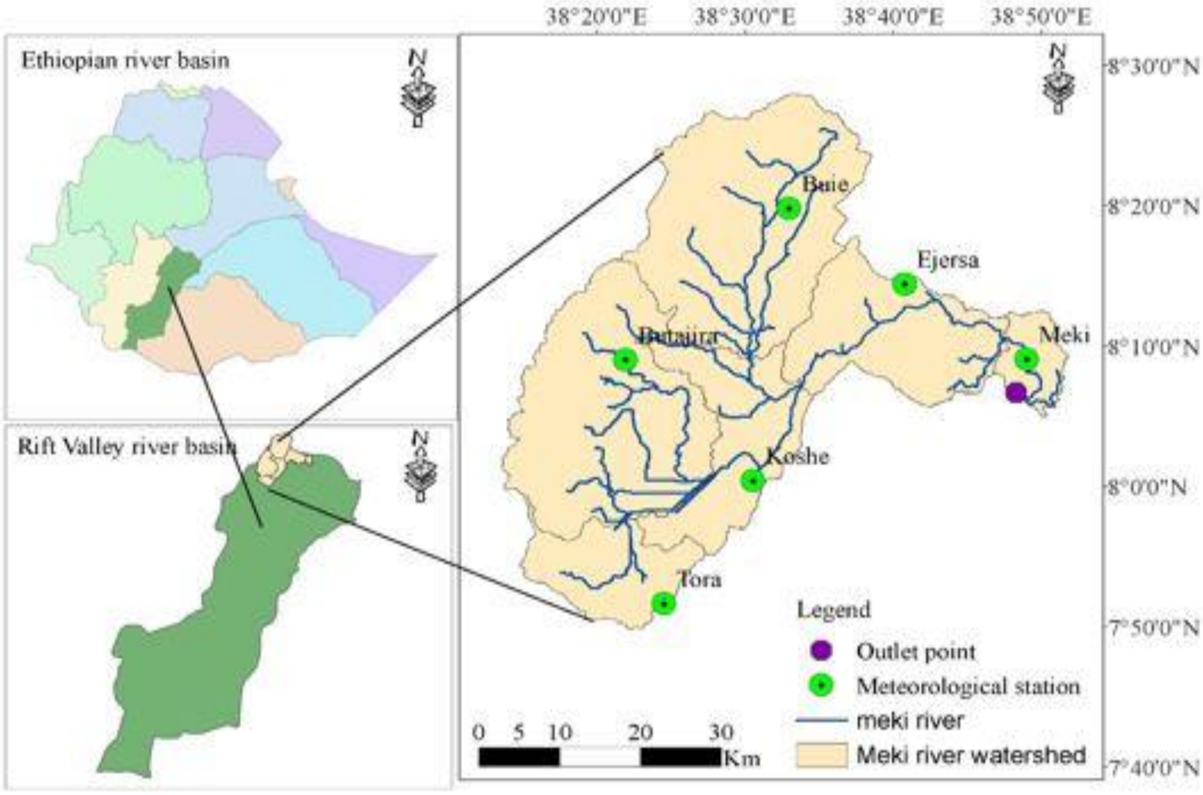


Figure 3.1**:** Location of Meki river watershed

3.1.2 Topography

Topography of the area is primarily determined by the rift system faulting. Rift margin faults have undergone a long period of erosion while those of the rift floor are mostly recent. The watershed lies within altitudes ranging from 1631m to 3614m mean sea level. The upstream of the watershed is steep and mountainous while the downstream is flat with a broad valley (Legesse, 2010b). Generally, the topography of study area is shown as follows in Figure 3.2.

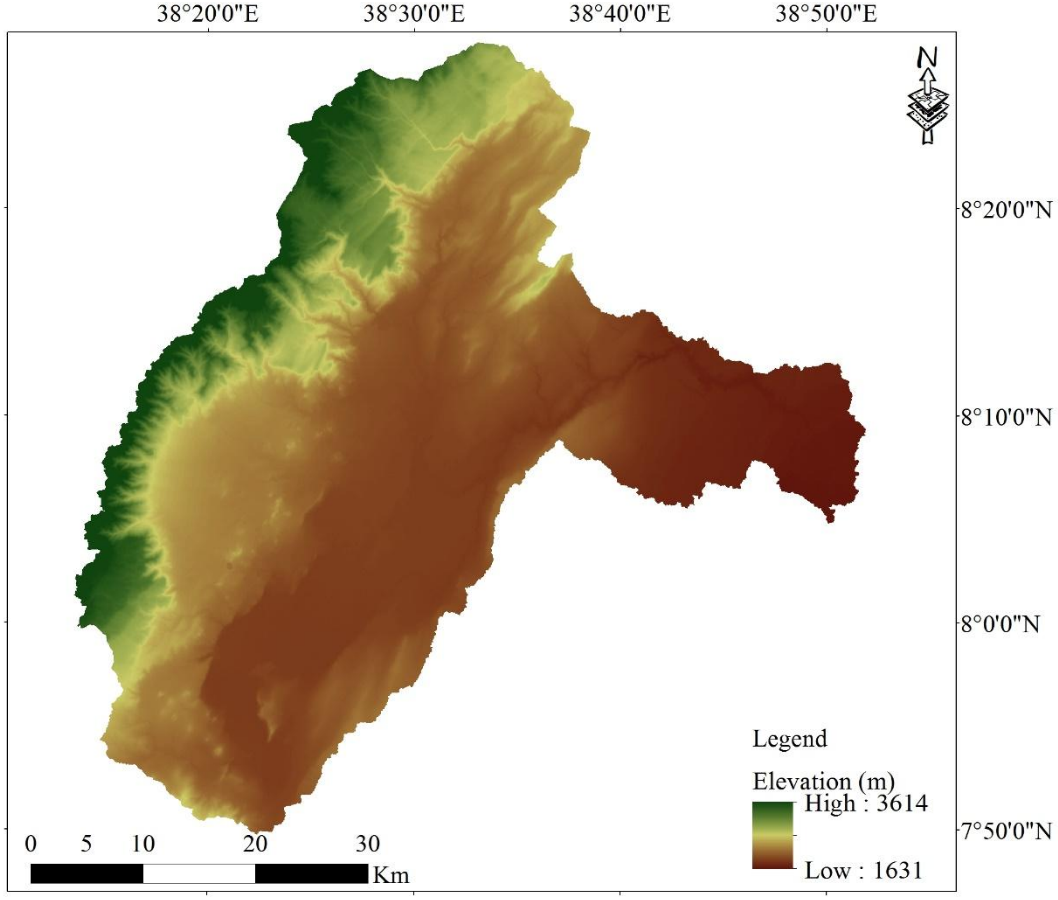


Figure 3.2: Topographic map of study area

3.1.3 Drainage

Meki River drains from the western mountains and escarpments including a vast swampy area and travels for about 100 km before draining to Lake Ziway. It is one of the major tributary of Lake Ziway. The upper part of study area is characterized by higher drainage density than the escarpments and the flat rift floor areas. Rift faults have affected the drainage of the area both by influencing the river courses and by impounding river water and causing some marshy areas, in the southern part of the study area (Legesse, 2010a).

3.1.4 Land Use Land cover (LULC)

The dominant LULC of the study area are categorized as forest, woodland, grass land, crop land, marshland, bare land, shrub land, and water body. Among these, the crop land is the most dominant one in the study area as shown in Figure 3.3.

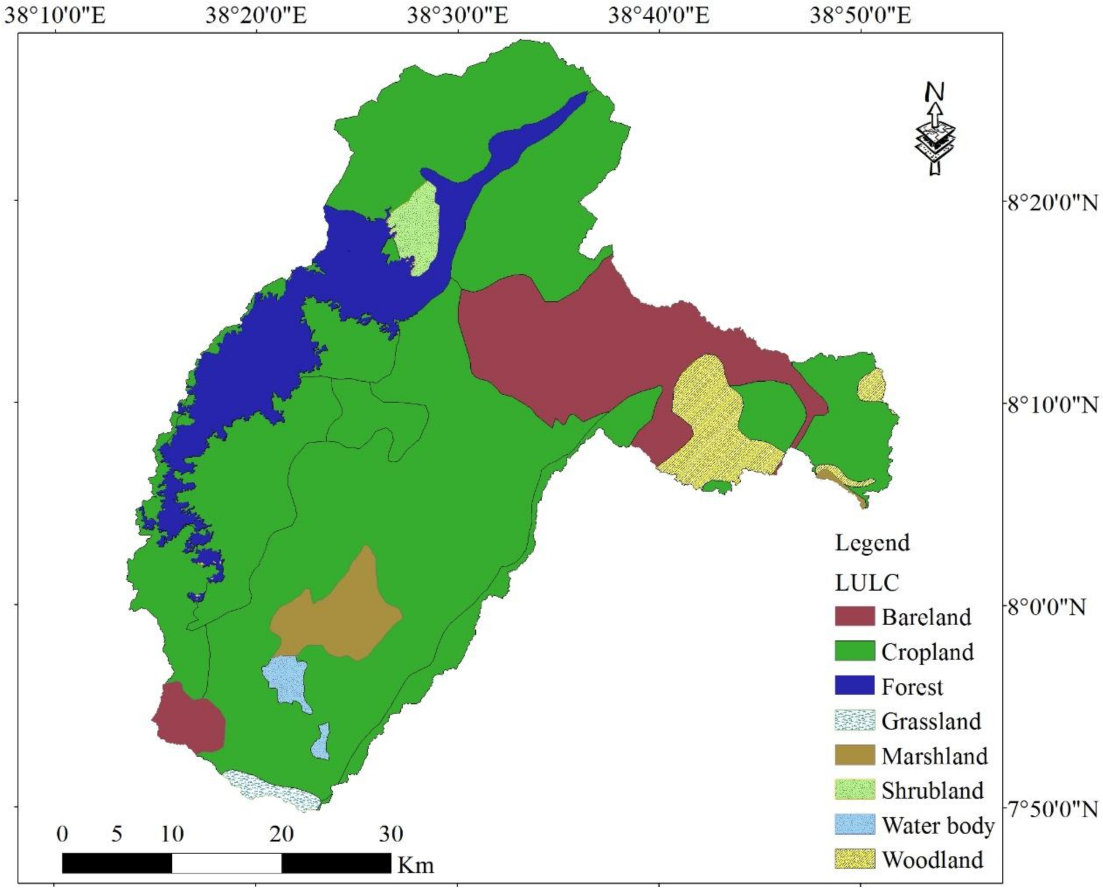


Figure 3.3: Land Use Land Cover map of Meki River Watershed

3.1.5 Soil

The study area has soils closely related to the parent material and the degree of weathering basalt; ignimbrite, acidic lava, volcanic ash and pumice, and riverine and lacustrine alluvium are the main parent materials. Generally, soil types in study area are grouped into three. The first group is well drained deep reddish brown to red friable clays to clay loams with strong structure. The second group of soil is a well-drained, moderately deep-to-deep dark gray, friable silty loam to sandy loam, soils with moderate structure and good moisture storing properties. The third group of soil is dark grayish, free draining friable silty-loam to sandy loam with moderate structure and good moisture storing properties (Legesse, 2010b). Generally, the dominant soils in the study area and their areal coverage are given in Table 3.1. The spatial distribution of these soils are shown in Figure 3.4.

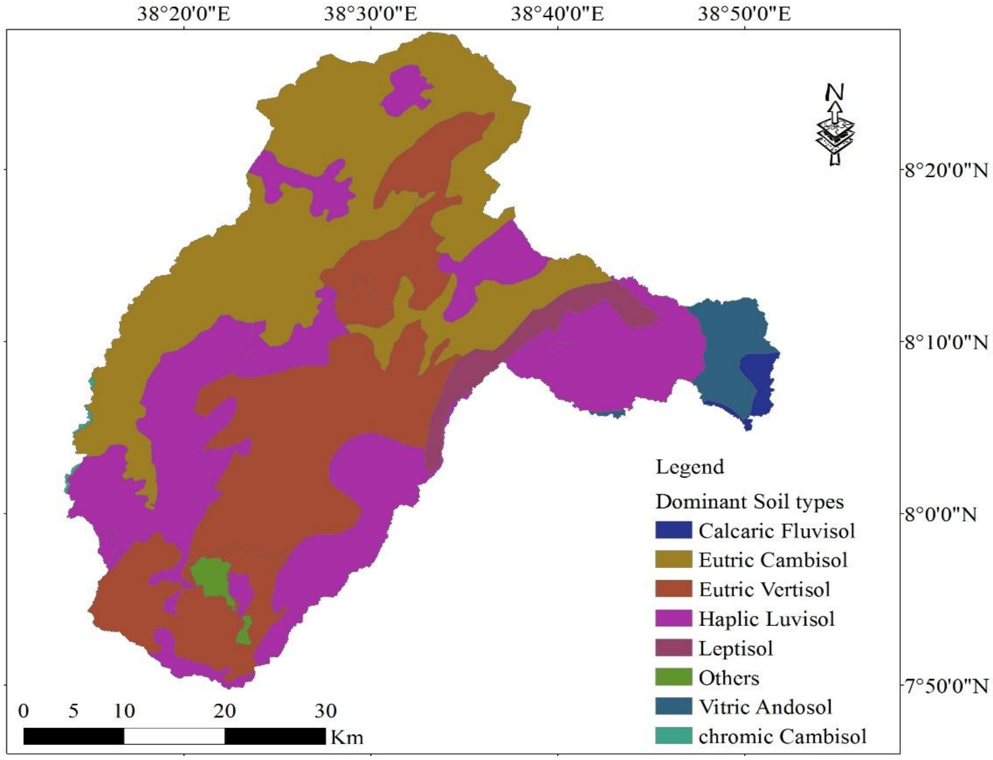


Figure 3.4: The spatial distribution of dominant soil type of the study area

Table 3.1: Dominant soil types of Meki river watershed

Dominant soil of study area	Area by Km^2	Areal coverage in %
Calcaric fluvisols	18.37	0.82 %,
Chromic Cambisol	2.69	0.12%,
Eutric Cambisol	722	32.23%,
Eutric Vertisol	641.98	28.66%,
Haplic Luvisol	704.032	31.43%,
Leptosol,	69.44	3.10%
Vitric Andosol	66.08	2.95%,
others	15.9	0.71%.

3.1.6 Rainfall

Three main seasons characterize the study area such as dry season (bega), rainy season (summer) and belg season (Legesse, 2010). The study area obtained rainfall with high intensity during summer season which extends from June to September. The recorded mean monthly rainfall all over watershed ranges from 25 mm to 210 mm as shown in Figure 3.5.

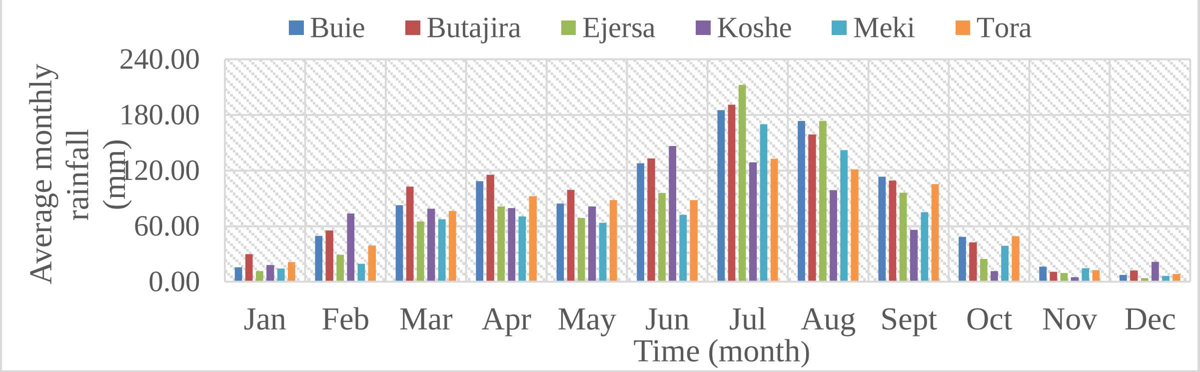


Figure 3.5: Mean monthly rainfall of Meki river watershed

3.2 Materials and Tools

The tools and data used for thesis work are shown in Table 3.2.

Table 3.2: Tools and data used for this study

Tools	Its Uses
ArcGIS10.1	Preparing input data for HEC-GeoHMS
Arc hydro & HEC-GeoHMS	Preparing input data for HEC-HMS
HEC-HMS4.3	For simulation for rainfall-runoff process
Microsoft excel,	Rearranging of input data
Easy fit	Used to best fitted probability distribution
Rainbow	Used to test homogeneity of rainfall data
Data used	
Digital Elevation Model 30 m x 30 m resolution	Hydrological (stream flow) data
Land Use Land Cover data	Meteorological (rainfall) data
Soil data	

3.3 Methods

3.3.1 Data Collection

3.3.1.1 Meteorological Data

To establish rainfall-runoff relationship for a watershed, meteorological data are required. In this study, those data were required for two purposes. Firstly, the data were used for computing areal rainfall over the watershed. Secondly, the data were used as input to HEC-HMS model in the hydrological model setup and development. Daily rainfall data of 15 stations in study area were collected from Ethiopian Meteorological Service Agency. However, only rainfall data of six stations like Buie, Butajira, Ejersa, Koshe, Meki and Tora were used due to their longer period of records. The daily rainfall data of these stations have been processed, checked for consistency and corrected wherever necessary while any missing records were augmented. These rainfall stations and their mean monthly precipitation values are listed in Table 3.3.

Table 3.3: Average annual rainfall of selected stations in Meki river watershed.

Station	Lat (Decimal degree)	Long (Decimal degree)	Altitude (m)	Mean Annual Rainfall (mm)
Buie	8.33	38.55	2020	1013
Butajira	8.15	38.37	2000	1060
Ejersa	8.24	38.68	1797	871
Koshe	8.06	38.51	1878	800
Meki	8.15	38.82	1662	754
Tora	7.86	38.41	2001	834

3.3.1.2 Hydrological Data

Stream flow data is very important for calibration and validation of the model. There is only one main stream flow gauging station in the study area that is at the entry to Lake Ziway particularly at 8°09' N latitude and 38°50' E longitude. Daily stream flow data of 24 year (i.e. 1987 to 2010) was taken from Ethiopian Ministry of Water Resources, Irrigation and

Electricity. In addition to this, daily stream flow data of two neighboring stations like Awash River at Hombole and Gedamso River were collected from the same place as Meki river stream flow data. The purpose of collecting these additional data was for filling missed stream flow data of study area.

3.3.1.3 Spatial Data

The spatial data like soil, Land Use Land Cover and Digital Elevation Model data were used for this thesis. This data were collected from different sources. Shuttle Radar Topography Mission (SRTM) Digital Elevation Model and Soil data were collected from Ethiopian Ministry of Water Resource, Irrigation and Electricity and LULC data was collected from Ethiopian Mapping Agency.

3.3.2 Data Preparation and Analysis

The collected data may contain errors due to failures of measuring device or recorder. Hence, before starting any analysis, the quality of collected data should be tested appropriately from errors, and filled for missing using different techniques. The required data quality control are performed mainly by preliminary data checking, plotting, spatial and temporal consistency check to ensure quality of data for further investigation (Vedula and Mujumdar, 2016).

3.3.2.1 Filling Missing Rainfall Data

There are three methods for estimating missed rainfall data. These are station average, normal ratio and quadrant methods. The station average and normal ratio method are the simplest method that weigh the mean rainfall at each gauging station while and quadrant method provides mean based on the distance between the gauging stations. The missed data is estimated using data of neighboring stations (Subramanya, 2008). Considering the normal annual precipitations vary considerably, the missed precipitation P_X is estimated by weighing the precipitations at various stations by the ratio of normal precipitation. The station average method is conceptually the same as the normal ratio method for estimating mean precipitation. Station average method may not be accurate when the total normal annual precipitation at any of other gauging stations (M) differs from normal annual precipitation of station ‘X’ by more than 10 %. For this study, both station average and normal ratio method were used for filling missed data because the difference of normal annual precipitation of station with missed data and the surrounding stations within study area were within range of 10 % for some years and out of this range for other years. Mathematically, station average and normal ratio methods are given as equation 3.1 and 3.2 respectively.

$$\mathrm{P}x = \frac{\mathrm{P1} + \mathrm{P2} + \mathrm{P3} + \cdots \mathrm{Pn}}{\mathrm{M}} ------------------------3.1$$

$$\mathrm{Px} = \frac{\mathrm{Nx}}{\mathrm{M!}}\ \frac{\mathrm{P1}}{\mathrm{N1}} + \frac{\mathrm{P2}}{\mathrm{N2}} + \cdots + \frac{\mathrm{Pn}}{\mathrm{Nn}}\ ------------------------3.2$$

Where, N1, N2, Nn are normal annual rainfall, P1, P2, Pn are precipitations at particular years, M is number of neighboring stations.

3.3.2.2 Filling Missed Stream Flow Data

The missed stream flow data of study area was filled using linear regression method by XLSTAT which correlates long term flow rate records with other hydrological stations. For this study, the correlation of Meki stream flow data with Awash stream flow data at Hombole and Gedamso stream flow data were tested using linear regression and found that Gedamso stream flow data has showed high correlation with Meki stream flow data as shown in Table 3.4. Hence, the missed Meki stream flow data was filled using linear equation of Y=1.80X+1.27.

Table 3.4: Correlation of two stream flow gauging stations with Meki River.

Stream gauging station	Coefficient of correlation(R^2)	Linear equation
Meki river versus Gedamso river	0.701	Y=1.80X+1.27
Meki river versus Awash at Hombole	0.443	Y=3.80X-1.89
Where: Y= Missed discharge at Meki river and X = discharge at Gedamso gauging station		

3.3.2.3 Homogeneity Test of Rainfall Data

Homogeneity test is an important issue to detect variability of the data. When the data is homogeneous, it means 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 it always changes due to measurement techniques and observational procedures, environment characteristics and location of stations.

The homogeneity and stationarity of rainfall data of these stations were tested using RAINBOW software. This software is very important and frequently used to test homogeneity of time series data (Buieshand, 1998 and Raes *et al*., 2006). This software rescaled time series data by dividing cumulative deviation of annual rainfall data to cumulative standard deviation value. Then plot the graph of rescaled cumulative deviation versus data time series and lines representing probability function (90, 95 and 99 %). From the plotted graph, it evaluates the maximum and range of cumulative deviation from the mean. The probability function lines are the lines at which homogeneity of data are rejected (Buieshand, 1998 and Raes *et al*., 2006).

According to Raes *et al*. (2006), if the range of cumulative deviation and maximum cumulative deviation of the data oscillate around zero line the data are homogeneous. Accordingly, the rainfall data of the selected stations were tested with RAINBOW software and oscillate around zero line. Hence, they found to be homogeneous. For a sampling, the homogeneity and stationarity test of Buie station is shown in Figure 3.6 and the rest stations are attached to (Appendix C).

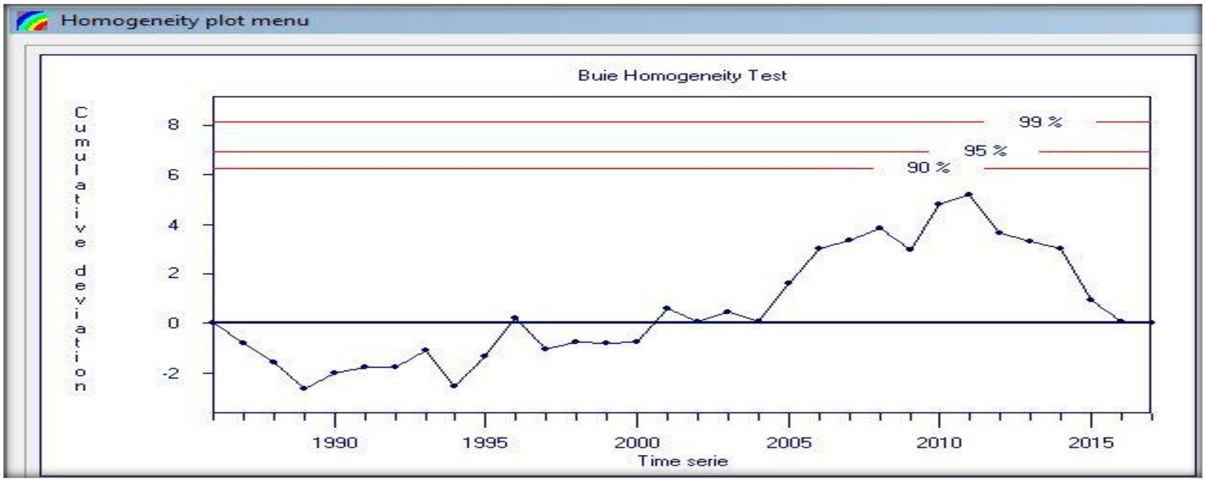


Figure 3.6: Homogeneity test of Buie stations using RAINBOW

3.3.2.4 Consistency Test of Rainfall Data

The trend of rainfall records at a station may change through time due to change in physical environment like wind pattern or exposure. Adjustment of measured data is necessary to provide a consistent record (Haile, 2011). Hence, the consistency of records at a station was tested by double mass curve. Double mass curve is plotted using cumulative annual rainfall of each station against the concurrent cumulative mean annual rainfall of all surrounding stations (Chane, 2011). If the conditions relevant to the recording of a rain gauge station have significant change during the period of record, inconsistency would arise in the rainfall data of that station. The rainfall data of the stations are adjusted by multiplying the recorded values of rainfall by the ratio of slopes of the straight lines before and after change. The inconsistency can be differentiated from the time that significant change take place. The change in the regime of the curve is corrected using equation 3.3.

$$Y2 = \frac{S2}{S1} * Y1 ---------------------------------- 3.3$$

Where, Y2 is corrected precipitation at station x, Y1 is original precipitation at station x, S2 is slope of double mass curve to be corrected, S1 is original slope of double mass curve

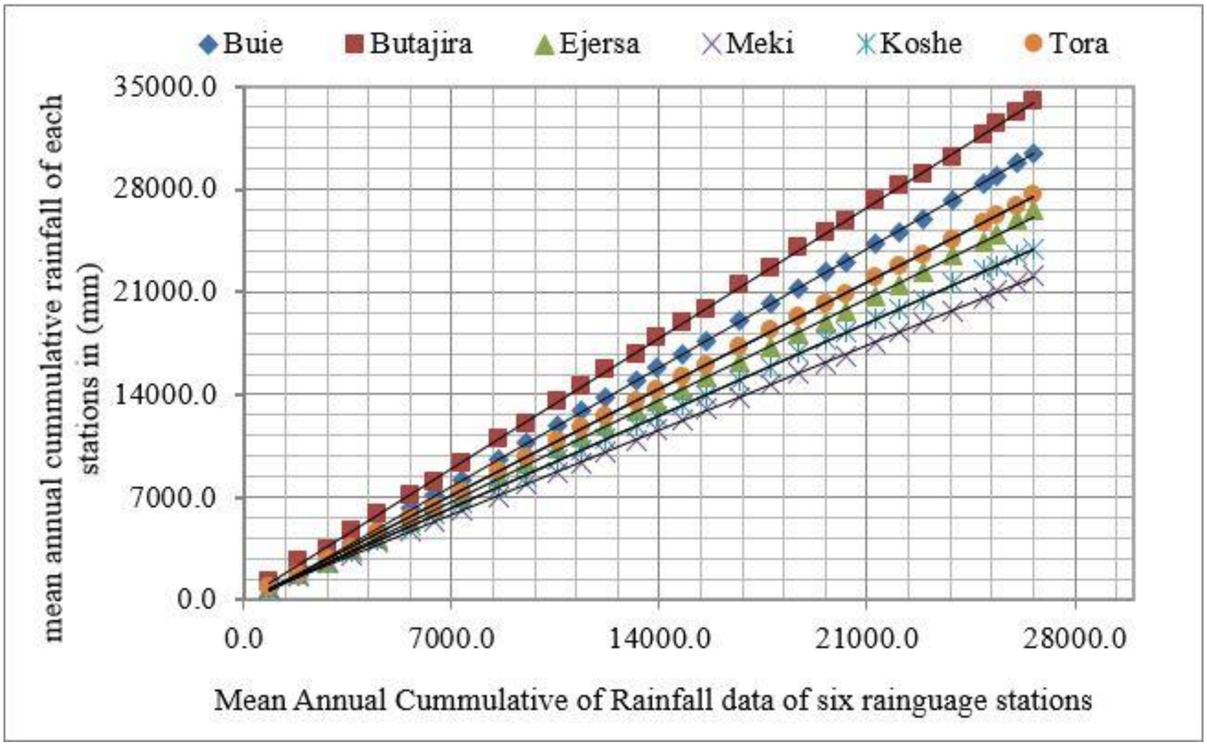


Figure 3.7: Double mass curve analysis of rainfall data of six stations

Figure 3.7 indicates that rainfall data of all these stations were found to be consistent from 1987 to 2017 years. This means that for all rainfall data of stations no significant change occurred in given duration.

3.3.3 Determination of Areal Rainfall

Areal Rainfall is the average rainfall over the watershed and is restricted to long-term average values. It is expressed as a mean depth over the watershed area (Subramanya, 2008). As mentioned earlier, the study area lies in a mountainous terrain and preliminary analysis of collected rainfall data clearly indicated as there was variability of rainfall with elevation Therefore, proper estimation of areal precipitation over watershed is very important due to variability of precipitation owing to topographic effects with elevation.

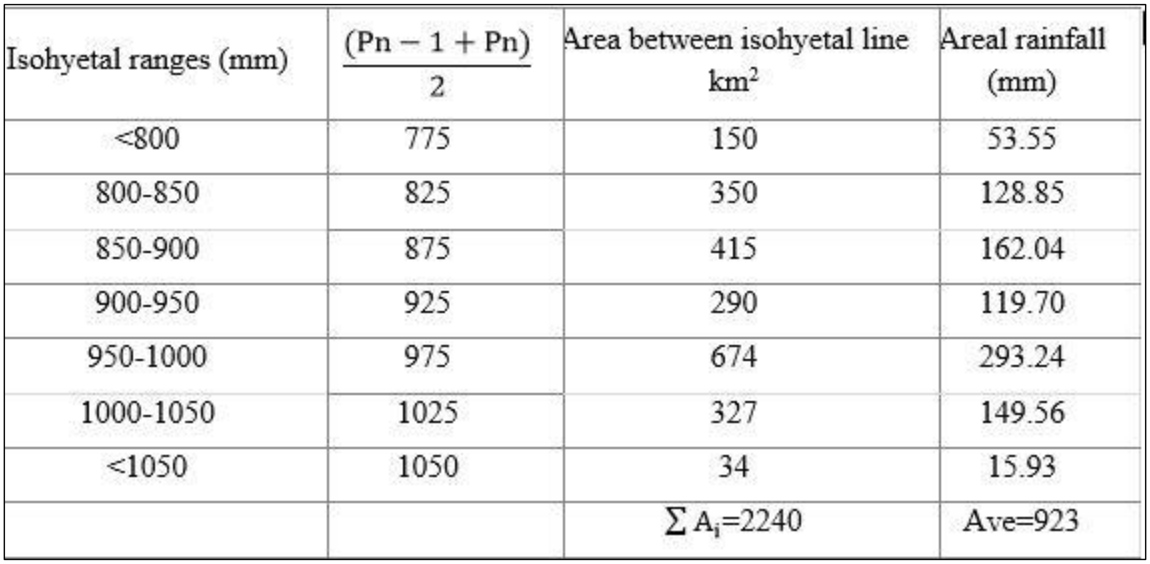
There are three major methods for determining the areal rainfall over the watershed. These are Arithmetic mean, Thiessen polygon and Isohyetal method (Subramanya, 2008). For this study area, the Isohyetal method was used to compute areal rainfall of the study area because there was spatial variation of rainfall. This method can be used for both mountainous and flat area. It considers the effect of elevation, slope and exposure on rainfall of the stations. Therefore, it is accurate than other methods (Subramanya, 2008). In this method the area between successive Isohyetal lines is computed and multiplied by the average rainfall between Isohyetal lines. William (2007) stated that, Isohyetal method is the most accurate method for computing areal precipitation than other methods when rainfall is varied spatially. However, it is very tedious and time consuming because new isohyets have to be made for each rainfall event (Subramanya, 2008). The Isohyetal contours have been constructed by ArcGIS tools using six rainfall stations. Mathematically, it is given as equation 3.4.

$$\mathrm{P_{av}} = \frac{\mathrm{P_1} + \mathrm{P_2} \;\; * \mathrm{A1} + \;\; \mathrm{P_2} + \mathrm{P_3} \;\; * \mathrm{A2} + \cdots \;\; \mathrm{P_{n-1}} + \mathrm{P_n} \;\; * \mathrm{A_n} \quad 2}{A_t} - - - - - - - - - - 3.4$$

Where, P_1, P_2, Pn are rainfall, A_t is total area of watershed, P_{av} is average rainfall.

A_1, A_2, $A_3 \ldots A_n$ are area between Isohyetal line

Table 3.5: Areal annual depth of precipitation computed by Isohyetal method.



Isohyetal ranges (mm)	$\frac{(Pn - 1 + Pn)}{2}$	Area between isohyetal line km^2	Areal rainfall (mm)
<800	775	150	53.55
800-850	825	350	128.85
850-900	875	415	162.04
900-950	925	290	119.70
950-1000	975	674	293.24
1000-1050	1025	327	149.56
<1050	1050	34	15.93
		$\sum A_i$=2240	Ave=923

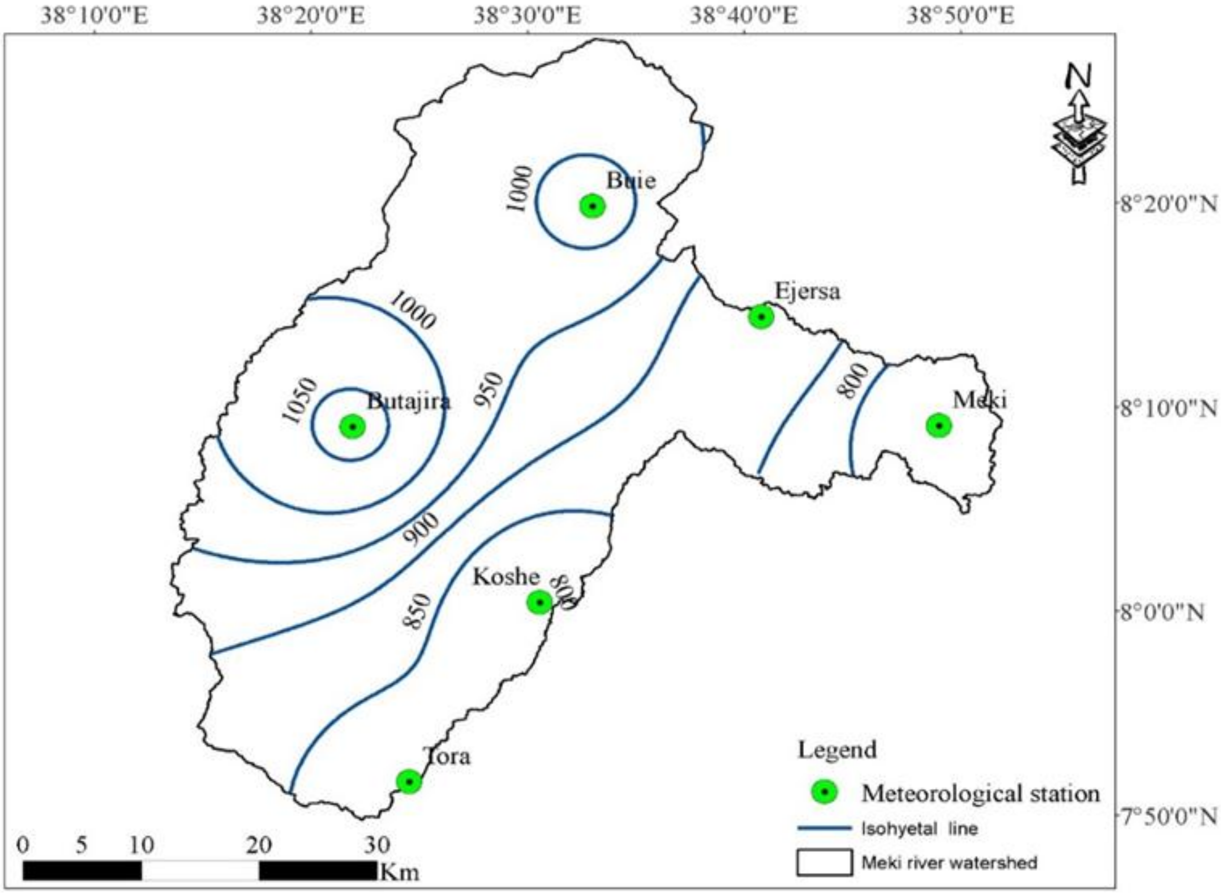


Figure 3.8: Isohyetal map of study area

3.4.4 Data Processing

3.4.4.1 Digital Elevation Model Data Processing

The Digital Elevation Model (DEM) data was available in the form of GCS-WGS-1984 raster form and it was already conditioned. To make it possible for hydrologic modeling purpose the DEM was converted into the Universal Transverse Mercator (UTM) projection raster form by considering zone of the study area which is Adindan UTM Zone 37N by using ArcGIS software. Specifically, Digital Elevation Model of study area was clipped from projected digital elevation model.

3.4.4.2 Curve Number Grid Preparation

The Soil Conservation Service Curve Number was used to account for spatial variability of runoff potential across the watershed. It described the surfaces potential for generating runoff as a function of soil type and land use. The curve number is determined from land use, Antecedent moisture Conditions (AMC) and soil types (Mishra and Singh, 2013). Accordingly, the curve number grid was prepared by processing land use and soil data and creating lookup table or determining curve number value after merging land use and hydrologic soil group.

I) Land Use Land Cover Data Processing

Land Use Land Cover (LULC) information is mandatory for generation of Curve Number lookup table. Hence accurate identification of LULC has a major impact on output of runoff generation. LULC data was available in the form of GCS-WGS-1984 raster form with 30 m x 30 m resolution. As a result, it should be changed into Universal Transverse Mercator (UTM) projection raster form by considering zone of the study area which is Adindan-UTM Zone 37N by using ArcGIS tools. Then, it was reclassified and converted to polygon shape file maps using raster to polygon function. At this stage the land use data can merge with soil data for curve number generation.

II) Soil Data Processing

After merging, the soil data was clipped to fit in the extent of study area. To compute Curve Number, soil data should contain information of hydrologic soil groups. Hydrologic soil groups are groups of soils having similar runoff potential under similar storm and conditions.

Hydrologic soil group is a parameter that defines the propensity drainage of soil (Brain, 2003). The hydrologic soil group designation can be either A, B, C, or D. Soil type ‘A’ has high infiltration rate; soil type ’B’ has moderate infiltration rates; soil type ‘C’ has low infiltration rate whereas soil type ‘D’ has very low infiltration rate (Hafidi, 2014). In contrary to this runoff condition of hydrological soil group increases from ‘A’ to ‘D’.

Factors that determine soil groups were soil texture, structure, drainage condition, soil types and even the location of the soil. Based on these information Hydrological soil group was assigned for each soil type. Table 3.6 summarizes the assigned hydrological soil group of study area.

Table 3.6: Parameters for assignment of soil group (Source: MOWR, 2007)

Soil Types	Soil Structure	Soil Texture	Drainage Condition	HSG
Chromic Cambisol	medium	sandy loam, sandy clay	well	B
Calcaric Fluvisol	medium	clay, clay loam, loam	Imperfectly	C
Eutric Cambisol	Coarse	sandy loam, sandy clay	excessively	A
Eutric Vertisol	fine	clay, clay loam	Very poor	D
Hapalic Luvisol	medium	clay, clay loam, sandy clay	well	B
Leptosol	Coarse	sandy loam, sandy clay	excessively	A
Vitric Andosol	medium	Loam, sandy loam	well	B

III) Merging of Soil and Land Use Data

As previously discussed both LULC and soil class of the study area were prepared in shape file format which were very important for Curve Number generation. Then these data were merged by using ArcGIS union tool.

IV) Creating Curve Number Look-up Table

Curve number look up table is the most fundamental input table for Curve Number grid generation and created by using create table function of ArcGIS tool. The CN value of the watershed was determined by using the United States Soil Conservation Service now called the Natural Resources Conservation Service Runoff Curve Number (CN) method. The lookup table was prepared based on LULC, Hydrological Soil Group (HSG) and Antecedent Moisture Condition (AMC) of soil. The Antecedent Moisture Condition is grouped in three classes like AMC-I is for dry soil having the lowest runoff potential, AMC-II for moderate (normal or average soil moisture condition), and AMC-III very wet soil that has the highest runoff potential (Mishra *et al*., 2013). However, for this study CN value was determined considering Antecedent Moisture Condition (AMC-II).

Table 3.7: Curve Number Lookup table (Source: Subramanya, 2008)

Land Use Types	Hydrological Soil Group			
	A	B	C	D
Water body	100	100	100	100
Medium Residential	61	75	83	87
Forest	30	60	73	79
Cultivated Land	68	78	86	89

The Soil Conservation Service Curve Number table gives Curve Number based on both LULC and Hydrological Soil Group. The merged land use and soil data, sink filled DEM and Curve Number lookup table were the input for HEC-GeoHMS to generate Curve Number and thus CN was generated using generate grid function of HEC-GeoHMS. The weighted Curve Number value of each sub-basin are needed in basin model for simulation process and these weighted Curve Number values over sub-basins of watershed were computed using ArcGIS.

3.5 Creation of Basin Model

To run the model, it is necessary to create basin in the HEC-HMS (Kneble *et al*., 2005). The basin model was created using HEC-GeoHMS software functionality within the ArcGIS environment. The first step in creating the basin model was to delineate the stream network and the watershed boundaries of area of interest. This process is commonly referred to as terrain preprocessing and is entirely based on the Digital Elevation Model. The process of generating input parameters for basin model were expressed below in details.

3.5.1 Terrain Pre-Processing Using ArcHydro

ArcHydro is a Geo-database design and a set of accompanying tools geared for support of water resources applications in GIS environment. The ArcHydro tools had been developed by ESRI and can be used to process Digital Elevation Model data to delineate watershed and drainage network pattern. Terrain Pre-processing was the first step in doing any kind of hydrologic modeling like delineating streams and watersheds. The Digital Elevation Model was the input for Terrain Pre-processing to delineate watersheds and drainage network.

Terrain pre-processing steps were Fill sinks, Flow direction, Flow accumulation, Stream definition, Stream segmentation, Catchment grid delineation, Catchment polygon processing, Drainage line processing, Drainage point processing, and longest flow path for the catchment and Slope determination. The results obtained from terrain pre-processing were used to create input files for Hydraulic Engineering Center Geo-Hydrological Modeling System (HEC-GeoHMS). Once defined the project for HEC-GeoHMS, a new data frame was created and all the terrain preprocessing data were extracted and imported to a new project. After the new project has been created, the basin processing menu was used to revise or customize the sub-basin delineation, dividing sub-basins and merging streams. Accordingly, HEC-GeoHMS produced many sub-basins but in order to increase performance of model, the watershed was merged into six sub-basins with sixteen reaches. HEC-GeoHMS consists different menus that provide different functions. These are preprocessing, project setup, basin processing, basin characteristics, basin parameters, HMS and utility. For each of stream segments and the related sub basins, a serious of physically based characteristics were generated by HEC-GeoHMS tools. These characteristics include the area, length and slope of each river segment as well as average basin slope and the longest flow path of each sub-basin. The resulting data is automatically stored in the attribute table of the river and sub basin layer. After successful completion of ArcHydro and HEC-GeoHMS process, a back ground shape file (basin model file, met model file and gage model file) and watershed characteristics were exported to HEC-HMS for processing of further analysis.

3.6 HEC-HMS Model

Hydrologic Engineering Centre-Hydrological Modeling System (HEC-HMS) developed by United States Army Corps of Engineer is a very flexible and efficient hydrological model for rainfall-runoff process from watershed. HEC-HMS model has become very popular and widely adopted in many hydrological studies due to of its ability to simulate runoff both in short and longtime events, its simplicity to operate (Najim, 2013). Moreover, it has a wide range of capabilities for conducting hydrological simulation through several simple modules to represent different component of hydrological cycle.

3.6.1 HEC-HMS Model Processing

The first phase of hydrological modeling was HEC-HMS model set-up. HEC-HMS model setup has four main model components such as basin model, metrological model, control specification and input data. The observed precipitation and discharge data were used to create the meteorological model. Meteorological model methods like Frequency Storm and Gage weights were used in this theses. The control specifications determine the time pattern for the simulation. Accordingly, the control specification for this simulation was from (01Jan 1987 to 31 Dec 2017) with hourly time step. To run the system, the basin model, the meteorological model, and the control specifications were combined. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow.

3.6.1.1 Rainfall loss modeling

Rainfall may lose through interception by vegetation and building, evaporations, infiltration deep percolation, surface storage. So, to know amount excess rainfall from watershed that joins river channel proper modeling of these loss is vital. For rainfall lose modeling, the HEC-HMS has options like deficit constant, initial and constant, Green-Ampt, Soil Conservation Service Curve Number, and Soil Moisture Accounting. In this study, Soil Conservation Service Curve Number was selected to model rainfall losses because it is a versatile and widely used approach for quick runoff estimation and also relatively easy to use with minimum data and give adequate results (Nasir and Alipur, 2014). Moreover, it is the most popular method for computing surface runoff (Burges *et al.*, 2001). The Soil Conservation Service Curve Number is estimated using Equation 3.5.

$$\mathrm{P_e} = \frac{(\mathrm{P}-\mathrm{I_a})^2}{(\mathrm{P}-\mathrm{I_a})+\mathrm{S}} ---------------------------------3.5$$

Where, Pe is the excess rainfall (mm), P is the precipitation, S is the potential maximum retention after runoff begin (mm), Ia is Initial abstraction (mm), CN is Curve Number.

Through studies of many small agricultural watersheds, Ia was found to be approximated by equation 3.6. Equation (3.6) assumes that 20% of the rain is absorbed before the start of the direct runoff and the remaining 80% is absorbed after the start of runoff (Ghahroudi, 2006 and Heshmatpoor, 2009).

$$\mathrm{I_a} = 0.2S ------------------------------------3.6$$

And thus the equation (3.5) became:

$$\mathrm{P_e} = \frac{(\mathrm{P}-0.2\mathrm{S})^2}{(\mathrm{P}+0.8\mathrm{S})} \text{ For } P > 0.2S\text{; otherwise } \mathrm{P_e} = 0 -----------------3.7$$

The potential maximum retention (S) is a function of Curve Number (CN) and is inversely proportion to CN. This means when Curve Number (CN) decreases the potential maximum retention increases. The potential maximum retention is given by equation 3.8

$$\mathrm{S} = \frac{25400}{CN} - 254 ---------------------------------3.8$$

The watershed Curve Number (CN) is affected by soil types, Land Use Land Cover (LULC), topography and Antecedent moisture condition (AMC). The CN values range from approximately 30 for permeable soils with high infiltration rates to 100 for water bodies (Arekhi, 2012). For watershed with different soil types, weighted CN is necessary and computed by equation 3.9

$$\mathrm{CNw} = \frac{(Ai * CNi)}{At} --------------------------------3.9$$

Where, Ai is area of sab-basin, $\mathrm{A_t}$ is total area of watershed, CNw is weighted Curve number over sub-basin. The Curve Number (CN) was already generated by HEC-GeoHMS and embedded into the basin model file thus the software automatically assigned the curve number value for each sub-basin.

3.6.1.2 Excess rainfall modeling method

For computation of excess precipitation there are seven different methods in HEC-HMS program namely Clark Unit Hydrograph, Modified Clark, Soil Conservation Service Unit Hydrograph, Snyder Unit Hydrograph and User Specified Unit Hydrograph. For this study, Soil Conservation Service Unit Hydrograph was selected to model excess precipitation. This method was preferred based upon input data needed and various researchers as discussed in literature review recommend this method for modeling of excess rainfall. It uses basin lag time which was already generated by HEC-GeoHMS as input.

3.6.1.3 Flood routing method

Different flood routing methods are available in HEC-HMS model. These are Kinematic wave, Lag, Modified pulse, Muskingum, and Muskingum-Cunge method. Muskingum method was selected for this study. Muskingum method most popular and frequently used for flood routing in natural channels and uses hydrologic routing principle (Chang, 2009). This method requires Muskingum k (flood wave traveling time) and weighting coefficient of discharge (x).

flood wave traveling time and Muskingum x range from 0.0016-150 and 0 to 0.5 respectively (Chang, 2009 and Kong *et al*., 2011).

According to Subramanya (2008) and Chang (2009), the Muskingum flood routing method uses equation 3.10.

$$S = k\ xI + \ 1 - x\ Q\ -----------------------------3.10$$

Where, I is inflow, Q is outflow, ds is change in storage, dt is change in times, S is storage, K is flood wave traveling time, x is weighting coefficient of discharge.

Mathematically, K is given as equation 3.11.

$$k = \frac{v}{l} ----------------------------------3.11$$

Where, v is allowable flow velocity, l is length of the reach

Allowable velocity is the velocity that causes neither erosion nor deposition of silt in river channel (Subramanya, 2008). Permissible velocity ranges from 0.75 to 2.0 (ERA, 2013). Hence, permissible velocity of 1.4 m/s was assumed to determine the initial value of flood traveling time (k).

3.6.1.4 ***Base flow modeling***

There are three base flow modeling options in HEC-HMS model. These are linear reservoir, constant monthly varying value and exponential recession (Halwatura *et al*., 2013). The constant monthly base flow was selected for this study by assuming the minimum mean monthly of observed stream flow as base flow contribution.

3.6.1.5 Model Calibration

Model calibration is the process of adjusting selected model parameters values and other variables in the model in order to match the simulated outputs with the observed values. Model calibration with observed data provides users with greater confidence to use model (Muthukrishmnan *et al*., 2006).

The successful application of the hydrologic model depends upon how well the model is calibrated which in turn depends on the technical capability of the hydrological model as well as the quality of the input data (Vaze *et al.,* 2011). Once a model was simulated for the initial parameter estimates, it was calibrated against known observed stream flow measured at the gauging station during a storm event that occurred between selected time events.

The model calibration was done by adjusting parameters like lag time, curve number, initial abstraction, flood wave traveling time (Muskingum-k) and weighting coefficient of discharge (Muskingum-x) until the simulated result was matched well with observed one. The process was completed automatically and manually by repeatedly adjusting the parameters, inspecting the goodness of fit between the simulated and observed values. The model calibration was done using 18 years (1987 to 2004) daily observed stream flow data.

3.6.1.6 Model Validation

Model validation is the key criteria to test performance of hydrological model with independent data serious (Vaze *et al*, 2011). Model calibration determines the best or least a reasonable parameters while validation ensures that whether calibrated parameters perform reasonably well under independent data sets without altering parameters used in calibration. The model validation was conducted using 6 years (2005 to 2010) daily observed stream flow data.

3.6.1.7 Model Performance Evaluation

The HEC-HMS model performance evaluation involved assessing the goodness of fit in the observed and simulated stream flow. The performance of HEC-HMS model was evaluated using statistical error test to determine the quality and reliability of simulated values. To evaluate the efficiency of the model, Nash Sutcliffe Efficiency (NSE), Root Mean Squared Error (RMSE) and Coefficient of Determination (R^2) were used because they are widely applicable in hydrological modeling (Moriasi *et al.*, 2007 and Vaze *et al.*, 2011).

A) Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe Efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Moriasi *et al.*, 2007). Mathematically, it is given as equation 3.12

$$\mathrm{NSE} = 1 - \frac{\mathrm{Q_{ob(t)}} - \mathrm{Q_{sim(t)}}\ ^{2}}{\mathrm{Q_{ob(t)}} - \mathrm{Q_{ob}}\ ^{2}} - 3.12$$

Where, NSE is Nash and Sutcliffe Efficiency, Qob is observed value at the ith time interval, Q_{sim} is simulated value at the i^{th} time interval, Q_{ob} is mean of the observed discharges

B) Coefficient of Determination (R^2)

The other widely used statistical measure is Coefficient of determination (R^2) which describes the degree of co-linearity between simulated and observed data. The correlation coefficient indicates the accuracy of a model.

Coefficient of Determination (R^2) ranges from zero to one. One indicates perfect prediction whereas zero shows poor prediction (Moriasi *et al.*, 2007). Mathematically, it is given by equation 3.13.

$$\mathrm{R}^{2} = \frac{(\mathrm{Q_{obs(t)}} - \overline{\mathrm{Q}}_{\mathrm{obs}})\quad(\mathrm{Q_{sim(t)}} - \overline{\mathrm{Q}}_{\mathrm{sim(t)}})^{2}}{((\mathrm{Q_{obs(t)}} - \overline{\mathrm{Q}}_{\mathrm{obs}})^{2}\quad(\mathrm{Q_{sim(t)}} - \overline{\mathrm{Q}}_{\mathrm{sim(t)}})^{2}} - - - - - - - - - - - - - - - - - 3.13$$

Where, R^2 is coefficient of determination, Q_{obs} is observed value at the ith time interval, $Q_{sim(t)}$ is simulated value at the i^{th} time interval, $\overline{Q}_{obs}$ is mean of observed discharges

$\overline{Q}_{sim\ t}$ *is* mean of simulated discharges value at i^{th} time interval.

C) Root Mean Squared Error (RMSE)

Root Mean Squared Error (RMSE) of observations is given by equation 3.14.

$$\mathrm{RMSE} = \sum_{i=1}^{n} \frac{Q_i - S_i\ ^{2}}{Q_i - Q} \text{ −−−−−−−−−−−−−−−−−−−−−−−−−−−−3.14}$$

Where, Qi is observed stream flow data, $\overline{Q}$ is average observed stream flow data, Si is simulated stream flow data.

3.7 Flood prediction

Flood prediction is very important statistical technique in understanding the nature and magnitude of peak discharge in a river. This method is useful to predict flood which helps to cause no damage to the public and government properties. There are different ways of determining forecasting flood.

3.7.1 Flood prediction by HEC-HMS Model

The HEC-HMS frequency storm method is a meteorological method used in meteorological model to estimate flood frequency from given statistical precipitation data. The method requires probability, intensity duration, storm duration, intensity position, storm area, and rainfall depth. For this study flood frequency analysis was conducted using rainfall depth of 2, 10, 25, and 100 years return periods to estimate peak flood. This rainfall depth of different return periods were obtained from Ethiopian Roads Authority (ERA). Ethiopian Roads Authority (ERA) divided the country into eight meteorological regions based on similarity of rainfall pattern and developed Intensity Duration Frequency (IDF) curves for 24 hours rainfall depth for each meteorological region. According to this classification, Meki river watershed is found in Rainfall Region three (RR3).

3.7.2 Flood prediction by probability distribution function

There are many statistical distribution functions used for prediction of flood from extreme events. Among this statistical distribution functions, the best fitted one was determined using Easy Fit software version. Easy Fit software is a data analyzer and simulation software which allows to fit probabilistic distributions to given data choosing the best fitted probability function and implements the result to make decision. Moreover, it is used as Windows compatible program, and as an add-on to Excel spread sheets (Pakgohar, 2014). It uses the maximum annual stream flow data to assign the rank of each statistical distribution. Accordingly, the maximum daily stream flow data of 24 years (1987-2010) of Meki river watershed was used. The Gumbel, Log-Pearson type III, Lognormal and Normal probability distributions were applied to be tested by Easy Fit software. These statistical distributions were preferred due to of their simplicity, suitability and efficiency. The Selection of best-fit probability distribution was based on the offered rank by all goodness of fit tests Kolmogorov Smirnov, Anderson Darling and Chi-Squared. Based on the rank of goodness of fit tests, Gumbel distribution function was found to be the best-fitted probability distribution both in Kolmogorov Smirnov and Chi-Squared tests. Hence, Gumbel method was used to predict the peak flood of 2, 10, 25, 50, and 100 year return periods and compared with HEC-HMS model results. According to Subramanya (2008), Gumbel method is given by equation 3.15.

A) Gumbel method

$$X_T = \overline{X} + K_T\sigma \text{ ------------------------------ } 3.15$$

$$\overline{\mathrm{X}} = \frac{{}_{i=1}^{N} X_i}{N} \text{ ------------------------------ } 3.16$$

$$K_T = -\frac{\overline{6}}{\pi}\ 0.5772 + \ln\ \ln\ \frac{\mathrm{T}}{\mathrm{T}-1} \text{ ------------------------------ } 3.17$$

$$\sigma = \frac{{}_{i=1}^{N}\ X_i - \overline{\mathrm{X}}\ ^2}{N-1} \text{ ------------------------------ } 3.18$$

Where, X_T is peak flood generated from corresponding return period, σ is standard deviation, K_T is frequency factor at different return period, $\overline{\mathrm{X}}$ is the mean value of the events, Xi is magnitude of the ith event, and N is the total number of events

3.8 Flow Chart of the Analysis

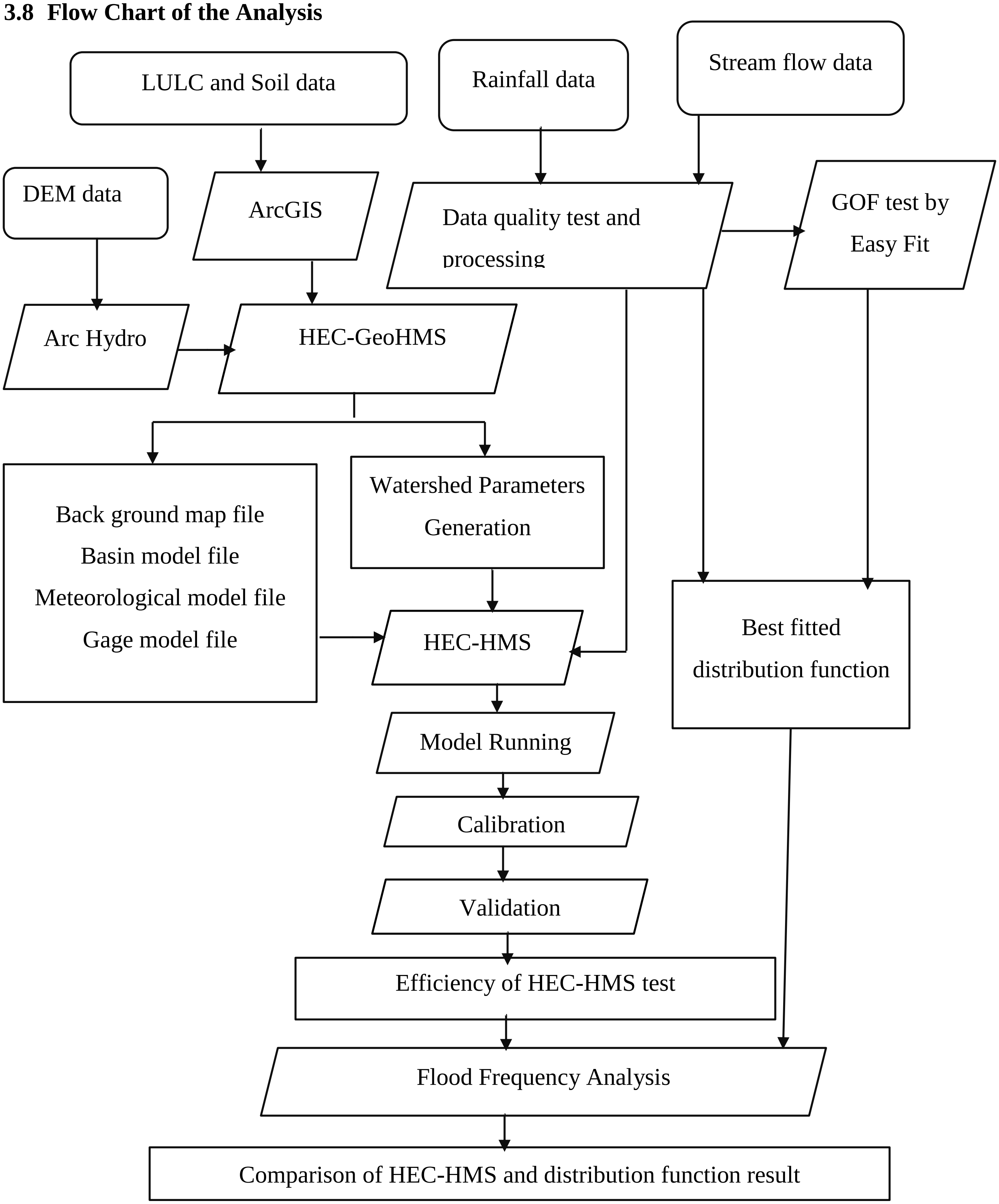
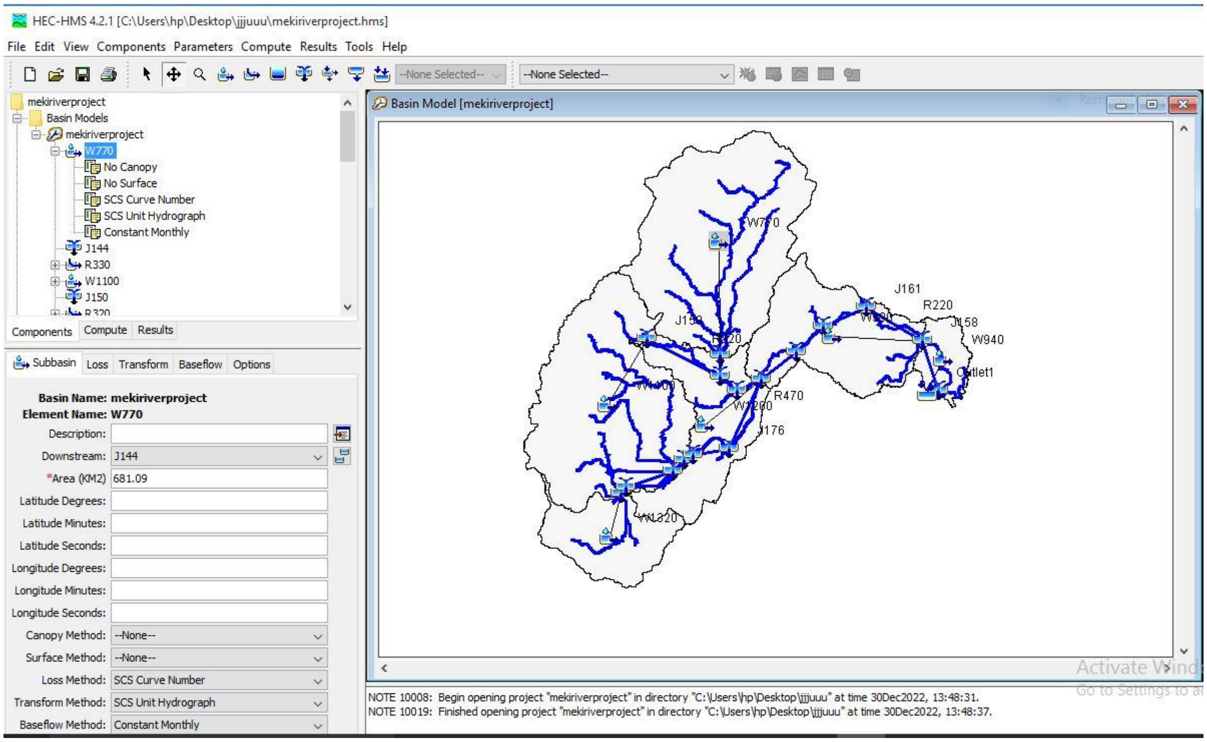


Figure 3.9: General Frame work of the Analysis

4. RESULTS AND DISCUSSIONS

4.1 Back Ground Map File

The back ground map file represents the physical watershed under consideration. For this study a background map file with 6 Sub-basins and 16 reaches were generated using HEC-GeoHMS as shown in Figure 4.1. Figure 4.1 shows the background map file with its elements like reaches and junctions. It encompasses Basin model file, Meteorological model file and Gage model file later used as input in HEC-HMS during rainfall runoff simulation.



Basin Name: mekiriverproject
Element Name: W770
Description:
Downstream: J144
*Area (KM2) 681.09
Latitude Degrees:
Latitude Minutes:
Latitude Seconds:
Longitude Degrees:
Longitude Minutes:
Longitude Seconds:
Canopy Method: --None--
Surface Method: --None--
Loss Method: SCS Curve Number
Transform Method: SCS Unit Hydrograph
Baseflow Method: Constant Monthly

```
NOTE 10008:  Begin opening project "mekiriverproject" in directory "C:\Users\hp\Desktop\jjjuuu" at time 30Dec2022, 13:48:31.
NOTE 10019:  Finished opening project "mekiriverproject" in directory "C:\Users\hp\Desktop\jjjuuu" at time 30Dec2022, 13:48:37.
```

Figure 4.1: Back ground map file of Meki river watershed.

4.2 Watershed parameters

As discussed under methodologies, important watershed characteristics like, Curve number, basin lag time, watershed area, basin slope, potential maximum retention (S) and the initial abstraction from watershed were determined. The CN value of study area was varied spatially. The minimum and maximum CN value of study area were 30 for area covered by forests and 100 for area covered by water body.

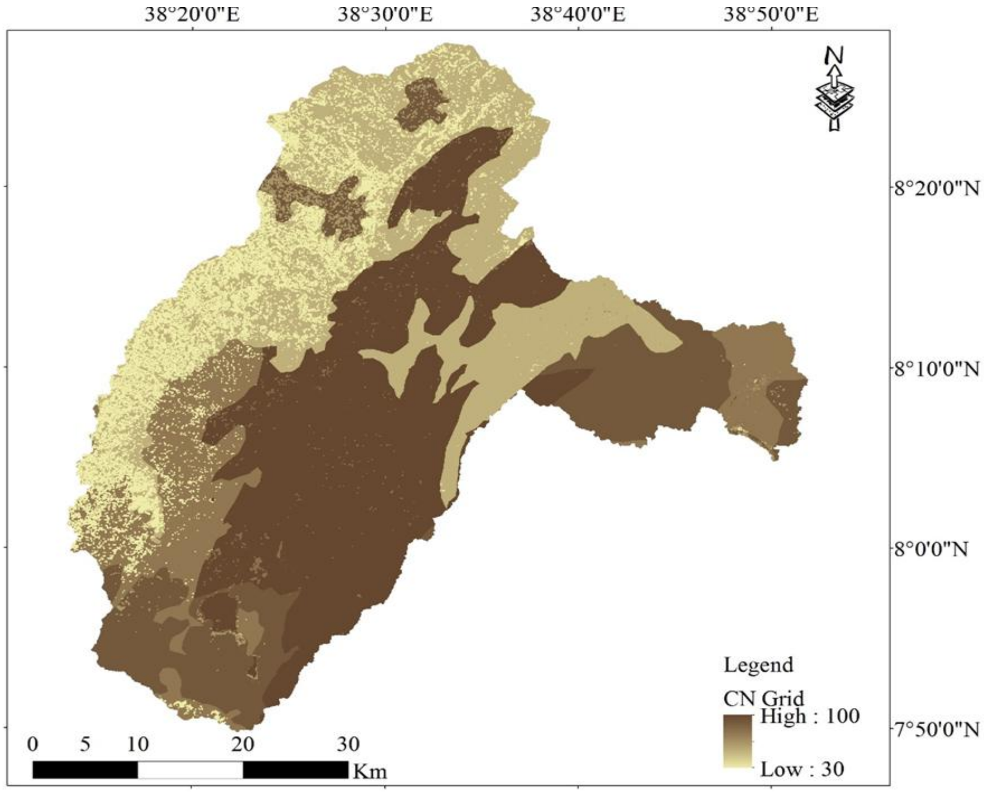


Figure 4.2Curve Number grid map of Meki river watershed.

However, in rainfall runoff simulation each sub-basin requires single value of CN. Hence, the weighted CN values were already extracted by HEC-GeoHMS for each sub-basin. The minimum and maximum weighted curve number values are 85.4 and 65.7 respectively. This minimum and maximum weighted CN values are found in sub-basin W1200 and W7700 respectively. Curve Number value is directly proportional to runoff generation. Sub-basin with minimum CN value contribute very lower runoff and high infiltration rate. In contrary to this the larger CN within sub-basin, the higher runoff potential from that sub-basin. Accordingly, high and low runoff generates from W1200 and W1100 respectively. For more clarification, the spatial distribution of CN is shown in Figure 4.3

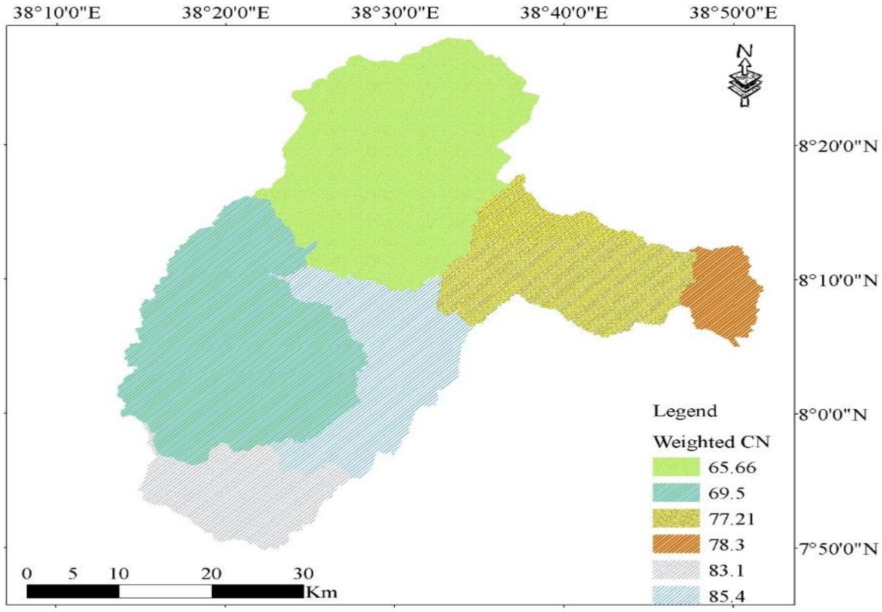


Figure 4.3: Weighted Curve Number map of the Meki river watershed.

Similarly, the minimum and maximum initial abstraction were 8.7 mm in W1200 and 26 mm in W7700 sub-basin. This indicates the low and high runoff value generated from W7700 and W1200 respectively. The maximum basin slope is 0.116 % and found in sub-basin W1320. This indicates sub-basin W1320 is the steepest compared to other sub-basins. The basin lag time of study area were between 12.8 and 75.8 hours. The lower the basin lag time surface runoff reaches outlet point very quickly. The watershed characteristics are shown in Table 4.1.

Table 4.1: Watershed parameters generated by HEC-GeoHMS for Meki river watershed

Sub-basin	Area (Km^2)	Lag Time (hr.)	Basin Slope (%)	CN	Potential maximum Retention (S) (mm)	Initial Abstraction (mm)
W770	681	75.8	0.168	65.7	132.8	26
W1100	629.2	54.3	0.228	69.5	111.5	22.3
W1320	200	37.72	0.116	83	51.5	10.3
W1200	297.6	23	0.362	85.4	43.5	8.7
W990	349.8	35.742	0.268	77.2	75	15
W940	82.4	12.8	0.781	78.29	70	14

4.3 Model Simulation Result

The simulated daily peak discharge at outlet of the study area is found to be 296.2 $m^3 \quad s$ and for each sub-basin and rivers, the daily simulated discharge are given in Table 4.2. Based on the result, the highest runoff is generated from W1100 sub-basin and the lowest runoff is contributed by W940 sub-basin. The water depth increases as river reaches approaches to the outlet point.

Table 4.2: Simulated results at each sub-basin and river reaches

Sub-basin	Daily peak discharge (m^3/s)	River channel	Routed flood (m^3/s)	River channel	Routed flood (m^3/s)
W7700	156.5	R480	33.9	R400	226.0
W1100	157.6	R470	34.0	R430	226.6
W1320	33.8	R500	33.8	R350	258.5
W1200	69.9	R540	33.7	R240	258.8
W990	103.4	R570	33.6	R150	259.2
W940	28.8	R600	33.4	R220	260.0
Outlet	296.2	R330	156.6	R420	278.1
		R320	157.8	R410	278.7

4.4 Model Calibration and Validation

4.4.1 Model Calibration

HEC-HMS model calibration was done by adjusting model parameters to match the simulated with observed flow data as much as possible with accepted range of deviation. Similarly, the Time to peak of simulated and observed event was occurred on the same day. The agreement between observed and simulated flows was further improved through adjusting the model parameters with model calibration process. After the model was calibrated for a period, the peak of simulated and observed stream flow were 286.8 m^3 /s, and 208.6 m^3 /s respectively. The time to peak for observed and simulated stream flow are on 15 and 16July, 1999 respectively.

Watershed Parameters like lag time, curve number, initial abstraction, flood wave traveling time (Muskingum-k), and weighted coefficient of discharge (Muskingum-x) were selected for model calibration. The optimization result indicates that all selected parameters were sensitive in optimizing HEC-HMS model. However, curve number and lag time were the most sensitive parameters. Table 4.3 indicates the initial and optimized value of the parameters and their objective function sensitivity values. From Table 4.3, the minimum and maximum initially computed values of Muskingum-k are 1:23 and 3:00 hour respectively. After model calibration, these initially computed values were adjusted as 1:18 and 2:77 hour respectively. Similarly, for each reaches, the Muskingum-k values were computed and adjusted during model calibration as indicated in Table 4.3. Moreover, the values of Muskingum-x for each reaches were determined by trial and error and is found to be 0.25 and optimized to 0.24.

Table 4.3: HEC-HMS optimized parameters of Meki watershed

Element	Parameter	Unit	Initial value	Optimized value	Objective function sensitivity
W7700	Lag time	HR	75.95	77.23	-0.37
	Curve Number		65.7	56.21	-0.17
W1100	Lag time	HR	53.6	54.3	-0.46
	Initial abstraction	MM	22.3	22.45	-0.23
W1320	Initial abstraction	MM	10.3	15.15	0.00
W1200	Initial abstraction	MM	8.7	9.13	0.00
	Curve Number		85.4	84.34	-0.32
R480	Muskingum-k	HR	3.00	2.77	0.00
	Muskingum-x		0.25	0.24	0.00
R330	Muskingum-k	HR	2:00	1.88	0.00
R320	Muskingum-k	HR	1:89	1.78	0.00
	Muskingum-x		0.25	0.24	0.00
R400	Muskingum-k	HR	1:75	1.65	0.00
R350	Muskingum-k	HR	1:23	1.18	-0.01

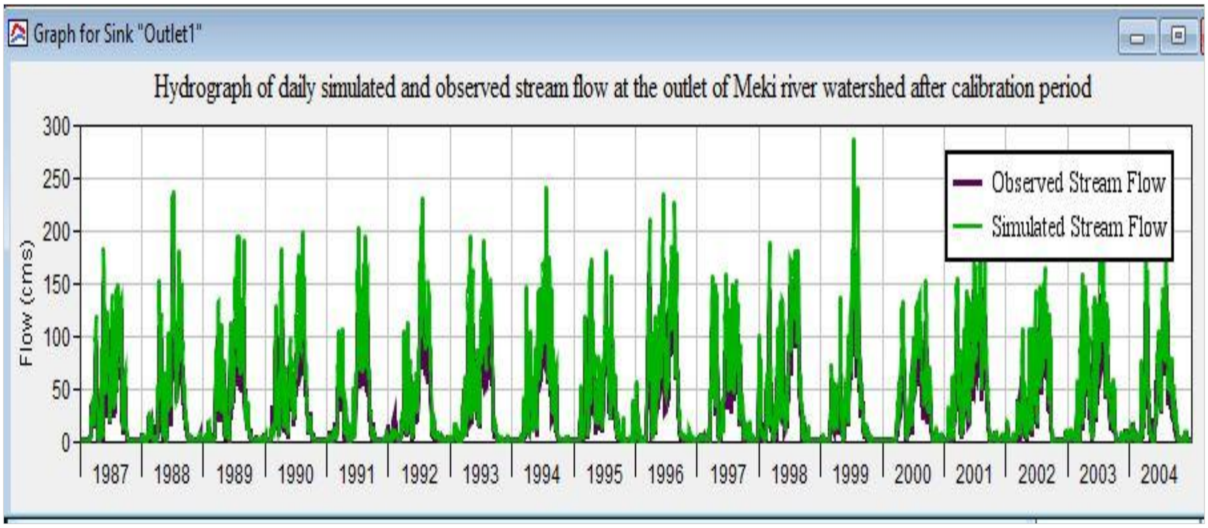


Figure 4.4: Simulated and observed flow hydrographs after calibration

Figure 4.4 indicates the simulated and observed flow hydrographs of Meki river watershed at outlet after calibration time period. The low flow and peak flow of simulated and observed hydrographs were well matched and followed the same pattern during calibration period. Moreover, the scatter plot of the measured and simulated stream flow during calibration period has a correlation coefficient (R^2) of 0.86 which indicates that there was high correlation between the simulated and observed stream data Figure 4.5.

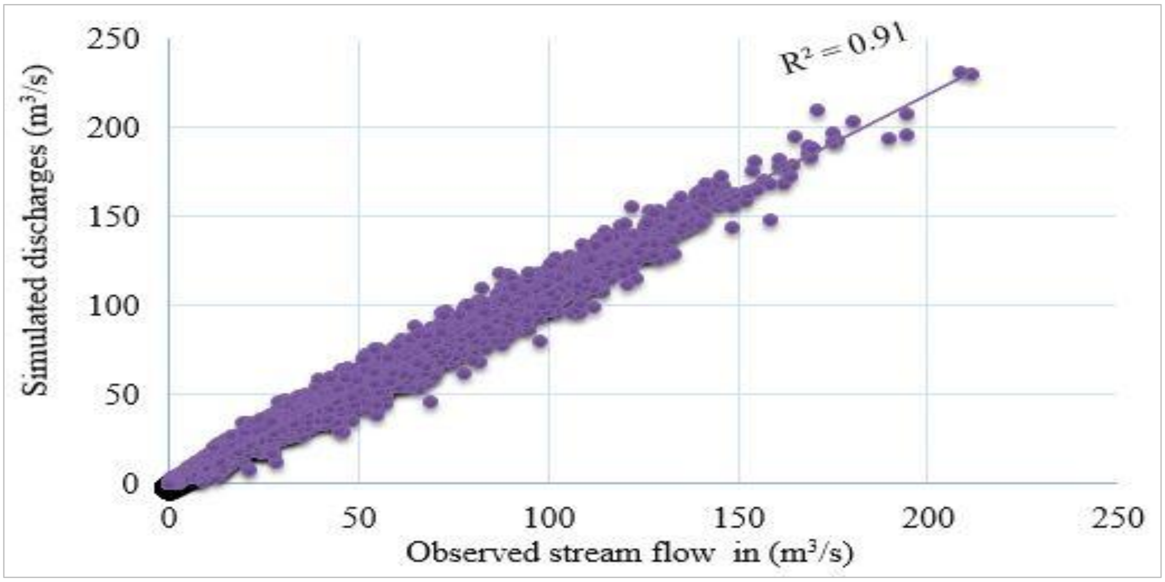


Figure 4.5: Scatter plot of observed and simulated flow after calibration

4.3.2 *Model Validation*

All the applied statistical error test were found within acceptable range during validation as calibration period which shows the predicted calibration result was verified. Figure 4.6 shows the low flows and peak flow of simulated and observed stream flow hydrographs were well matched and followed the same pattern during validation period. This shows that the HEC-HMS model can performs well in simulated stream flow data for study area.

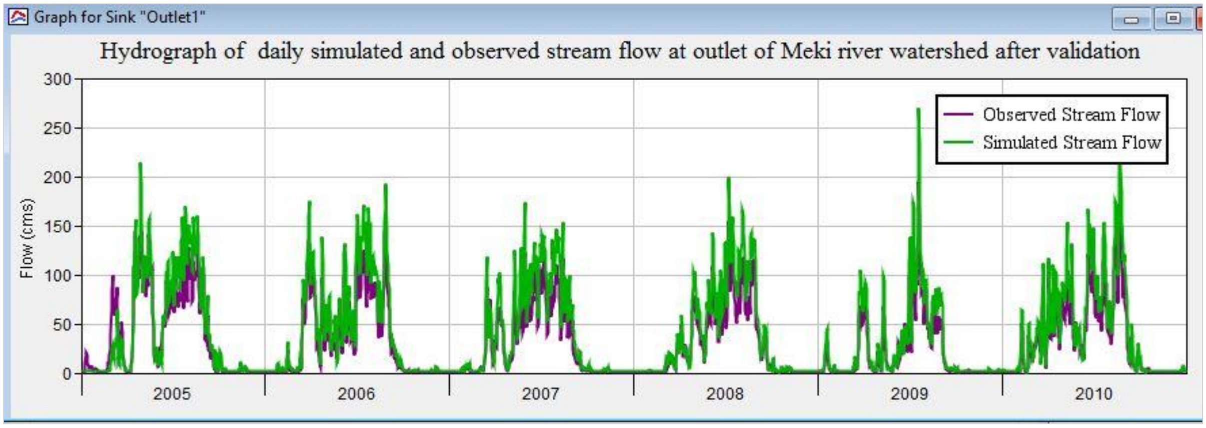


Figure 4.6: Simulated and observed stream flow hydrographs after validation

The scatter plot of measured and simulated flow at validation period shows fair linear correlation between the simulated and observed data as calibration time period Figure 4.7. The shape and scatter of simulated and observed stream flow hydrograph at outlet of watershed during validation period shows similar pattern as model calibration time period.

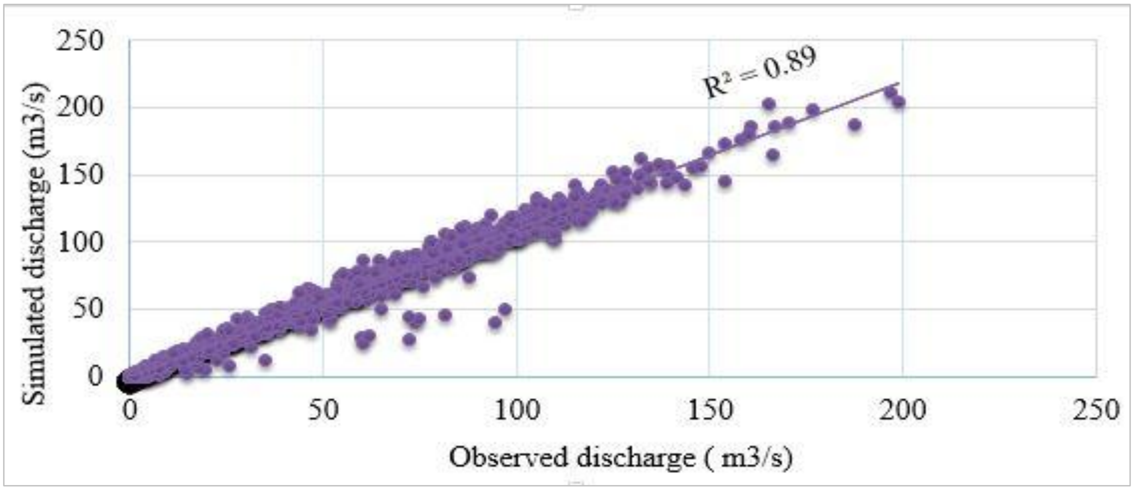


Figure 4.7: Scatter plot of observed and simulated flow after validation

4.5 Model Performance evaluation

The performance of model evaluated using Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Error **(**RMSE) and Coefficient of determination (R^2). Moriasi *et al.* (2007) studied model evaluation guidelines for systematic quantification of accuracy in Watershed simulations and stated that, the model to be very good, the value of NSE and R^2 should be between 0.75 and 1.0, whereas, the value of RMSE should be 0 to 0.5. Similarly, Schaefli and Gupta (2007), Kashid (2010) and Vaze (2011) stated that, if the value of NSE and R^2 during calibration and validation are between 0.75 and 1 the model performance rating is classified as very good model.

For this study, the value of NSE and R^2 were greater than 0.75 both in calibration and validation time period whereas RMSE was 0.5 and 0.4 during model calibration and validation time period respectively. The calibration and validation result indicated that there was strong relationship between simulated and observed stream flow data. Hence, based on these statistical error test criterias HEC-HMS model performance rating is classified as very good model. As the model predictive capability was demonstrated being reasonably well in calibration and validation phase, the HEC-HMS model can simulate daily stream flow from rainfall data efficiently for this study area.

Hence, the model performance was accepted and can be used for future peak flood prediction under different management scenario. Moreover, the observed stream flow data of study area can be well represented with the simulated stream flow data.

Table 4.4: Summary of model performance evaluation

Performance Rating	After calibration	After validation	Remark
Root Mean Squared Error	0.5	0.4	Very good
Nash-Sutcliffe Efficiency	0.832	0.804	Very good
Coefficient of determination	0.91	0.89	Very good

4.6 Flood prediction

4.6.1 Flood Prediction by HEC-HMS

Flood frequency analysis of 2, 10, 25, 50, and 100 year return periods were conducted using HEC-HMS model for Meki river watershed considering rainfall depth of 24 hours and obtained peak flood with different amount. Accordingly, the minimum and maximum peak flood at the outlet of Meki river watershed were found to be 133.2 m^3/s and 346.19 m^3/s. This indicates the minimum peak flood of Meki River watershed was occurred at 2 year return period of 24 hour storm duration and the maximum flood was obtained from 100 year return period of 24 hour storm duration. By assuming the same basin lag time for 2, 10, 25, 50 and 100 year return periods the peak discharge and shape of hydrograph for all these return periods were predicted and their hydrograph were shown in Figure 4.8.

Table 4.5: Simulated peak flood of different return period by HE-HMS.

Return period (year)	24 hour storm (mm)	peak flood (m^3/s) by HEC-HMS
2	47.54	133.2
10	67.66	178.1
25	77.92	239.7
50	85.62	313.2
100	93.34	346.19

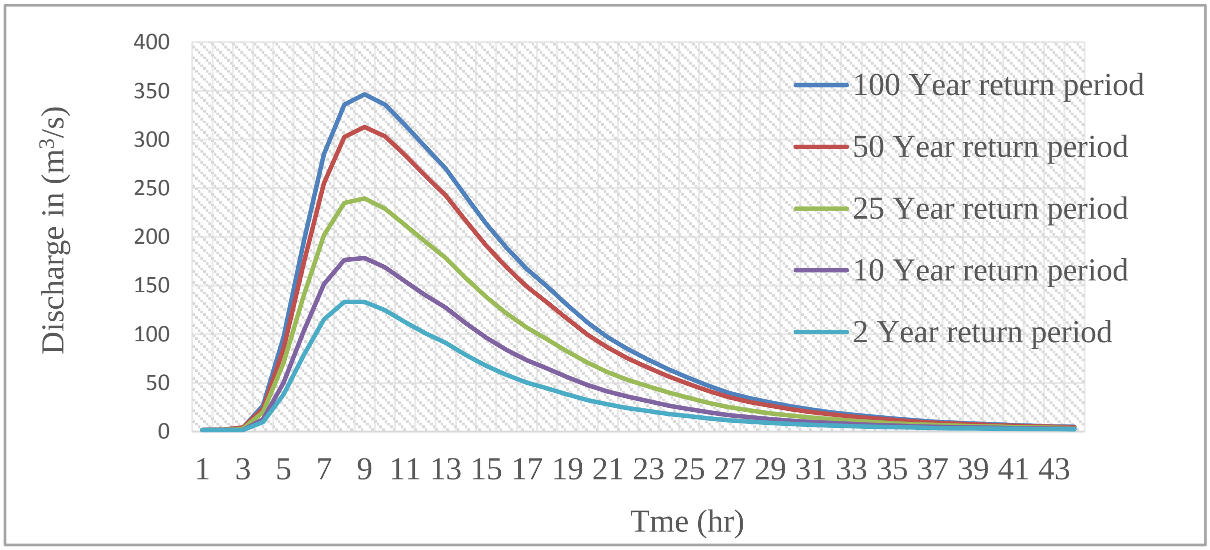


Figure 4.8: Comparison of Hydrograph of different return period

4.6.2 Comparison of HEC-HMS and Gumbel distribution Result

The Gumbel distribution was the most fitted to given stream flow data. The predicted peak flow by this probability function is shown in Table 4.6.

Table 4.6: Peak discharge found from flood frequency analysis.

No.	Return period (year)	Peak flood (m^3/s)	
		Simulated	Computed
		HEC-HMS	Gumbel
1	2	133.2	126.7
2	10	178.1	167.8
3	25	239.7	223.5
4	50	313.2	287.9
5	100	346.19	331.87

The result obtained from Gumbel method was found to be very close to simulated result by HEC-HMS model as shown in Figure 4.9. However, the peak flood predicted by HEC-HMS was greater than peak flood computed by Gumbel method. This indicates that, the simulated peak discharge by HEC-HMS model can further used for flood mapping and mitigation measures.

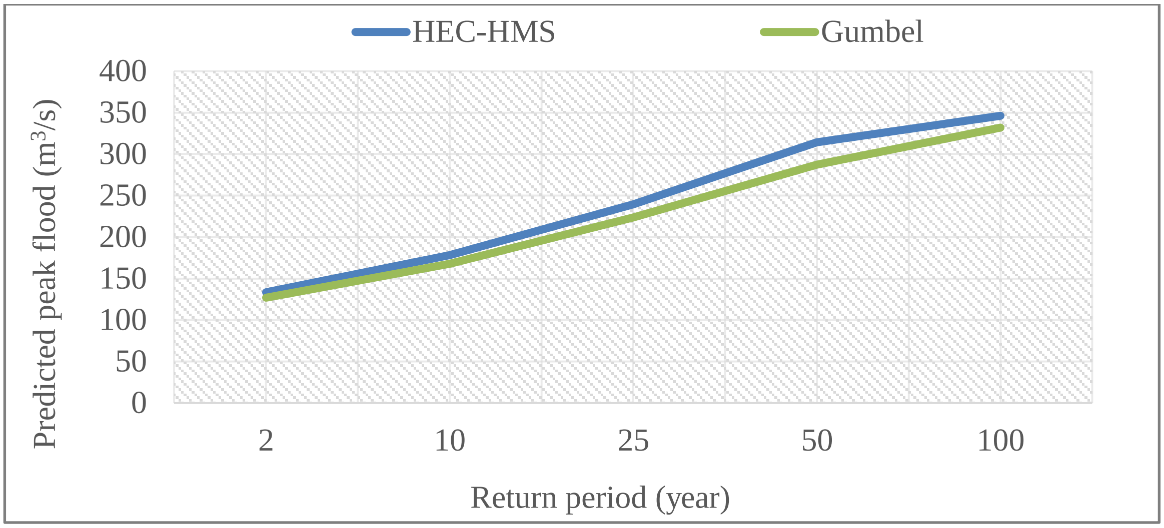


Figure 4.9: Graphical Comparison of HEC-HMS result with Gumbel method.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Rainfall runoff modeling is very important for simulating the response of watershed to rainfall and produce flow hydrograph, which is extensively used for flood forecast and water resources planning. In this study HEC-HMS model was used to model stream flow of Meki watershed.

Hydro-metrological, soil, LULC and DEM data were used for this thesis. ArcGIS and HEC-GeoHMS were used to generate basin model and input parameters like Curve number, lag time and initial abstractions.

The homogeneity and consistency of rainfall data were tested by rainbow software and double mass-curve methods. Moreover, its missed value was computed by simple ratio and normal ratio method where areal rainfall was computed by Isohyetal methods. In addition to this, missed value of stream flow was computed by linear regression methods.

The Soil Conservation Service Curve Number, Soil Conservation Service Unit Hydrograph, constant base flow and Muskingum method were used to compute the rainfall loss component, runoff component, base flow modeling and channel routing respectively.

The model was calibrated and validated using 18 years (1987-2004) and 6 years (2005-2010) daily observed stream flow data respectively.

The minimum and maximum curve number of study area are 30 for area cover by forest and 100 for area cover by water body. Similarly, the maximum lag time and initial abstraction are occurred in sub-basin W7700 while minimum lag time is occurred for sub-basin W940.

The lag time, curve number, initial abstraction and flood traveling time (Muskingum-k) and discharge weighting factor (Muskingum-x) were the main parameter that can affect output.

The Root Mean Squared Error, Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2) were used to assess performance of the model, and have been found to be 0.5, 0.832 and 0.91 respectively, during calibration and 0.4, 0.804, and 0.89 during validation, indicating a very good performance of the model which in turn shows the HEC-

HMS model is well suited for simulation of stream flow data from rainfall data of the study area.

From goodness of fit test by easy fit, Gumbel method was ranked first both in Kolmogorov Smirnov and Chi-squared and concluded as the best fitted probability distribution function to given observed stream flow time series data.

After model setup was adjusted, flood frequency analysis was conducted for 2, 10, 25, 50, and 100 years return periods considering rainfall depth of 24 hour storm of Meki river watershed that was derived by ERA, 2013. Accordingly, the predicted peak flood by hec-hms and Gumbel method at 2, 10, 25, 50, and 100 year return periods were 133.2, 178.1, 239.7, 313.2 and 346.19 and 126.7, 167.8, 233.5, 287.9 and 331.87 m^3/s respectively.

Peak flood predicted by HEC-HMS model is greater than Gumbel distribution. Hence, the predicted peak flood by HEC-HMS model will help further researchers to prepare flood inundation map and take appropriate measure to control its impact for this study area.

5.2 Recommendation

Based on the findings of this study, the following recommendations are forwarded.

- Factors like LULC, topography, Soil Moisture Condition (SMC) and soil types can greatly affect Curve Number (CN) value which mainly determine the amount of flood generated. So, further researcher should take great attention to this factors while determining CN.
- The collected rainfall and stream flow data have some missed values. Hence, the missed value were filled by different filling methods. However, the way of selection of this methods depend upon different assumptions that may be subjective. Thus, it may result some error on filled data value. Therefore, to prefer data filling method it should be scientific way which may not vary from person to person.
- The peak flood was predicted from storm data through HEC-HMS simulation and from stream flow data by Gumbel method for 2, 10, 25, 50, and 100 year return period. However, the maximum peak flood was obtained from simulation by HEC-HMS for corresponding return period. As peak value highly determine design discharge and life span of any structures. So, the government should use these peak flood value obtained from HEC-HMS to take appropriate action to mitigate flood damages for this study area.

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APPENDICES

Appendix A, Table1: Corrected monthly rainfall (mm) of Buie metrological station

Year	Jan	Feb	Marc	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1987	0.0	49.9	220.8	82.5	174.5	54.6	84.8	99.0	78.7	4.7	0.0	0.0	849.5
1988	**2.20**	**36.4**	6.4	151.9	12	124	163	176.1	126	56.2	0	3.5	858.8
1989	0	72.5	106.6	63.7	2.9	60.2	169	165.9	90.4	22.1	0	56.65	810.4
1990	51.3	0	287.6	92.1	109.5	39.1	40.6	213.2	237	59.4	1.9	0	1131.5
1991	0	2.6	91	168.9	**0.2**	18	96	278.8	265	109	0	0	1029.7
1992	0.5	78.5	48.3	8.2	90.3	21.5	111	223.3	241	96.6	63	4.4	986.1
1993	7.6	8.4	50.9	10.8	148	96.7	91.6	247.2	217	114	112	0	1104.4
1994	0	0	0	57.8	27.1	47.5	173	170.7	166	91.2	0	10.8	744.1
1995	14.6	0	57.9	89.8	254.5	171	116	223	196	165	3.6	0	1291.9
1996	29.1	117	0	191.1	34.9	138	207	249.3	266	90.3	12	4.7	1338.7
1997	17.4	32.9	53.8	101.8	11.2	103	178	149.4	31.3	78.9	19	0	776.9
1998	46	57.4	117	53.2	85.4	134	260	152.3	65.6	74.8	0	0	1046.2
1999	1.2	0	54.3	**10.2**	48.2	199	342	154.4	43.4	132	0	0	983.6
2000	0	0	20	62.1	57.2	54.1	161	180.5	270	96.2	81	15.6	998.4
2001	26	62	201.1	49.5	162.3	211	**254**	194.8	44.6	10.4	0	5.2	1220.6
2002	52.8	39.9	44.9	49.8	101	118	161	198.6	112	0	0	23.8	901.3
2003	4	21.4	122.2	146.8	17.3	151	251	166.1	132	0	4.8	42.1	1058.0
2004	59.3	4.7	23.1	158.1	2.6	114	211	193.9	118	26.8	9.5	0	921.2
2005	56.2	17.4	143.9	103.3	158.9	123	147	353.9	90	34.8	37	0	1264.7
2006	14.5	33.7	206.2	161.8	95.9	76	299	222.5	74.6	33.2	0	12.5	1229.5
2007	17.7	244	31.5	70.2	97.3	174	287	154.4	98.2	21.2	3.5	0	1198.3
2008	0	0	0	0	86.2	186	332	187.1	122	17.8	148	0	1079.4
2009	19.2	0	68.7	74.9	0	22.2	244	140.7	117	141	0	11	838.6
2010	0	152	141.1	262.4	114.4	209	206	269.4	154	0	9.2	0	1517.8
2011	0	50.6	49	403.7	149.4	218	180	85.5	0	14	0	0	1150.3
2012	0	20.1	111.4	66.9	110.6	221	95	99.7	0	0	2.5	0	727.3
2013	0	136	88.5	54.1	156.9	211	190	57.4	47.5	0.6	0	0	942.0
2014	29	170	34.4	59.7	48.7	181	249	118.5	82.2	1.87	0	0	974.0
2015	0	11.5	0	105.9	98.3	92.9	156	96.7	1.98	0	0	40.8	604.2
2016	1.3	31.8	175.8	135.2	100.9	178	99	74.9	25	12.9	0	0	834.5
2017	37.8	83.8	2.3	312.9	62.9	215	183	80.425	1.5	0	0	**0.0**	979.9

Appendix A, Table 2: Corrected monthly rainfall (mm) of Butajira metrological station.

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
1987	0.0	148.9	328.3	91.4	246.1	60.1	94.7	121.3	135.9	21.2	0.0	0.0	1247.9
1988	27.6	95.9	5.5	147.0	36.0	165.9	218.7	191.5	164.7	71.7	0.0	0.0	1124.5
1989	3.0	129.2	250.7	156.5	24.6	94.5	280.8	161.3	127.4	51.0	0.0	32.5	1311.5
1990	0.0	270.9	120.3	260.5	152.1	132.2	197.5	175.7	134.3	22.0	0.0	0.0	1465.5
1991	44.0	139.8	200.6	33.1	1.3	95.7	191.6	206.1	117.3	3.6	0.0	2.7	1035.8
1992	46.1	50.3	7.1	80.5	39.4	90.0	247.6	182.9	99.1	47.2	2.6	11.5	904.2
1993	19.4	44.5	3.7	191.5	97.9	95.7	183.3	148.0	103.1	62.7	0.0	2.0	951.7
1994	0.0	0.0	118.0	87.9	80.1	246.6	269.1	100.9	108.8	3.0	14.1	2.7	1031.2
1995	0.0	72.9	115.2	409.5	98.6	63.1	124.2	116.2	66.6	9.5	0.0	93.0	1168.8
1996	149.0	0.0	314.3	103.9	212.2	277.3	133.0	199.4	72.5	9.0	13.2	0.0	1483.8
1997	111.8	0.0	126.4	190.8	35.2	199.1	101.1	207.6	108.1	109.8	50.4	0.0	1240.3
1998	115.7	107.7	217.8	111.9	200.7	94.7	194.0	223.4	120.7	73.3	0.0	0.0	1459.9
1999	3.0	15.2	91.0	35.3	69.4	92.5	205.9	214.6	111.7	215.8	0.0	0.0	1054.4
2000	0.0	0.0	6.1	122.2	75.4	57.8	150.0	133.3	55.5	57.0	90.0	118.3	865.6
2001	0.0	59.0	262.6	59.2	196.1	234.3	136.6	189.3	120.5	24.0	9.4	1.8	1292.8
2002	49.2	38.8	143.5	82.4	105.0	182.0	93.6	249.3	167.8	0.0	0.0	48.3	1159.9
2003	10.4	58.3	129.0	155.1	43.4	230.1	272.0	114.9	122.6	0.3	7.7	44.0	1187.8
2004	75.4	6.1	58.5	190.4	6.9	109.1	145.3	116.1	136.1	67.2	2.1	0.2	913.4
2005	27.0	7.0	94.0	220.7	266.9	166.1	394.8	169.0	274.6	133.7	29.8	0.0	1783.6
2006	3.0	53.4	176.1	324.8	98.9	229.2	218.8	175.4	229.1	53.3	0.4	9.9	1572.3
2007	5.6	185.1	67.0	91.3	116.0	147.8	185.8	146.5	93.9	10.9	2.1	0.0	1052.0
2008	0.0	1.7	0.0	37.1	141.4	151.3	145.1	197.7	88.5	65.0	76.7	0.0	904.5
2009	35.5	4.5	23.8	31.0	42.7	26.3	187.0	68.1	34.0	52.2	0.0	0.0	505.1
2010	0.0	71.0	53.1	46.8	126.8	141.6	68.2	140.4	71.2	23.2	8.8	4.5	755.6
2011	3.1	0.0	66.9	23.0	183.7	121.1	161.3	147.9	121.1	43.4	14.2	0.0	885.8
2012	0.0	12.4	50.7	62.2	68.8	120.0	269.6	143.9	88.0	15.8	0.0	3.5	834.9
2013	12.7	0.0	111.7	91.7	78.3	274.2	453.2	164.7	48.1	50.1	0.0	0.0	1284.7
2014	170.0	129.4	0.0	72.7	97.8	76.8	403.4	412.4	161.0	13.0	5.6	0.0	1542.1
2015	0.0	0.8	22.3	0.0	52.1	78.0	79.8	56.4	70.6	6.6	0.0	0.0	366.6
2016	7.2	5.0	9.0	57.2	61.6	52.2	63.8	34.0	21.6	6.8	4.4	0.0	322.8
2017	0.0	7.8	13.2	11.8	15.4	23.2	54.4	24.0	10.6	0.0	0.0	0.0	160.4

Appendix A, Table 3: Corrected monthly rainfall (mm) of Ejersa metrological station**.**

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Octo	Nov	Dec	Annual
1987	0.0	42.2	96.3	68.4	182.6	54.7	109.3	99.0	75.3	0.0	0.0	0.0	727.8
1988	3.1	73.4	3.2	126.6	6.7	41.9	229.7	149.7	103.8	51.1	0.0	3.9	793.1
1989	0.6	42.5	95.1	177.0	3.2	52.8	121.1	187.3	129.6	22.0	0.0	6.2	837.4
1990	0.0	203.3	75.4	93.0	50.8	24.7	185.7	123.9	54.5	0.0	0.0	0.0	811.3
1991	0.0	17.8	118.8	0.0	19.3	89.4	199.2	200.1	152.2	1.4	0.0	0.0	798.2
1992	5.0	51.0	15.6	86.1	39.0	43.0	235.2	193.2	113.0	47.0	0.0	0.0	828.1
1993	27.3	41.1	0.0	165.3	108.3	51.3	335.6	355.1	11.0	60.6	0.0	0.0	1155.6
1994	0.0	0.0	33.2	16.7	47.3	143.9	296.0	190.3	218.6	0.0	4.2	7.6	957.8
1995	0.0	33.0	79.6	144.9	37.9	44.1	171.6	85.1	98.3	0.0	0.0	30.8	725.3
1996	0.0	0.0	91.8	64.3	212.4	286.6	173.1	312.1	169.6	0.0	18.1	0.0	1328.0
1997	73.9	0.0	39.5	116.2	6.4	111.5	301.2	149.5	47.3	62.5	0.0	0.0	908.0
1998	58.2	7.0	101.8	34.1	111.0	80.8	288.7	260.7	66.5	80.8	0.0	0.0	1089.6
1999	0.0	0.0	50.0	19.0	24.7	89.5	274.9	160.5	70.2	119.1	0.0	0.0	807.9
2000	0.0	0.0	12.1	65.1	58.4	72.7	174.5	137.1	134.1	51.3	63.4	0.0	768.7
2001	0.0	45.1	228.5	9.1	79.6	217.2	336.7	171.0	28.9	0.0	0.0	0.0	1116.1
2002	15.7	0.0	32.3	49.9	36.4	12.5	124.0	65.0	32.8	0.0	0.0	21.1	389.7
2003	6.2	45.1	71.6	141.5	28.0	84.0	269.1	145.4	76.0	0.0	2.0	26.0	894.9
2004	73.3	0.0	64.5	229.7	2.4	70.8	111.3	151.2	92.1	20.4	0.0	0.9	816.6
2005	20.1	46.2	103.8	111.5	118.3	145.0	148.1	211.9	87.1	3.6	8.1	0.0	1003.7
2006	8.7	104.6	137.9	57.7	82.1	107.6	246.9	127.5	50.4	23.7	0.0	6.2	953.3
2007	6.1	18.5	64.9	37.3	72.0	136.7	123.0	146.9	74.3	10.0	4.7	0.0	694.4
2008	0.0	0.0	1.8	23.2	83.5	97.1	171.8	235.9	123.0	4.5	160.4	0.0	901.2
2009	46.6	0.0	40.3	32.6	14.0	50.1	203.8	144.1	64.3	105.7	0.0	15.2	716.7
2010	0.0	69.2	68.6	120.4	101.8	98.3	191.0	240.4	113.9	0.0	0.0	0.0	1003.6
2011	0.0	0.0	80.0	28.2	86.5	107.5	129.5	169.0	149.4	0.0	27.2	0.0	777.3
2012	0.0	0.0	54.2	111.8	43.5	89.2	301.2	169.0	104.0	0.0	0.0	0.0	872.9
2013	0.0	0.0	93.2	106.6	35.1	348.3	230.7	118.9	111.4	34.3	0.8	0.0	1079.3
2014	0.0	40.7	81.9	6.5	44.9	43.7	163.8	311.4	106.9	60.8	0.0	0.0	860.6
2015	0.0	0.0	17.5	0.0	171.9	65.1	161.2	109.1	77.1	0.0	0.0	0.0	601.9
2016	12.1	0.0	0.0	269.3	103.8	104.3	312.0	126.8	131.8	0.0	0.0	0.0	1060.1
2017	0.0	18.5	64.0	1.2	118.3	3.5	264.7	128.2	114.6	7.0	0.0	0.0	720.0

Appendix A, Table 4: Corrected monthly rainfall (mm) of Koshe metrological station

Year	Jan	Feb	Ma	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1987	0.0	76.4	198.5	86.3	197.1	48.4	71.5	138.0	73.0	18.5	0.0	0.0	907.7
1988	0.0	32.8	3.4	102.2	30.0	52.5	152.0	82.3	152.4	51.8	0.0	0.0	659.4
1989	5.0	115.5	89.4	34.2	34.2	256.1	147.6	203.2	116.7	7.8	0.0	31.3	1041.0
1990	0.0	260.0	38.8	68.4	40.2	61.9	177.6	104.4	75.6	8.6	0.0	0.0	835.5
1991	3.5	81.5	155.7	3.5	13.9	35.9	218.9	151.7	90.6	9.4	0.0	7.6	772.2
1992	41.4	47.8	11.0	82.6	40.4	111.5	229.2	125.8	62.6	18.9	3.4	10.3	784.9
1993	54.6	2.7	332.3	125.1	56.5	263.4	174.7	143.0	151.9	0.0	0.0	0.0	1304.2
1994	4.0	30.8	28.4	22.5	163.3	182.8	89.9	152.8	0.0	0.0	0.0	0.0	674.5
1995	6.3	166.1	189.9	67.7	51.0	140.4	83.7	118.3	15.8	0.0	30.5	115.7	985.4
1996	3.5	88.3	64.3	147.0	100.2	88.5	189.1	88.6	0.0	8.0	0.0	47.9	825.4
1997	0.0	104.9	125.4	18.3	149.8	123.6	84.0	38.2	153.1	13.9	0.0	88.8	900.0
1998	63.5	58.2	20.3	72.2	78.3	112.7	200.3	87.8	84.9	0.0	0.0	0.0	778.2
1999	0.0	60.8	31.2	10.7	109.6	171.2	110.2	77.5	127.5	0.0	0.0	0.0	698.7
2000	0.0	7.9	107.3	58.0	57.6	122.7	95.9	135.5	40.0	50.5	40.2	0.0	715.6
2001	68.3	141.4	34.5	170.9	79.3	183.1	135.9	82.5	15.9	0.0	1.8	9.3	922.9
2002	36.0	70.8	88.4	38.2	46.4	119.6	126.5	39.1	0.0	**0.0**	4.4	53.3	622.7
2003	1.3	23.5	104.8	0.0	55.8	158.4	127.2	175.8	0.0	0.0	50.5	47.4	744.7
2004	1.2	61.6	114.3	0.2	66.5	106.8	77.5	55.8	62.9	0.0	0.0	121.4	668.2
2005	0.0	92.5	139.7	124.9	61.5	231.0	163.3	110.9	25.7	5.6	0.0	3.3	958.4
2006	34.9	105.8	149.9	146.4	76.4	234.2	104.8	50.2	**46.5**	0.0	1.2	8.7	959.0
2007	61.3	52.0	40.6	172.2	141.6	174.2	168.4	136.2	12.3	0.0	0.0	0.0	958.8
2008	0.0	0.0	**7.9**	**147.3**	197.1	166.2	171.4	66.6	49.1	140.7	0.0	34.6	980.9
2009	0.0	58.2	4.5	35.1	25.3	149.4	48.9	69.0	76.6	0.0	12.3	0.0	479.3
2010	86.3	173.7	104.8	139.7	56.0	84.1	131.6	70.8	18.6	0.0	11.6	12.5	889.7
2011	0.0	65.6	44.1	50.0	108.3	150.0	149.1	22.7	0.0	6.4	0.0	0.0	596.2
2012	0.0	61.8	95.1	0.0	80.0	239.6	133.4	101.2	0.0	0.0	0.0	7.4	718.4
2013	0.0	111.7	91.7	16.9	224.8	286.7	105.4	131.6	105.4	2.7	0.0	35.3	1112.1
2014	55.3	82.6	31.4	50.0	30.7	172.5	200.4	93.7	176.2	9.9	0.0	0.0	902.6
2015	0.8	20.0	0.0	110.9	6.3	40.5	42.5	69.7	2.0	0.0	0.0	32.3	325.0
2016	22.8	2.1	0.0	292.3	120.9	183.9	49.9	0.0	0.0	0.0	0.0	0.0	671.9
2017	7.2	22.1	**0.0**	**70.6**	**19.8**	**90.6**	**39.6**	**144.1**	**0.5**	**0.0**	**0.0**	**0.0**	394.5

Appendix, Table 5: Corrected monthly rainfall (mm) of Meki metrological station

Year	Jan	Feb	Ma	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1987	0.0	13.6	116.5	66.4	231.2	27.2	111.9	167.6	67.3	2.3	0.0	0.0	804.0
1988	0.7	51.0	16.0	83.2	20.3	129.1	142.4	134.6	99.9	51.6	0.0	0.0	728.8
1989	3.0	36.9	118.5	84.8	17.4	83.0	14.5	195.9	122.7	174.0	109.9	10.0	970.6
1990	0.0	0.0	0.0	257.5	20.1	17.2	215.8	211.8	79.9	18.6	0.0	0.0	820.9
1991	0.0	49.2	164.5	0.1	11.6	27.5	66.8	175.6	21.0	7.6	0.0	11.7	535.5
1992	18.3	54.7	2.2	68.6	56.3	47.9	290.8	243.3	76.2	59.8	0.0	19.0	937.1
1993	31.4	31.4	1.4	120.2	61.4	65.0	188.2	147.4	46.1	56.9	0.4	0.0	749.8
1994	0.0	0.0	29.1	14.1	68.1	129.0	250.2	98.9	44.3	0.0	5.1	0.0	638.8
1995	0.0	0.7	35.2	80.6	79.4	19.0	90.9	46.6	8.4	8.0	0.0	41.1	409.8
1996	122.9	2.9	161.9	78.2	154.5	179.2	147.8	202.1	93.6	7.5	14.7	4.4	1169.6
1997	53.2	5.0	76.4	174.3	13.7	146.3	147.8	124.8	56.9	111.9	21.6	0.0	931.9
1998	64.2	50.4	37.3	54.1	31.8	50.3	141.2	183.3	88.8	90.7	0.0	0.0	792.1
1999	2.4	3.8	78.0	7.1	8.3	68.2	196.2	123.6	50.8	162.9	0.0	0.0	701.3
2000	0.0	0.0	21.5	77.4	63.3	56.6	112.7	181.4	138.3	18.1	63.0	19.2	751.5
2001	0.0	44.1	147.7	15.3	113.6	50.3	180.5	154.8	52.6	0.0	0.0	0.0	758.9
2002	0.0	8.6	42.1	72.3	12.7	55.1	121.7	145.6	29.3	0.0	0.0	24.2	511.6
2003	31.3	20.3	86.5	166.5	9.7	44.5	269.4	94.5	15.7	0.0	0.0	55.5	793.9
2004	7.8	0.0	13.6	141.4	0.0	18.7	111.4	127.1	114.7	33.2	33.2	0.0	601.1
2005	49.2	29.8	88.0	18.6	71.1	36.7	172.2	118.6	147.5	0.0	0.0	0.0	731.7
2006	0.0	64.9	117.3	64.5	48.7	77.7	182.2	110.2	91.2	22.7	0.0	0.0	779.4
2007	11.3	21.9	35.5	100.3	137.9	138.8	159.5	116.3	66.8	0.0	0.0	0.0	788.3
2008	0.0	0.0	0.0	17.2	54.0	63.8	174.1	185.1	84.9	49.2	147.4	0.0	775.7
2009	38.5	1.1	50.4	30.6	33.3	31.1	192.1	84.9	70.1	101.4	0.0	8.0	641.5
2010	0.0	30.9	183.8	58.1	151.2	55.7	139.2	187.5	100.2	0.0	0.0	0.0	906.6
2011	0.0	0.0	71.5	23.9	38.1	108.2	102.4	126.6	97.4	0.0	13.9	0.0	582.0
2012	0.0	0.0	17.9	43.1	38.4	46.3	489.3	194.9	96.3	5.3	0.0	1.1	932.5
2013	0.0	0.0	111.7	72.2	9.2	119.6	228.2	87.6	91.8	43.2	0.0	0.0	763.5
2014	6.3	32.1	111.2	11.9	126.6	18.5	166.3	194.2	112.4	78.9	0.0	0.0	858.4
2015	0.0	3.1	38.7	0.0	85.4	104.5	112.2	85.3	57.2	0.0	0.0	0.0	486.4
2016	0.0	0.0	6.8	177.6	82.9	138.2	152.2	52.3	55.8	93.0	47.2	0.0	806.0
2017	0.0	40.7	104.0	11.0	118.2	90.3	194.3	105.1	52.4	7.1	0.0	0.0	723.1

Appendix, Table 6: Corrected monthly rainfall (mm) of Tora metrological station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	nnual
1987	0.0	47.0	245.0	90.0	350.0	61.7	43.1	124.0	101.5	34.0	0.0	0.0	1096.3
1988	1.9	46.3	10.5	226.1	54.5	54.3	130.8	139.2	111.4	117.8	0.0	0.0	892.8
1989	2.7	106.6	115.4	122.8	18.6	120.5	107.1	127.8	136.0	54.2	0.0	14.5	926.2
1990	0.0	220.7	64.1	134.0	28.8	73.5	149.5	102.2	143.6	8.2	0.0	0.0	924.6
1991	11.1	84.1	70.0	14.3	20.6	43.5	162.1	128.6	105.2	10.0	0.0	47.2	696.7
1992	80.2	35.1	59.4	115.0	68.7	70.6	140.2	136.8	69.9	110.8	2.6	8.9	898.2
1993	38.7	113.8	2.6	183.3	155.8	107.9	135.3	252.9	118.3	153.1	0.0	0.0	1261.7
1994	0.6	10.4	47.6	69.5	48.0	164.4	201.7	149.5	108.0	0.0	4.1	0.0	803.8
1995	0.0	71.7	93.6	302.9	51.5	64.3	150.7	104.9	143.1	25.6	0.0	38.6	1046.9
1996	96.7	1.2	188.4	71.6	172.3	158.7	147.9	165.6	151.8	3.4	1.0	0.0	1158.6
1997	35.4	0.0	109.1	160.3	32.0	145.6	142.4	80.2	51.8	153.4	3.3	0.0	913.5
1998	44.1	79.6	28.8	113.6	227.9	49.0	168.4	158.7	113.5	38.7	0.0	0.0	1022.3
1999	0.0	0.0	84.7	27.9	38.7	127.7	94.8	52.0	110.2	184.2	0.0	0.0	720.2
2000	0.0	0.0	0.4	113.6	63.8	46.6	45.4	81.9	151.2	65.1	142.0	60.8	770.8
2001	0.0	0.0	170.3	26.1	154.9	93.8	107.1	194.3	69.0	1.3	5.4	0.0	822.2
2002	20.3	10.6	52.4	117.5	31.3	59.6	85.8	117.2	111.1	0.0	0.0	8.6	614.4
2003	30.0	16.5	54.0	109.9	19.7	21.0	157.0	34.5	100.0	0.0	0.0	29.9	572.5
2004	102.6	0.0	121.4	13.2	70.0	66.3	114.7	118.0	99.7	45.9	8.8	0.3	760.8
2005	54.4	18.2	113.0	116.5	220.1	79.2	161.6	114.3	54.7	79.9	6.5	0.0	1018.4
2006	0.0	42.9	142.5	130.6	145.7	132.8	129.6	75.6	84.9	30.5	0.0	3.0	918.1
2007	5.0	161.2	25.6	57.0	112.0	121.0	162.6	74.8	111.5	38.7	0.0	0.0	869.4
2008	0.0	0.0	5.0	15.4	100.6	124.7	130.5	202.2	109.7	13.9	159.5	0.0	861.5
2009	3.0	1.5	90.8	7.6	26.1	50.3	178.9	132.5	66.0	138.9	0.0	23.0	718.6
2010	7.2	59.5	105.9	154.2	136.0	125.3	113.0	147.8	228.5	51.2	0.0	23.0	1151.6
2011	3.9	6.2	59.1	29.8	89.6	111.3	138.4	122.2	97.7	0.0	0.0	0.0	658.1
2012	0.0	0.0	66.3	44.5	37.7	93.0	276.9	64.1	112.9	0.0	0.0	0.0	695.4
2013	56.3	0.0	105.8	99.4	23.5	224.8	104.9	73.2	95.7	58.3	0.0	0.0	841.8
2014	0.0	45.3	50.0	31.4	81.1	72.1	228.7	306.4	140.5	70.0	41.9	0.0	1067.4
2015	0.0	0.0	10.0	0.0	64.7	29.2	60.2	53.0	28.9	1.3	0.0	0.0	247.3
2016	31.1	20.0	47.0	126.0	14.9	2.1	67.0	71.0	82.8	16.0	12.9	0.0	490.8
2017	33.0	17.0	33.0	32.0	75.0	33.0	73.0	52.0	57.0	19.0	0.0	0.0	424.0

Appendix A, Table 7*: Mean monthly stream flow data at the outlet of Meki river watershed*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1990	0.31	11.35	20.20	21.69	5.28	5.82	17.08	19.81	15.17	6.42	1.86	0.87
1991	0.50	2.60	7.17	2.84	0.89	3.76	24.49	34.90	20.14	3.48	0.87	0.66
1992	1.47	0.87	5.92	3.71	5.54	2.06	19.26	29.71	19.99	8.67	2.69	0.81
1993	4.92	0.98	0.98	13.44	17.52	12.31	25.19	57.52	19.90	11.61	4.45	0.89
1994	0.80	0.51	0.60	3.23	5.57	4.97	22.99	60.03	47.13	4.39	0.98	0.62
1995	1.38	1.35	5.92	6.47	3.91	1.81	19.32	25.23	19.20	9.15	2.52	0.81
1996	1.21	2.19	4.43	4.93	5.27	1.85	17.55	34.11	24.51	5.55	1.99	1.21
1997	0.32	0.27	0.99	9.95	2.89	4.36	16.60	16.60	5.40	14.29	6.18	0.92
1998	1.60	0.74	12.12	3.27	11.77	5.23	27.62	70.11	29.24	23.12	2.55	0.42
1999	0.09	0.07	2.84	0.12	0.51	2.84	20.64	22.42	10.16	23.55	4.73	0.28
2000	0.02	0.00	0.00	0.05	0.83	0.64	6.31	14.02	11.01	8.25	2.96	0.94
2001	0.01	0.18	3.06	1.91	4.61	10.89	23.11	37.37	23.19	2.55	0.94	0.52
2002	4.08	3.12	1.58	2.10	5.27	1.48	14.64	20.06	12.46	2.46	1.95	1.63
2003	1.00	0.58	1.56	4.03	2.20	4.92	17.16	29.15	18.34	3.99	0.36	0.81
2004	0.93	0.29	0.70	15.43	0.74	2.18	13.81	30.70	19.99	8.69	2.69	0.81
2005	1.47	2.41	1.34	3.33	12.91	8.06	12.99	26.27	17.95	6.14	2.01	1.53
2006	1.97	2.89	5.41	5.74	4.97	1.81	18.93	28.61	17.55	8.91	1.55	1.02
2007	0.77	1.95	3.13	4.30	5.48	6.66	40.91	41.66	23.37	5.55	0.69	0.51
2008	0.43	1.83	4.89	5.61	4.30	3.17	9.76	20.76	15.24	9.10	1.32	0.81
2009	1.04	0.10	0.12	0.56	0.52	2.50	17.12	29.52	18.61	9.37	2.55	0.79
2010	1.02	1.09	2.59	10.69	7.73	1.39	25.08	31.70	18.55	18.58	15.31	12.04
Aver	1.21	1.68	4.07	5.87	5.18	4.22	19.55	32.39	19.39	9.23	2.91	1.38

Appendix A Table 8: Rainfall Depth of 24 hours versus Frequency (Source: ERA, 2013

Return Period	24 hr. Rainfall Depth (mm) versus Frequency (yr.)							
Years	2	5	10	25	50	100	200	500
RR-A1	50.30	66.02	76.28	89.13	98.63	108.06	117.48	130.00
RR-A2	51.92	65.52	74.45	85.70	94.07	102.45	110.91	122.27
RR-A3	47.54	59.61	67.66	77.92	85.62	93.34	101.13	111.58
RR-A4	50.39	63.83	72.28	82.55	89.97	97.20	104.32	113.63
RR-B1	58.87	71.26	79.29	89.35	96.84	104.37	112.02	122.41
RR-B2	55.26	69.95	79.68	92.03	101.29	110.61	120.07	132.87
RR-C	56.52	71.04	80.54	92.52	101.48	110.50	119.66	132.06
RR-D	56.23	76.84	90.37	107.46	120.23	133.05	146.00	163.44

Appendix A Table 9*: consistency analysis of rainfall data of Meki river watershed*

Year	Mean Annual Cumulative of all stations(mm)	Annual Accumulative Of Rainfall(Mm)					
		Buie	Butajira	Ejersa	Meki	Koshe	Tora
1987	842.9	1669.15	1324.5	893.1	728.8	659.4	892.8
1988	1825.7	2800.65	2636.0	1790.5	1699.4	1700.4	1819.0
1989	2824.0	3830.32	3501.5	2601.8	2520.3	2535.9	2743.6
1990	3635.3	4816.42	4737.3	3400.0	3055.8	3308.1	3540.3
1991	4525.1	5920.80	5841.6	4228.1	3892.9	4093.0	4538.5
1992	5613.0	6664.90	7100.3	5383.7	4742.7	5097.2	5600.2
1993	6421.3	7956.80	8094.5	6341.5	5381.5	5821.7	6404.0
1994	7359.4	9295.50	9293.3	7066.8	6091.3	6601.1	7450.9
1995	8576.7	10072.40	10997.1	8394.8	7060.9	7682.5	8809.5
1996	9521.8	11118.60	11997.4	9302.8	7892.8	8482.5	9723.0
1997	10553.2	12102.20	13577.3	10392.4	8684.9	9560.7	10845.3
1998	11380.9	13100.60	14531.7	11100.3	9386.2	10259.4	11765.5
1999	12080.9	14100.60	15031.7	11150.3	9786.2	12259.4	12065.5
2000	12192.6	14321.20	15697.3	11869.0	10137.7	10975.0	12536.3
2001	13214.9	15222.50	16790.1	12885.1	10896.6	11897.8	13558.5
2002	13914.8	16280.45	17850.0	13574.8	11608.2	12520.5	14372.9
2003	14790.1	17201.65	18937.8	14369.7	12302.1	13265.2	15195.4
2004	15570.3	18466.35	19851.2	15186.3	13003.2	13933.4	16006.2
2005	16697.1	19695.85	21434.8	16190.0	13834.9	14891.8	17224.6
2006	17765.7	20894.15	22607.1	17243.3	14694.3	15850.8	18342.7
2007	18692.5	21973.52	24059.0	18137.7	15402.6	16809.6	19312.1
2008	19609.7	22812.12	25001.5	18938.9	16098.2	17790.5	20183.6
2009	20259.7	24329.92	25800.2	19655.6	16600.7	18269.9	20792.2
2010	21297.2	25480.22	27203.1	20659.2	17556.3	19159.6	21943.8
2011	22072.1	26207.52	28210.0	21536.5	18278.3	19755.8	22701.9
2012	22869.0	27149.52	29044.9	22309.4	18940.8	20474.2	23497.3
2013	23872.9	28123.51	30229.6	23488.8	19704.3	21586.3	24539.1
2014	24907.1	28727.68	31771.7	24449.3	20562.7	22488.9	25706.4
2015	25345.7	29562.18	32438.3	24951.2	21039.1	22813.9	26153.7
2016	26043.3	30542.11	33290.1	25891.3	21625.1	23485.8	26904.6
2017	26610.3	3251.71	33952.4	26631.4	22138.2	23880.3	27598.6

Appendix B; Table 1*: Definition of Hydrologic soil Groups (Source: Subramanya, 2008)*

Hydrologic Soil Group	Its 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 clay pan 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.

Appendix C

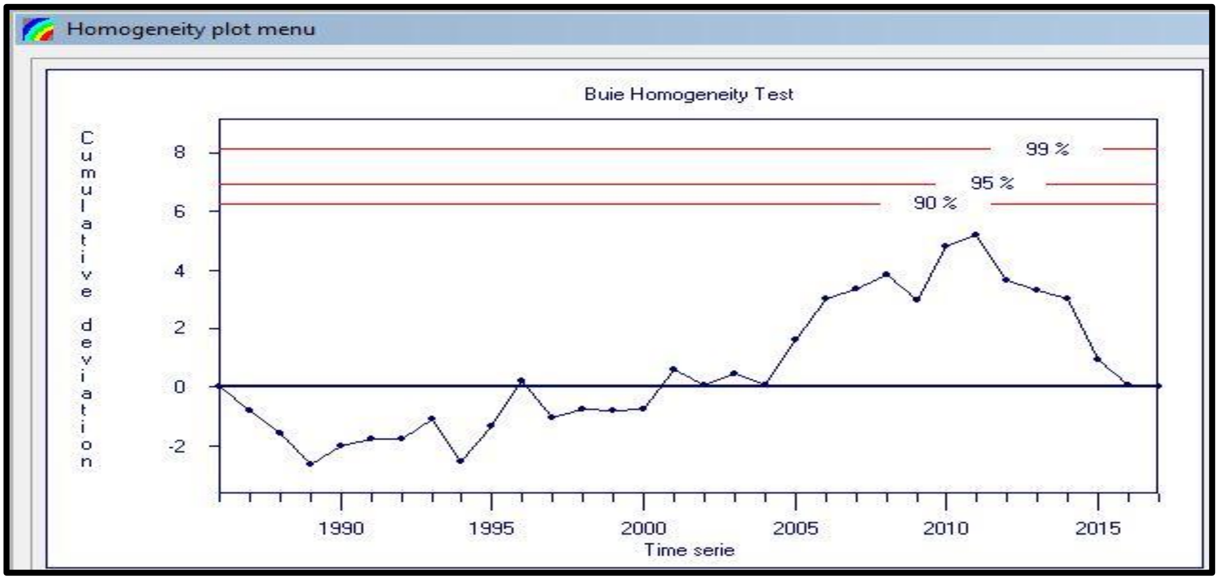


Figure 3.1: Homogeneity and stationarity test of Buie station

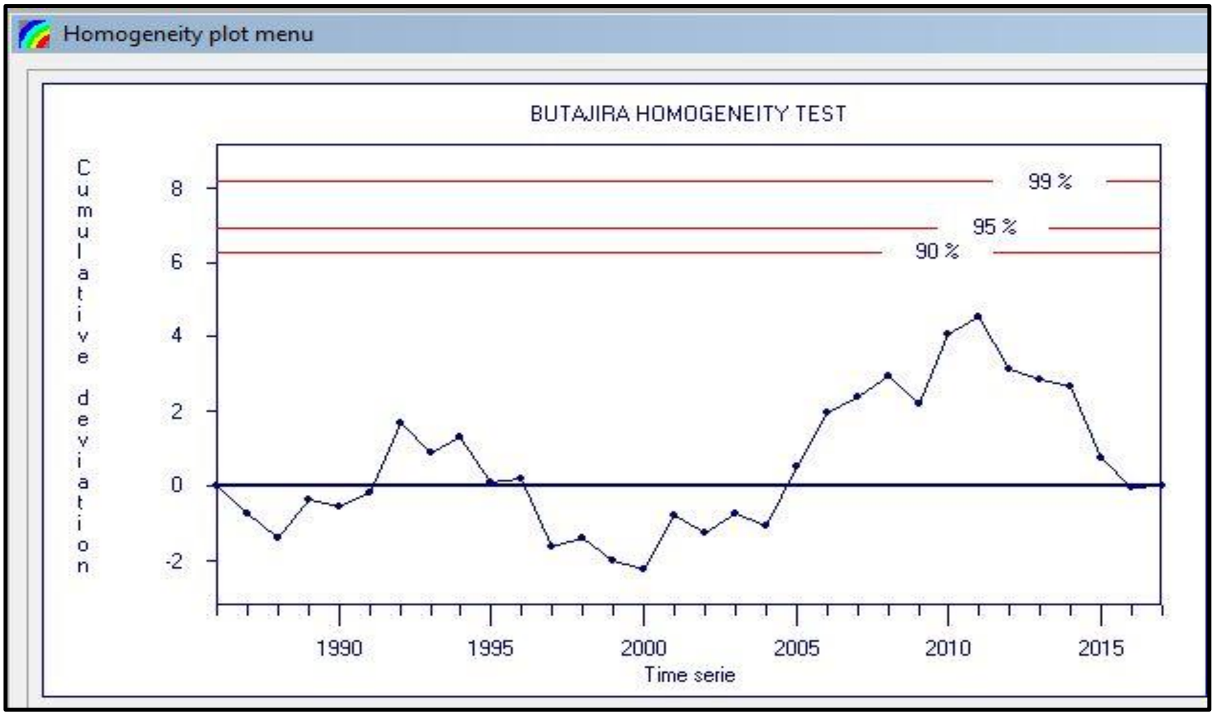


Figure 3.2: Homogeneity and stationarity test of Butajira station

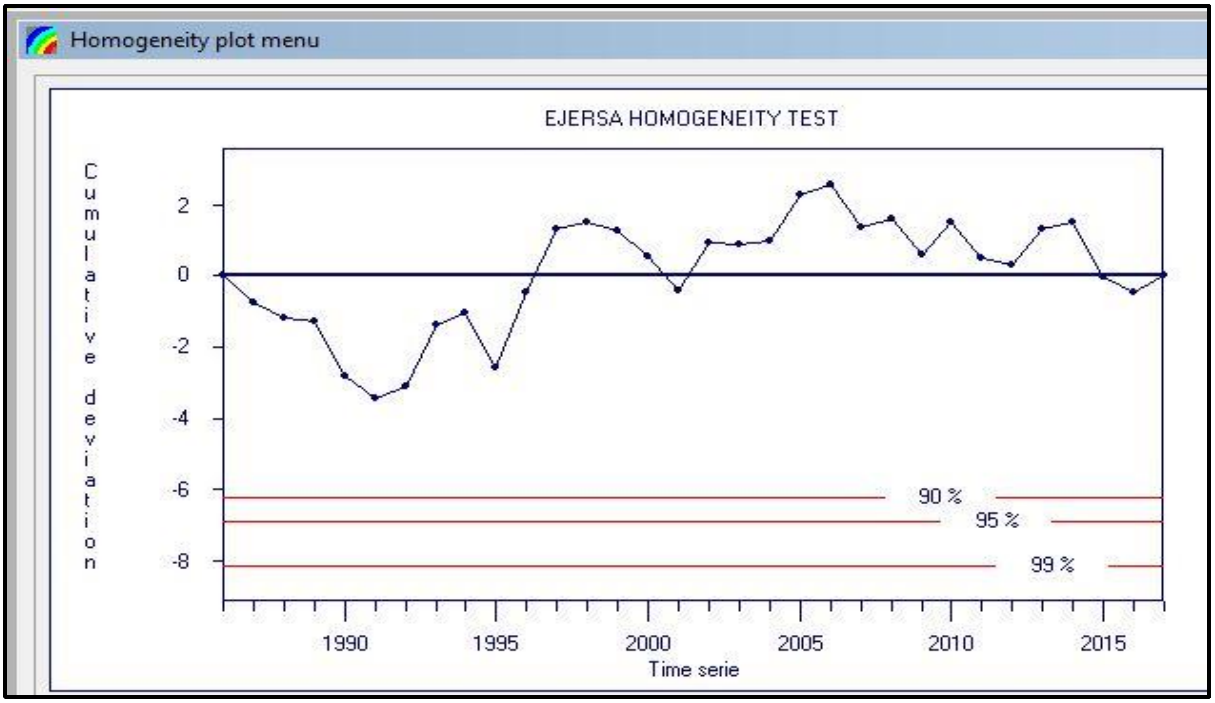


Figure 3.3: Homogeneity and stationarity test of Ejersa station

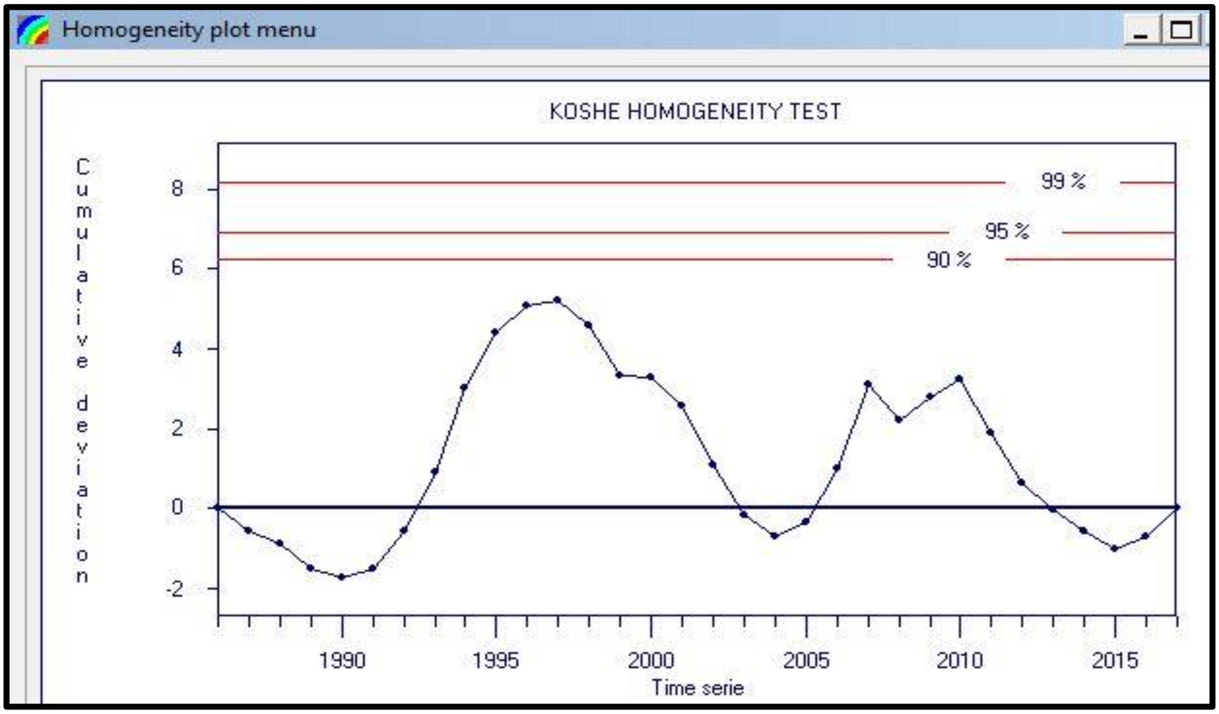


Figure 3.4: Homogeneity and stationarity test of Koshe station

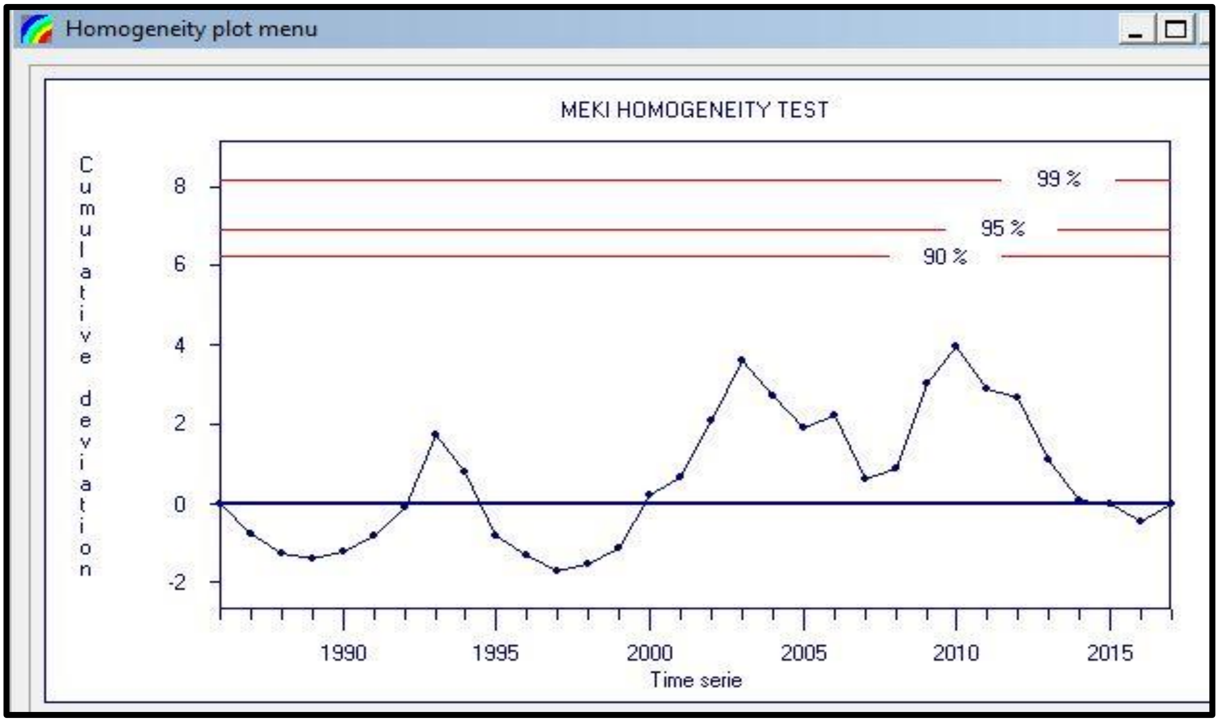


Figure 3.5: Homogeneity and stationarity test of Meki station

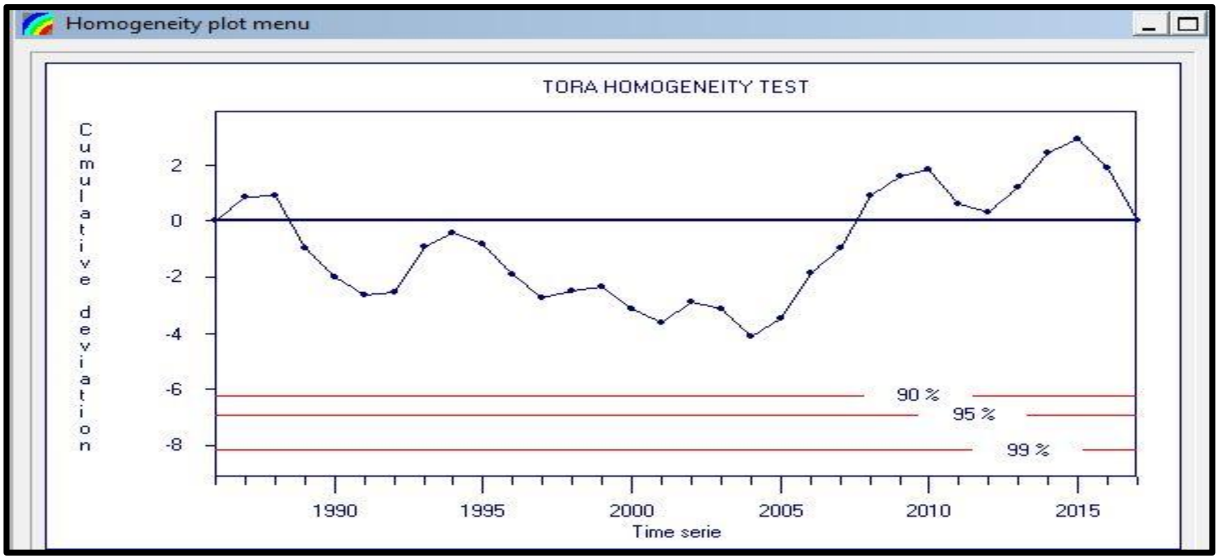
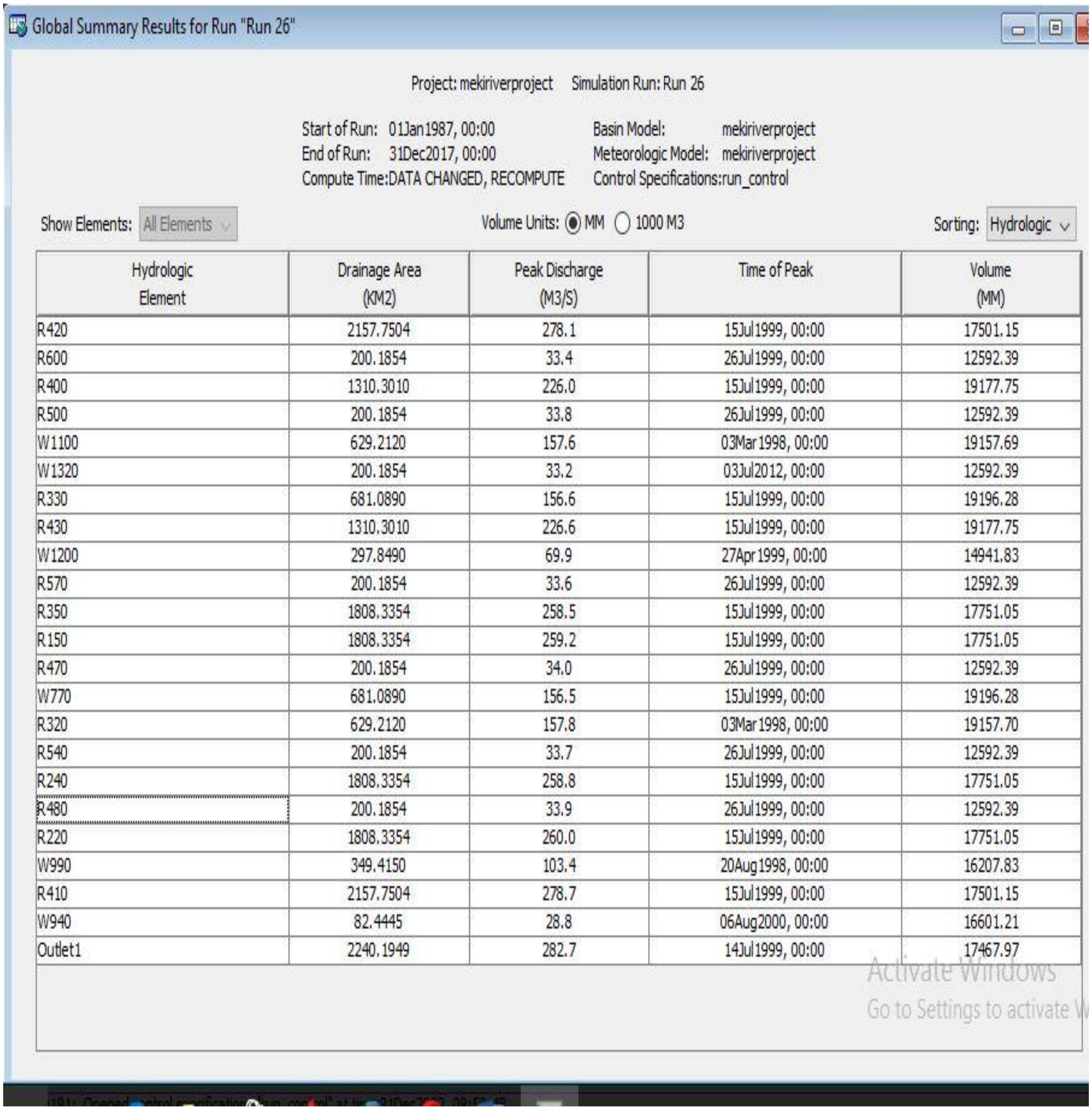


Figure 3.6: Homogeneity and stationarity test of Tora station

Table 3.9: Statistical distribution best fit analysis result by Easy Fit5.6

Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
	Statistics	Rank	Statistics	Rank	Statistics	Rank
Gumbel	0.07292	1	0.218559	2	0.03889	1
Logpearson3	0.0752	2	0.21288	1	0.12325	2
Lognormal	0.07558	3	0.22103	3	0.36018	3
normal	0.15793	4	1.0482	4	1.6624	4



Project: mekiriverproject Simulation Run: Run 26

Start of Run: 01Jan1987, 00:00
End of Run: 31Dec2017, 00:00
Compute Time:DATA CHANGED, RECOMPUTE

Basin Model: mekiriverproject
Meteorologic Model: mekiriverproject
Control Specifications:run_control

Show Elements: All Elements
Volume Units: ● MM ○ 1000 M3
Sorting: Hydrologic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
R420	2157.7504	278.1	15Jul1999, 00:00	17501.15
R600	200.1854	33.4	26Jul1999, 00:00	12592.39
R400	1310.3010	226.0	15Jul1999, 00:00	19177.75
R500	200.1854	33.8	26Jul1999, 00:00	12592.39
W1100	629.2120	157.6	03Mar1998, 00:00	19157.69
W1320	200.1854	33.2	03Jul2012, 00:00	12592.39
R330	681.0890	156.6	15Jul1999, 00:00	19196.28
R430	1310.3010	226.6	15Jul1999, 00:00	19177.75
W1200	297.8490	69.9	27Apr1999, 00:00	14941.83
R570	200.1854	33.6	26Jul1999, 00:00	12592.39
R350	1808.3354	258.5	15Jul1999, 00:00	17751.05
R150	1808.3354	259.2	15Jul1999, 00:00	17751.05
R470	200.1854	34.0	26Jul1999, 00:00	12592.39
W770	681.0890	156.5	15Jul1999, 00:00	19196.28
R320	629.2120	157.8	03Mar1998, 00:00	19157.70
R540	200.1854	33.7	26Jul1999, 00:00	12592.39
R240	1808.3354	258.8	15Jul1999, 00:00	17751.05
R480	200.1854	33.9	26Jul1999, 00:00	12592.39
R220	1808.3354	260.0	15Jul1999, 00:00	17751.05
W990	349.4150	103.4	20Aug1998, 00:00	16207.83
R410	2157.7504	278.7	15Jul1999, 00:00	17501.15
W940	82.4445	28.8	06Aug2000, 00:00	16601.21
Outlet1	2240.1949	282.7	14Jul1999, 00:00	17467.97

Figure4.1: Simulated discharge at each sub-basins and reaches before model calibration.