JIMMA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
JIMMA INSTITUTE OF TECHNOLOGY
FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING
HYDROLOGY AND HYDRAULIC ENGINEERING CHAIR
MASTERS OF SCIENCE PROGRAM IN HYDRAULIC ENGINEERING

RAINFALL-RUNOFF MODELING CONSIDERING SOIL MOISTURE ACCOUNTING ALGORITHM, CASE STUDY: WABE CATCHMENT, OMO GIBE BASIN, ETHIOPIA.

By:

Ageza Debelu Balemi

A Thesis Submitted to the Chair of Hydrology and Hydraulic Engineering, Jimma Institute of Technology, Jimma University in Partial fulfillment of the Requirements for the Degree of Masters of Science in Hydraulic Engineering.

April 2021
Jimma, Ethiopia

JIMMA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
JIMMA INSTITUTE OF TECHNOLOGY
FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING
HYDROLOGY AND HYDRAULIC ENGINEERING CHAIR
MASTERS OF SCIENCE PROGRAM IN HYDRAULIC ENGINEERING

RAINFALL-RUNOFF MODELING CONSIDERING SOIL MOISTURE ACCOUNTING ALGORITHM, CASE STUDY: WABE CATCHMENT, OMO GIBE BASIN, ETHIOPIA.

By:

Ageza Debelu Balemi

A Thesis Submitted to the Chair of Hydrology and Hydraulic Engineering, Jimma Institute of Technology, Jimma University in Partial fulfillment of the Requirements for the Degree of Masters of Science in Hydraulic Engineering.

Advisor: Mr. Fayera Gudu (Assistant Prof.) ______________

Signature

Co-Advisor: Mr. Seife Belete (MSc.) ______________

Signature

April 2021
Jimma, Ethiopia

DECLARATION

I declare that this research entitled "Rainfall-runoff modeling considering soil moisture accounting algorithm, case study: Wabe catchment, Omo gibe basin, Ethiopia" is my original work and has not been submitted as a requirement for the award of any degree in Jimma University or elsewhere.

Mr. Ageza Debelu Balemi ______________ ______________

Name Signature Date

As research Adviser, I hereby certify that I have read and evaluated this thesis paper prepared under my guidance, by Ageza Debelu Balemi entitled "RAINFALL-RUNOFF MODELING CONSIDERING SOIL MOISTURE ACCOUNTING ALGORITHM, CASE STUDY: WABE CATCHMENT, OMO GIBE BASIN, ETHIOPIA" and recommend and would be accepted as a fulfilling requirement for the Degree Master of Science in Hydraulic Engineering.

Advisor: Mr. Fayera Gudu (Assistant Prof.) ______________ ______________

Name Signature Date

Co-Advisor: Mr. Seife Belete (MSc.) ______________ ______________

Name Signature Date

APPROVAL

The undersigned certify that the thesis entitled: "**Rainfall-Runoff Modeling Considering Soil Moisture Accounting Algorithm, Case Study: Wabe Catchment, Omo Gibe Basin, Ethiopia**" is the original work of Ageza Debelu 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.

Advisor: Mr. Fayera Gudu (Assistant Prof.) ______________ ______________

Name Signature Date

Co-Advisor: Mr. Seife Belete (MSc.) ______________ ______________

Name Signature Date

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. Ageza Debelu entitled; "**Rainfall-Runoff Modeling Considering Soil Moisture Accounting Algorithm, Case Study: Wabe Catchment, Omo Gibe 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

______________________ ______________________ ______________________

Name of External Examiner Signature Date

______________________ ______________________ ______________________

Name of Internal Examiner Signature Date

ABSTRACT

Hydrologic studies on rainfall-runoff have been extensively applied by water resource planners to simulate the hydrological response in many regions around the world to fulfill various desirable needs with a purpose of effective and proper planning and managing of water resources for present and future uses. Therefore, the main objective of this study was to use a continuous soil moisture accounting (SMA) algorithm in a Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) to model and predict stream flow in the Wabe catchment, Omo-Gibe River Basin in Ethiopia. Long term daily rainfall data from 4 rain gauging stations from1985 to 2016 years, daily river flow of 1 stream gauging station from 1987 to 2007 years, land use and soil data of the watershed, and DEM were obtained from relevant sources. These data were then analyzed and interpreted, and used to set up the HEC-HMS model. In this study, soil moisture accounting loss method, Clark unit hydrograph transformation method, linear reservoir base flow method and Muskingum routing method were adopted. In order to fix the horologic parameters of each watershed, first the sensitivity analysis was carried out with the base data, and then the model calibration was performed using data from 1987 to 1999 and validation for the period from 2000 to 2007 at a daily time step. The sensitivity analysis of different model parameters were ranked according to their sensitivity in terms of percent change in simulated runoff volume, peaks and Nash-Efficiency. Sensitivity analysis helped to understand the behavior of the model and relationships between the key model parameters and the variables. The model performance was evaluated based on computed statistical parameters and visual checking of plotted hydrographs. For the calibration period, the performance of a continuous model ranges from good to very good with a coefficient of determination R^2 = 0.727, Nash-Sutcliffe Efficiency NSE = 0.711, percentage error in volume PEV=2.36%, percentage error in peak PEP = 6.25%, Percent Bias (PBIAS) = 2.35 and Root Mean Squared Error (RMSE)/observations' standard deviation ratio—RSR = 0.5. Similarly, the continuous model performance for the validation period ranges from good to very good with R^2 = 0.861, NSE = 0.807, PEV = 0.42%, PEP = -2.91%, PBIAS = -0.42 and RSR = 0.4. The performance results obtained showed that, the SMA model in the HEC-HMS was found to give a good prediction of stream flow in the Wabe Catchment. Finally, the peak flood results of the HEC-HMS model were compared to the statistical distribution models results of two methods those selected based on their ranks of goodness of fit. The forecasted peak flood by HEC-HMS, General Pareto distribution (GDP) and General Extreme Value (GEV) distribution methods, at 2, 5, 10, 25, 50, 100, 200 and 500 year return periods were 479, 644.7, 755.5, 896.8, 1003, 1110.2, 1219.3 and 1367.5; 407.13, 618.23, 722.17, 812.34, 856.74, 887.52, 908.86 and 927.38; and 542.89, 711.47, 817.22, 944.48, 1034.53, 1120.39, 1202.59 and 1306.14 m^3/s respectively. Then, these predicted peak flood will help in water resources and flood management for this study area.

Keywords: *Continuous hydrological Modeling, HEC-HMS model, Peak Flood, Soil moisture accounting, Wabe Watershed.*

ACKNOWLEDGEMENT

First, I would like to thank and praise my God for his guidance and success in my life. Furthermore, Special thanks to Jimma Institute of Technology, which provides me the chance to carry out my graduate study in Jimma University. I extended my sincere gratitude to my main advisor Mr. Fayera Gudu (Assistant Prof.) and co-advisor Mr. Seife Belete (MSc.) for their constructive and timely comments at all my work and professional guidance to prepare this thesis work.

I also forwarded my thanks to my gratitude Department of Hydraulic and Water Resources Engineering and particularly for staff members for their considerable support in providing me required information, data and other relevant reference materials. Acknowledgments are due to my parents for their love and encouragement during my study. Finally, yet importantly, I would like to extend my deepest thanks to all my friends for their encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

a.m.s.l	above mean sea level
CDF	Cumulative Distribution Function
DEM	Digital Elevation Model
DMC	Double Mass Curve
GIS	Geographic Information Center
GW	Groundwater
HEC-GeoHMS	Hydrologic Engineering Centre-Geospatial Hydrologic Modelling
HEC-HMS	Hydrologic Engineering Centre – Hydrologic Modeling System
HBV	Hydrologiska Byråns Vattenbalansavdelning
HSPF	Hydrological Simulation Program-Fortran
MMS	Modular Modeling System
MRAE	Mean Ratio of Absolute Error
NRCs	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
PDM	Probability Distributed Models
PET	Potential Evapotranspiration
R^2	Coefficient of Determination
RE	Relative Error
RMSE	Root-Mean-Square Error
RSR	Observations Standard Deviation Ratio
SMA	Soil Moisture Accounting
SMAR	Soil Moisture Accounting and Routing
SNNPRS	Southern Nation Nationalities and people’s Regional States
SWAT	Soil and Water Assessment Tool
TOPMODEL	Topography Based Hydrological Model
US	United States
USACE	United States Army Corps of Engineers
USDA-NRCS	United States Department of Agriculture, Natural Resources Conservation Service.

1. INTRODUCTION

1.1 Background

Adequate knowledge of rainfall-runoff processes is very important to estimate the amount and peak runoff generated within a given catchment. Knowing the amount and peak runoff within a given catchment is vital for sustainable water resources to project planning and management. Adopting a modeling concept and understanding rainfall partitioning and the primary factors causing runoff will greatly simplify the activities of estimating runoff volumes and flood peaks (Shahid *et al*., 2020). The type of modeling method used is usually determined by the goal, data availability, and ease of use (Beven, 2011).

The Hydrologic Modelling System HEC-HMS, developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC), is an integrated modeling method for all hydrologic processes in dendritic watershed systems. It is made up of various components for rainfall loss, direct runoff, and routing. Because of its ability to simulate runoff in both short and long time events, its ease of use, and the use of common methods, HEC-HMS has become very popular and has been adopted in many hydrological studies (Gebre, 2015). Hydrographs generated by HEC-HMS is used in studies of urban drainage, water supply, potential urbanization effects, flow forecasting, flood risk mitigation, floodplain regulation, more recently in assessing the effect of climate change, land-use change, and systems operation, either directly or in conjunction with other software. (Scharffenberg *et al*., 2018).

In more advanced Rainfall-Runoff models, hydrologic processes are simulated using numerical solutions of mathematical governing equations. The development trend of Rainfall-Runoff models has targeted the reduction of hypotheses and simplifications, by adding and/or completing various components such as atmospheric, surface, subsurface, and groundwater (GW) processes (Scharffenberg *et al*., 2018).

Infiltration as a major phenomenon in runoff generation has been modeled by loss methods such as SCS, Green-Ampt, Deficit-Constant and Constant Fraction. Infiltration rate is a function of initial soil moisture content that determines the magnitude of flood runoff peak and volume. Most of the loss methods are empirical relationships without much sense of physical processes. In SCS, initial soil moisture has been classified into dry, moderate, and wet conditions. Such a coarse classification may lead to increased simulation error (Ponce and Hawkins, 1996). Hydrologists have attempted to improve infiltration methods by considering more governing physical processes using a continuous simulation framework. Among such improvements, SMA simulates several components of the hydrologic cycle such as canopy interception, surface depression, infiltration into the soil profile storage, percolation to the GW aquifer, and base flow caused by available soil storage vs. maximum saturated capacity of the soil layer. This continuous loss method has been incorporated in the latest versions of the HEC-HMS model like HEC-HMS 4.7 (Scharffenberg *et al*., 2018). Unlike event-based, continuous hydrologic models take into account soil moisture balance over a long time and are suitable for simulating daily, monthly, and seasonal streamflow (Ouédraogo *et al*., 2018, Singh and Jain, 2015).

Rainfall-runoff models must capture the antecedent soil moisture condition. SMA-based models continuously change soil moisture based on recent hydrologic activity and soil-water processes, and the model calculates the initial soil conditions after a suitable spin-up cycle. However, several recent studies have investigated the deficiencies of the NRCS CN method. It results in poor prediction of runoff depth and peak flow as well as an under prediction of the parameters. This is attributed to the fact that the method is empirical, and therefore may not be suitable across a wide range of catchments (Holberg, 2015).

Even though, the HEC-HMS model has been tested and calibrated on a global scale, there has been little effort in Ethiopian catchments. The Omo gibe basin has widespread farming activities and unpredicted flood events. It has been seriously affected by land degradation and flood problems, especially in the lowlands (Mersha, 2017). The Wabe Catchment which is part of this basin faces the same problem. Therefore, an accurate estimation of the peak flow and total volume is critically important to implement appropriate soil and water conservation, erosion control, and flood protection measures in time. Despite the different modeling activities that are practiced in the basin, the HEC-HMS model was not tested, calibrated, and validated in the Wabe Catchment. Therefore, this study aims to investigates the sensitivity of various parameters on peak and volume flows via incorporating increasingly sophisticated soil moisture accounting, to examining the rainfall-runoff relationship, and to predict flood in Wabe Catchment.

1.2 Statement of the Problem

Water resource plays a crucial role in the economic development of the developing countries like Ethiopia. The Wabe catchment (Omo-Gibe River Basin) has explosive population growth and resulting new demands on limited water resources require efficient management of existing water resources and building new facilities to meet the challenge. In water resources management system, it is well known that to combat water shortage issues, maximizing water management efficiency based on runoff simulation was important (Fentaw *et al*., 2018).

The Wabe catchment (Omo-Gibe River Basin) has rapidly increasing population, extensive agricultural practices and unpredicted flood. The assessment of water resources in the catchment has not well conducted yet, which has revealed a lacked comprehension on water resources systems with its potential water availability. The area is highly vulnerable to land-use change (deforestation and over-cultivation) and climate change that affects the magnitude of seasonality of surface flow that increases the frequency of extreme events such as drought and floods. Communities in the downstream region of the catchment experience floods caused by heavy rainfall generated from upstream highland area of Gurage Mountains. Consequently, the unpredictable nature of the flooding combined with increased frequency and magnitude is resulting in crop failure and unprecedented human health impacts (Mersha, 2017).

Alternatively there is several ongoing and planning water resources projects in the watershed , these works require a reliable estimation of volume and peak flood at a site of interested. However, in most developing countries like Ethiopia, there is typically a scarcity of data on stream flow. Except for a stream flow gauging station at the Wabe River's exit near Welkite, there is no reported streamflow data at the outlet of each sub-basin in the Wabe watershed. Regardless of the data scarcity, researchers have performed rainfall-runoff modeling in numerous river basins around the world for a variety of purposes.

To alleviate or minimize these problem and for sustainable water resources management, this research apply HEC-HMS model to examine rainfall-runoff relationship considering soil moisture accounting algorithm in Wabe catchment and predict flood in the study region.

1.3 Research Objectives

1.3.1 General Objective

The General objective of this study is to examine the rainfall-runoff relationship considering the soil moisture accounting algorithm in the Wabe catchment and flood predictions in the study region.

1.3.2 Specific Objective:

1. To identify the flow-sensitive parameters of the Wabe catchment.
2. To evaluate the performance of the HEC-HMS model for Wabe catchment.
3. To predict flood at different return periods.

1.4 Research Questions

1. What are the flow-sensitive parameters in the Wabe catchment?
2. Does the HEC-HMS hydrological model performed well for daily simulation of the runoff at the Wabe catchment?
3. How much peak flood will be generated at different return periods?

1.5 Significance of the Study

The result of this study gives valuable first-hand information regarding with characteristics of the study area, amount of flood at different return periods to improve effective watershed management for planning and designing of water resources projects within the selected watershed. The research finding may help implementers, the policy makers, planners, and donors in the water sector and as starting data for any further investigation. It may be helpful to understand the different barriers, which can affect the watershed management practice.

1.6 Scope of the Study

The study was conducted in the Wabe catchment, which is the part of the upper Omo gibe river basin. This study primarily focused on identifying the flow-sensitive parameters of the Wabe catchment, evaluating the performance of the HEC-HMS model for the Wabe catchment and predicting flood at different return periods. This study used the meteorological data of 31 years (1985-2016) from four stations and a streamflow data of 15 years (1987-2007) for model comparisons best fit, and the result and conclusion have been drawn based on these time-series data.

1.7 Organization of the Thesis

This thesis report consists of five chapters. The contents of each chapter are organized as follows: In the first chapter the background information, problem statement, general and specific objectives, Significance of the study, and scope of the study are discussed. In the second chapter, a literature review about the subject matter is presented and it gives a scientific review of this study. In the third chapter methodologies followed for simulation of rainfall-runoff and flood prediction are presented step-by-step. Description of the study area, Data used in the study, their sources, and the methods used for data quality control are mentioned. The fourth chapter presents the results and discussion. It gives a detailed about sensitive parameters, model performance, and flood prediction in the catchment scale. The fifth chapter summarizes the conclusion and recommendation for future study.

2. LITERATURE REVIEW

2.1 Hydrological Process

The hydrologic cycle is defined as “the pathway of water as it moves in its various phases through the atmosphere to the Earth, over and through the land, to the ocean, and back to the atmosphere” (Te Chow, 2010). It begins at the surface of large water bodies: oceans and lakes when direct solar radiation vaporizes these large reservoirs. This part of the hydrologic cycle is very important in water distribution in the form of precipitation over the global terrestrials provided that the moisture is driven away by wind currents.

As the term rainfall-runoff model suggests, the major input into the model is rainfall, and the output is an estimate of runoff. The intermediate steps that transform rainfall to runoff are the hydrologic processes. Among the hydrologic processes typically modeled precipitation, interception, infiltration, evapotranspiration, surface flow, and streamflow. It is evident that before any modeling effort can be performed, one has to understand the above physical processes, their extent of the effect on the abstraction from or addition of water to a catchment (Beven, 2011).

2.1.1 Rainfall

The term precipitation denotes all forms of water that reach the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost, and dew. Of all these, only the first two contribute significant amounts of water. Rainfall being the predominant form of precipitation causing streamflow, especially the flood flow in the majority of rivers, unless otherwise stated the term rainfall synonymously with precipitation (Te Chow, 2010).

The magnitude of precipitation varies with time and space. Differences in the magnitude of rainfall in various parts of a country at a given time and variations of rainfall at a place in various seasons of the year are obvious and this variation is responsible for many hydrological problems such as floods and droughts. A given drainage basin is divided into various parts or sub-basins, and rain gauge stations are evenly distributed over that basin. The rain catch at one station in a basin may be different from that of second station in the same basin. An average value of these rain catches is worked out, so as to get an idea of average precipitation on the entire basin.

The following methods are generally used to work out the mean rainfall on an area, such as Thiessen polygon, arithmetical mean and Isohyetal method. After comparing the various methods for calculating areal average, concluded that all methods are gives comparable result, especially when the time period is long (Feldman, 2000).

2.1.2 Runoff Process

The development of the runoff processes is critical in modeling applications. A considerable portion of the precipitation returns to the atmosphere through evapotranspiration. Evapotranspiration occurs from vegetation, land surface, and water bodies. On the other hand, some of the precipitation that falls on vegetation, before evaporating, falls through the leaves or runs down stems and branches, and reaches the soil. Moreover, some of the precipitation may infiltrate to the ground from land surfaces and water bodies. A model of the study area is developed by separating this complex hydrological cycle into manageable pieces (Feldman, 2000).

2.2 Hydrological Modelling

Hydrological models are simplified representations of the actual hydrological cycle that are widely used to help provide sustainable solutions for integrated water resources planning and management. Hydrologic models can be classified based on their capabilities and limitations. Hydrological models can be divided into two broad categories, physical and abstract (mathematical) (Te Chow, 2010). A physically based model is a mathematically idealized representation of real phenomenon, which includes the physical process of the catchment (Devia *et al*., 2015). Physical models can be further divided into two groups: scale models and analog models. A scale model is a physical representation of the real system that maintains relationships between important aspects of the system; analog models are based on analogous ways to represent the process being studied (i.e., the flow of electricity follows the same fundamental principles as the flow of water).

Models that are developed using logical programming languages and mathematical concepts to explain the land phase of the hydrological cycle in space and time are called abstract (mathematical) models (Jajarmizadeh *et al*., 2012). Mathematical model can be classified as deterministic or stochastic (Te Chow, 2010). In deterministic models, outcomes are determined by known relationships among states and events, without consideration of random variation. In other words, the deterministic model will produce the same output for a single input value and does not account for randomness. In a stochastic model, on the other hand, different values of output can be produced for a single set of inputs that have some randomness. The deterministic models can be divided into three broad categories: lumped, distributed, and semi-distributed models (Cunderlik, 2003). Lumped models treat the catchment as a whole, with state variables that represent averages over the entire basin (Beven and Freer, 2001). Distributed models have state variables that represent local averages, in which the catchment is divided into cells or grid net and flows are passed from one cell (node) to another as water drains through the basin (Xu, 2002).

Distributed models usually require an extensive amount of data for parameterization (Arnold *et al.*, 2012). Further, Due to lack of data, a full understanding of hydrological basins is unachievable via fully-distributed models (Geethalakshmi *et al*., 2008). However, lumped models do not account for land use and the spatial variability of the hydrological process (Ghaffari, 2011). A model that has some advantages of both types of spatial representation is called a semi-distributed model. The semi-distributed model partly accounts for variation in space with the division of the catchment into sub-basins. This model is more physically based in comparison with the lumped model but requires less data than the fully-distributed model (Jajarmizadeh *et al*., 2012). This model category can be further divided into event-based and continuous hydrological models. Event-based models account for a single hydrological event, i.e., storm, flood, soil moisture, for a relatively short period of time, while continuous hydrological models simulate multiple state variables (e.g. soil moisture, surface storage) for a longer period.

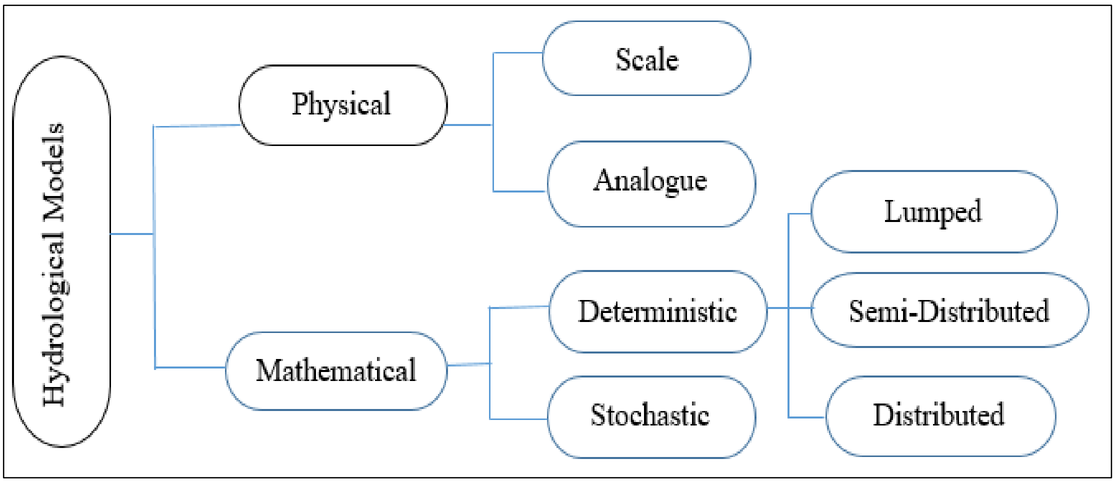


Figure 2.1 Hydrological model classification.

Distributed hydrological models such as the European Hydrological System Model (MIKE-SHE) and Modular Modeling System (MMS), and semi-distributed models like the Hydrological Engineering Center Hydrological Modelling System, Soil and Water Assessment Tool (SWAT), Topography Based Hydrological Model (TOPMODEL), Hydrologiska Byråns Vattenbalansavdelning (HBV) and Hydrological Simulation Program-Fortran (HSPF) are developed for a runoff estimation based on the data availability and complexity of the hydrological systems. Flood modelling has been greatly improved in recent years with the advent of geographic information systems, "radar-based" rainfall estimation using next-generation radar (NEXRAD), high-resolution digital elevation models, and distributed hydrological models. More recently, flood modelling has been further improved with the advent of service-oriented architecture and numerical weather. In the case of flood predictions, rainfall-runoff models are very practical because they are even useful in the catchments with a limited amount of input data (Ghaffari, 2011).

2.3 Hydrologic Model Selection

There are ranges of possible model structures within each class of models. Hence, choosing a particular model structure for a particular application is one of the challenges of the model user community. The four criterions for selecting model structures as below suggested by (Beven, 2000). Consider models which are readily available and whose investment of time and money appeared worthwhile, decide whether the model under consideration will produce the outputs needed to meet the aims of a particular project, prepare a list of assumptions made by the model and check the assumptions likely to be limiting in terms of what is known about the response of the catchment. This assessment will generally be a relative one, or at best a screen to reject those models that are obviously based on incorrect representations of the catchment processes and make a list of the inputs required by the model and decide whether all the information required by the model can be provided within the time and cost constraints of the project. For choice of models, the main driven question is research problems or the main thing that initiate to do the thesis. If data reconstruction need, it is possible to use linear models LM, LPM, SMAR and HBV. For flow forecasting LPM, SMAR and also for impact assessment and prediction HEC-HMS, SWAT, MIK-SHE and the like and also different criterions are set by (Beven, 2000).

Therefore, HEC-HMS model was selected rather than the other model for this hydrological component relationship is for the following reasons: uses readily available inputs for weather, soil, land, and topography allows considerable spatial detail for basin scale modeling, capable of simulating change in watershed characteristics using different scenarios, capable of simulating long-term(continuous) rainfall-runoff, capability for application to all watersheds scale, capability for interface with a geographical information system (GIS) and the model simulates the major hydrological process in the watersheds. After sufficient literature reviews for model selection, it was found that only the HEC-HMS model supports the SMA as one of its loss methods for simulation of long-term (continuous) rainfall-runoff. Therefore, the HEC-HMS model, which was developed by the US Army Corps of Engineers, was selected for this study.

2.4 Description of the Selected Model

2.4.1 Arc GIS

For all GIS related tasks, the Environmental Systems Research Institute´s (ESRI) ArcMap software, version 10.4 was used in this study. ArcMap is the main component of ESRI´s ArcGIS suite of geospatial processing software. Most of the GIS tasks were performed based on the functionality of the ArcMap extensions such as Arc-Hydro and HEC-GeoHMS.

2.4.2 Arc-Hydro Tools

Arc-Hydro is an extension of different Arc GIS version, which is developed in ESRI water resource team in order to support water resources applications. Within the availability of DEM and GIS tools, watershed properties can be extracted by using compatible version of Arc-Hydro automatically (Li, 2014). It simplifies the process of delineating watershed, sub-watersheds, stream network and some other watershed characteristics that collectively describe the drainage patterns of a basin. The results from this Arc Hydro tools can be used to create input files for hydrologic models (HEC-GeoHMS) (Merwade, 2012). These data are then used to develop a vector representation of catchments and drainage lines. Using this information, a geometric network is constructed.

2.4.3 HEC-GeoHMS

The Hydrologic Engineering Center Geospatial Hydrologic Modeling Systems (HEC-GeoHMS) is a public domain extension for the spatial analyst extension of ESRI's

ArcGIS program. It's used to set up the HEC-HMS hydrological model's input parameters (Fleming and Doan, 2013). It aids in the visualization of spatial data and the extraction of physical characteristics of watersheds such as SMA parameters, 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).

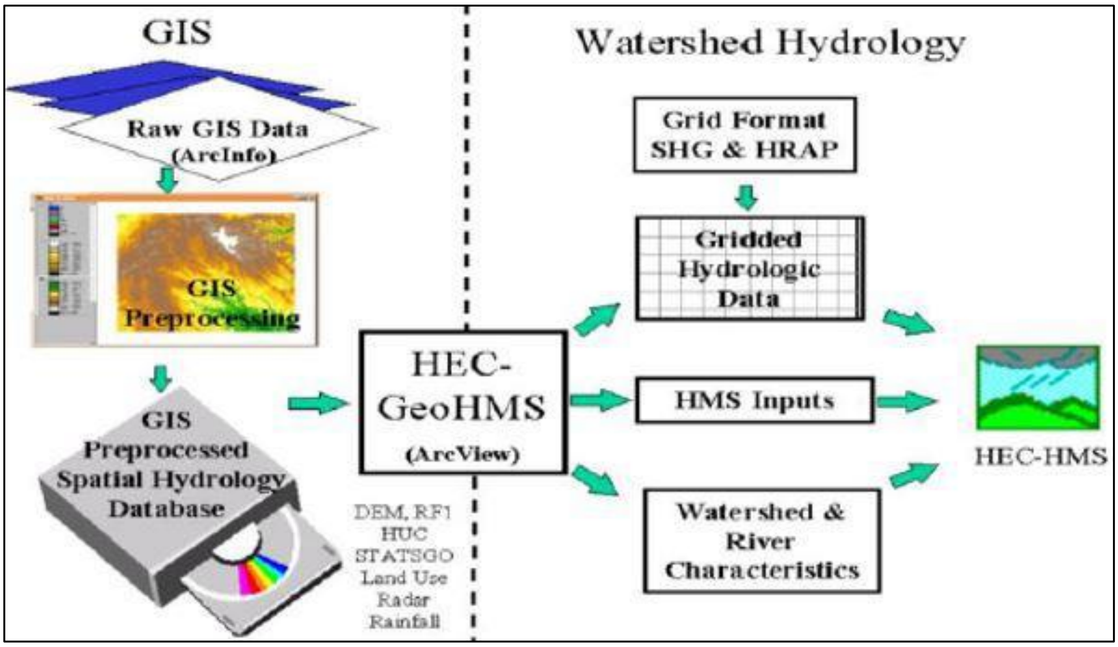


Figure 2.2 Overview of GIS, HEC-GeoHMS and HEC-HMS (Fleming and Doan, 2013).

2.4.4 HEC-HMS Model

The Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), developed by US Army Corps of Engineers, is a physically based and deterministic model, primarily applied in a lumped or semi-distributed manner, although it has capabilities for distributed modeling. It is intended to simulate the precipitation-runoff process of dendritic watershed systems (Scharffenberg *et al*., 2018). HEC-HMS represents any mass or flux with a mathematical model. HEC-HMS simulates the main mechanisms and connections between processes to calculate water balance. Figure: 2.3 represents the hydrological processes used in HEC-HMS and inter-relations among them.

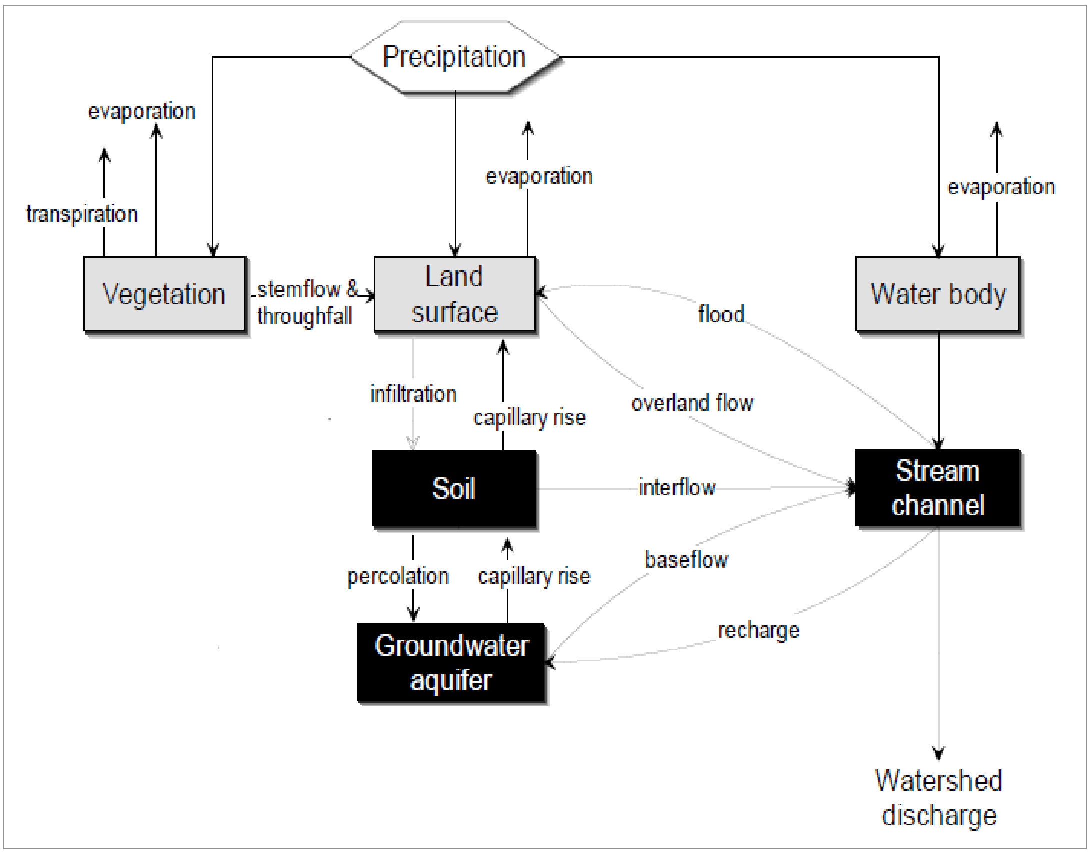


Figure 2.3: Overview of HEC-HMS hydrological processes (Scharffenberg *et al.*, 2018).

HEC-HMS has been used for a variety of purposes, including flood forecasting, post-fire response analysis, storm water management, and climate impact assessment (McEnroe, 2010, Meenu *et al.*, 2013). HEC-HMS has the capability to simulate both continuous and event-based hydrological phenomena. The primary distinction is that evapotranspiration and groundwater seepage flow can be ignored for event-based modeling, but not in continuous hydrological modeling. Soil moisture has a significant influence on the hydrological response of a watershed; still, it is rarely tracked in simulation models, due to the complexity of the model structure and challenge of parameter estimation (Holberg, 2015). In HEC-HMS, the Soil Moisture Accounting Algorithm (SMA) and deficit-constant methods are the only loss methods that account for the evapotranspiration process. The SMA loss method simulates the movement of water over time through a set of storage zones in the groundwater and soil profile layers (Scharffenberg *et al.*, 2018). The more detail explanation about HEC-HMS is provided in chapter three.

2.4.4.1 Capability of HEC-HMS

The HEC-HMS model is now widely used and accepted for many official purposes, such as floodway determinations for the Federal Emergency Management Agency in the United States (Scharffenberg *et al*., 2018). Watershed physical description, meteorological description, hydrologic simulation, parameter estimation, analyzing simulation, forecasting future flow, sediment, and water quality are the capability of HEC-HMS model. The representation of watershed accomplished with basin model and computation proceeds from upstream elements in the downstream direction. Simulating infiltration, surface streamflow, and base flow, hydrologic routing, water impoundment, and diversion structures are taken place in physical watershed; shortwave radiation, long wave radiation, RF, evapotranspiration, and snowmelt are taken place in the meteorological model; whereas starting date and time, ending date and time, and a time interval are taken place in the control specifications.

2.4.4.2 Advantages HEC-HMS

Know a day it has merits, notably its support by the US Army Corps of Engineers, the future enhancements in progress, and its acceptance to various size catchment and applicability by many government agencies and private firms. Additionally, it is in the public domain and peer-reviewed and available to download free of charge from HEC's web site. Various private companies are registered as official "vendors", offer consulting support, and add on software. However, the direct download from HEC includes extensive documentation, and scientists and engineers versed in hydraulic analysis should have little difficulty applying.

Therefore, the model applicability and efficiency to simulate rainfall streamflow was done in various regions of the world. Especially, the model widely applied in Abay river basin in Ethiopia more recently (Gebre and Ludwig, 2015). Moreover, many findings of the investigators are in the way of publication in the remaining river basins. The suggested criterions are; freely the model availability, the model efficiency to meet the target objective of the study, the model representations of assumed process in the catchment, and availability of all information required by the model within time and cost constraints.

2.5 Flood

Flood is a natural event or occurrence where an area that is usually dry land, suddenly gets submerged under water. It is probably the most devastating, widespread, and frequent natural and climate hazards that occur in almost every region of the world and then causes physical suffering, economic losses, limit the efficiency of drainage, and disturb existence of life (Pathak *et al.*, 2017). Weather-related disasters are increasing in intensity and are expected to increase with climate change (Parry *et al*., 2007). Approximately 70% of all disasters occurring in the world are related to hydro-meteorological events (BARRIENTOSA and Swainc, 2014). Flood disasters account for about a one third of all natural disasters throughout the world and are responsible for more than half of the fatalities (Berz, 2000). From 1992 to 2001, as reported 1.2 billion people were affected and 96, 500 killed by flooding worldwide.

In Ethiopia, floods are common and have been occurring throughout the country with varying time and magnitude. Flood disasters are caused by rivers overflow or burst their banks and inundate downstream flood plain land. Particularly, large scale flooding in the country is common in the low land flat parts due to high intensity of rainfall from the highland parts of the country. Flooding in Ethiopia is mainly linked with the national topography of the highland mountains and lowland plains with natural drainage systems formed by the principal river basins. Most floods in the country occur as a result of heavy rainfall causing rivers to overflow and inundate areas along the river banks in lowland plains (Getahun and Gebre, 2015).

2.5.1 Factors Affecting Flood Flow

Floods are highly affected by the physical and climatic characteristics of the catchments such as storm duration, intensity, and magnitude, catchment size, shape, relief, drainage density, morphology, land cover, presence or absence of storage, soil type, and land use (Pathak *et al.*, 2017). Many hydraulic structures' planning, design, and management problems require a detailed knowledge of flood event characteristics, such as flood peak, volume, and duration. As a rule, annual maximum flow-frequency functions estimated from statistical analysis of long records of annual maximum flow are the most reliable frequency functions. However, long records of data are seldom available. Even if a long record was available, the watershed conditions may have changed dramatically due to urbanization or other non-stationary processes, or no large events may have occurred during the period of record (Te Chow, 2010). Therefore, an accurate flow-frequency function may not be derived from the historical data alone. A calibrated watershed model with RF events of known storm frequency is often used to develop a flow-frequency function and to compare with other estimates of statistical distribution functions. The calibration of the model is typically based on available historical events of similar frequencies.

2.5.2 Flood Frequency Analysis

Flood-frequency is a set of peak flows and that associated with exceedance probabilities or recurrence intervals (Hamed and Rao, 2019). The climate change has serious impacts on flood frequency, magnitude, location, and duration. In order to estimate the probability of a peak flow of a given magnitude or, conversely, to assess the magnitude of a flow with a given probability, flood frequency analysis is very vital. The recurrence interval is a way of measuring the frequency of a flood of a specific size occurring. The main objective of flood frequency analysis is to establish a relationship between flood magnitude and recurrence interval or return period (Hamed and Rao, 2019). The resulting flood-frequency analysis 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 (Shiferaw *et al*., 2018). Over or under-estimation of design flood results in losses like a waste of resources, and infrastructural damage.

Flood frequency analyses are used to predict design floods for sites along a river. The technique involves using observed annual peak flow discharge data to calculate statistical information such as mean values, standard deviations, skewness, and recurrence intervals. These statistical data were used to construct frequency distributions, which are graphs and tables that tell the likelihood of various discharges as a function of recurrence interval or exceedance probability. 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 (Hamed and Rao, 2019). Based on Goodness of Fit (GOF) test the best frequency distribution is chosen from the existing statistical distributions such as Gumbel, Normal, Log-normal, Exponential, Weibull, Pearson General extreme value, General pareto and Log-Pearson 3 etc.

2.5.3 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 (Mehrannia and 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 and Pakgohar, 2014).

2.5.4 Distribution Fitting Evaluation Methods

Goodness of Fit (GOF) test measures the compatibility of a random sample with a theoretical probability distribution function. The results are presented in the form of interactive tables that help to decide which model describes your data in the best way. A couple of goodness-of-fit test have been conducted such as Kolmogorov-Smirnov test, Anderson-Darling test along with the chi-square test at significance level for choosing the best probability distribution (Alam *et al*., 2018).

2.6 Previous Studies

Previous studies on HEC-HMS proved its ability to simulate and forecast stream flow based on different datasets and catchment types (Xu, 2002). Most of these studies clearly indicated that, the results of the model simulation were location specific in that different combinations of a model set containing the loss methods, runoff transform methods, and base flow separation techniques were found to respond variably. Currently, many researchers have applied HEC-HMS for event or continuous based rainfall runoff modeling all over the world and have obtained satisfactory results. Namara *et al*. (2020) utilized HEC-HMS for rainfall runoff model in Awash Bello sub-catchment, Ethiopia. SCS-CN, SCS-UH, Muskingum and monthly constant method were used for precipitation loss modeling, transform modeling, flood routing and base flow modeling respectively. They suggested that HEC-HMS is applicable and the result was accepted. Derdour *et al.* (2018) developed a rainfall runoff model in a semi-arid region of Ain Sefra watershed in Algeria through employing a HEC-HMS model. They used frequency storm, Soil Conservation Service-Curve Number (SCS-CN) and Soil Conservation Service-Unit Hydrograph (SCS-UH) methods for meteorological modeling, excess precipitation modeling and excess precipitation transformation to direct runoff and obtained nearly the same computed and observed flow. Tassew *et al*. (2019) have applied HEC-HMS for stream flow simulation in Lake Tana Basin Upper Blue Nile Ethiopia. They used SCS-CN, SCS-UH and Muskingum method for precipitation loss, direct runoff and flood routing respectively.

Bashar and Zaki (2005) employed the Hydrologic Modeling System (HMS) model for continuous hydrologic simulation of the Blue Nile. Aimed to evaluate the performance and potentiality of the HMS with the SMA algorithm, on the Blue Nile as a case study in the Nile basin. They suggested that, the model showed satisfactory performance and more rainfall-runoff data; seasonal parameterization and modeling the Blue Nile watershed in sub-basins of smaller areas may improve the results. Singh and Jain (2015) have applied continuous soil moisture accounting (SMA) algorithm in a Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) to model stream flow in the Vamsadhara River Basin in India. They suggested that, the SMA procedure in the HEC-HMS conceptual model performed satisfactorily and can been used for long-term runoff modeling in the Vamsadhara River Basin. Ouédraogo *et al.* (2018) used the soil moisture accounting (SMA) model specified in the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) settings for the continuous modeling of stream flow in the Mkurumudzi catchment, Kenya. Based on the performance results, the SMA model in the HEC-HMS was found to give a satisfactory prediction of stream flow.

All these studies showed a satisfactory performance. Based on the model result they suggested that HEC-HMS is valid and applicable for Event based in the Ethiopian context and it can been used for runoff modeling. However, very few studies have been reported long-term hydrological simulation using HEC-HMS in Ethiopia river basins. So generally, aim of this study is to examine rainfall-runoff modelling and evaluate the performance and potentiality of the HMS with the SMA algorithm and to predict peak flood in Wabe catchment as a case study in the Omo Gibe river basin.

3. MATERIAL AND METHODS

3.1 Description of Study Area

The Wabe River, a tributary of Gibe River, draining to the Omo-Gibe River, is located at the southwestern part of the country. The Wabe catchment is about 1782 km^2 in area coverage and stretches from the western part of Guraghe ridge to the Gibe river. It is found in the Southern Nations, Nationalities and People's (SNNP) Region of Guraghe zone at average distance of 160Km from the capital city of Addis Ababa. The Wabe catchment is located between latitudes of 8^0 00'30"N to 9^0 00'25"N and longitudes of 37^0 04' 05"E to 38^0 25'00"E. The altitude in Wabe catchment ranges between 1016 masl at the outlet and 3576 masl at the Wabe River source, one major tributary of the Gibe river. Figure: 3.1 shows the location of the study area.

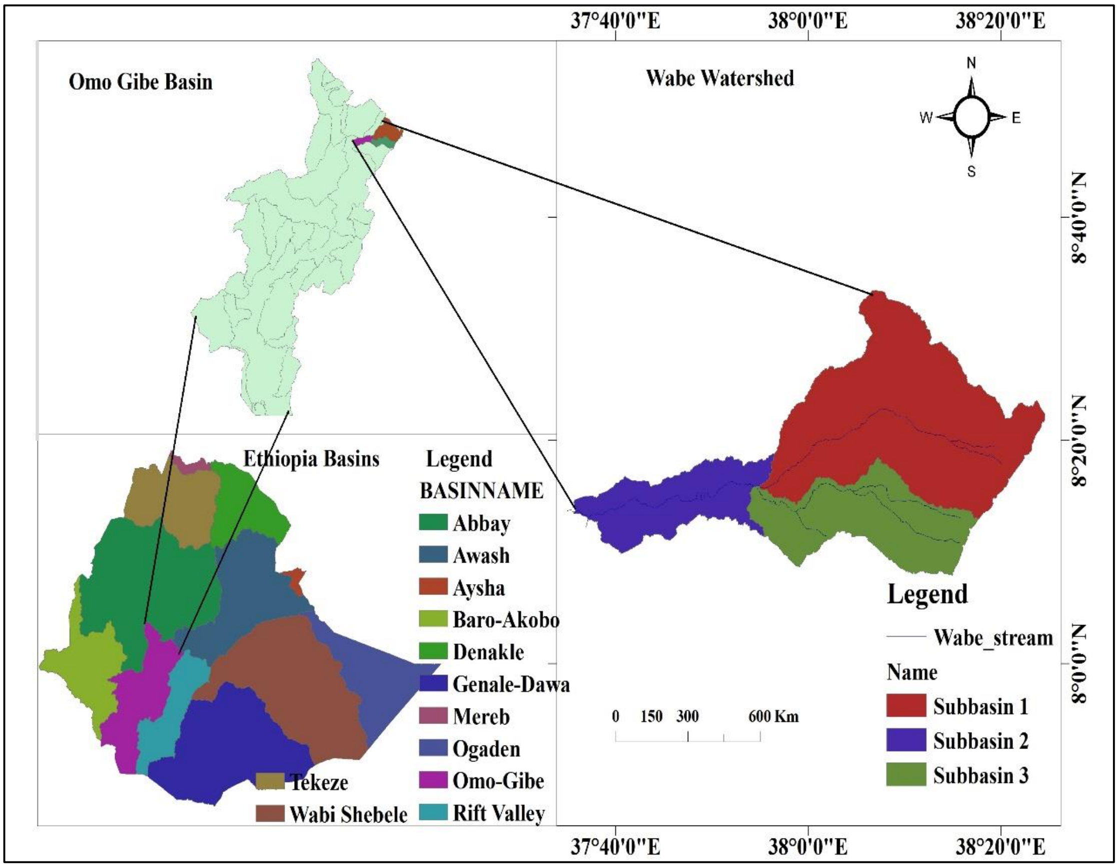


Figure 3.1 Location of study area.`

The mean annual rainfall varies between 1117.73 mm in northern to 1256.71 mm in the southern catchments. The majority of the Wabe catchment characterized by a sub humid warm to semi-arid climate with medium rainfall, and most of the annual rainfall received during summer seasons. The mean monthly maximum and minimum temperature of the Wabe catchment are 26.68 and 12.97 °C respectively.

3.2 Materials and Software Used

For the development of hydrological modeling in order to simulate rainfall-runoff relationships and to determine the watershed characteristics and runoff generation of Wabe catchment using a continuous SMA algorithm in the HEC-HMS conceptual model for watershed, different Software /tools were used. The Software/tools that were used includes Geographic information system (GIS), Arc Hydro tools, Hydrologic Engineering Center-Hydrologic Model System (HEC-HMS), Hydrologic Engineering Center-Geological Hydrologic Model System (HEC-GeoHMS), Rainbow, SPAW, Easy fit and Excel spreadsheet.

3.3 Data Type and Data Sources

A good understanding of the topographical, hydrological and climatic condition of the study area and proper set of data defining them are very important for analyzing and replicating the actual hydrologic situation. The input data used in the present study were spatial data (digital elevation model (DEM), soil map and land use/land cover) gathered from the Ethiopian Ministry of Water, Irrigation and Electricity, and meteorological data (daily precipitation and daily temperature) were acquired at the Ethiopian National Meteorological Agency. In addition, daily stream flow was obtained from Ministry of Water, Irrigation and Electricity of Ethiopian. These data obtained from various sources as described in Table: 3.1. The data collected from these sources were processed and analyzed before using as input for hydrological model.

Table 3.1 HEC-HMS input data type and their sources.

Data Type	Source	Scale/period	Description
DEM	Ministry of Water, Irrigation and Energy (MoWIE)	30 m × 30 m	Digital Elevation Model
LULC	Ministry of Water, Irrigation and Energy (MoWIE)	2006	Land-use classification map
Soil	Ministry of Water, Irrigation and Energy (MoWIE)	2013	Soil classification map
Hydrological	Ministry of Water, Irrigation and Energy (MoWIE)	1987–2007	Daily stream flow data
Meteorological	National Meteorological Service Agency (NMSA)	1985–2016	1. Daily rainfall data 2. Daily Tmax and Tmin

3.3.1 Soil Data

The primary source of information used to develop the soil profile parameters required for the SMA-based model is the Soil Database. HEC-HMS model requires different soil textural and physicochemical characteristics such as the number of carbon contents in organic compounds, availability of the water in the soil, hydraulic conductivity of the soil, and bulk density of soil layer (Setegn *et al.*, 2008). The physical properties govern the movements of water and air in the soil profile and have major impact on the cycling of water. Therefore, hydrologic properties of soil were reclassified and reformatted to inputting into the model.

The soil data was compiled and modified from different sources to get the appropriate soil format for inputting in to the model. Besides the common soil data sources, FAO, HWSD, and USDA, soil data that were collected for local studies like, irrigation practices and other related applications, were also used to organize soil database. These various sources were considered in order to identify and quantify the various soil parameters prior to reorganizing and categorizing into suitable HEC-HMS soil format and classes. The main soil water characteristics (SOL_AWC, SOL_K, and SOL_BD) of the catchments were estimated using SPAW (Soil-Plant-Air-Water) tool developed by USDA once the texture of the soil type was identified. Figure 3.2 and Table 3.2 shows the soil texture classes in the sub-watershed with their area coverage percentage respectively used for inputs and the specific soil data parameters used in this study was explored further in the SMA parameter estimation part.

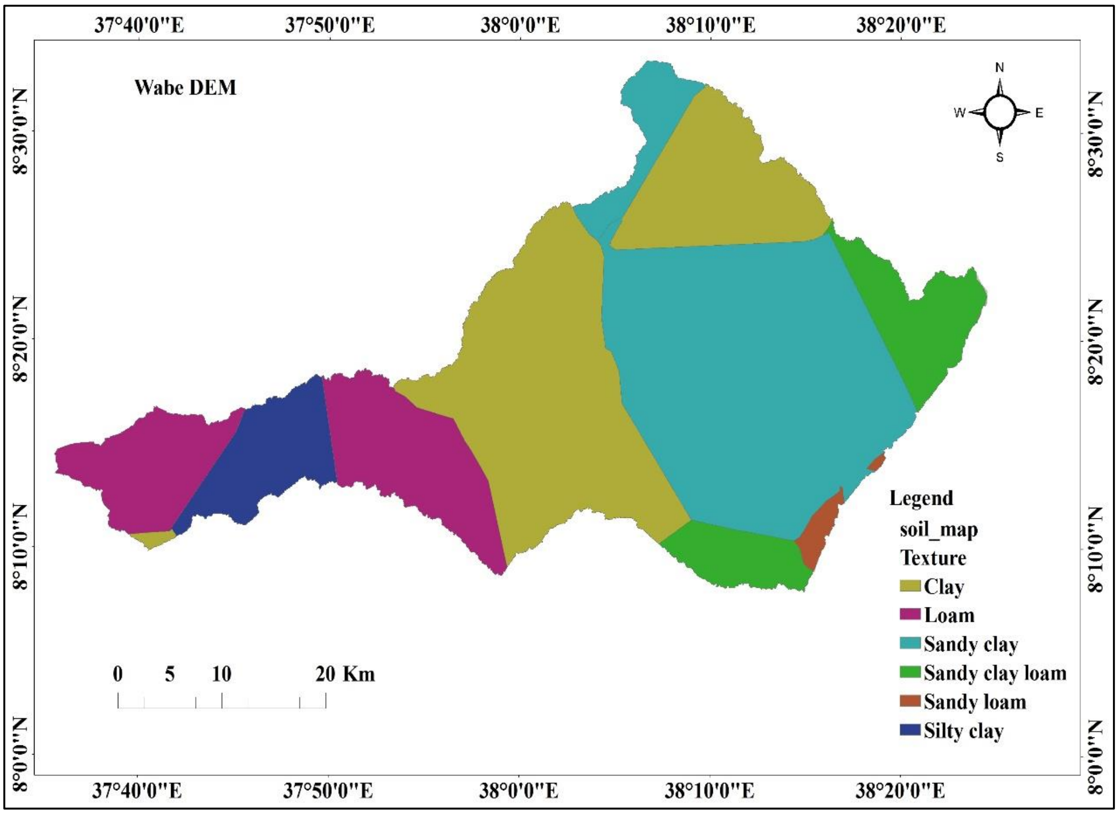


Figure 3.2 Soil classes (Textural) of Wabe catchment.

Table 3.2: Soil classes (Textural) and their percentage of area cover.

Soil Classes/Texture	Area cover (Km^2)	% Area cover
Clay	591.357	33.196
Loam	266.245	14.946
Sandy clay	647.692	36.358
Sandy clay loam	157.436	8.838
Sandy loam	15.191	0.853
Silty clay	103.495	5.810

3.3.2 Digital Elevation Model (DEM)

Digital Elevation Model (DEM) is a digital representation of landscape, and it was specifically made available in the form of a raster map. It is the primary input of the HEC-HMS hydrologic model (Prodanović *et al*., 2009). Digital Elevation Model (DEM) is primarily used to delineate the watershed and stream network in the aforementioned study area. It is also used for topographic calculations such as watershed slope and longest flow path. The Digital Elevation Model of 30 m by 30 m resolution of Wabe sub-watershed was extracted from that of the Omo-Gibe basin and delineated Wabe sub-watershed. The digital elevation model of the Wabe sub-watershed was presented in Figure 3.3.

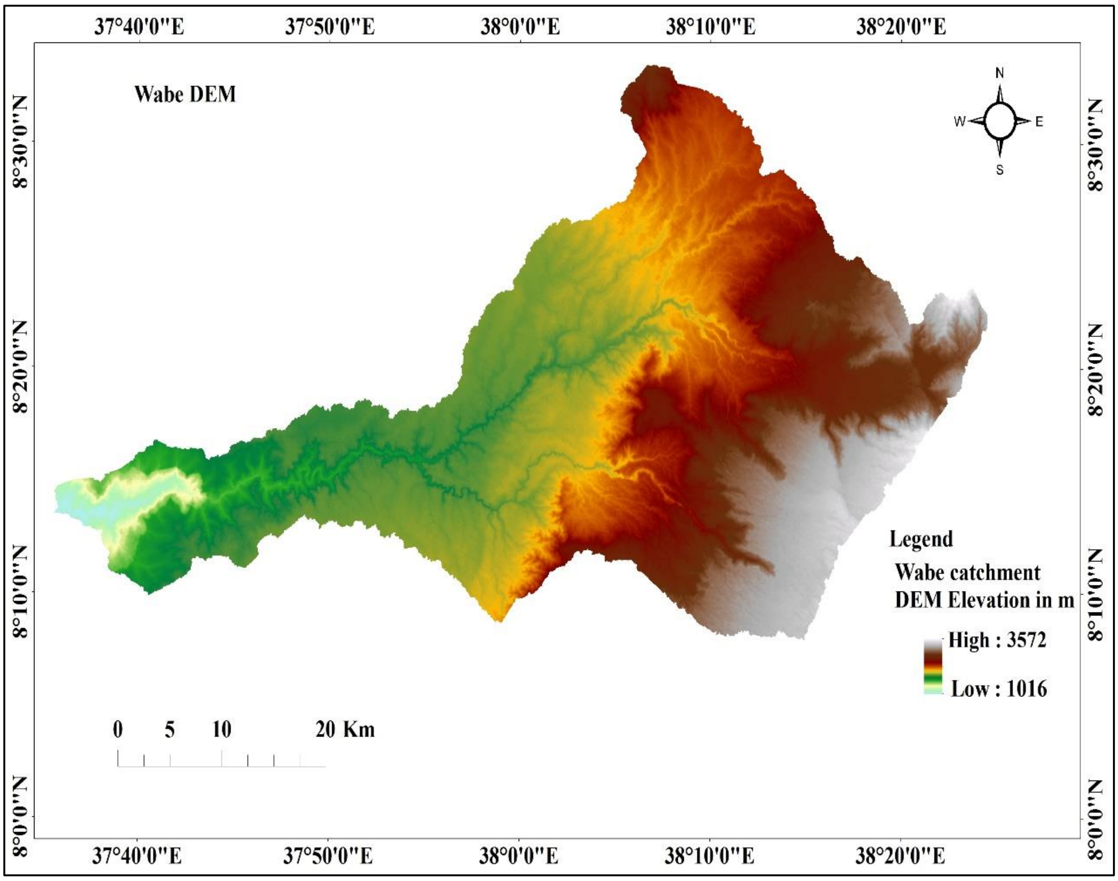


Figure 3.3 Digital elevation model of Wabe catchment.

3.3.3 Land Use/Land Cover Data

Land use/land caver data are the influential factors that determine hydrological parameters such as runoff, evapotranspiration, infiltration capacity of the soil, and upper soil erosion in the study area (Fentaw *et al.,* 2018). The land use/land caver map of Wabe sub-watershed extracted from the land use/land caver map of the Omo-Gibe river basin that obtained from the ministry of water, irrigation, and energy (MoWIE). It was used to determine the canopy storage grid and impervious surface percentage required for the SMA-based model. The land use/land caver datasets used in this study are the 30 m resolution land use data. The land-use map of Wabe watershed and the dominant land use/land cover type in the database are as shown in Figure 3.4 and Table 3.3 respectively.

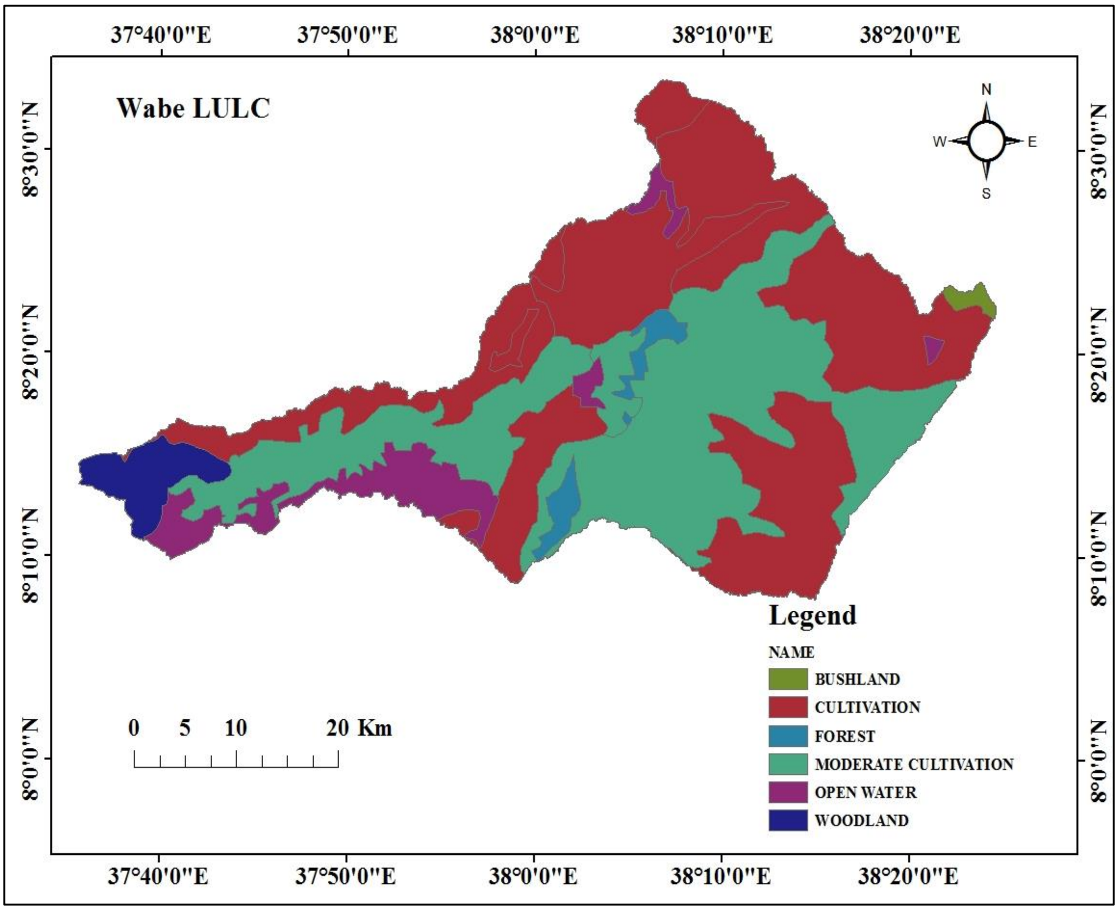


Figure 3.4 Land-use/land-cover of the Wabe catchment *(*LULC, 2006*)*.

Table 3.3: Land-use Land-cover map of Wabe catchment.

Name of LULC	Area cover (Km^2)	% Area cover
Bush land	8.520	0.479
Cultivation	871.106	48.918
Forest	33.621	1.888
Moderate cultivation	678.537	38.104
Open water	125.943	7.073
Woodland	63.025	3.539

3.3.4 Meteorological Data

The HEC-HMS model requires meteorological and hydrological input data at daily time step for daily runoff generation. The meteorological data required for the study are minimum temperature, maximum temperature, precipitation, relative- humidity, wind speed and sunshine hours. Daily meteorological data of 31 years (1985–2016) collected from the National Meteorological Service Agency (NMSA) (Table 3.4).

Four of meteorological stations were selected based on the availability of the station's data and representativeness in the study area from collected station's. The selected meteorological stations were Arbuchulule, Welkite, Butajira police station and Imdibir.

Table 3.4: Location of meteorological stations.

Station name	Latitude	Longitude	Elevation
Arbuchulule	8.472	38.252	2434
Butajira	8.150	38.366	2000
Imdibir	8.130	37.935	2076
Welkite	8.270	37.750	2000

3.3.5 Hydrological Data

The daily streamflow data for Wabi gauged station was collected from Ministry of Water, Irrigation and Energy from the period 1987–2007 with some missed value. The Wabi gaging station is located near Welkite at 8^0 00' 30" and 37^0 42'12" latitude and longitude respectively.

3.4 Hydro-Meteorological Data Analysis

Hydrological modeling depends on hydro-meteorological and hydrological data. Reliability of the collected raw hydro-meteorological data significantly affects quality of the model input data and, consequently, the model simulation. Therefore, rough data screening of raw meteorological and hydrological data, completion of identified missing data and check consistency and homogeneity of the estimated data sets are necessary. Engineering studies of water resources development and management depend heavily on hydro-meteorological data. These data should be stationary, consistent and homogeneous when they were used for frequency analyses or to simulate a hydrological system.

Rough screening of the data will allow visual detection of whether the observations have been consistently or accidentally credited to the wrong day, whether they show gross errors (e.g. from weekly readings instead of daily ones) or whether they contain misplaced decimal points. In this study no data detected in this procedure since there are no outcropping daily data in entire stations and period of records.

3.4.1 Filling Missing Precipitation Data

The continuity of the record may be broken with missing data due to failure of the observer to take reading at regular interval, vandalism of the recording gauges and instrumental failure. The rainfall data taken from the four stations has missing data ranging from 1.4% to 13.5%. Therefore, it is required to estimate these missing records before undertaking further data analysis.

A number of methods have been proposed for estimating missing precipitation. The station average method is the simplest one. It was used when the average annual precipitation at the adjacent gauges differed from the average annual precipitation at the considered gauge by less than 10%. The normal ratio and quadrant method provide a weighted mean, with the former biasing the weights on mean annual precipitation at each gauge and the later having weights that depend on the distance between gauges where recorded data are available and the point where the value is required. The Isohyetal method is the fourth alternative. Normal ratio method was used in this research paper. The method is used when the normal annual precipitation of the index stations differ by more than 10% of the missing stations (Shinbrot *et al*., 2020).
The general formula for computing missing precipitation by this method was:

$$\mathrm{Px} = \frac{\mathrm{Nx}}{\mathrm{M}}\left[\frac{\mathrm{P1}}{\mathrm{N1}} + \frac{\mathrm{P2}}{\mathrm{N2}} + \frac{\mathrm{P3}}{\mathrm{N3}} + \ldots + \frac{\mathrm{Pm}}{\mathrm{Nm}}\right] \tag{3.1}$$

Where: Px = is the precipitation for the station with missing records.

P_1, P_2, P_3 and P_m are the adjacent stations precipitation values.

N_1, N_2, N_3 and N_m are the long-term mean annual precipitation values at the respective stations and M is the number of stations surrounding the station X.

After the precipitation data gap filled, monthly average precipitation data for 31 years (1985–2016) were computed and plotted, as described in figure 3.5. As the collected data from national meteorological agency indicates, the monthly average precipitation was varied with each station and station obtains a minimum of 8.25mm to 269mm per month. There is only one peak in a year reflecting the unimodal rainfall distribution in the Wabe sub-watershed. High rainfall data observed at Welkite meteorological station and low rainfall observed at Butajira, whereas the medium rainfall recorded at Imdibir and Arbuchulule stations.

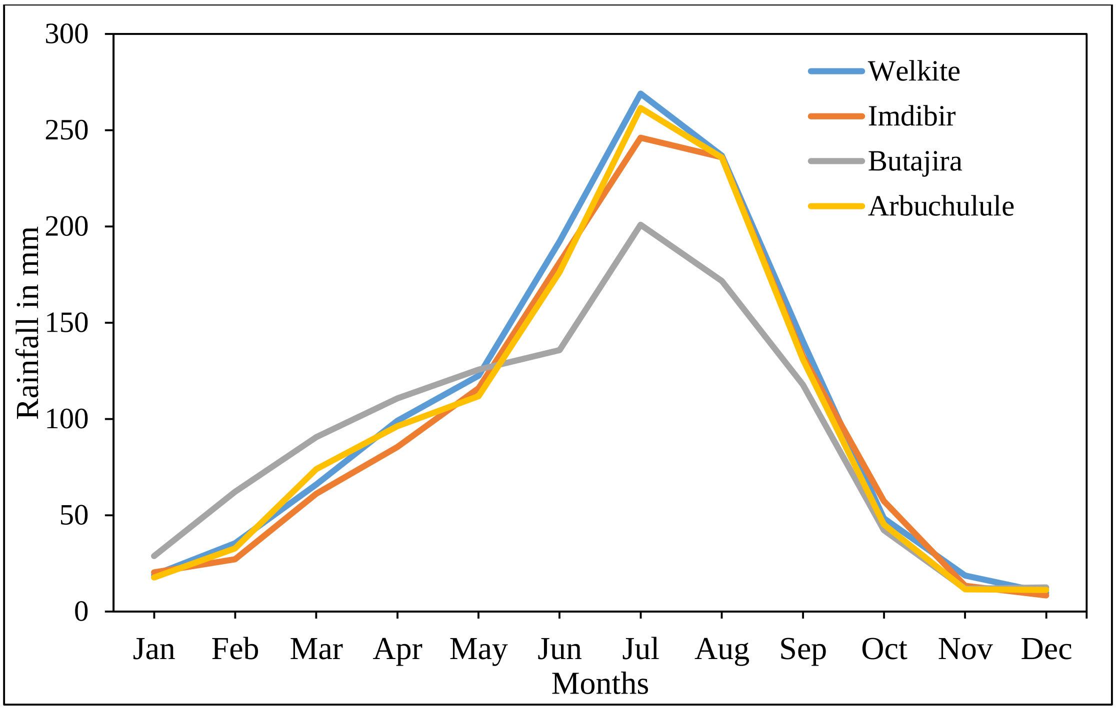


Figure 3.5 Monthly average precipitations of four stations in Wabe watershed.

3.4.2 Checking the Consistency of Precipitation Data

Estimating missing precipitation is one problem that hydrologists need to address. Second problem occurs when the catchment rainfall at rain gages is inconsistent over a period and adjustment of the measured data is necessary to provide a consistent record. A consistent record is one where the characteristics of the record have not changed with time. Inconsistency may result from change in gauge location, exposure, instrumentation, or an observational procedure is not real and on time. To overcome the problem in consistency a technique most widely applied called double mass curve was used. Double-Mass Curve (DMC) analysis is a graphical method for identifying or adjusting inconsistencies in a station record by comparing its time trend with those of other stations nearby (Searcy and Hardison, 1960). Sometimes a significant change may occur in and around a particular rain gage station. Such a change occurring in a particular year was start affecting the rain gauge data, being reported from that particular station. After a number of years it may be felt that the data of station is not giving consistent rainfall values.

In order to detect any such inconsistency, and to correct and adjust the reported rainfall values a technique, called double mass curve method is generally a doubted. Proportionality between the measurements at the suspect station and those in the region is reflected in a change in the scope of the trend of the plotted points. The data series, which is inconsistent, adjusted to consistent values by proportionality. Double mass curve plot made for all four stations. The curve is a plot of rainfall record of a station and cumulative rainfall collected at a gauge where measurement condition may have changed significantly against the average of the cumulative rainfall for the same period of record collected at several gauges in the same region. The data was arranged in the reverse order that is the latest record as the first entry and the oldest record as the last entry in the list. The use of the double-mass curve for checking the consistency of precipitation records was explained by the following example in which the annual records of four precipitation stations. First the annual precipitation data for each year were tabulated and then cumulated in chronological order. The cumulative precipitation for each station is then plotted against the cumulative precipitation of the pattern. Double mass curve plot made for all four metrological stations shown in figure (3.6). From the double mass curve figures the stations were consistent to each other.

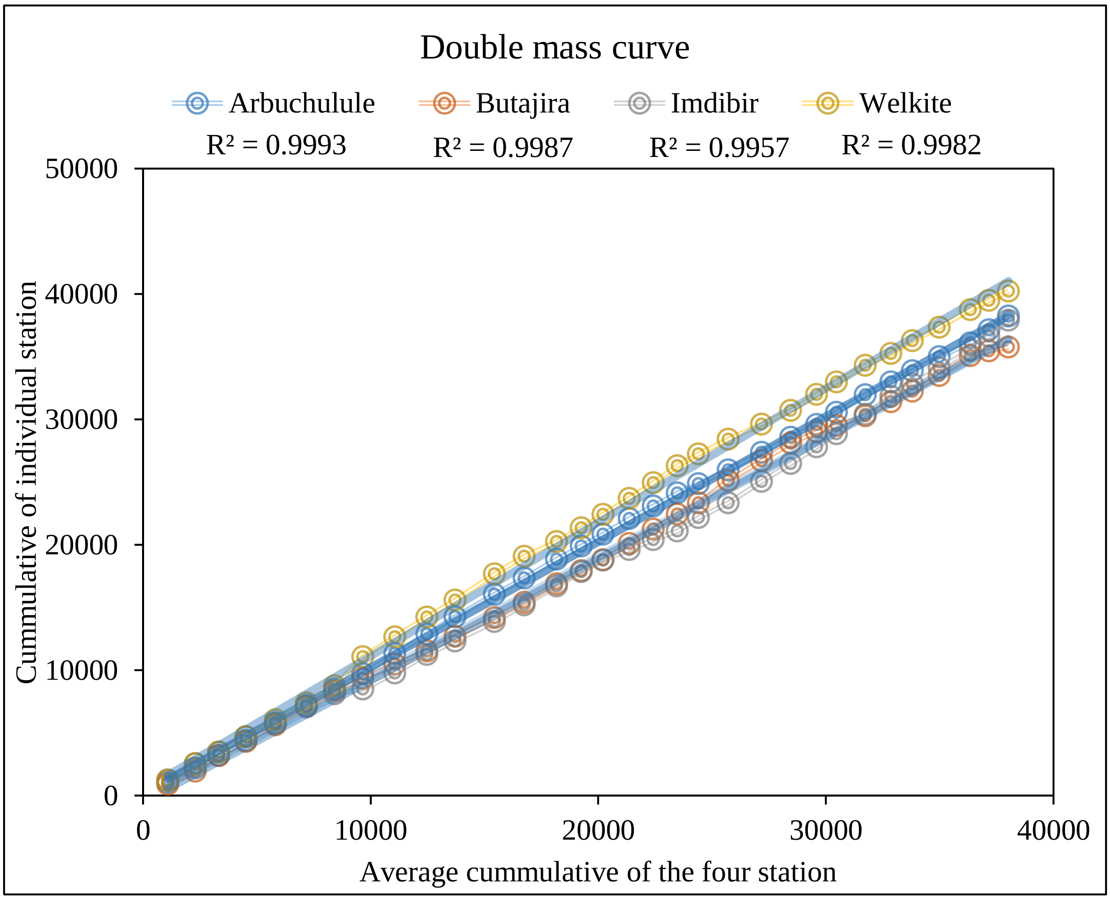


Figure 3.6 Double mass curve for consistency check.

3.4.3 Precipitation Data Homogeneity Test

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

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

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

$$S_K = \sum_{i=1}^{K} (X_i - \overline{X}) \tag{3.2}$$

$K = 1, 2, 3 \ldots n$

Where: S_K is the cumulative deviation, K is the number of year, X_i is series of rainfall data and $\overline{X}$ is the mean of rainfall data.

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

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

$$Q = \max\left[\frac{S_K}{S}\right] \quad (3.3)$$

$$R = \max\left[\frac{S_K}{S}\right] - \min\left[\frac{S_K}{S}\right] \quad (3.4)$$

Where; Q is maximum cumulative deviation, R is the range of cumulative deviation and S is the sample standard deviation.

High values of Q or R are an indication that time series data is not from the same population and the fluctuations are not purely random. The cumulative deviation versus time series graph of annual rainfall for all stations, were drawn using rainbow software. In this graph, the vertical-axis is rescaled and lines representing various probabilities with which the homogeneity of the data can be rejected were plotted. The rescaled S_K's fluctuated around zero although they were far off the lines where the homogeneity is rejected. Hence, the precipitation time series data were considered as homogeneous.

The homogeneity statistics menu for all station indicates that the cumulative deviation and maximum of cumulative deviation at 90%, 95% and 99% were not rejected. This also indicates the homogeneity of the precipitation time series data. Figure 3.7 shows the homogeneity test result for Welkite station's annual rainfall. The homogeneity test result for other station's annual rainfall was attached in Appendix-A.

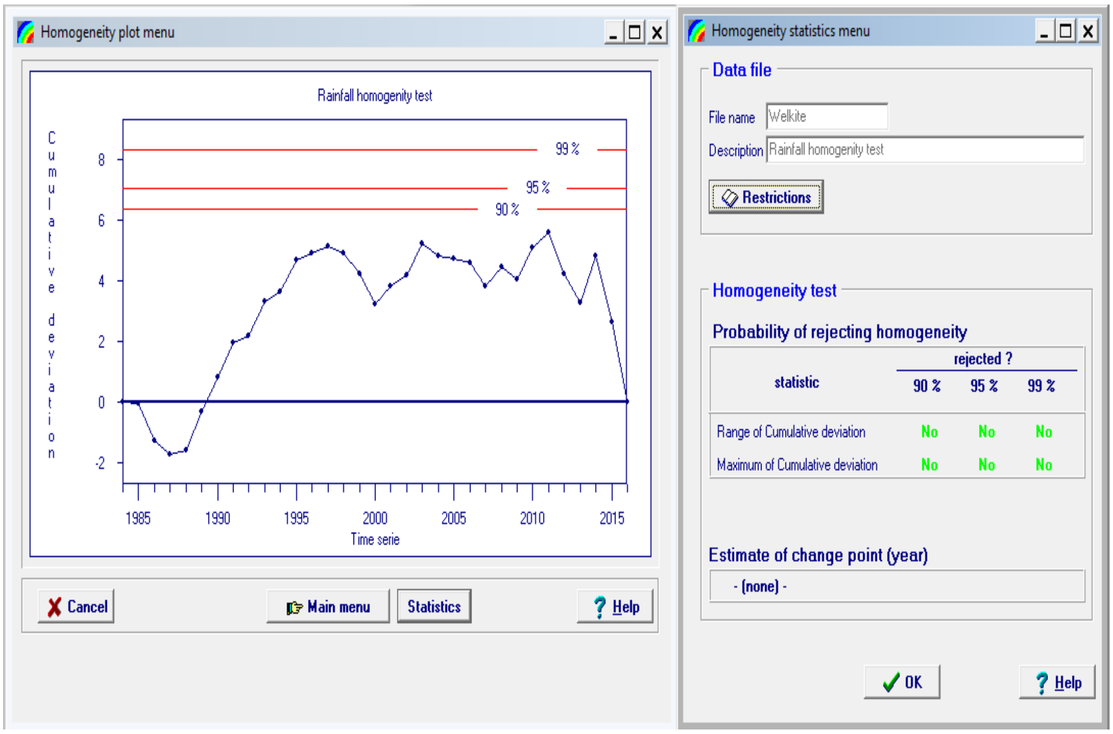


Figure 3.7 Homogeneity test for Welkite station.

3.4.4 Estimation of Areal Rainfall

Rain gauge records rainfall at a single point. The average depth of rainfall over the area under the area of consideration is one of the most essential parameter in hydrological studies. HEC-HMS requires areal rainfall as an input data to convert it in to runoff (Feldman, 2000). Various methods are available that are used to convert the point rainfall values in to an average value over a catchment. Among these, there are eight methods available in HEC-HMS 4.7 for estimating precipitation at the watershed scale (Table 3.5).

Table 3.5: Precipitation Calculation Methods in HEC-HMS 4.7.

Category Method	Method
	Specified Hyetograph
	Gage Weights (Thiessen Polygon)
Precipitation	Inverse Distance Gage Weighting
	Gridded Precipitation
	SCS Hypothetical Storm
	HMR 52 Strom
	Frequency Strom
	Standard Project Storm (SPS)

The Gauge Weight (Thiessen Polygon) method is one of the common methods of determining average precipitation for a watershed when there is more than one gauging station available. This approach has been suggested by several researchers (Ali *et al*., 2011, Gyawali and Watkins, 2013). This approach assigns a weight for each gauge in proportion to its closest basin area. Thiessen polygons for the Wabe River at the outlet were generated by Arc-GIS 10.1 along with Arc Hydro and HEC-GeoHMS extension tools using four rain-gauging stations, and are presented in Figure 3.8. In Figure 3.8, the coverage area of every single gauging station is distinguished by color boundaries. This is the privilege of selecting these station which all of them are lies inside the catchment boundary. Following the generation of the Thiessen polygons, the areas of each Thiessen polygon and its weight were calculated and presented in Table 3.6.

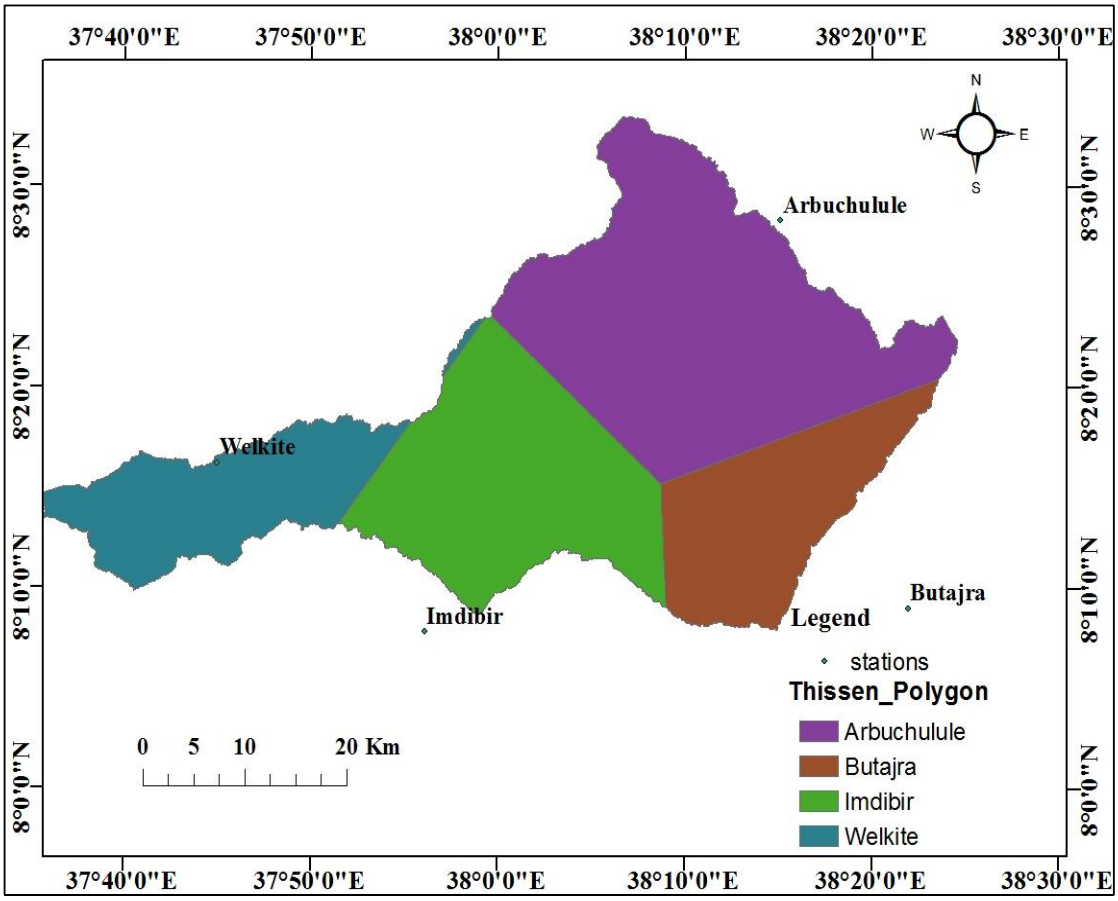


Figure 3.8 Thiessen polygon developed for Wabe catchment.

A sub-basin that lies on a given polygon will take the areal rainfall of that polygon in direct proportional to the area of that sub-basin. The gauge weight for each sub-basin will be the ratio of area of the sub-basin that lies in the polygon and the area of the polygon.

Table 3.6: Thiessen gauge weight developed for Wabe catchment.

Rainfall Stations	Area weight (Km^2)	Gauge weights (%)
Arbuchulule	737	41.36
Butajira	295	16.55
Imdibir	468	26.26
Welkite	282	15.83
Total	1782	100

This means Thiessen polygons were created and then area weights computed based on intersecting the Thiessen polygons with the sub-basin polygons. Results from the gage weight analysis are shown in Table 3.7. The sub-basin precipitation time series were obtained by multiplying the gauge weight by gauge precipitation for each sub-basin.

Table 3.7: Precipitation gage weights using Thiessen polygons.

Subbasin	Arbuchulule	Butajira	Imdibir	Welkite	Sum
Subbasin 1	0.6961	0.1306	0.1699	0.0034	1
Subbasin 2	0	0	0.1074	0.8926	1
Subbasin 3	0.0461	0.3646	0.5893	0	1

3.4.5 Estimation of Areal Temperature

The point maximum and minimum temperature data for four stations were collected from NMSA. For stations which have no maximum and minimum temperature data the average mean temperature was predicted from the neighboring stations and the conversion of point data into areal was followed the procedure of rainfall conversion. As shown on the (Figure 3.9), Wabe catchment have been an average monthly minimum temperature of 12.97 ^{0}C and average monthly maximum temperature of 26.68 ^{0}C.

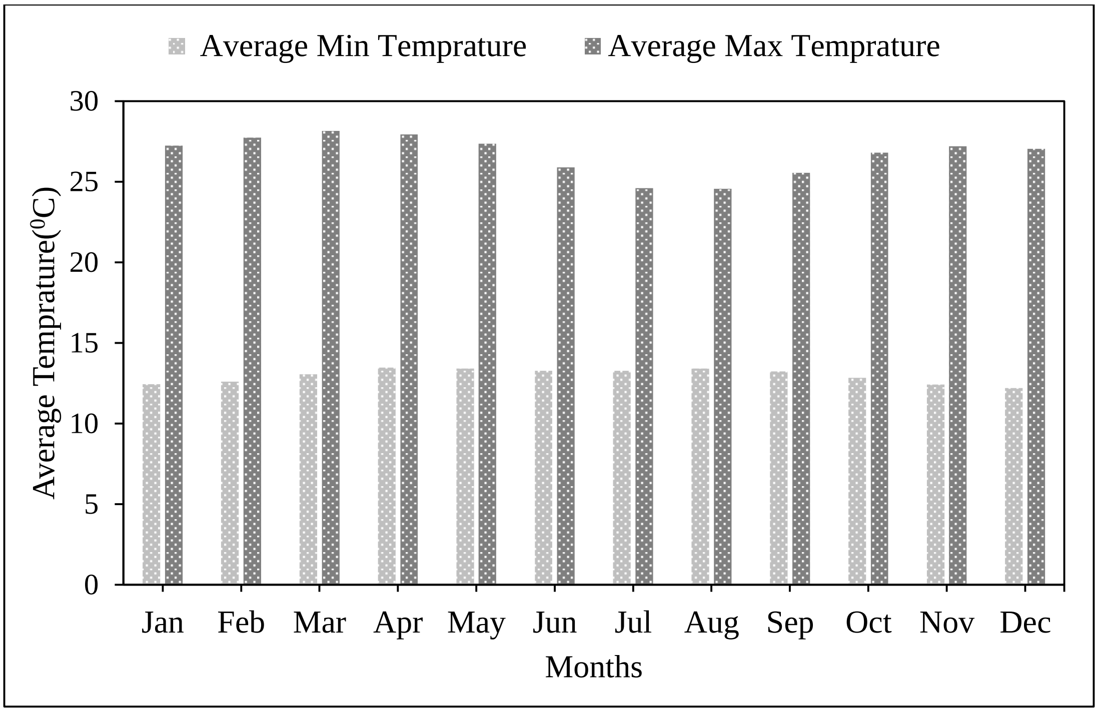


Figure 3.9 Average monthly max. and min. temperature of Wabe catchment.

3.4.6 Estimation of Potential Evapotranspiration

Potential Evapotranspiration was a collective term that includes evaporation from the land surface and vegetation cover. It can be collected from meteorological station if available or computed from meteorological data. The recent version of HEC-HMS includes different options to estimate evapotranspiration. Nowadays, Penman-Monteith method, the Priestley-Taylor method and the Hargreaves method are the most used methods based on their efficiency and data requirement. One of the three methods were selected to calculate the potential evapotranspiration from the watershed depending up on the data available. The model was also read if a separate daily PET (Potential Evapotranspiration) values are applied for potential evapotranspiration method. The data requirements for the application of these three PET methods are very different. The Penman- Monteith method requires solar radiation, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiation, air temperature and relative humidity. The Hargreaves method requires air temperature only (Jabloun and Sahli, 2008).

Due to the scarcity of the data, the Hargreaves method was selected for this study. This is advantageous for areas with limited data where only temperature data is available. The Hargreaves-Samani equation is expressed as (Hargreaves and Samani, 1982):

$$\mathrm{Eto} = 0.0023\ \mathrm{Ra}\ (\mathrm{Tmean} + 17.8) * (\mathrm{Tmax} - \mathrm{Tmin})^{0.5} \qquad (3.5)$$

Where: Eto = Potential Evapotranspiration and Ra=Extraterrestrial Radiation.

T_{max} and T_{min} are the daily maximum and minimum temperature (°C) respectively.

$$\mathrm{Ra} = \frac{24(60)}{\pi} \mathrm{Gscdr}\ [\omega s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega s)] \qquad (3.6)$$

$$\omega s = \arccos[-\tan(\varphi)\tan(\delta)] \qquad (3.7)$$

$$\mathrm{dr} = 1 + 0.033\cos\left(\frac{2\pi}{365}\mathrm{J}\right) \qquad (3.8)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365}\ \mathrm{J} - 1.39\right) \qquad (3.9)$$

The monthly average Potential Evapotranspiration for the whole Wabe sub-catchment was computed. The result of the computation shows that the Wabe sub-catchment obtains a maximum monthly average Potential Evapotranspiration of 160.813 mm/month in the month of March and a minimum monthly average Potential Evapotranspiration of about 132.19mm/month in the month of July (Figure 3.10).

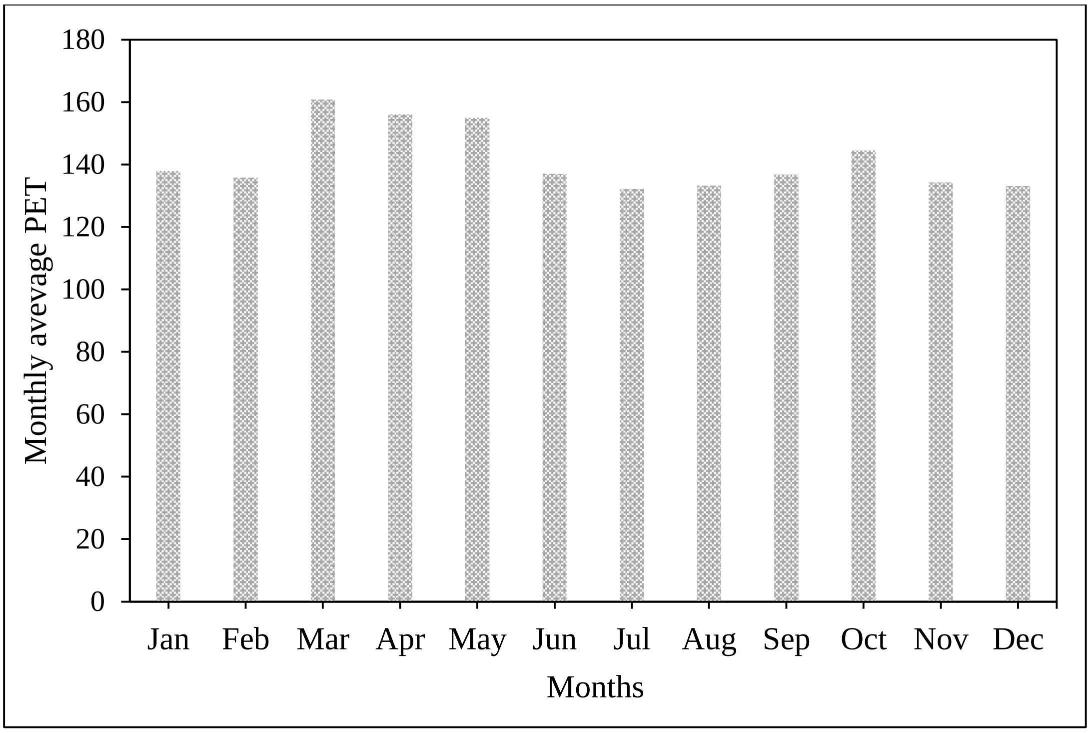


Figure 3.10 Monthly average PET of Wabe sub-catchment.

3.4.7 Hydrological Data Analysis

Like meteorological data, the initial step taken during the hydrological data analysis was quick visual scan of the data time series to detect gross errors such as untrue peak flow, missed recordings, and flows of constant rate. It helps to detect the year with magnitude change in the data, long periods of missing records and short-term missing data. Because unlike rainfall, stream flow shows strong serial correlation; the value on one day is closely related to the value on the previous and following days especially during periods of low flow or recession.

Wabe watershed have only one streams gaging station which flows throughout the year. The Wabi gauging station of Wabe river is located near to the outlet of watershed and this station was the only station installed on the main river and represent the area of the watershed. Missing data is a serious problem in many hydro-meteorological time series data. A number of methods have been proposed for estimating missed data of Hydro-meteorological. However, in this case there was no information from neighboring stations, so the mean on the same day and month but at different years is taken as estimation of the missing value on that particular date (Ismail *et al.,* 2017). For this study, the hydrological data after filling as indicated in figure 3.11.

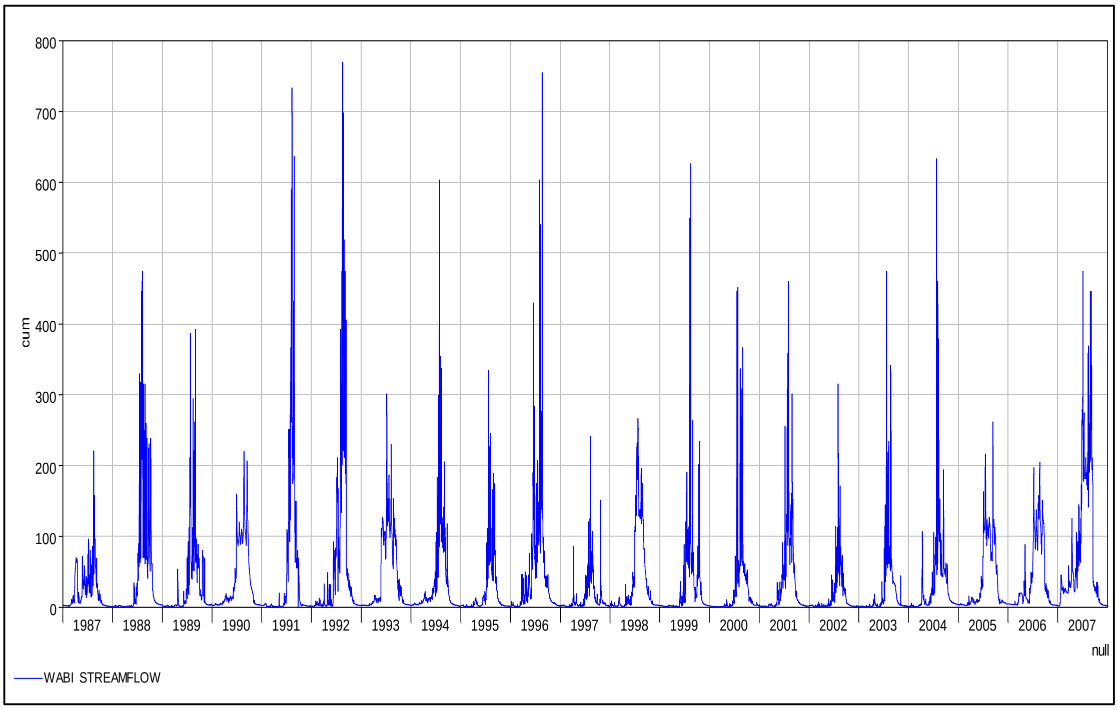


Figure 3.11 The stream flow graph at Wabi station.

3.5 SMA Algorithm Setup and Parameter Estimation

In addition to building the model schematic in HEC-HMS, the SMA model components must be defined for each sub-basin in case of continuous hydrological model and it's conceptual framework shown as figure 3.12. The required inputs for the SMA model are presented in Table 3.8. For these modeling methods, a total of 12 parameters and five initial conditions are required to estimate canopy, soil, surface, and groundwater storage parameters. Seven of the 12 parameters are estimated using soil, DEM and land cover databases in GIS. Four parameters are calculated from streamflow recession analysis, and the final parameter and the initial conditions were calibrated.

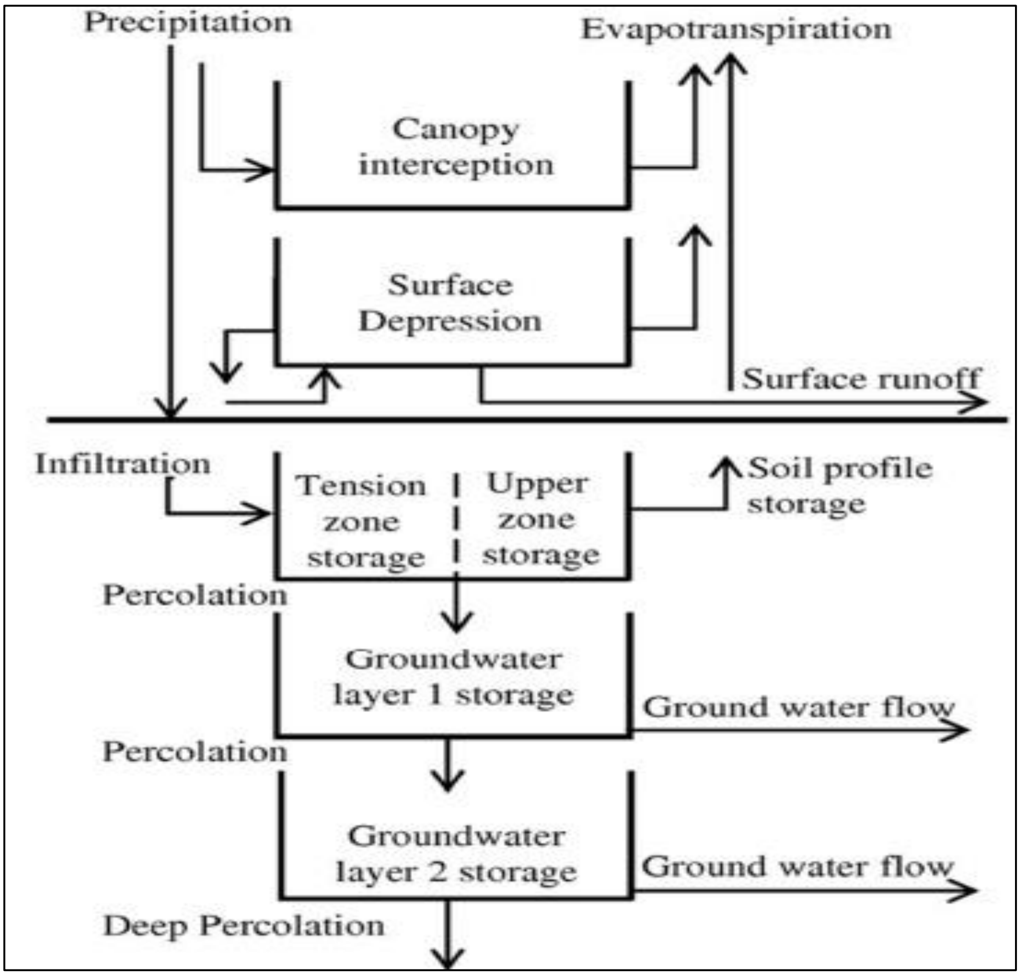


Figure 3.12 SMA conceptual framework.(Fleming, 2002).

3.5.1 SMA Parameters Grid Generation

Depending on the method (HMS Processes) selected to use for HMS model, each sub-basin must have parameters. These parameters are assigned using the Subbasin Parameters option found in HEC-GeoHMS. This function overlays subbasins over grids and computes an average value for each basin. For this study, the only required grids were for the SMA method.

To do so, select Parameters and then Subbasin Parameters from Raster. The window opened used to select the rasters that allowed for extracting parameters. The rasters listed for the SMA method were: (1) Total Storm Precipitation Grid, (2) 2-Year Rainfall Grid, (3) Percentage Impervious Grid, (4) Max Canopy Storage Grid, (5) Max Surface Storage Grid, (6) Max Soil Infiltration Grid, (7) Max Soil Percolation Grid, (8) Soil Tension Storage Gird, (9) Max Soil Storage Grid, (10) GW1 Max Storage Grid, (11) GW2 Max Storage Grid, (12) GW1 Max Percolation Grid, (13) GW2 Max Percolation Grid.

Table 3.8:SMA model parameters (Scharffenberg and Fleming, 2006).

Models	Parameters	Methods
	Initial canopy storage (%)	Calibration
Canopy	Maximum canopy storage (mm)	Land cover database
	Crop coefficient	Calibration
Surface	Initial surface storage (%)	Calibration
	Maximum surface storage (mm)	DEM analysis
	Soil (%)	Calibration
	Groundwater 1 (%)	Calibration
	Groundwater 2 (%)	Calibration
SMA	Max infiltration rate (mm/h)	Soil Database
	Impervious (%)	Land cover database
	Soil storage (mm)	Soil Database
	Tension storage (mm)	Soil Database
	Soil percolation (mm/h)	Soil Database
	GW 1 storage (mm)	Stream Recession
	GW 1 percolation (mm/h)	Soil Database
	GW 1 coefficient (h)	Stream Recession
	GW 2 storage (mm)	Stream Recession
	GW 2 percolation (mm/h)	Calibration
	GW 2 coefficient (h)	Stream Recession

Rasters 1 and 2 are optional for the SMA method and they were not developed for this study. Raster 3 also not created. Rasters 4-9 was developed during this study. Rasters 10-11 are constant value rasters, and thus do not need to be created. They are simply assigned as the constant values to each Subbasin in our Subbasin attribute table. Raster 12 can be taken as equivalent to Raster 7. Raster 13 is not created, because it is an extremely conceptual parameter. It simply assigned as GW2 Max Percolation Rate during HMS model calibration (Erşahin, 2020, Holberg, 2015).

Finally after the parameters were estimated, the grids are developed following the procedures: (i) go to arc toolbox, (ii) conversion tools (iii) to raster, (iv) feature to raster and (v) select polygon feature class for input features, select parameter for field, save the raster to working geodatabase and type 30 for the cell size then click ok(see APPENDIX-B).

3.5.2 Parameter Estimation Using Land Cover Data

The maximum depth of water that can be intercepted by vegetation is representing the canopy interception. The canopy storage capacity varies with the meteorological factors and vegetation structure. The values of canopy storage was obtained using land cover map analysis and canopy interception values provided in Table 3.9, as suggested by (Bennett and Peters, 2000).

Impervious area was defined as the percentage of the area under urban civilization for the sub-basin using Google Earth with the aid of the Land Use map. In this study, the percent of impervious was simple taken as 5% from the previous literature of the basin (Mersha, 2017). The real value would be defined more accurately in the hydrologic modelling process, by searching the value that give the best efficiency.

Table 3.9: Canopy interception values (Holberg, 2015).

Type of Vegetation	Canopy Interception (mm)
General Vegetation	1.270
Grasses and Deciduous Trees	2.032
Trees and Coniferous Trees	2.540

3.5.3 Parameter Estimation Using DEM Data

Surface storage represents the maximum amount of water that can pond on the soil surface before surface runoff begins. The precipitation not captured by the canopy interception can inflow to the surface storage, which can then infiltrate or evaporate. If the inflow exceeds the soil infiltration rate, it will contribute to surface runoff. The surface storage capacity is related to the terrain slope (%) of the catchment surface stated by (Bennett and Peters, 2000) and values for the surface storage were obtained from the analysis of the DEM maps as derived from Tables 3.10.

Table 3.10: Surface depression storage values(Fleming, 2002).

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

3.5.4 Parameter Estimation Using Soil Database

The maximum infiltration rate was determined as the upper limit of the rate of water entry from surface storage into the soil (Saxton and Willey, 2006). The values for maximum infiltration rate were obtained based on the soil analysis in the catchment and represent the saturated hydraulic conductivity taken from Table 3.11.

Soil water storage was taken as the porosity in Table 3.11, which is the available space that water can occupy in the soil or in the other case the total storage of water available in the soil profile. Tension storage, which is the upper soil layer parameter values, was obtained from Soil-Plant-Air-Water (SPAW) computer software (6.02.75, United States Department of Agriculture-USDA, Washington, DC, USA) (Saxton and Willey, 2006) by considering it as the field capacity of the soil based on the soil texture and organic matter data from FAO values(See figure 3.13 as an example). To estimate these parameters initial values respectively, multiplying the depth of the soil layer by the porosity and field capacity respectively as shown in the equation (3.10) and (3.11):

$$\text{Soil profile storage} = \text{Porosity} * \text{Soil depth} \tag{3.10}$$

$$\text{Tension zone storage} = \text{Field capacity} * \text{Soil depth} \tag{3.11}$$

Where: The soil depth of the upper layer of the catchment was 300m as taken from FAO soil database.

The soil percolation rate and the first groundwater layer (GW1) percolation rate were chosen as the average hydraulic conductivity of all sub-basins as obtained from SPAW software based on soil texture and organic matter data from FAO (Singh and Jain, 2015).

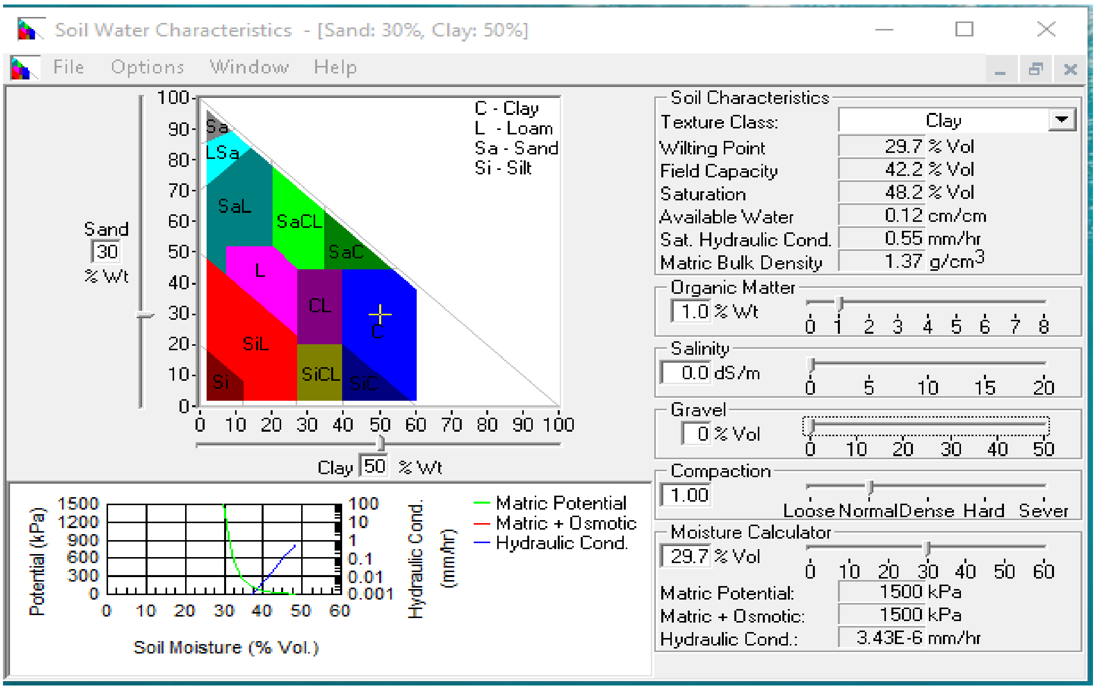


Figure 3.13 The SPAW program used to calculate the Soil Water Characteristics.

Table 3.11: Soil textures and properties taken from SPAW and(Rawls *et al*., 1982).

According to **(**Rawls *et al*., 1982**)**			Taken from SPAW	
Soil Texture	Porosity (cm^3/cm^3)	Saturated hydraulic conductivity (mm/hr)	Field capacity (%)	Hydraulic conductivity (mm/hr)
Clay	0.475	0.6	42.2	0.55
Silty clay	0.479	0.9	41.9	0.73
Loam	0.463	13.2	24.9	9.3
Sandy clay loam	0.398	4.3	26.9	3.6
Sandy loam	0.453	25.9	15.8	23.2
Sandy clay	0.43	1.2	36.4	0.53

3.5.5 Parameter Estimation Using Streamflow Recession Analysis

Storage coefficients and depths of GW1 and GW2 were estimated based on a stream flow recession analysis method of historical flow data suggested by (Fleming, 2002). The values of the percolation rate of GW2 were obtained during the calibration process. Hydrographs for four independent storms events for the Wabe River at outlet were analyzed for this process. A typical hydrograph can be divided into three parts: rising limb, peak, and falling limb, or recession. The recession curve or the depletion curve represents the water withdrawal from the basin storage. Streams convey stored water from three different sources: stream channels, surface soil (interflow), and groundwater. The tail-end of the receding limb represents the time when groundwater is the only source contributing to streamflow, as both surface runoff and interflow have stopped as stated by (Linsley *et al.*, 1975). There should be an inflection point visible in this area of the graph to help you identify the correct portion of the hydrograph. To estimate the recession coefficient and groundwater storage for GW1 and GW2 layer from GW1 recession curve and Streamflow hydrograph respectively by using the following function (Fleming and Neary, 2004).

$$Qt = Qo * Kr = Qo * e^{-\alpha t} \quad (3.12)$$

$$\alpha = -\ln Kr \quad (3.13)$$

where Q_o is initial streamflow, Q_t is the stream flow at the time t and K_r is a recession constant for the period between time 0 and time t. (Linsley *et al.*, 1975) propose a one day time interval for streamflow recession analysis. The storage coefficient was calculated as:

$$\text{Storage coefficient} = \frac{1}{\alpha} \quad (3.14)$$

Then calculate the groundwater storage (St) using equation (3.15).

$$St = \frac{Qt}{\alpha} * A \quad (3.15)$$

Where: A is the area of the watershed.

Figure 3.14 shows the principle how to break up a streamflow hydrograph into its various components and calculate the groundwater 1 and 2 storage and coefficient.

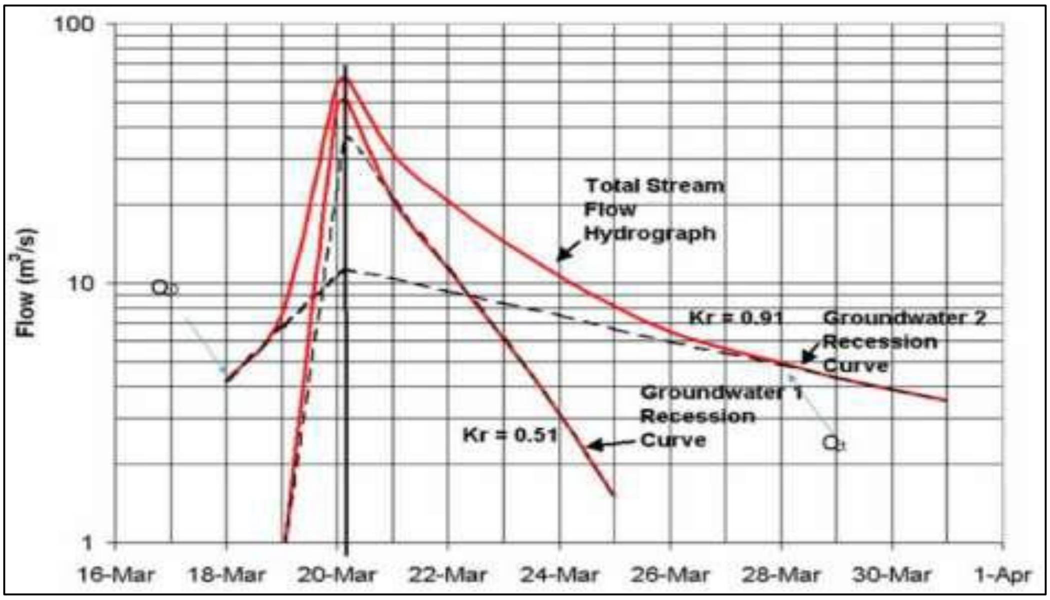


Figure 3. 14 Principle of the Streamflow Recession Analysis (Ahbari *et al.*, 2018).

Four selected storm events for four different seasons and years were analyzed at this stage (see Figure 3.15 as an example).

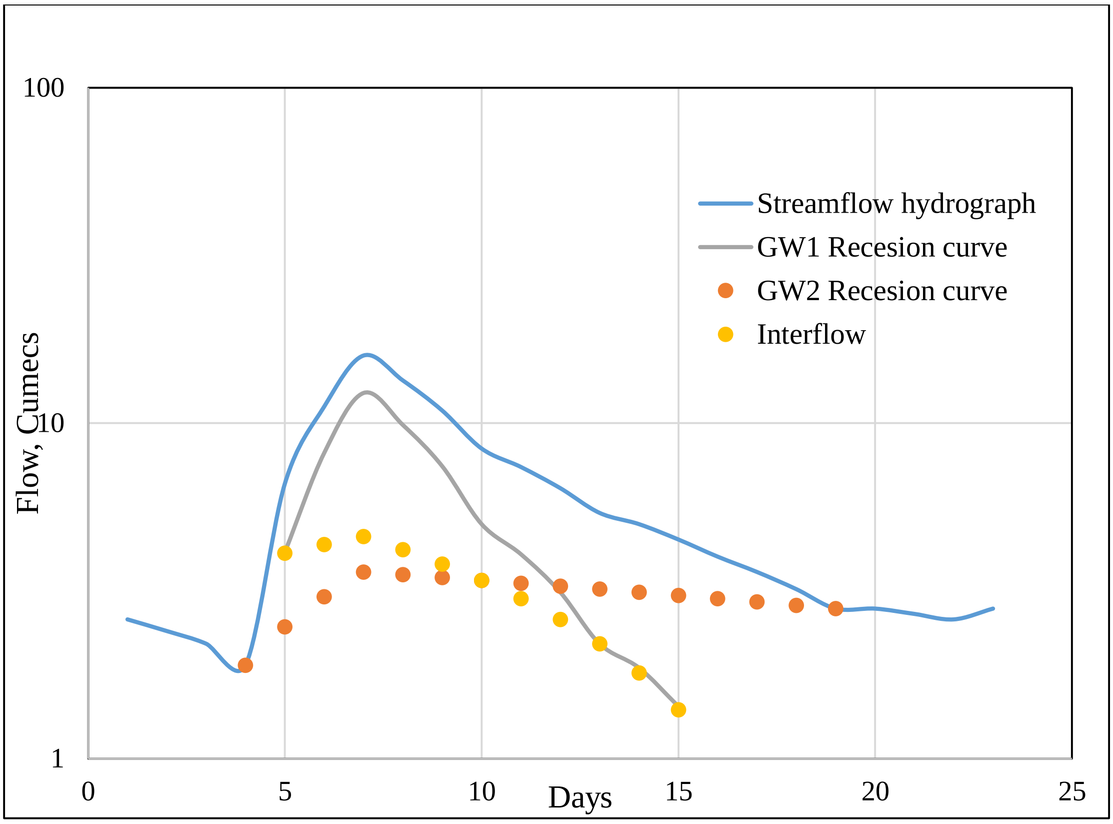


Figure 3.15 Storm Event 1 graph decomposition for stream flow recession's analysis.

Based on these four estimates, average groundwater recession coefficients and maximum storage values were obtained for the GW2 and GW1. Table 3.12 summarizes the calculation results for the Wabe River GW2 and GW1 parameter estimation.

Table 3.12: Streamflow Recession Analysis.

Event Nº	Month	Ground water 2			Ground water 1		
		Kr	maximum storage(mm)	storage coefficient(hr)	Kr	maximum storage(mm)	storage coefficient(hr)
1	Jun-99	0.87	0.33	55.28	0.76	0.013	28.69
2	Jul-96	0.75	5.3	165	0.45	0.213	58.54
3	Nov-04	0.88	0.2	92	0.66	0.17	35.23
4	Aug-92	0.91	12.5	273.76	0.72	0.339	73.69
Basin average		-	4.58	146.51	-	0.183	49

3.6 Development of HEC-HMS Basin Model

Hydrologic Engineering Center- Hydrologic Modelling System (HEC-HMS) is the physically based and conceptual semi distributed model designed to simulate the rainfall-runoff processes in a wide range of geographic areas such as large river basin, water supply and flood hydrology to small urban and natural watershed runoff (Mokhtari *et al.*, 2016). It is widely applied in rainfall-runoff simulation by taking losses, direct runoff, metrological, base flow and river routing and reservoir component into account. For rainfall-runoff modeling, HEC-HMS requires Back ground map file of the study area, Basin model file, Gage file, Subbasin parameter and Meteorological model file. These all input data's for HEC-HMS basin model was prepared by two major processes. These are terrain preprocessing and hydrologic processing. Arc Hydro Tools did terrain preprocessing. While, hydrologic processing was done by using HEC-GeoHMS tools. They were performed using procedures provided in HEC-GeoHMS User's (Fleming and Doan, 2013) and studies done by (Erşahin, 2020, Merwade, 2012).

3.6.1 Terrain Preprocessing: Arc Hydro Tool

Terrain preprocessing is delineation of watershed using existing DEM. Before carrying out terrain pre-processing, the input terrain data DEM was refined using DEM reconditioning. Then, the DEM was preprocessed in Arc Hydro to derive sub-basins and drainage network of the catchment. It must be competed in sequential order before any HEC-GeoHMS processing functions can be processed. The main steps included are fill sinks, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid delineation, catchment polygon processing, drainage line processing, adjoint catchment and drainage point processing and slope to delineate basin. The results in raster and vector format from terrain preprocessing were used for subbasins and reach network delineation by HEC-GeoHMS. The step by step results of terrain preprocessing was attached in Appendix-C.

3.6.2 Hydrologic Processing: HEC-GeoHMS

HEC-GeoHMS has been developed as a geospatial hydrology tool kit for engineers and hydrologist. The program is an extension of Arc GIS and allows users to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate subbasins and streams, construct inputs to hydrologic models, and assist with report preparation. Using HEC-GeoHMS eight data sets can be derived from DEM that collectively describe the drainage patterns of the watershed (Fleming and Doan, 2013). This includes basin slope, river slope, river length, longest flow path, basin lag time, SMA parameter estimation and time of concentration. HEC-GeoHMS consists of different menus that provide different functions specially, during preprocessing in Arc GIS work environment. These menus are preprocessing, project setup, basin processing, basin characteristics, basin parameters, HMS and utility, etc. (Figure 3.16).

The following steps taken from (Merwade, 2012). Those were used to extract the basin model: (1) Data collection such as DEM, soil and land use/cover; (2) data assembly; (3) terrain preprocessing. For this study, this latter part which means the terrain preprocessing step was processed by using Arc Hydro Tools; (4) Hydrologic Modelling System (HMS) Project Setup: The input files for the HEC-HMS project were developed using the HMS project set up menu in HEC-GeoHMS, this helps to copy all the terrain preprocessing data to the HEC-HMS project; (5) basin processing; (6) the extraction of basin and stream characteristics such as length, upstream and downstream elevations, and river slopes. It can help to extract the physical characteristics of sub-basins, such as longest flow path, basin centroid, centroid elevation, centroidal longest flow lengths, and basin slopes. To calculate basin slope, watershed slope was required which was calculated using Arc Hydro tool; (7) the estimation of hydrologic parameters, such as the SMA parameters, surface storage, lag time and time of concentration initial values were estimated using HEC-GeoHMS model processing; (8) the creation of HMS model files, such as background shape file, the basin model, meteorological model file, gage file and a project file; (9) the utility menu also used to develop gage weight (Thiessen polygon) file. As every sub-basin has no observation station within it, the precipitation values for each sub-basin were then estimated by the most commonly used Thiessen Polygon method and weights were worked out in HEC-GeoHMS software (see the figure 3.8 in areal precipitation).

After the successful completion of HEC-GeoHMS processing indicated on figure 3.16, a background shape file consists of Basin model file, Met model file and Gage model file together with watershed hydrologic elements were exported to HEC-HMS to use as an input file for further analysis (Figure 3.17).

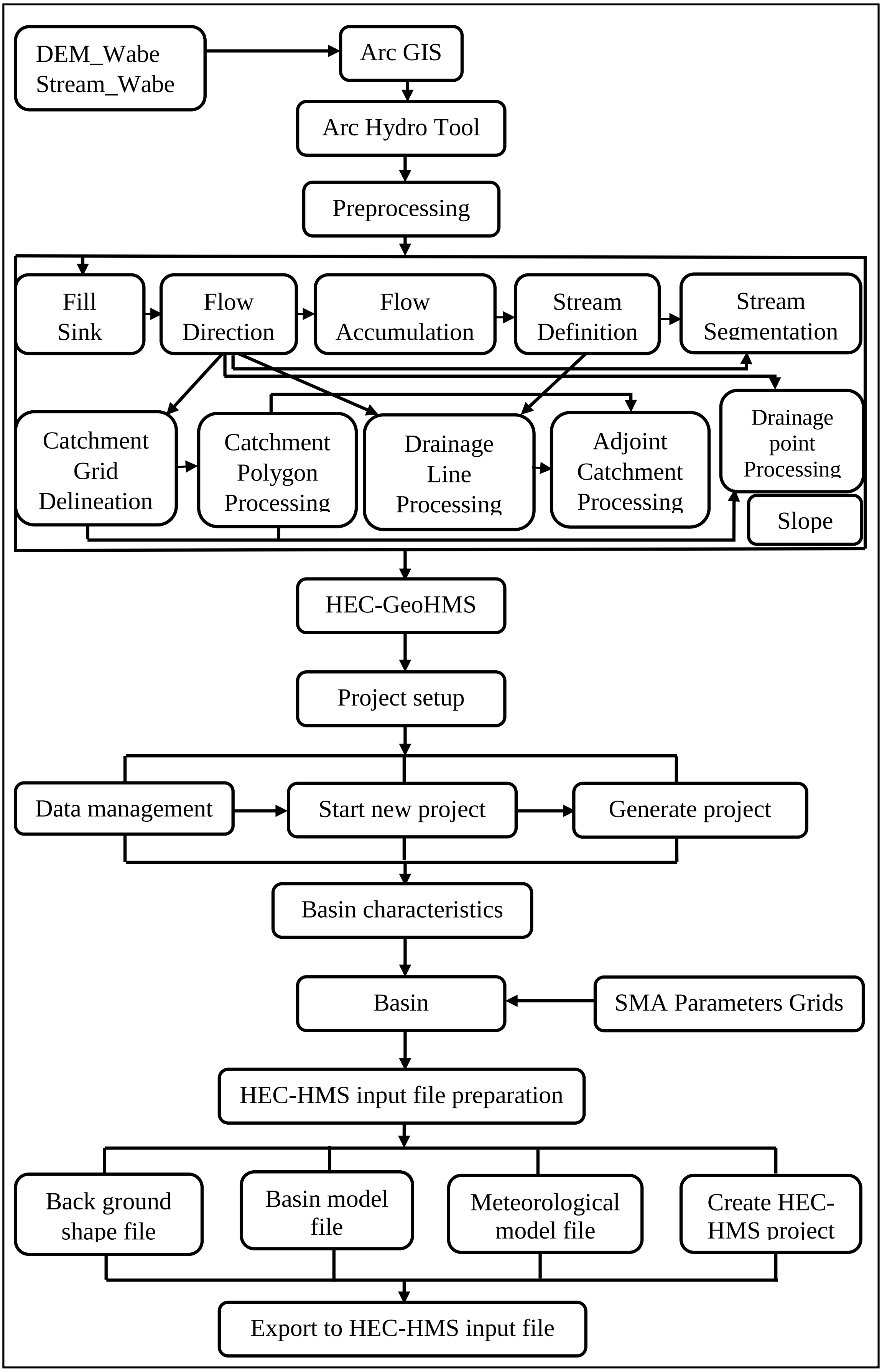


Figure 3.16 HEC-HMS input data preparation work flow diagram.

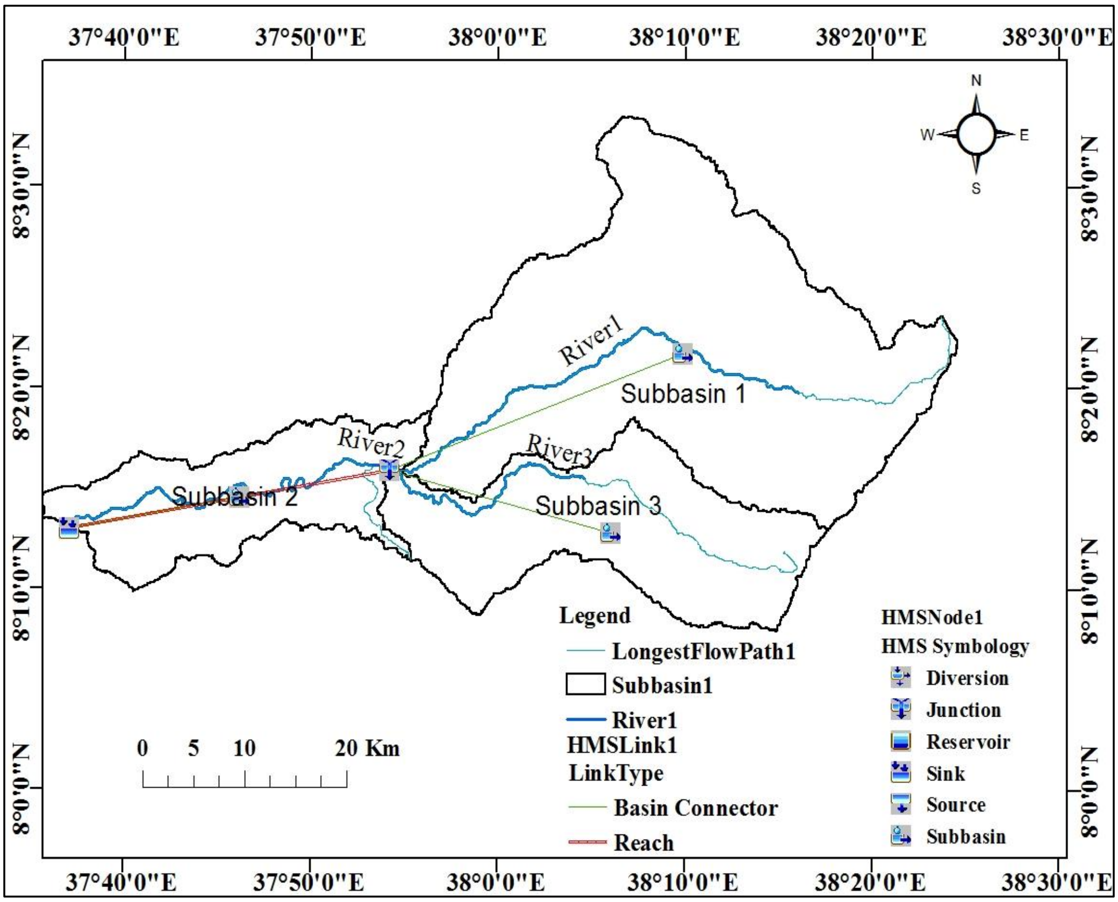


Figure 3.17 Background map file with its elements developed by HEC-Geo HMS.

3.7 HEC-HMS Model Setup

The HEC-HMS uses separate models to represent each component of the runoff process that compute runoff volume, models of direct runoff, and models of base flow. Before the model run, it must have the following four components: basin, meteorological, input data (time series, paired data, and gridded data) and control specification components. Each of these components have their own functions at each steps and they should be carried out carefully to avoid either under or over estimation of the expected result. HEC-HMS contains four main another components: (i) An analytical model to calculate overland flow runoff as well as channel routing, (ii) an advanced graphical user interface illustrating hydrologic system components with interactive features, (iii) a system for storing and managing data specifically large, time variable data sets and (iv) a means for displaying and reporting model outputs (Erşahin, 2020). Each components of the model used for this study were presented in detail as follow.

3.7.1 Basin Model

Basin models are one of the important components in HEC-HMS project set up. These models contains the hydrologic element (sub-basin, reach, junction, source, sink and reservoir) and their connectivity that represent the movement of water through the drainage system. In this research paper, only the first three components are used. The Basin model principally used to convert atmospheric conditions into stream flow at given locations in the watershed. With the input information for respective models, HEC-HMS follows four major processes for converting rainfall into runoff during the hydrologic modeling process, such as loss (i.e., loss from the total precipitation), transform (i.e. direct runoff at outlet from excess precipitation), base flow (groundwater flow as supply to the stream flow), and routing models (change in magnitude, shape and speed of flow from upstream to downstream). It has different methods for loss, transform, base flow and routing models. For this study the Soil Moisture Accounting (SMA), Clark unit hydrograph, linear reservoir, and Muskingum methods were selected for each component of the runoff process as loss, rainfall excess transform, baseflow and reach routing respectively. These methods were selected based on the purpose of the study, hydrologic modeling type, applicability and limitations of each method, availability of data, suitability for the same hydrologic condition, stability, wide acceptability, and well-established researcher recommendations.

3.7.1.1 Loss Model

The loss models in HEC-HMS normally used to determine the runoff volume by computing the volume of water that is intercepted, infiltrated, stored, evaporated, or transpired and subtracting it from the precipitation. It contains nine different loss methods, some of which are designed primarily for simulating events, while others are intended for continuous simulation. The Soil Moisture Accounting (SMA) Loss Method included in HEC-HMS was adopted to model losses combined with canopy and surface methods in continuous simulation. It uses five layers to represent the dynamics of water movement above and in the soil. The layers include canopy interception, surface depression storage, soil, upper groundwater, and lower groundwater, as shown in Figure 3.12. The canopy is a component of the sub-basin which is intended to represent the presence of plants in the area. The canopy method specified in the HEC-HMS settings is mainly used for continuous simulations. All rainfall is trapped until the maximum canopy storage which represents the maximum amount of water that can be held on leaves is filled. Subsequently, the excess precipitation falls on the soil surface after the maximum canopy storage is filled. The surface method specified in the HEC-HMS settings represents the maximum amount of water that can pond on the soil surface after the pores in the soil are filled to the soil's field capacity. The water on the surface then ponded in the depression storage until runoff begins to occur as part of the precipitation percolating deep into the groundwater zone. Runoff starts when the precipitation rate exceeds the infiltration rate of the soil and the storage in the depressions is full. The estimation of required inputs for the SMA method are presented in section 3.5. Note that the initial conditions for all methods were estimated from calibration.

3.7.1.2 The Transform Model

The transform prediction models in HEC-HMS simulate the process of the direct runoff of excess precipitation on the watershed, and they transform the precipitation excess into point runoff. The models transform the rainfall excess into direct surface runoff through a unit hydrograph, and the Clarks unit hydrograph method was used as the transform models in this study. The Clark unit hydrograph method explicitly represents two critical processes of translation of excess rainfall and attenuation due to effects of storage in the sub-basins. The parameters required for the Clark UH transform method are time of concentration and the storage coefficient. While time of concentration was estimated from the GIS processing of the basin characteristics including topography and the length, the storage coefficient was evaluated by calibration. The basic concepts and assumptions behind each unit hydrograph method can be also found in the HEC-HMS technical manual in (Feldman, 2000). According to a Kirpich method shown in Equation (3.16) and a relation shown in Equation (3.17) were also combined to apply in this study for estimating the initial values for the time of concentration and lag time in each sub-basin, which were used as input data.

$$\mathrm{TC} = 0.0195\mathrm{L}^{0.77}\mathrm{S}^{-0.385} \tag{3.16}$$

Where: TC is the time of concentration (min), L is the length of the main river (m), and S is the mean slope of the main river (m/m).

$$\mathrm{T_L} = 0.6\mathrm{TC} \tag{3.17}$$

Where: T_L is the lag time (min) and TC is the time of concentration.

3.7.1.3 A Base Flow Separation Model

While the total runoff is transformed into direct runoff, basic information in relation to base flow is required, and a linear reservoir method base flow separation technique was employed in this study which is associated with SMA (Feldman, 2000). The linear reservoir method adopted to model base flow required the following parameters:

- Groundwater 1 initial (m3/s): initial base flow at the beginning of the simulation for the first layer of groundwater.
- Groundwater 1 coefficient (h): the response time of the sub-basin as specified in the SMA model.
- Groundwater 1 reservoir is used so that the base flow is routed through several sequential reservoirs. The base flow is attenuated when the number of reservoirs is increased.

The same parameters are also defined for the second layer of groundwater.

3.7.1.4 Routing Models

Routing process helps to determine how flood wave changes its magnitude, shape, and speed at its inflow point of a watershed with time as a function. The flood routing for a watershed depends on channel roughness, length, slope, shape, flow at upstream and downstream. Hydrologic routing represents lumped routing based on the storage-outflow relationship which relates storage with inflow and outflow of a watershed (Feldman, 2000). Muskingum routing storage, inflow and outflow can be expressed as follows:

$$Q_j + 1 \;=\; C_1 I_j + 1 \;+\; C_2\, I_j \;+\; C_3\, Q_j \tag{3.18}$$

Where I_j and I_{j+1} are inflows in periods of j and j+1, respectively at the upstream end. Q_j and Q_{j+1} are discharges in periods of j and j+1, respectively at the downstream end. C_1, C_2, and C_3 are coefficients that can be derived from:

$$C1 \;=\; \frac{\Delta t - \;2KX}{2K\,(1 \;-\; X) \;+\; \Delta t} \tag{3.19}$$

$$C2 \;= \frac{\Delta t \;+\; 2KX}{2K\,(1 \;-\; X) \;+\; \Delta t} \tag{3.20}$$

$$C3 \;= \frac{2K\,(1 - \;X) \;-\; \Delta t}{2K\,(1 \;-\; X) \;+\; \Delta t} \tag{3.21}$$

Where K is the travel time of a flood wave passing through the reach, X is a measure of the degree of storage having a range of $0 \leq X \leq 0.5$, and Δt is the time interval for the simulation.

For this study the initial value of the wave travel time (k parameter) for reach was calculated from the equation 3.22. Running the model with this initial value, later the parameters was optimized.

$$K = \frac{V}{L} \tag{3.22}$$

Where: k – flood wave travel length, V – permissible velocity, L – reach length

Here the permissible velocity value should be in the range that neither causes erosion of the channel nor letting deposition of sediment. According to ERA drainage manual, this permissible velocity is classified into numerous categories depending on the channel geometry. Based on this assumption, 2.5 m/s permissible velocity was used in equation 3.22 in order to calculate the initial value of k.

3.7.2 Meteorological Models

The meteorological component is also the first computational element by means of which time series (rainfall and evaporation) data is spatially and temporally distributed over the river basin. These data are associated with rain gages that the user defines in the meteorological model. It was used to prepare meteorological boundary conditions for sub-basins and the precipitation and evapotranspiration were included for continuous modeling (Feldman, 2000).

3.7.3 Control Specification Model

The control specification defines the time period and time step of the simulation run. It controls the starting time, ending time and the time interval of the simulation. They do not contain much parameter data. Control specifications was created using a control specification manager in the components menu of the model. For this study, since the available data are daily, one day computation time step was used during model calibration and validation.

3.7.4 Time Series Data Entry Model

Input data is required as parameter or boundary conditions in basin and meteorological models. HEC-HMS model require time series meteorological data for runoff simulation and a time series of observed flow data for calibrating a model.

3.8 Sensitivity Analysis

Sensitivity analysis is a critical component of rainfall-runoff modeling that helps to identify influential parameters and parameter precision required for calibration. Some of these parameters are more sensitive than others, so that a minor change in the value can lead to a big difference between the observed and simulated flow. Thus, the most sensitive parameters of the model need to be precisely estimated in order to make accurate predictions.

To do so, the model was first run with the base data, i.e. the initial estimates obtained using the methods explained in earlier sections. Thereafter, out of the various soil moisture accounting parameters, one parameter at a time method was employed: the value of each parameter in each sub-basin was varied from -30% to +30% in increments of 10%, keeping all other parameters constant. The output values of simulated runoff data (volume, peaks, and Nash-Sutcliffe Efficiency (NSE)) were analyzed to determine variation with respect to the initial estimates of the parameters. In this study the parameters were ranked from most to least sensitive based on elasticity ratio (e) (Wałęga *et al*., 2014). The elasticity ratio is invariant to the dimensions of the variables and is given by Equation (3.23) (McCuen, 2016). A greater elasticity ratio indicates a more highly sensitive variable.

$$\mathrm{e} = \frac{\Delta\ \mathrm{O}/\mathrm{O}}{\Delta\ \mathrm{I}/\mathrm{I}} = \frac{\%\ \text{change of output}}{\%\text{change of input}} \qquad (3.23)$$

Where: O, I are the output and the input variables, respectively.

3.9 Model Calibration and Validation

Before a hydrological model can be considered to have results that are reliable, it needs to be calibrated and validated using observed stream flow. The model was calibrated for the identified sensitive parameters to evaluate the goodness of fit between the simulated and observed data, and conclude whether the model is able to predict and present credible results. Model calibration is the process of adjusting identified sensitive parameters values and other variables in the model in order to match the model outputs with the observed values. Optimization trials available with the HEC-HMS model was used for optimizing the initial estimates of the model parameters. The objective function measures the goodness-of-fit between the simulated and observed stream flow. In this Study, out of different objective functions provided in HMS optimization manager, the peak-weighted root mean square (PWRMSE) was used to get the finally optimized parameter values since, this function gives more weight to large errors than small errors and it gives a greater overall weight to errors near the volume and peak discharge. Two search methods are available in HEC-HMS model for minimizing the objective functions. Those are the Univariate gradient search Algorithm method (UG), Nelder, and Mead Algorithm method. The UG evaluates and adjusts one parameter at a time while holding other parameters constant and Nelder and Mead uses a downhill simplex to evaluate all parameters simultaneously and determine which parameter to adjust. For the present study, the peak-weighted root mean square (PWRMSE) method was used as an objective function with the Nelder-Mead method as the search method for optimization. However, the auto-calibration process in the HEC-HMS may not converge to desired optimum results, so in addition, a manual calibration was performed. After the model is calibrated, the model must be validated for another dataset without changing the optimized parameters to estimate the accuracy of the model.

3.10 Model Performance Evaluation

In general, the model should have to be reproduce observed peaks, time, and volume. The objective of calibration is to minimize the difference between simulated values and observed (measured) values. While a visual inspection is often a first pass in calibration the statistical methods are more than meets the eye. A good model efficiency criterion have at least three important components: one dimensionless statistic, one absolute error index statistic and one graphical technique as recommended by (Moriasi *et al*., 2007).

In this study, to assessing the goodness of fit in the observed and simulated stream flow, the HEC-HMS model performance was evaluated using the following statistical evaluation criteria:

1. Percentage Error in simulated volume (PEV)

$$PEV = \left[\frac{Vol_o - Vol_s}{Vol_o}\right] x\, 100 \tag{3.24}$$

Where: Vol_o, Vol_s are the observed and simulated volumes, respectively

2. Percentage error in simulated peak Flow (PEPF)

$$PEPF = \left[\frac{Q_{o(peak)} - Q_{s(peak)}}{Q_{o(peak)}}\right] x\, 100 \tag{3.25}$$

Where: $Q_{o(peak)}$, $Q_{s(peak)}$ are the observed and simulated flows, respectively.

3. Coefficient of determination (R^2)

$$R^2 = \left[\frac{\sum_{i-1}^{n}(Y_i^{obs} - \overline{Y}^{obs})(Y_i^{sim} - \overline{Y}^{sim})}{\sqrt{\sum_{i-1}^{n}(Y_i^{obs} - \overline{Y}^{obs})^2}\sqrt{\sum_{i-1}^{n}(Y_i^{sim} - \overline{Y}^{sim})^2}}\right]^2 \tag{3.26}$$

4. Nash-Sutcliffe model Efficiency given by:

$$NSE = 1 - \left[\frac{\sum_{i-1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i-1}^{n}(Y_i^{obs} - \overline{Y}^{obs})^2}\right] \tag{3.27}$$

5. The absolute error index represented by the Root Mean Squared Error (RMSE)-standard deviation ratio (RSR) of observations given by:

$$RSR = \frac{RSME}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i-1}^{n}(Y_i^{obs} - Y_i^{sim})^2}\right]}{\left[\sqrt{\sum_{i-1}^{n}(Y_i^{obs} - \overline{Y}^{obs})^2}\right]} \tag{3.28}$$

6. Percent Bias (PBIAS): measures the average tendency of the simulated data to be larger or smaller than the observed data.

$$PBIAS = \left[\frac{\sum_{i-1}^{n}(Y_i^{obs} - Y_i^{sim})\ x\ 100}{\sum_{i-1}^{n}(Y_i^{obs})}\right] \tag{3.29}$$

Where: Y_i^{obs} is the i^{th} observation for the constituent being evaluated, Y_i^{sim} is the i^{th} simulated value constituent being evaluated, $\overline{Y}^{obs}$ is the mean observed data for the constituent being evaluated, $\overline{Y}^{sim}$ is the mean of simulated data for the constituent being evaluated and n is the total number of observations.

Once the performance metrics are calculated, the model is assigned a performance rating for each matric based on the Table 3.13.

Table 3.13: Performance ratings for recommended statistics (Moriasi *et al.*, 2007).

Performance Ratings	PEV(%)	PEPF(%)	R^2	NSE	RSR	PBIAS
Very Good	< ±10	< 15	$0.75<R^2\leq1$	0.75<NSE≤1	0<RSR≤0.6	PBIAS< ±15
Good	±10-±15	15 to 30	$0.65<R^2\leq0.75$	0.65<NSE≤0.75	0.6<RSR≤0.7	±15≤PBIAS< ±20
Satisfactory	±15- ±25	30 to 40	$0.5<R^2\leq0.65$	0.5<NSE≤0.65	0.7<RSR≤0.8	±20≤PBIAS< ±30
Unsatisfactory	>±25	>40	$R^2\leq 0.5$	NSE≤0.5	RSR>0.8	PBIAS≥±30

3.11 Flood Frequency Analysis

Flood frequency analysis is the most important statistical technique used to predict design floods for sites along a river to minimize flood hazards and increases safety of structures. There are different ways of flood prediction.

3.11.1 Flood Frequency Analysis by using probability distribution function

There are a variety of statistical distribution functions that can be used to forecast floods caused by extreme events. Using the Easy Fit 5.6 professional software, the best-fit statistical distribution function was determined. It assigns the rank of each statistical distribution based on the annual maximum stream flow data (Table 3.14). Based on the rank of goodness of fit tests like Kolmogorov Smirnov, Anderson Darling and Chi-Squared; the General Pareto distribution (GDP) and General Extreme Value (GEV) distributions are selected to calculate the probability of exceeding flood streamflow.

Table 3.14 Goodness of fit test result by Easy fit 5.6 professional software.

No	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.10734	2	0.40465	2	1.018	4
2	Gen. Pareto	0.1048	1	0.27619	1	0.33343	1
3	Log-Pearson 3	0.12944	3	0.4251	3	0.80751	2
4	Lognormal	0.13499	4	0.46733	4	0.90412	3
5	Lognormal (3P)	0.16349	6	0.48389	5	1.0822	5
6	Normal	0.13932	5	0.57646	6	1.4584	6

The probability distributions selected for these studies and their essential properties are discussed below:

A) Generalized Pareto Distribution (GPD)

The generalized Pareto distribution is a special case of the Wakeby distribution. It allows a continuous range of possible shapes that includes both the exponential and Pareto distributions as special cases (Hamed and Rao, 2019). The general equation for the Probability and Cumulative Distribution Function of the GPD are:

$$f(x) = \begin{cases} \frac{1}{\delta}\left(\frac{1}{\delta}\left(1 + k\frac{(x-\mu)}{\delta}\right)\right)^{-1-1/k} & k \neq 0 \\ \frac{1}{\delta}\exp\left(-\frac{(x-\mu)}{\delta}\right) & k = 0 \end{cases} \quad (3.30)$$

$$F(x) = \begin{cases} 1 - \left(1 + k\frac{(x-\mu)}{\delta}\right)^{-\frac{1}{k}} & k \neq 0 \\ 1 - exp\left(-\frac{(x-\mu)}{\delta}\right) & k = 0 \end{cases} \quad (3.31)$$

The recurrent period flood computation is given by:

$$XT = \mu - \frac{\delta}{k}(1 - T^k) \quad (3.32)$$

Where: $k -$ Continuous shape parameter, $\delta -$ continuous scale parameter($\delta > 0$), $\mu -$ continuous location parameter and return period.

B) General Extreme Value (GEV) distributions

The GEV distribution is usually fitted using the method of maximum likelihood, or the method of L-moment that is used frequently in hydrological application. The GEV distribution that is widely recommended for flood frequency analysis as it has the probability density function and cumulative distribution function. It is broadly applied in earth system sciences and hydrology to study extremes of several natural phenomena, including RF, streamflow, wind speeds, wave heights and others (Hamed and Rao, 2019). The general equation for the Probability and Cumulative Distribution Function of the GEV distribution are:

$$f(x) = \begin{cases} \frac{1}{\delta}\exp\left(-(1+kz)^{-1/k}\right)(1+kz)^{-1-1/k} & k \neq 0 \\ \frac{1}{\delta}\exp\left(-z - \exp(-z)\right) & k = 0 \end{cases} \quad (3.33)$$

$$F(x) = \begin{cases} exp\left(-(1+kz)^{-\frac{1}{k}}\right) & k \neq 0 \\ exp(-exp(-z)) & k = 0 \end{cases} \quad (3.34)$$

Where: $z \equiv \frac{x-\mu}{\delta}$,

The recurrent period flood computation is given by:

$$XT = \mu - \frac{\delta}{k}\left[1 - \left\{-log\left(1 - \frac{1}{T}\right)\right\}^{-k}\right] \quad (3.35)$$

Where: $k -$ Continuous shape parameter, $\delta -$ continuous scale parameter($\delta > 0$), $\mu -$ continuous location parameter and return period.

After a distribution (or a set of distributions) is chosen to match the data series, the parameters of such distributions must be estimated. The parameters of a mathematical model can be estimated using a number of methods. The method of moments, the maximum likelihood method, least squares, the probability weighted moments method (PWM), maximum entropy, mixed moments (MIX), the generalized method of moments, and the incomplete means method are examples of these methods. Maximum Likelihood Moments is used to estimate parameters in this analysis (using Easy fit Application Tool) as provided in Table 3.15.

Table 3.15 Statistical Parameters for selected distribution methods.

No	Distribution	Parameters
1	Gen. Extreme Value	k=-0.0573 σ=164.56 μ=351.97
2	Gen. Pareto	k=-0.5285 σ=419.25 μ=163.81
3	Log-Pearson 3	α=1617.6 β=-0.01097 γ=23.738
4	Lognormal	σ=0.4306 μ=5.9921
5	Lognormal (3P)	σ=0.64018 μ=5.5882 γ=115.98
6	Normal	σ=187.37 μ=438.1

3.11.2 Flood Frequency Analysis by using HEC-HMS model

The Frequency storm method is a meteorological method used in meteorological model of HEC-HMS to estimate flood frequency from given statistical precipitation data. The method needed probability, intensity duration, storm duration, intensity position, storm area, and rainfall depth. Flood frequency analysis was carried out for this study using rainfall depths of 2, 5, 10, 25, 100, 200 and 500 years of return periods.

The storm rainfall depth used for this study area is obtained from the rainfall intensity-duration frequency curves. So, to obtain the watershed-wide intensity–duration–frequency (IDF) curves over the study area, the annual maximum daily rainfall events were identified for 31 years of observation (1985 – 2016) using rain gauges inside and around the study area. Consequently, the watershed-average rainfall values were calculated using the widely used Thiessen polygon method for mapping the maximum annual rainfall event. Then, the best probability distribution function was fitted to the spatially averaged maximum daily rainfalls using the Easy Fit 5.6 professional software. Based on the Kolmogorov and Anderson–Darling (AD) goodness-of-fit test, the generalized extreme value (GEV) distributions were determined as the best probability distributions of daily rainfall depths. Also, the parameters of each distribution were obtained via Maximum Likelihood Estimation (MLE) method (Table 3.17).

Table 3.16: Goodness of fit test result by Easy fit 5.6 software from rainfall event.

N$^{\underline{0}}$	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.07962	1	0.214	1	0.25744	3
2	Gen. Pareto	0.11849	5	4.2538	6	N/A	
3	Log-Pearson 3	0.08171	2	0.24966	3	0.21394	1
4	Lognormal	0.09251	4	0.31153	4	1.9524	4
5	Lognormal (3P)	0.0827	3	0.22133	2	0.25373	2
6	Normal	0.15193	6	1.0925	5	7.9409	5

Table 3. 17: Statistical Parameters for selected distribution methods.

N$^{\underline{0}}$	Distribution	Parameters
1	Gen. Extreme Value	k=0.11132 σ=8.3973 μ=36.741
2	Gen. Pareto	k=-0.21674 σ=17.593 μ=28.161
3	Log-Pearson 3	a=6.5663 β=0.10322 γ=3.0383
4	Lognormal	σ=0.26033 μ=3.716
5	Lognormal (3P)	σ=0.46976 μ=3.0894 γ=18.061
6	Normal	σ=12.814 μ=42.62

The values of watershed-average 24hr rainfall depths with different return periods are computed by using the generalized extreme value (GEV) distributions as (equation 3.35) above, which is presented in Table 3.18. As a result, the rain fall depth for each return period for the selected time interval of my analysis was calculated using the equation (3.36) below, which took the 24hr maximum rainfall depth developed for the study area, which is known as a rainfall intensity-duration-frequency(IDF) relationship.

$$R_{Rt} = \frac{t(b + 24)^n}{24(b + t)^n} \tag{3.36}$$

Where: R_{Rt}= Rainfall depth Ratio Rt: R24, Rt= Rainfall depth in a given duration t, R_{24}= 24 hr rainfall depth, and **b** and **n** = coefficients b=0.3 and n= (0.78-1.09).

Table 3.18: 24 hr rainfall depths (mm) vs. return periods (year) (source: own work).

N⁰	Return period (year)	Daily rainfall depth (mm)
1	2	47.53
2	5	59.12
3	10	67.64
4	25	79.48
5	50	89.11
6	100	99.44
7	200	110.56
8	500	126.61

3.12 General Framework of the Research

Data input, process and analysis were the general procedures followed to achieve the objectives of this study. The overall framework of the methodology followed from data collection and analysis to the results, throughout the study is shown in Figure 3.18.

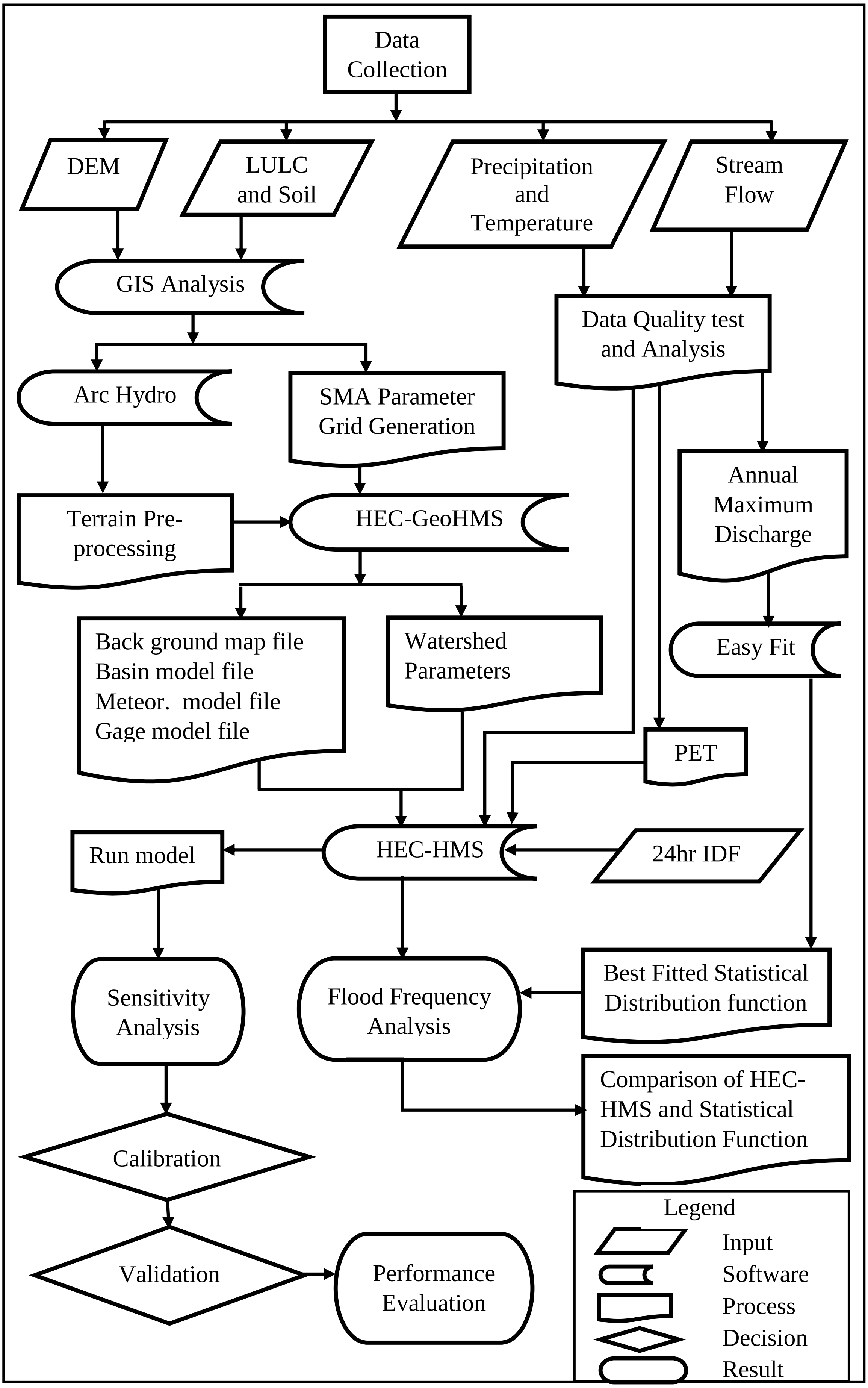


Figure 3.18 General schematic representations of work flow diagram for the study.

4. RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Physiographic Characteristics of the Watershed

The outlet point of the watershed (the geographical reference point of the hydrological gauging station) was considered in this study to delineate the boundary of the watershed area using the HEC-GeoHMS extension in ArcGIS. Further processing of the DEM using HEC-GeoHMS also resulted in generating three sub-basins, one routing reaches, and the major physiographic characteristics of the watershed, which is collectively known as the Background map file as shown in Figure 4.1 and Table 4.1.

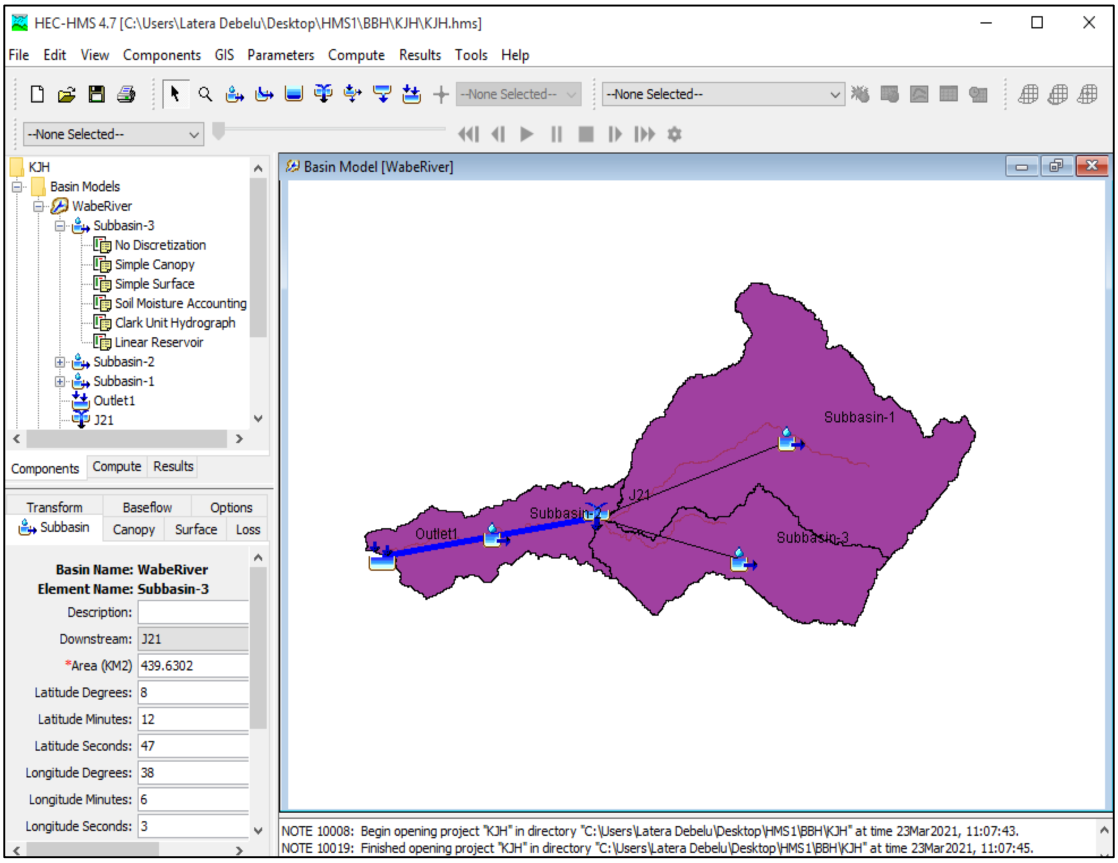


Figure 4.1 Background map file of Wabe catchment.

Table 4.1: physiographic characteristics of the Wabe catchment.

	Area	Perimeter	Basin Slope	Main River Flow	
Sub-Basin	(km2)	(m)	(%)	Flow Length(m)	Slope(m/m)
Sub-Basin 1	1030.16	267060	24.58	52670.73265	0.01703
Sub-Basin 2	312.54	172320	17.42	43615.848455	0.015637
Sub-Basin 3	439.63	186420	25.62	28097.440456	0.011211

4.1.2 Sensitivity Analysis

One of the objectives of this research study is to perform a sensitivity analysis of the HEC-HMS model with the soil moisture accounting SMA parameters. In this study, the sensitivities of thirteen SMA parameters (except the five initial conditions for the five storage layers in the SMA model) were investigated by varying each parameter by 10% increments from -30 to +30 percent. This sensitivity analysis was carried out using a one parameter at a time approach, in which one parameter was changed while the others remained unchanged. The percentage of variation in simulated volume, peak, and Nash-Sutcliffe Efficiency (NSE) were plotted against the percentage of variation of each parameter, as shown in Figures 4.2-4.4.

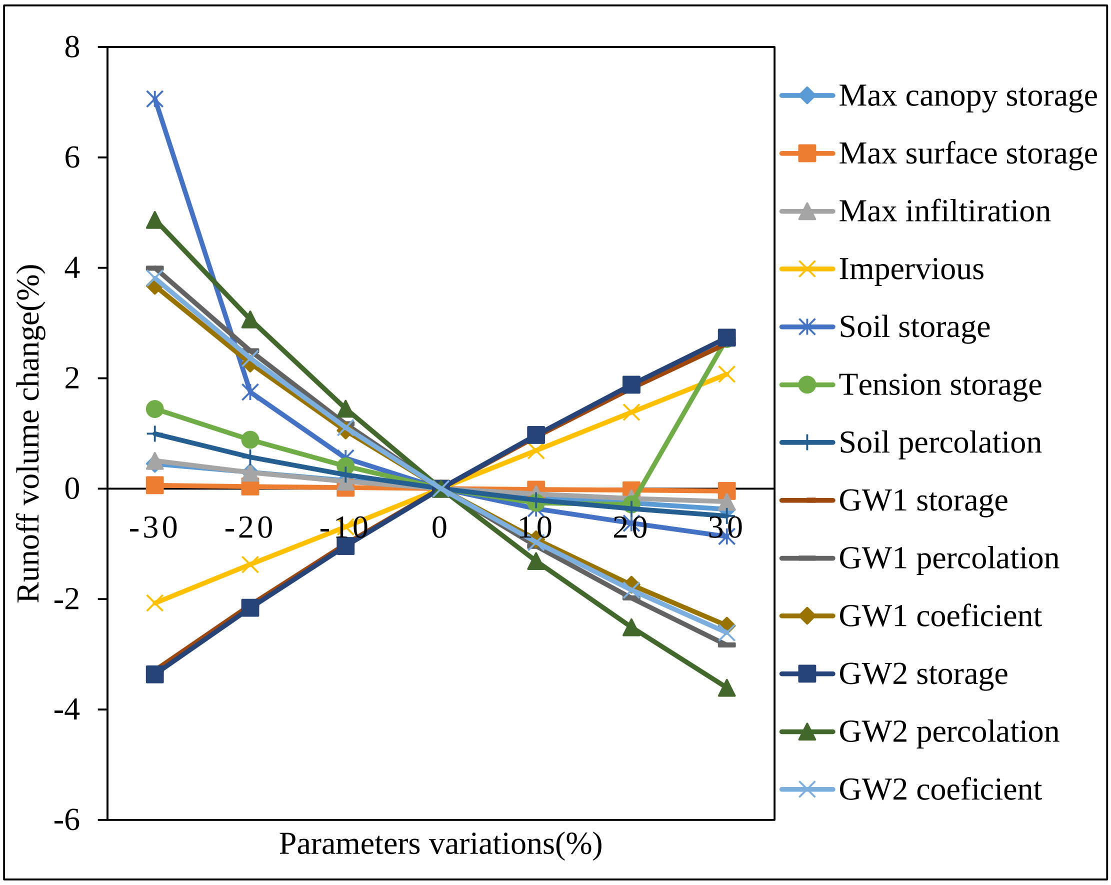


Figure 4.2 Percentage changes in simulated volume plotted against the percentage variation of each parameter.

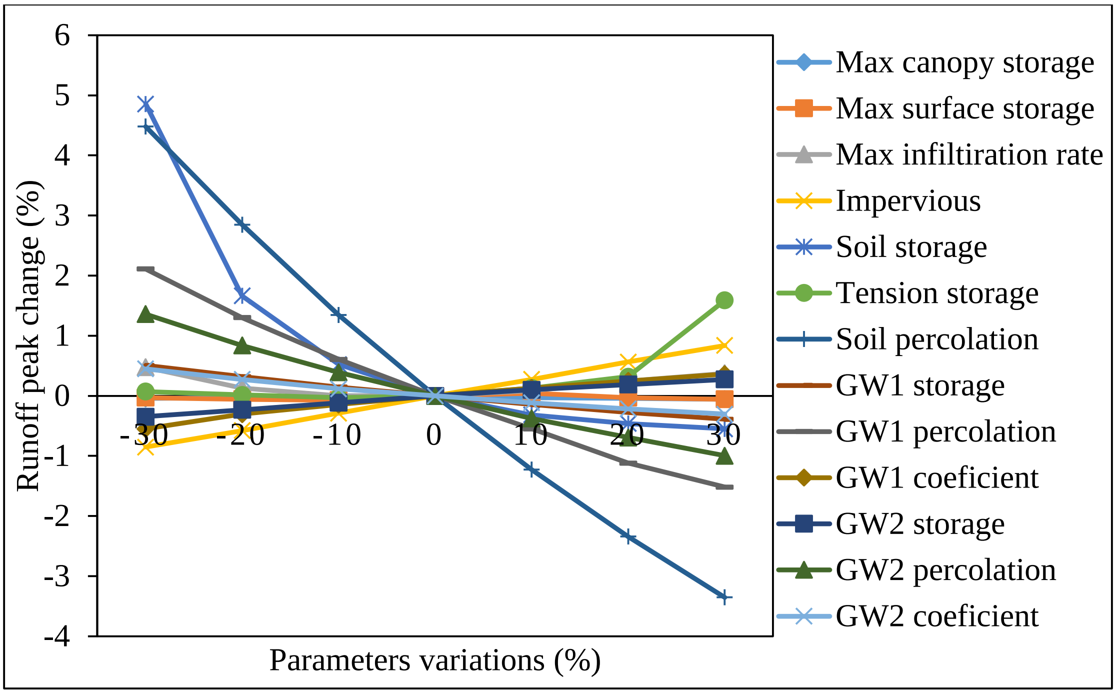


Figure 4.3 Percentage changes in simulated Peak flow plotted against the percentage variation of each parameter.

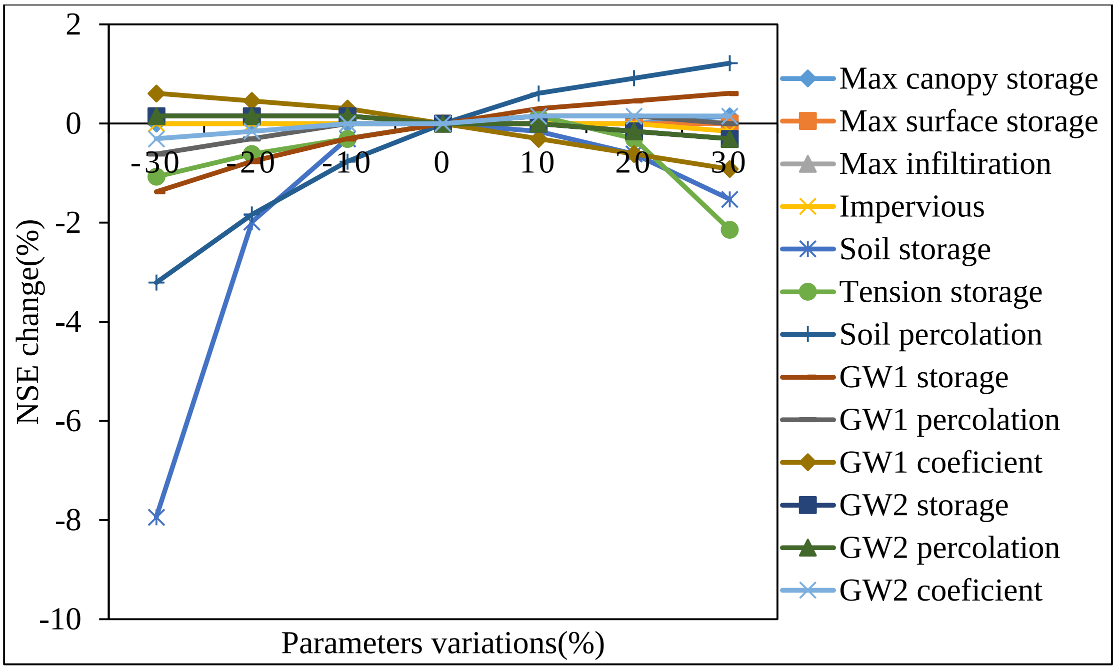


Figure 4.4 Percentage changes in simulated NSE plotted against the percentage variation of each parameter.

After analyzing the elasticity of the different parameters, they were ranked from the most to the least sensitive. The sensitivity analysis was done to determine the sensitivity of the computed runoff volume, the computed peak, and the Nash-Sutcliffe to the SMA model parameters. The runoff volume was found to be more sensitive to the GW2 percolation rate, GW1 percolation rate and GW2 storage coefficient (Table 4.2). The runoff peak was found to be more sensitive to the soil percolation rate, soil storage, GW1 percolation rate, and GW2 percolation rate (Table 4.3). Finally, the Nash-Sutcliffe Efficiency was found to be more sensitive to soil storage, soil percolation, and tension storage respectively (Table 4.4). However, evaluation of this parameter requires close observation and field surveys for accurate determination, which could not be obtained in this study due to fund constraints. However, each parameter has a different effect on the components of total discharge (runoff, interflow, and baseflow), which may be further explored in future research.

Table 4.2: Ranking sensitivity of SMA parameters for runoff volume.

Rank	Parameter Average	Elasticity Ratio
1	GW 2 percolation (mm/h)	0.14
2	GW 1 percolation (mm/h)	0.11
3	GW 2 coefficient (h)	0.11
4	GW 2 storage (mm)	0.10
5	GW 1 coefficient (h)	0.10
6	GW 1 storage (mm)	0.10
7	Soil storage (mm)	0.10
8	Impervious (%)	0.08
9	Tension storage (mm)	0.07
10	Soil percolation (mm/h)	0.04
11	Max canopy storage (mm)	0.01
12	Max infiltration rate (mm/h)	0.01
13	Max surface storage (mm)	0.00

Table 4.3: Ranking sensitivity of SMA parameters for runoff peaks.

Rank	Parameter Average	Elasticity Ratio
1	Soil percolation (mm/h)	0.13
2	Soil storage (mm)	0.06
3	GW 1 percolation (mm/h)	0.06
4	GW 2 percolation (mm/h)	0.04
5	Impervious (%)	0.03
6	GW 1 storage (mm)	0.01

7	Tension storage (mm)	0.01
8	GW 1 coefficient (h)	0.01
9	GW 2 coefficient (h)	0.01
10	GW 2 storage (mm)	0.01
11	Max infiltration rate (mm/h)	0.01
12	Max surface storage (mm)	0.00
13	Max canopy storage (mm)	0.00

Table 4.4: Ranking sensitivity of SMA parameters for NSE.

Rank	Parameter Average	Elasticity Ratio
1	Soil storage (mm)	0.08
2	Soil percolation (mm/h)	0.07
3	Tension storage (mm)	0.03
4	GW 1 storage (mm)	0.03
5	GW 1 coefficient (h)	0.03
6	GW 2 percolation (mm/h)	0.01
7	GW 1 percolation (mm/h)	0.01
8	GW 2 storage (mm)	0.01
9	GW 2 coefficient (h)	0.01
10	Max infiltration rate (mm/h)	0.01
11	Impervious (%)	0.00
12	Max canopy storage (mm)	0.00
13	Max surface storage (mm)	0.00

4.1.3 Model Calibration and Validation

4.1.3.1 Model Calibration

The HEC-HMS model calibration was done by adjusting model parameters manually to match the simulated with observed flow data from the Wabi gauging station for the period 1987 to 1999. The calibration was started using the initial values that were also used for sensitivity analysis. These values were manually modified until a good agreement between the simulated and observed streamflow was obtained. The best fit of hydrograph was evaluated using visualization and computed statistics values. The comparison of observed and simulated streamflow graphs is shown in Figure 4.5 for the calibration period (1987 to 1999).

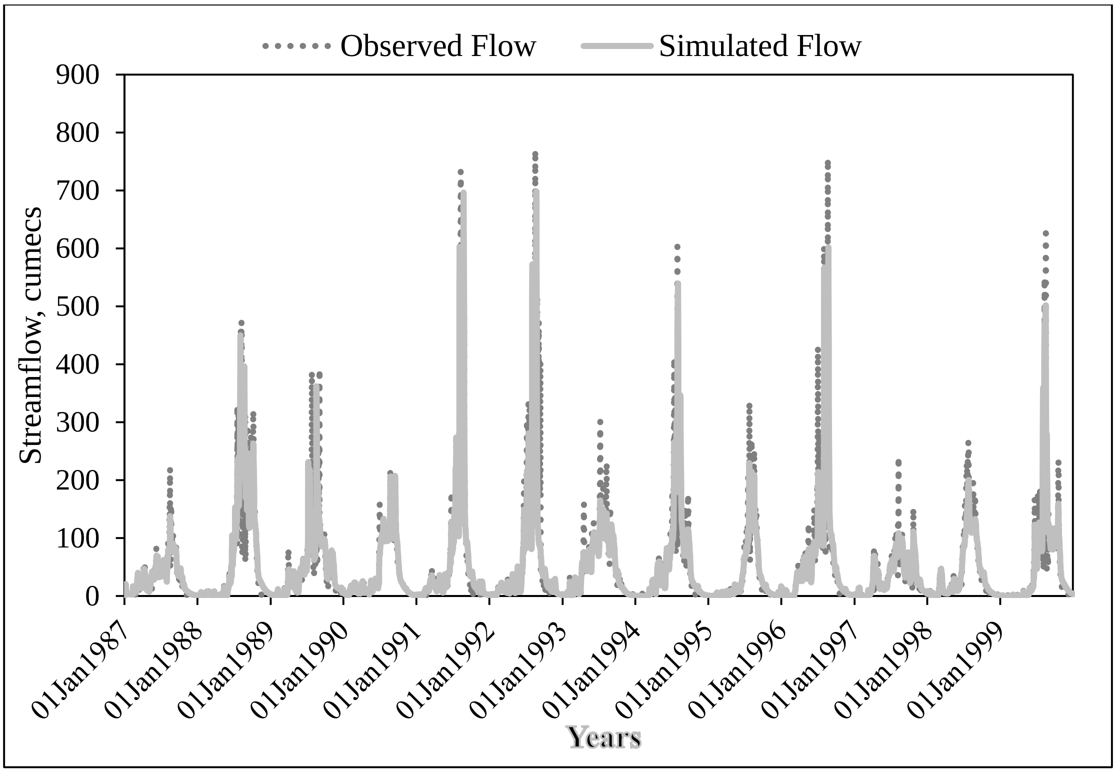


Figure 4.5 Daily observed and simulated streamflow during the calibration period.

The comparison shows a close agreement between simulated streamflow and observed streamflow in terms of timing of peak and peak value, streamflow distribution, and rising and recession of streamflow. To obtain a closer agreement between the simulated and observed streamflow, various parameters were optimized during calibration. Table 4.5 shows the initial parameters estimated and optimized parameters after calibration for the study area.

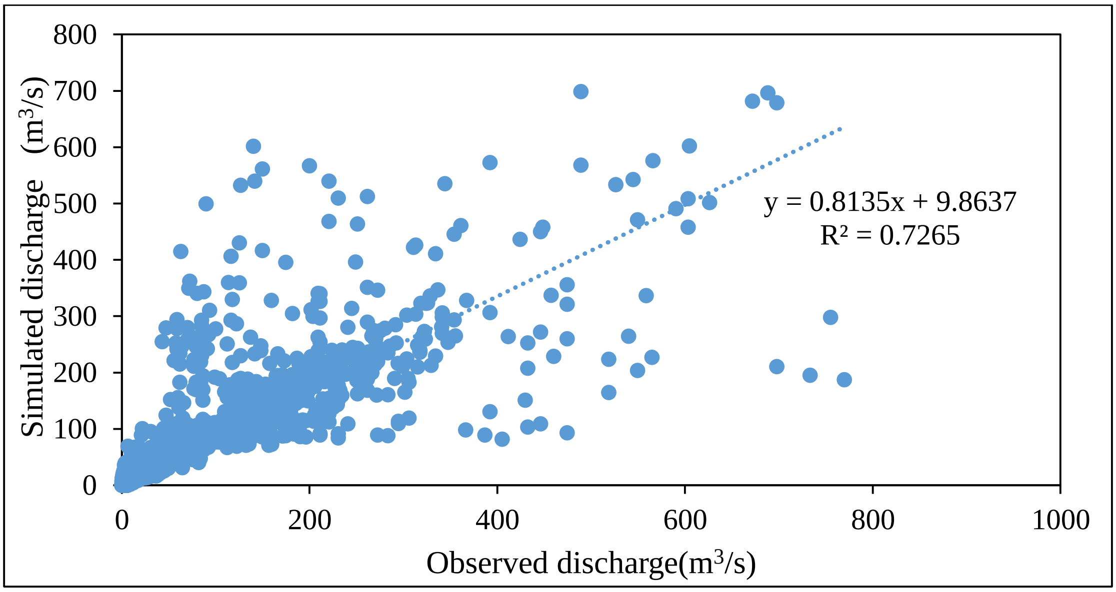


Figure 4.6 Scattering plot (R^2) during calibration results.

Table 4.5: The initial and optimized model parameters.

Parameters	Sub-basin 1		Sub-basin 2		Sub-basin 3	
	Initial	Optimized	Initial	Optimized	Initial	Optimized
Max canopy storage (mm)	1.27	2.27	1.13	1.2	1.23	2.11
Max surface storage (mm)	9.18	10	11.32	1.5	11.50	2
Max infiltration rate (mm/h)	6.70	7.23	8.44	5.42	7.43	10.5
Impervious (%)	5	10	5	10	5	10
Soil storage (mm)	133.58	165	140.69	170	134.38	160
Tension storage (mm)	113.16	95	94.42	100	104.48	120
Soil percolation (mm/h)	0.86	0.6	6.29	1.02	2.97	1.5
GW 1 storage (mm)	0.183	25	0.183	25	0.183	25
GW1 percolation (mm/h)	0.86	0.6	6.29	1.02	2.97	1.5
GW1 coefficient(h)	49	50	49	50	49	50
GW 2 storage (mm)	4.58	55	4.58	55	4.58	55
GW2 percolation (mm/h)	____	0.2	____	0.95	___	0.45
GW2 coefficient(h)	146.51	200	146.51	200	146.51	200
Time of concentration(h)	6.74	10	6.021	9	4.88	7
Storage coefficient(h)	8.58	28	7.33	26	7.99	20
Reach	K(hr)		X			
	Initial	Optimized	Initial	optimized		
R30	0.34	18	0.25	0.01		

4.1.3.2 Model Validation

Model validation was involved running the model using the same input parameters optimized in the calibration process. Based on the determined parameters, the model was run for the validation period (2000 to 2007) to check the capability of the model to predict runoff at the Wabi gaging station. In the same way, the comparison between observed and simulated streamflow graphs is shown in Figure 4.7. For the validation period (2000 to 2007). The comparison illustrates an acceptable agreement between the simulated streamflow and the observed streamflow in terms of timing of peak and peak value, streamflow distribution, and rising and recession of streamflow.

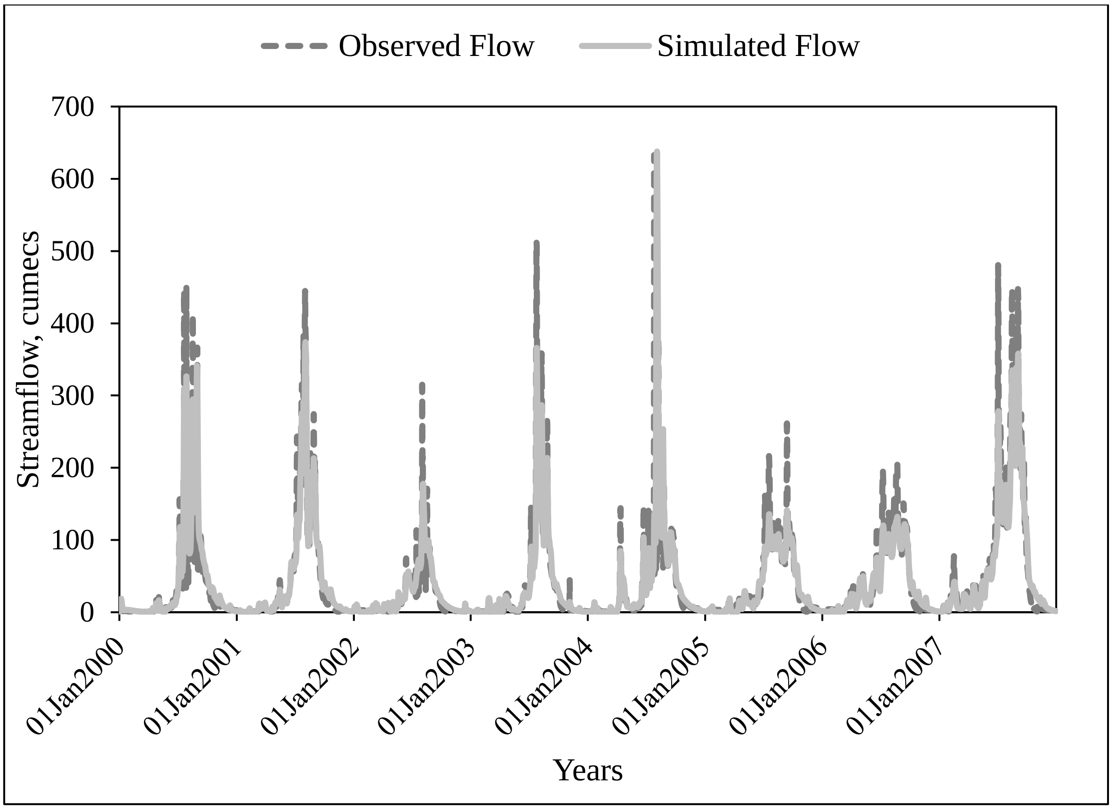


Figure 4.7 Daily observed and simulated discharge for the entire validation period.

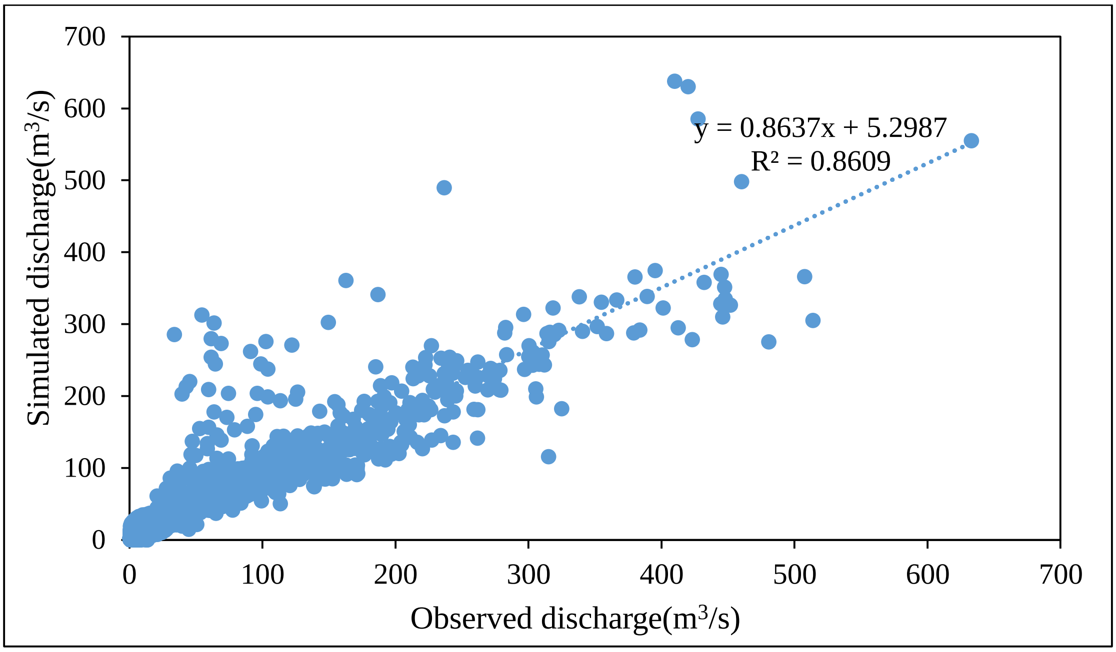


Figure 4.8 Scattering plot (R^2) during validation results.

4.1.4 Model Performance evaluation

Evaluation of the Continuous model performance was conducted for both calibration and validation periods. Time series of simulated and observed flows were obtained from the results of a simulation run in the HEC-HMS model of the Wabe catchment, and were then analyzed in Excel to determine the statistics used for model performance evaluation. The statistics that were used are explained in Section 3.10 presented earlier. The performance ratings of these statistics are described in Table 3.13.

The summary of different statistical performance evaluations of the model taken from the calibration and validation of the continuous SMA algorithm in the HEC-HMS conceptual model is described in Table 4.6. According to Tables 3.13, the model performance ranges from good to very good model.

Table 4.6 Performance evaluation of the continuous HEC-HMS model.

Performance Ratings	PEV (%)	PEPF (%)	NSE	R2	RSR	PBIAS
Calibration	2.36	6.25	0.711	0.727	0.5	2.35
Validation	0.42	- 2.91	0.807	0.861	0.4	- 0.42

Finally, the output of the peak flow, runoff volume, and statistical summary from the model and the scattered plot during calibration and validation period, and the other outputs from the model are attached on the APPENDIX-D.

4.1.5 Flood Frequency Analysis Results

Flood frequency analysis is the most important statistical technique used to predict design floods for sites along a river to minimize flood hazards and increases the safety of structures. There are different ways of flood prediction and their results are discussed below.

4.1.5.1 Flood Frequency Analysis Results of Probability Distribution Function

The probability distribution functions employed for flood frequency analyses are used to forecast and plan floods for riverside locations. In case, the statistical information such as mean values, standard deviations, skewness, and recurrence intervals are calculated using observed annual maximum flow discharge data as shown below in table 4.7. These statistical data are then used to create frequency distributions, which are graphs and tables that show the probability of different discharges as a function of recurrence interval or exceedance (figure 4.12 and Table 4.9) respectively.

Table 4.7 Annual Maximum peak flow data of observed period.

Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Q(m^3/s)	220	474	392	220	733	769	301	603	334	755	240
Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	
Q(m^3/s)	266	626	452	460	315	474	633	261.6	197	474.5	

Probability Density and Cumulative Functions

From different distribution models employed to examine the probability distribution and cumulative distribution of the peak flood, the most two fitted models were selected for comparison. The Peak flood was examined using different Probability Density and Cumulative Functions. After analysis, the best fit two Probability Density functions were selected for further analysis. As can be seen, the Table 3.15 the General Pareto distribution (GDP) and General Extreme Value (GEV) distributions were selected based on the goodness of fit evaluated using three methods.

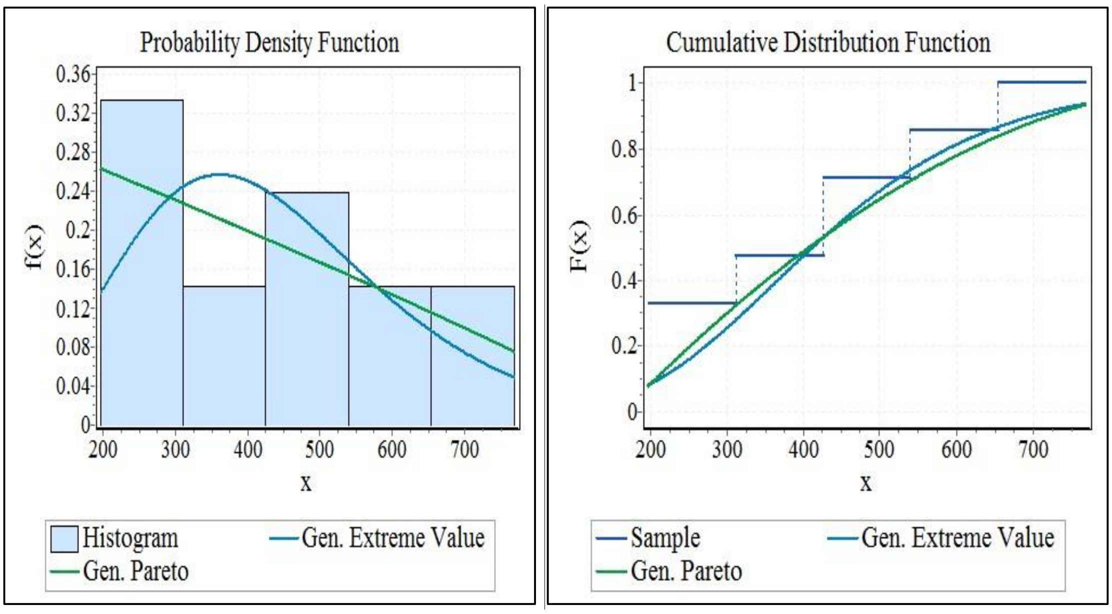


Figure 4.9 Probability and Cumulative Distribution Function.

A) P-P Plot

A graph of empirical CDF values plotted against theoretical CDF values is known as a probability-probability (P-P) plot. It's used to see how well a particular distribution matches the observed data. If the stated theoretical distribution is the correct model, this plot will be approximately linear.

B) Q-Q Plot

A graph of the input (observed) data values plotted against the theoretical (fitted) distribution quantile is known as a quantile-quantile (Q-Q) plot. Both axes of this graph are in input data set units.

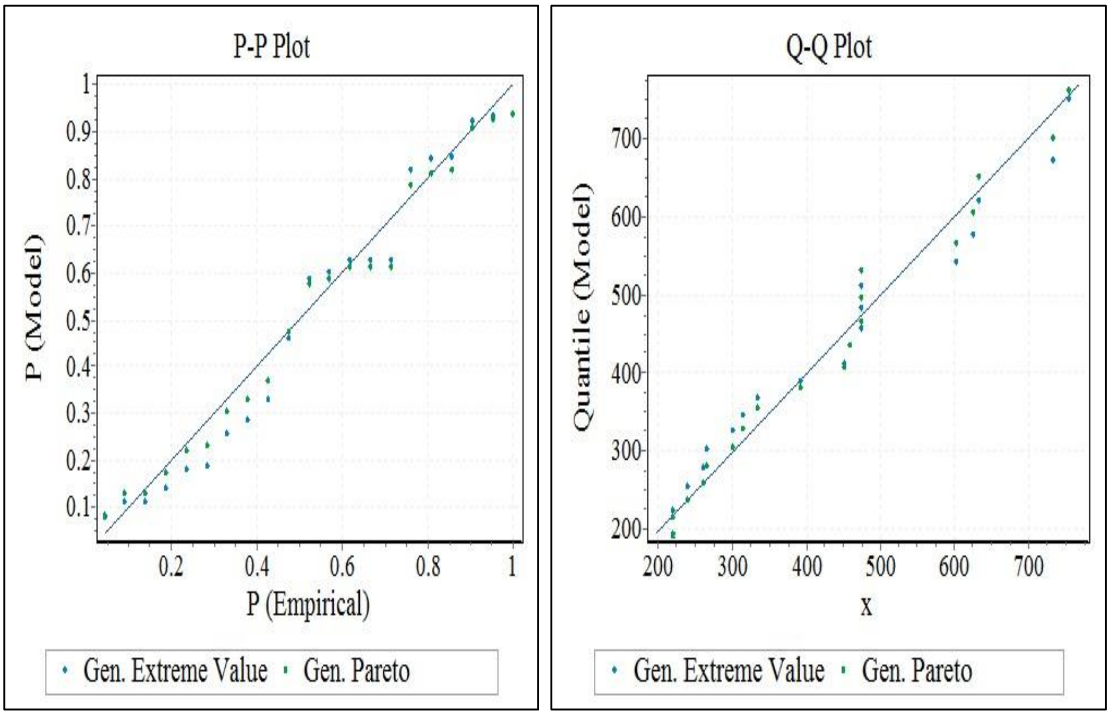


Figure 4.10 Easy-fit probability and quantile plot for Annual Maximum streamflow.

4.1.5.2 Flood Frequency Analysis Results of HEC-HMS model

Flood frequency analysis of 2, 5, 10, 25, 50, 100, 200, and 500 year return periods was computed using calibrated HEC-HMS model based on frequency storm method analysis for Wabe River watershed considering rainfall depth of 24-hour and obtained peak flood with different amount as seen in Table 4.9 below. Table 4.8 shows rainfall intensity for each return period, computed using (equation 3.36) at different time interval from 24hr rainfall depth (Table 3.18), which is known as a rainfall intensity-duration-frequency (IDF) relationship. The minimum and maximum peak floods at the Wabe River watershed's outlet were found to be 479.0 m^3/s and 1367.5 m^3/s, respectively. This means that the Wabe River watershed's lowest peak flood occurred at a 2-year return period of 24-hour storm duration, while the maximum flood occurred at a 500 year return period of 24-hour storm duration.

Table 4.8: 24hrs Incremental Rainfall for Each Return Period.

Duration(hr)	Rainfall in depth(mm) versus return period							
	2	5	10	25	50	100	200	500
0.08	10.46	13.01	14.89	17.49	19.61	21.89	24.33	27.87
0.25	21.87	27.21	31.13	36.58	41.01	45.76	50.88	58.27
1	37.02	46.05	52.68	61.90	69.40	77.45	86.11	98.61
2	41.84	52.05	59.56	69.98	78.45	87.55	97.34	111.47
3	43.75	54.42	62.26	73.16	82.02	91.53	101.76	116.54
6	45.83	57.01	65.23	76.64	85.92	95.89	106.61	122.09
12	46.95	58.40	66.82	78.51	88.02	98.22	109.21	125.07
24	47.53	59.12	67.64	79.48	89.11	99.44	110.56	126.61

By considering the same calibrated basin parameters for 2, 5, 10, 25, 50, 100, 200, and 500 year return periods, the peak discharge and shape of hydrograph for all these return periods were forecasted and their hydrograph was shown in Figure 4.11. The graphs of 2, 5, 10, 25, 50, 100, 200, and 500-year flood discharges computed in the HEC-HMS were attached in Appendix-D.

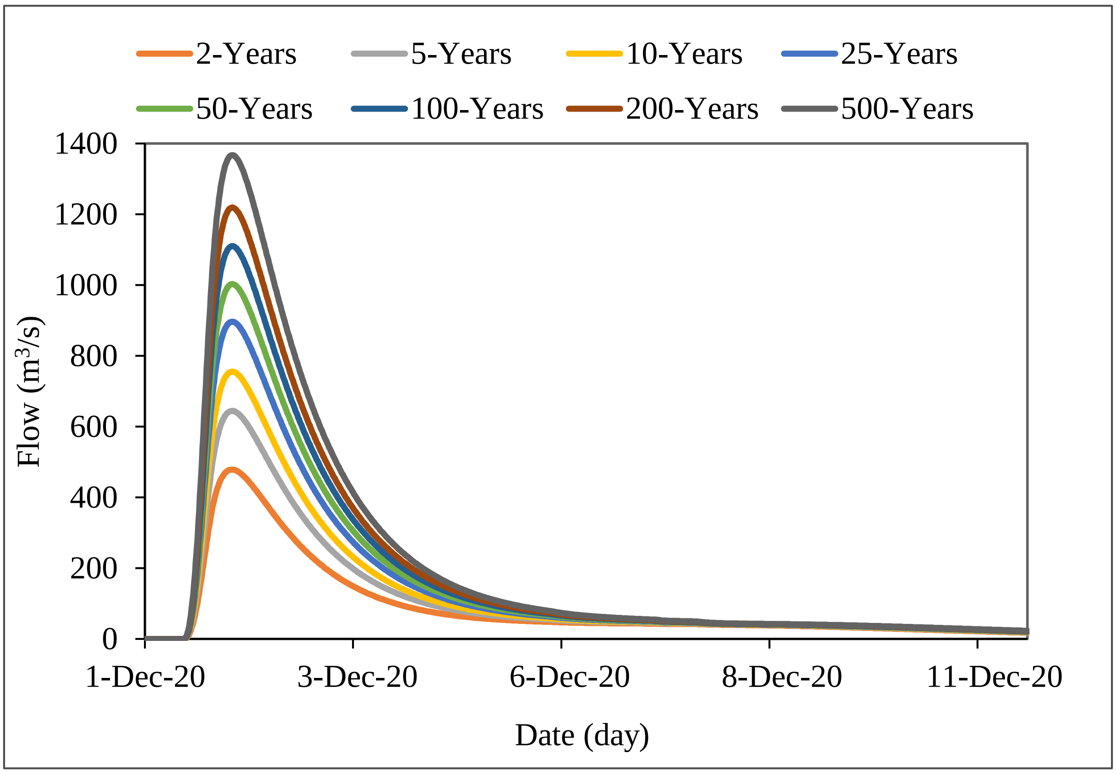


Figure 4.11 Hydrograph resulted for flood frequency analysis in HEC-HMS model.

4.1.5.3 Flood-frequency Curve comparison

Finally, the results of the HEC-HMS model were compared to the probability distribution function results of two methods that were chosen based on their ranks. The performance of the HECHMS model result shows a high similarity with General Extreme Value (GEV) distribution, which is the most fitted probability distribution among the other distribution models, as can be seen from the result. This demonstrates the HEC-HMS model's good performance in frequency analysis for the study area.

Table 4.9 Peak discharge found from HEC-HMS and probability distribution.

N⁰	Return periods (years)	Peak discharge from HEC-HMS and probability distribution		
		HEC-HMS (m^3/s)	GPD(m^3/s)	GEV(m^3/s)
1	2	479.0	407.13	542.89
2	5	644.7	618.23	711.47
3	10	755.5	722.17	817.22
4	25	896.8	812.34	944.48
5	50	1003.0	856.74	1034.53
6	100	1110.2	887.52	1120.39
7	200	1219.3	908.86	1202.59
8	500	1367.5	927.38	1306.14

A flood frequency curve is a graph that depicts the relationship between flood magnitudes and recurrence interval for a particular location.

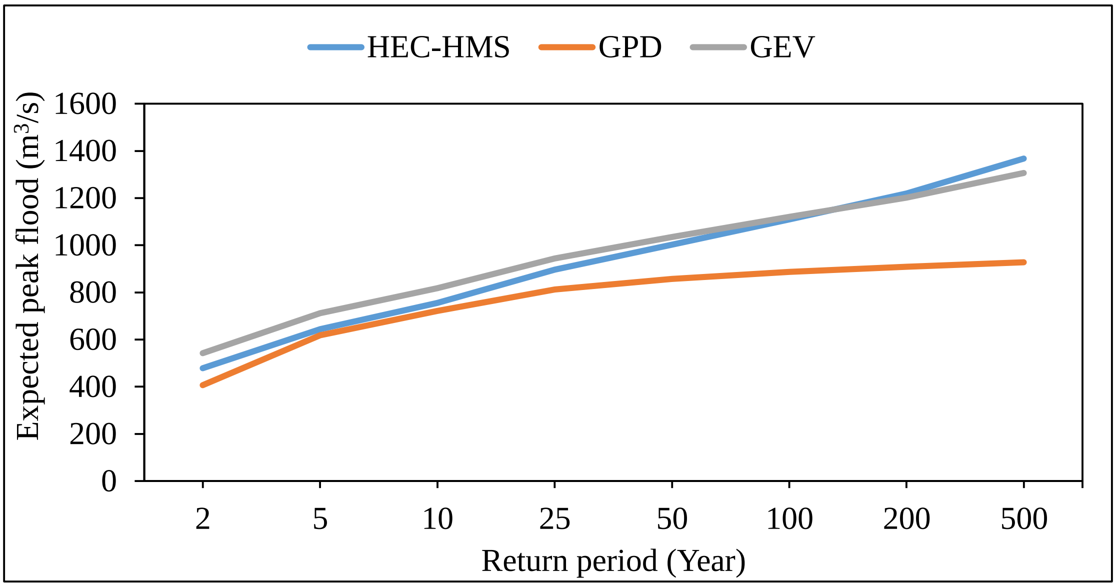


Figure 4.12 Flood Frequency Curve Comparison result.

The calibrated HEC-HMS model were also used to estimate direct runoff volume, and the peak discharges for the three ungauged sub-catchments of Wabe watershed for various average recurrence intervals (2, 5, 10, 25, 50, 100, 200, and 500 years). The peak discharges (m^3/s) and volumes (millions m^3) for the sub-catchments, are listed in Table 4.10.

Table 4.10: Peak discharges (m^3/s) and volumes (Mm^3) for the sub-catchments.

Return periods (years)	Parameters of Discharges	Sub-basin 1	Sub-basin 2	Sub-basin 3	Outlet (Wabi station)
2	Peak (m^3/s)	311.5	127.4	216.2	479.0
	Volume(Mm^3)	60.1722	17.9164	19.8473	97.8566
5	Peak (m^3/s)	428.5	165.9	284.6	644.7
	Volume(Mm^3)	74.8183	22.3243	25.9242	122.9856
10	Peak (m^3/s)	506.4	191.4	330.7	755.5
	Volume(Mm^3)	84.5412	25.2422	29.9923	139.6932
25	Peak (m^3/s)	605.3	223.8	389.4	896.8
	Volume(Mm^3)	96.8863	28.9553	35.1786	160.9363
50	Peak (m^3/s)	679.4	248.4	433.7	1003.0
	Volume(Mm^3)	106.1409	31.7513	39.0756	176.8828
100	Peak (m^3/s)	754.4	273.2	478.2	1110.2
	Volume(Mm^3)	115.4755	34.5755	43.0019	192.9679
200	Peak (m^3/s)	830.6	298.5	523.4	1219.3
	Volume(Mm^3)	124.9636	37.4509	46.9854	209.3128
500	Peak (m^3/s)	934.5	332.9	584.7	1367.5
	Volume(Mm^3)	137.8389	41.355.6	52.3853	231.4915

4.2 Discussions

Before using the HEC-HMS model to get an accurate prediction of runoff in the Wabe catchment, the model needed to be well-calibrated using the SMA parameters. To achieve a high degree of precision, the various data used in SMA modeling necessitates close observation and field surveys. For the current research, however, no such observations or surveys were conducted; instead, all data was gathered from secondary sources collected from various organizations. With this kind of data estimation, the results obtained are highly satisfactory. Evapotranspiration plays an important role in continuous modeling, but it is often overlooked in event-based modeling, which assumes zero evapotranspiration during rainfall. Due to the lack of data such as humidity, wind speed, and other variables, evapotranspiration was calculated using the Hargreaves method.

Since, sensitivity analysis was performed to understand how the results of the model respond to changes in model parameters. Some parameters are more sensitive than others on the results of the model, so the task here is to find sensitive parameters. In model calibration, knowledge of sensitive parameters is useful in trying to align model performance with observed results. During this study, the sensitivity analysis of the soil moisture accounting (SMA) parameters, the soil percolation rate, soil storage, and groundwater layer parameters were found to be some of the most sensitive parameters for runoff simulation. Bashar & Zaki (2005) applied a continuous hydrological modeling for the Blue Nile and they found soil storage to be the most sensitive parameter followed by Tension zone storage and soil percolation parameters. According to Abiyot and Yilma (2008) also conducted HEC-HMS model for Kulfo and Bilate catchments in the Abaya-Chamo sub-basin, soil storage was reported as the most sensitive parameter. Fleming and Neary (2004) performed a similar sensitivity analysis of a continuous HEC-HMS model for the Dale Hollow basin in Kentucky and Tennessee. They discover the maximum infiltration rate, the maximum soil depth, and the tension zone depth to be the most sensitive parameters. However, Ouédraogo *et al.* (2017) also used HEC-HMS to perform runoff simulations in the Ruiru reservoir catchment. They discover soil storage to be the most sensitive parameter, followed by the groundwater storage coefficient and the soil tension storage capacity. Singh and Jain (2015) also conducted continuous hydrological modeling in Vamsadhara River Basin (India) using the SMA model and found soil storage to be the most sensitive parameter. Ouédraogo *et al*. (2018) also conducted continuous hydrological modeling in the Mkurumudzi river catchment in Kenya using the SMA model and discover the groundwater layer parameters and the impervious area that were found to be some of the most sensitive parameters for runoff simulation. Some findings are similar to the current study results.

The performance and accuracy of the model depended on the coefficient of determination (R^2) value. The value of R^2 measures how well the correlation between simulations compared to the observations with ranges from 0 to 1. A value of 0 indicated no correlation, and a value of 1 implied that the prediction equals the measured. In this study, the R^2 value is 0.727 for calibration and 0.861 for validation. These showed the performance and accuracy of the model is good for calibration and very good for validation (Moriasi *et al.*, 2007). The peak flow prediction produced in the model simulation was almost equal to the peak flow from observation .

Reliable estimates of streamflow from a catchment are required to help policy makers to take decisions on water resources planning and management. A runoff model helps to understand the response of water systems due to changes in the land-use and meteorological events (Abdessamed *et al*., 2018). There are wide ranges of Rainfall-Runoff models currently used by researchers and practitioners; however, their applications are highly dependent on the purposes for which the modeling is undertaken (Bitew *et al*., 2019). As many of the Rainfall-Runoff models are used merely for research purposes for the purpose of understanding the hydrological processes that govern a real-world system, some were developed and employed as tools for simulation and prediction that in turn allows decision makers for proper planning and operation in the context of flood risk management, inundation and flood hazard mapping, for real time reservoir operation and water resources allocation. For instance, the real-time flood forecasting and warning that is operational in many countries, utilizes the results of rainfall-runoff modeling. So far, these hydrological models also estimate flood frequencies, provide inputs for flood routing and inundation prediction. For the case of this study, the main target of rainfall-runoff modeling was to predict peak flood at the outlet of the sub-catchment that was later used in the computation of flood inundation mapping and it can be used for decision makers concerning the flood damage.

For instance, as the HEC-HMS predict the peak flood (discharge) for different return period, which is similar compared to the discharges obtained from observation by probability distribution functions, as shown in figure 4.12 and table 4.9. As a result, it is recommended that the design of any hydraulic system built along or across the river consider this peak flood to reduce the flood's negative effects. For further study, the HEC-HMS model's simulated peak discharge can be used for flood mapping and mitigation.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Rainfall-runoff modeling is critical for simulating a watershed's response to rainfall and producing a flow hydrograph, which is widely used in flood forecasting and water resource planning. The HEC-HMS model was used to simulate streamflow in the Wabe watershed in this study. The required Hydro-metrological, soil, LULC, and DEM data were used for this study. ArcGIS extensions: Arc Hydro Tools and HEC-GeoHMS were used to generate basin model and input parameters like SMA parameters, lag time, and time of concentration.

Before using the rainfall data, the missed value was completed by normal ratio method where areal rainfall was computed by Thiessen polygon methods and also its homogeneity and consistency were tested by using rainbow software and double mass-curve methods respectively. In addition to this, the missed value of streamflow was computed by takening the mean on the same day and month but at different years on that particular date. Due to the lack of data such as humidity, wind speed, and other variables, evapotranspiration was computed using the Hargreaves method.

The HEC-HMS conceptual model was successfully calibrated and validated for the Wabe catchment on a continuous time scale. Sensitivity analysis of the continuous model revealed that the soil percolation rate, soil storage, and groundwater layer parameters were the most sensitive parameters. The maximum surface storage was found to be the least sensitive parameter. The overall Nash-Sutcliffe Efficiency criteria were 0.711 and 0.807 for the calibration and validation periods, respectively, indicating a good and very good model fit. Percentage errors in volume (PEV) for the calibration and validation periods were found to be 2.36% and 0.42%, respectively, indicating very good fit. The percentage errors in peak (PEPF) were found to be 6.25% and – 2.91% for the calibration and validation periods, respectively, with the performance of the model being rated as very good. The coefficients of determination (R^2) for the calibration and validation periods were 0.727 and 0.861, respectively, indicating a good and very good model fit. Similarly, the percent bias (PBIAS) was discovered to be 2.35 and -0.42 during the calibration and validation periods, respectively, indicating a very good model fit. The RSR, which assesses the appropriateness of the model, was found to be 0.50 and 0.4 during the calibration and validation periods, respectively, indicating very good performance.

Flood frequency analysis is the most important statistical technique used to predict design floods for sites along a river to minimize flood hazards and increases the safety of structures. There are different ways of flood prediction. For this study, the Probability Distribution Functions and frequency storm method of HEC-HMS model. After analysis, the best fit two Probability Distribution Functions were selected for further analysis. The General Pareto distribution (GDP) and General Extreme Value (GEV) distributions were selected based on the goodness of fit evaluated using three methods in easy fit 5.6 software.

By using the calibrated basin parameters of the HEC-HMS model, flood frequency analysis was conducted for 2, 5, 10, 25, 50, 100, 200, and 500 year return periods considering rainfall depth of 24-hour storm of Wabe River watershed. Accordingly, the forecasted peak flood by HEC-HMS, General Pareto distribution (GDP) and General Extreme Value (GEV) distribution method at 2, 5, 10, 25, 50, 100, 200 and 500 year return periods were 479, 644.7, 755.5, 896.8, 1003, 1110.2, 1219.3 and 1367.5; 407.13, 618.23, 722.17, 812.34, 856.74, 887.52, 908.86 and 927.38; and 542.89, 711.47, 817.22, 944.48, 1034.53, 1120.39, 1202.59 and 1306.14 m^3/s respectively.

The peak flood predicted by the HEC-HMS model is greater than the other two Probability Distribution functions. As a result, it is recommended that the design of any hydraulic system built along or across the river take this maximum flood into account to reduce the flood's negative effects. For further study, the HEC-HMS model's simulated peak discharge can be used for flood mapping and mitigation.

5.2 Recommendations

According to the findings of this study, the following recommendations are forwarded for future or further study:

- Based on the modeling work undertaken in the selected catchments of the Wabe catchment, better results were obtained. Therefore, the simulation results can be used directly or in conjunction with other software for different hydrological and environmental studies and flow forecasting, future urbanization impact assessment, flood damage reduction, reservoir design studies, and overall systems operation.
- The model can be further improved by using multiple streamflow gauging stations. This will enhance the model calibration inside the catchment leading to a more accurate estimation of the model parameters for each sub-basin. So, it is recommended that to install another gaging station in the catchment. The modeling study was conducted according to daily rainfall and discharge, which is again the maximum limit for the HEC-HMS model. Therefore, it is recommended to check the modeling of the Wabe catchment using the HEC-HMS conceptual model by incorporating hourly rainfall and discharge data. Various data involved in SMA modeling needs careful observation and field surveys to achieve a high level of accuracy. For this research, there are no observation and field surveys were conducted; instead, all data was gathered from secondary sources collected from various organizations due to the limitation of budget and time. To get an accurate prediction of runoff in the Wabe catchment it is recommended that, the researchers should be conduct close observation and field surveys.
- In this study, the peak flood (discharge) expected to occur for different return periods in HEC-HMS are very large, compared to the discharges obtained from observation by statistical distribution model. As a result, it is recommended that the design of any hydraulic system built along or across the river should consider this maximum flood to reduce the flood's negative effects. For further study, it is recommended the HEC-HMS model's simulated peak discharge can be used for flood mapping and mitigation.

REFERENCES

Ahbari, A., Stour, L., Agoumi, A. & Serhir, N. 2018. Estimation of initial values of the HMS model parameters: Application to the basin of Bin El Ouidane (Azilal, Morocco). *J. Mater. Environ. Sci,* 9**,** 305-317.

Alam, M. A., Emura, K., Farnham, C. & Yuan, J. 2018. Best-fit probability distributions and return periods for maximum monthly rainfall in Bangladesh. *Climate,* 6**,** 9.

Ali, M., Khan, S. J., Aslam, I. & Khan, Z. 2011. Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan. *Landscape and Urban Planning,* 102**,** 271-279.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A. & Van Liew, M. W. 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, 55**,** 1491-1508.

BARRIENTOSA, H. & Swainc, A. 2014. Linking Flood Management to Integrated Water Resource Management in Guatemala: A critical review. *International Journal of Water,* 4**,** 53-74.

Bashar, K. & Zaki, A. SMA based continuous hydrologic simulation of the Blue Nile. A paper published in the International Conference of UNESCO Flanders FUST FRIEND/NILE Project" Towards a Better Cooperation". Sharm El-Sheikh, Egypt, 2005.

Bennett, T. H. & Peters, J. C. 2000. Continuous soil moisture accounting in the hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). *Building partnerships.*

Berz, G. Flood disasters: lessons from the past—worries for the future. Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering, 2000. Thomas Telford Ltd, 3-8.

Beven, K. & Freer, J. 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of hydrology,* 249**,** 11-29.

Beven, K. J. 2000. Uniqueness of place and process representations in hydrological modelling. *Hydrology and earth system sciences,* 4**,** 203-213.

Beven, K. J. 2011. *Rainfall-runoff modelling: the primer*, John Wiley & Sons.

Coron, L., Thirel, G., Delaigue, O., Perrin, C. & Andréassian, V. 2017. The suite of lumped GR hydrological models in an R package. *Environmental modelling & software,* 94**,** 166-171.

Cunderlik, J. 2003. *Hydrologic model selection for the CFCAS project: assessment of water resources risk and vulnerability to changing climatic conditions*, Department of Civil and Environmental Engineering, The University of Western ….

Derdour, A., Bouanani, A. & Babahamed, K. 2018. Modelling rainfall runoff relations using HEC-HMS in a semi-arid region: Case study in Ain Sefra watershed, Ksour Mountains (SW Algeria). *Journal of water and land development,* 36**,** 45-55.

Devia, G. K., Ganasri, B. P. & Dwarakish, G. S. 2015. A review on hydrological models. *Aquatic Procedia,* 4**,** 1001-1007.

Erşahin, B. 2020. Simulation of streamflow using hydrologic modeling system HEC-HMS.

Feldman, A. D. 2000. *Hydrologic modeling system HEC-HMS: technical reference manual*, US Army Corps of Engineers, Hydrologic Engineering Center.

Fentaw, F., Mekuria, B. & Arega, A. 2018. Impacts of climate change on the water resources of guder catchment, Upper Blue Nile Ethiopia. *Waters,* 1**,** 16.

Fleming, M. 2002. *Continuous hydrologic modeling with HMS: parameter estimation and model calibration and validation.* Msc Thesis, Tennessee Technological University.

Fleming, M. & Doan, K. 2013. *HEC-GeoHMS Geospatial Hydrologic Modeling Extenssion: user's manual*, US Army Corps of Engineers, Hydrologic Engineering Center

Fleming, M. & Neary, V. 2004. Continuous hydrologic modeling study with the hydrologic modeling system. *Journal of hydrologic engineering,* 9**,** 175-183.

Gebre, S. L. 2015. Application of the HEC-HMS model for runoff simulation of Upper Blue Nile River Basin. *Hydrology: Current Research,* 6**,** 1.

Gebre, S. L. & Ludwig, F. 2015. Hydrological response to climate change of the upper blue Nile River Basin: based on IPCC fifth assessment report (AR5). *Journal of Climatology & Weather Forecasting,* 3**,** 1-15.

Geethalakshmi, V., Kitterød, N. & Lakshmanan, A. 2008. A literature review on modeling of hydrological processes and feedback mechanisms on climate. CLIMARICE Report.

Getahun, Y. & Gebre, S. 2015. Flood hazard assessment and mapping of flood inundation area of the Awash River Basin in Ethiopia using GIS and HEC-GeoRAS/HEC-RAS model. *Journal of Civil & Environmental Engineering,* 5**,** 1.

Ghaffari, G. 2011. The impact of DEM resolution on runoff and sediment modelling results. *Research Journal of Environmental Sciences,* 5**,** 691.

Gyawali, R. & Watkins, D. W. 2013. Continuous hydrologic modeling of snow-affected watersheds in the Great Lakes basin using HEC-HMS. *Journal of Hydrologic Engineering,* 18**,** 29-39.

Hamed, K. & Rao, A. R. 2019. *Flood frequency analysis,* CRC press.

Hargreaves, G. H. & Samani, Z. A. 1982. Estimating potential evapotranspiration. *Journal of the irrigation and Drainage Division,* 108**,** 225-230.

Holberg, J. 2015. Downward model development of the soil moisture accounting loss method in HEC-HMS: Revelations concerning the soil profile.

Ismail, W. N. W., Zin, W. Z. W. & Ibrahim, W. 2017. Estimation of rainfall and stream flow missing data for Terengganu, Malaysia by using interpolation technique methods. *Malays. J. Fundam. Appl. Sci,* 13**,** 214-218.

Jabloun, M. D. & Sahli, A. 2008. Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data: Application to Tunisia. *Agricultural water management,* 95**,** 707-715.

Jajarmizadeh, M., Harun, S. & Salarpour, M. 2012. A review on theoretical consideration and types of models in hydrology. *Journal of Environmental Science and Technology,* 5**,** 249-261.

Li, Z. 2014. Watershed modeling using arc hydro based on DEMs: a case study in Jackpine watershed. *Environmental Systems Research,* 3**,** 1-12.

Linsley, R., Kohler, M. & Paulhus, J. 1975. Hydrology for Engineers, 1 2. McGraw-Hill, New York.

Mccuen, R. H. 2016. *Modeling hydrologic change: statistical methods*, CRC press.

Mcenroe, B. 2010. Guidelines for continuous simulation of streamflow in Johnson County, Kansas, with HEC-HMS. *Department of Civil, Environmental and Architectural Engineering, Univ. of Kansas*.

Meenu, R., Rehana, S. & Mujumdar, P. 2013. Assessment of hydrologic impacts of climate change in Tunga–Bhadra river basin, India with HEC-HMS and SDSM. *Hydrological Processes,* 27**,** 1572-1589.

Mehrannia, H. & Pakgohar, A. 2014. Using easy fit software for goodness-of-fit test and data generation. *Intl J Math Arch,* 5**,** 2229-5046.

Mersha, A. 2017. *Comparative analysis of the effects of Land Use/Land Cover Changes on Hydrology and Sedimentation: The Case of Wabeand Meki Catchments, Central Ethiopia.* Doctoral dissertation Desertation, Addis Ababa University.

Merwade, V. 2012. Watershed and stream network delineation using ArcHydro tools.*URL:http://web.ics.purdue.edu/~vmerwade/education/terrain_processing. pdf*.

Mokhtari, E. H., Remini, B. & Hamoudi, S. A. 2016. Modelling of the rain–flow by hydrological modelling software system HEC-HMS–watershed's case of wadi Cheliff-Ghrib, Algeria. *Journal of Water and Land Development,* 30**,** 87-100.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE,* 50**,** 885-900.

Namara, W. G., Damise, T. A. & Tufa, F. G. 2020. Rainfall Runoff Modeling Using HEC-HMS: The Case of Awash Bello Sub-Catchment, Upper Awash Basin, Ethiopia. *International Journal of Environment,* 9**,** 68-86.

Ouédraogo, W. A. A., Raude, J. M. & Gathenya, J. M. 2018. Continuous modeling of the Mkurumudzi River catchment in Kenya using the HEC-HMS conceptual model: Calibration, validation, model performance evaluation and sensitivity analysis. *Hydrology,* 5**,** 44.

Parry, M., Parry, M. L., Canziani, O., Palutikof, J., Van Der Linden, P. & Hanson, C. 2007. *Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC*, Cambridge University Press.

Pathak, P., Kalra, A. & Ahmad, S. 2017. Temperature and precipitation changes in the Midwestern United States: implications for water management. *International Journal of Water Resources Development,* 33**,** 1003-1019.

Ponce, V. M. & Hawkins, R. H. 1996. Runoff curve number: Has it reached maturity? *Journal of hydrologic engineering,* 1**,** 11-19.

Prodanović, D., Stanić, M., Milivojević, V., Simić, Z. & Arsić, M. 2009. DEM-based GIS algorithms for automatic creation of hydrological models data. *Journal of Serbian Society for Computational Mechanics,* 3**,** 64-85.

Raes, D., Willems, P. & Gbaguidi, F. RAINBOW–A software package for hydrometeorological frequency analysis and testing the homogeneity of historical data sets. Proceedings of the 4th International Workshop on Sustainable management of marginal drylands. Islamabad, Pakistan, 2006. 12.

Rawls, W. J., Brakensiek, D. L. & Saxtonn, K. 1982. Estimation of soil water properties. *Transactions of the ASAE,* 25**,** 1316-1320.

Saxton, K. E. & Willey, P. H. 2006. The SPAW model for agricultural field and pond hydrologic simulation. *Watershed models***,** 401-435.

Scharffenberg, B., Bartles, M., Brauer, T., Fleming, M. & Karlovits, G. 2018. Hydrologic model system HEC-HMS user manual. 4.3 ed.: U.S Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (CEIWR-HEC) 609 Second Street.

Scharffenberg, W. A. & Fleming, M. J. 2006. *Hydrologic modeling system HEC-HMS: user's manual*, US Army Corps of Engineers, Hydrologic Engineering Center.

Searcy, J. K. & Hardison, C. H. 1960. *Double-mass curves*, US Government Printing Office.

Setegn, S. G., Srinivasan, R. & Dargahi, B. 2008. Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. *The Open Hydrology Journal,* 2.

Shahid, M., Rahman, K. U., Balkhair, K. S. & Nabi, A. 2020. Impact assessment of land use and climate changes on the variation of runoff in Margalla Hills watersheds, Pakistan. *Arabian Journal of Geosciences,* 13**,** 1-14.

Shiferaw, T., Adugna, T. & Hussen, M. 2018. *Flood inundation mapping and hazard assessment: a case of Upper-middle gilo river, ethiopia.*

Shinbrot, X. A., Muñoz-Villers, L., Mayer, A., López-Purata, M., Jones, K., López-Ramírez, S., Alcocer-Lezama, C., Ramos-Escobedo, M. & Manson, R. 2020. Quiahua, the First Citizen Science Rainfall Monitoring Network in Mexico: Filling Critical Gaps in Rainfall Data for Evaluating a Payment for Hydrologic Services Program. *Citizen Science: Theory and Practice,* 5.

Singh, W. R. & Jain, M. K. 2015. Continuous hydrological modeling using soil moisture accounting algorithm in Vamsadhara River basin, India. *Journal of Water Resource and Hydraulic Engineering,* 4**,** 398-408.

Tassew, B. G., Belete, M. A. & Miegel, K. 2019. Application of HEC-HMS model for flow simulation in the lake tana basin: the case of gilgel abay catchment, upper blue nile basin, Ethiopia. *Hydrology,* 6**,** 21.

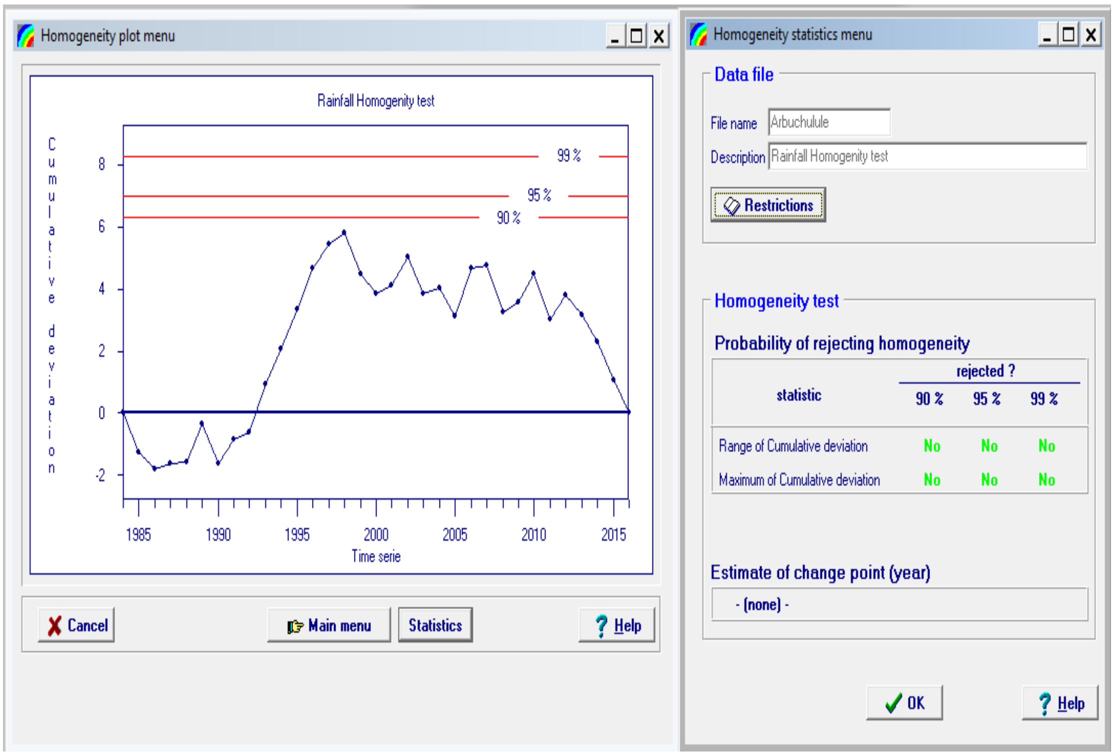
Te Chow, V. 2010. *Applied hydrology*, Tata McGraw-Hill Education.

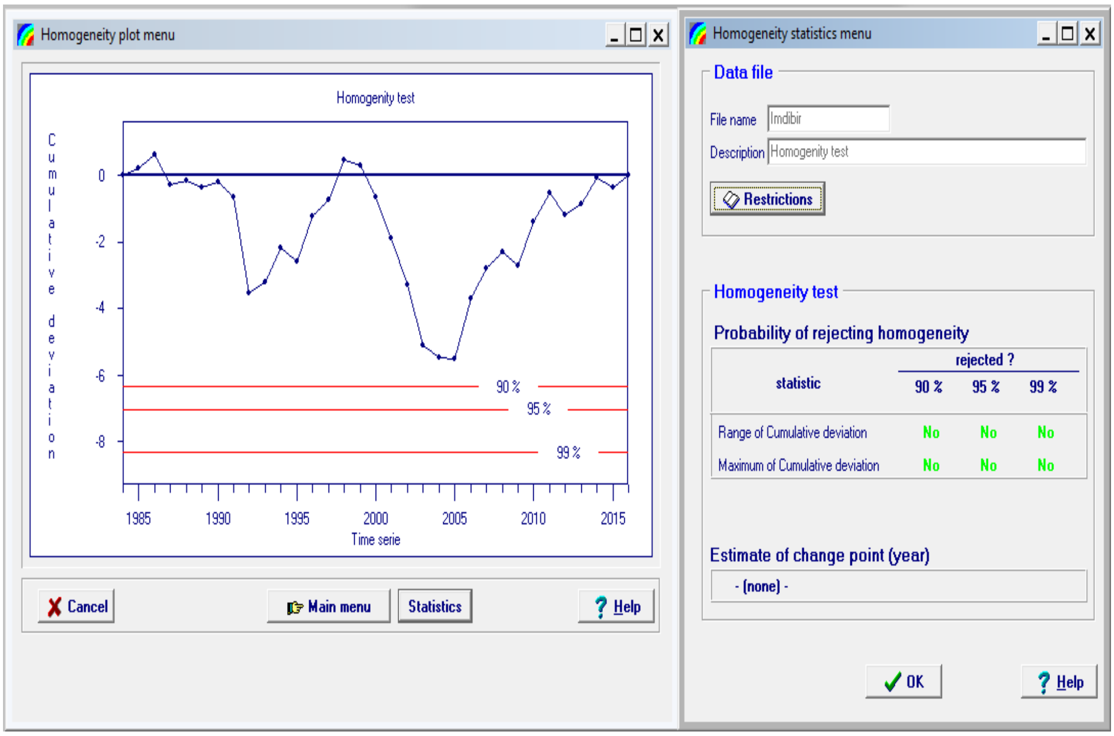
Wałęga, A., Rutkowska, A. & Policht-Latawiec, A. 2014. Sensitivity of Beta and Weibull Synthetic Unit Hydrographs to Input Parameter Changes. *Polish Journal of Environmental Studies,* 23.

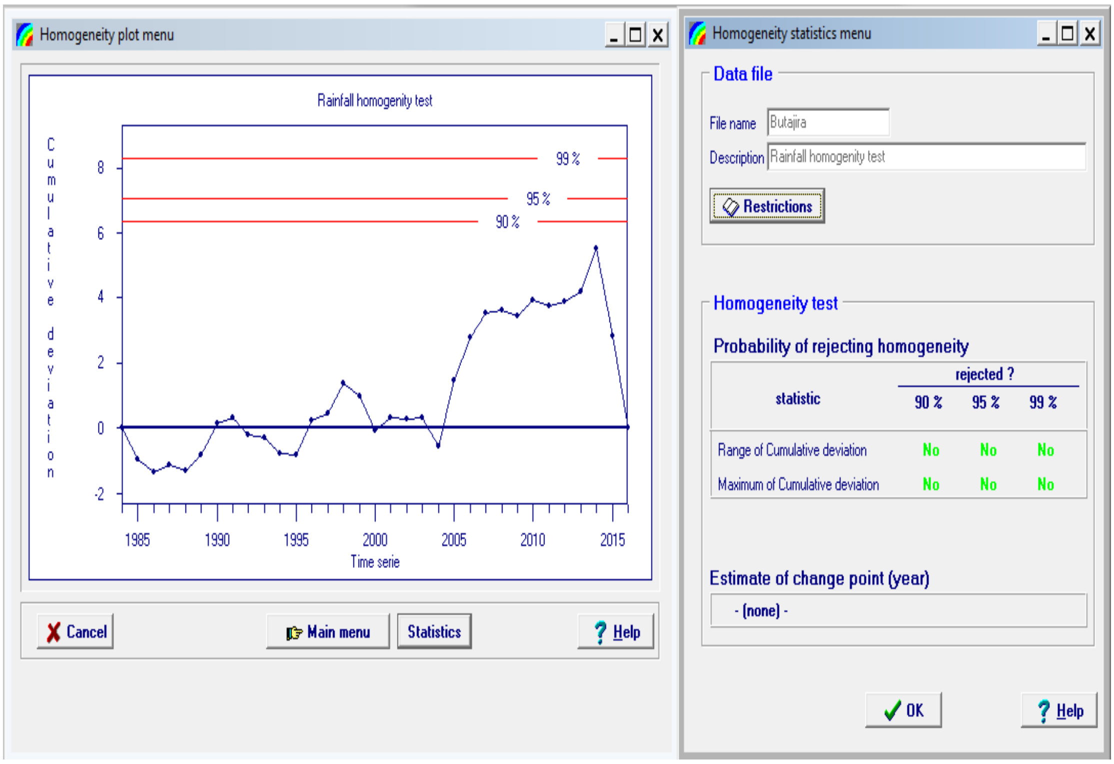
Xu, C.-Y. 2002. Hydrologic models. *Textbooks of Uppsala University. Department of Earth Sciences Hydrology*.

APPENDIXES

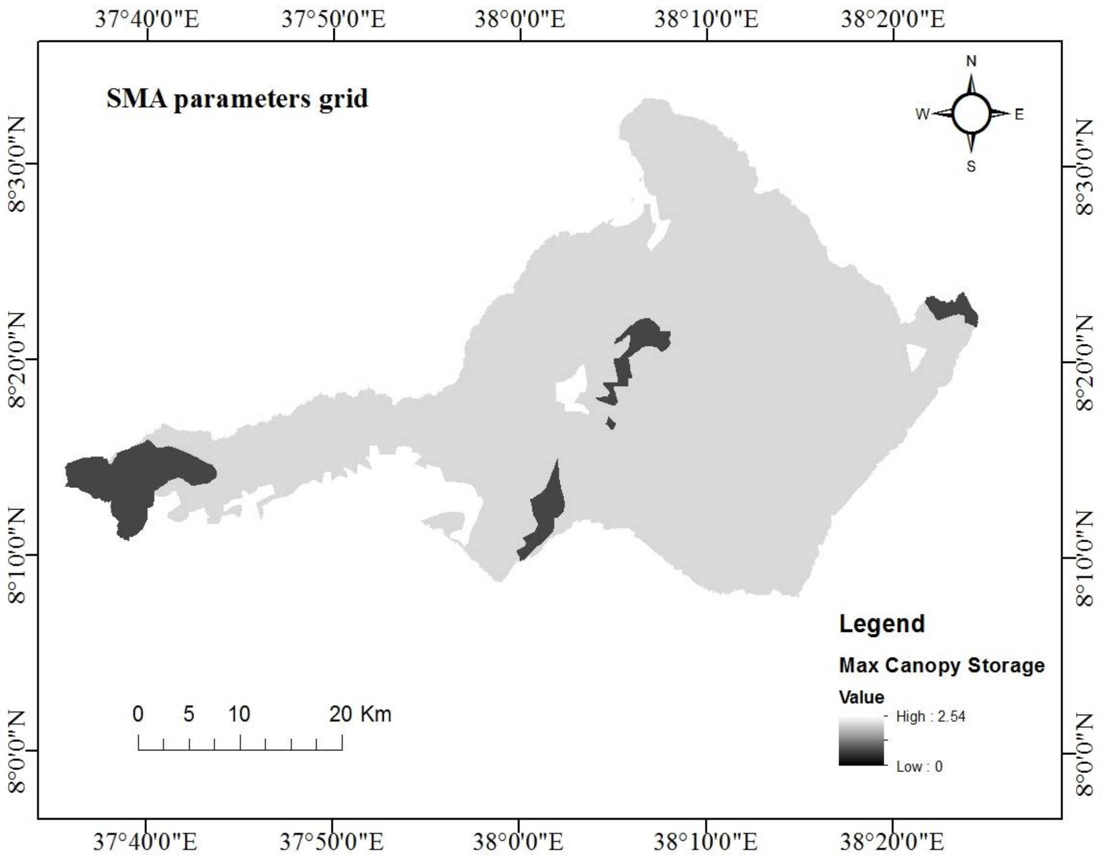
APPENDIX-A: Homogeneity test graph using RAINBOW Software

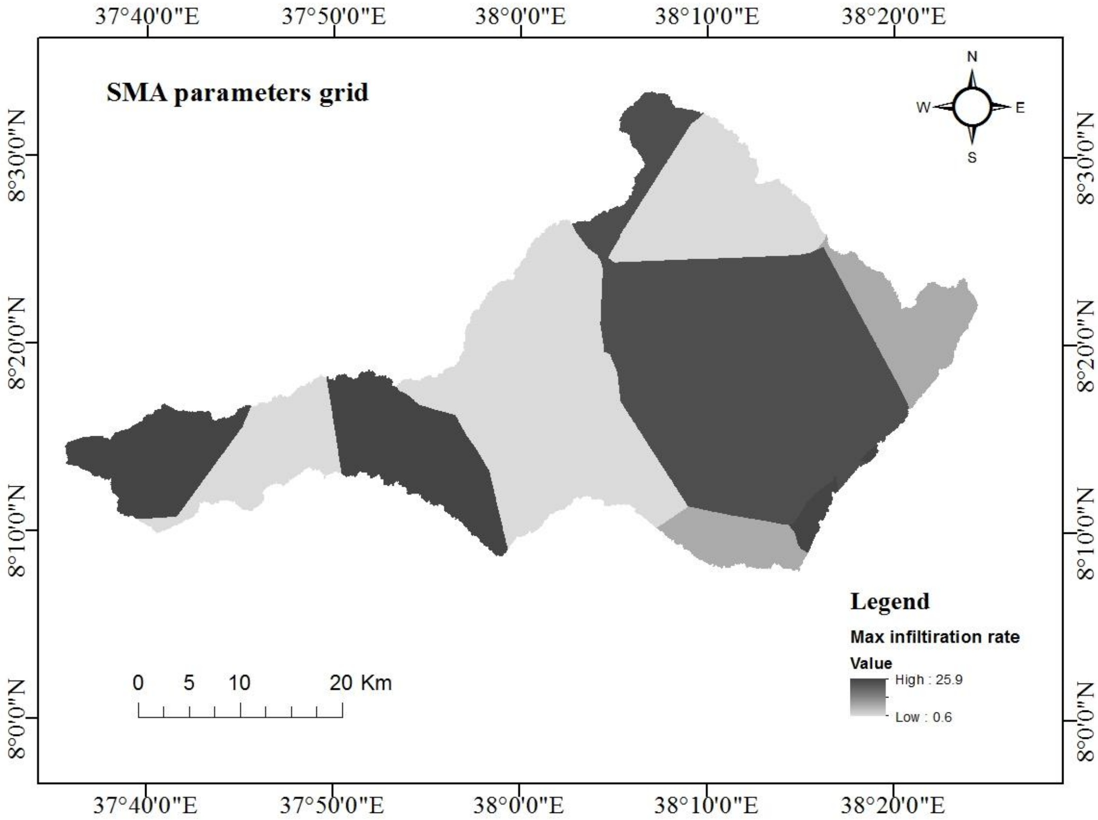


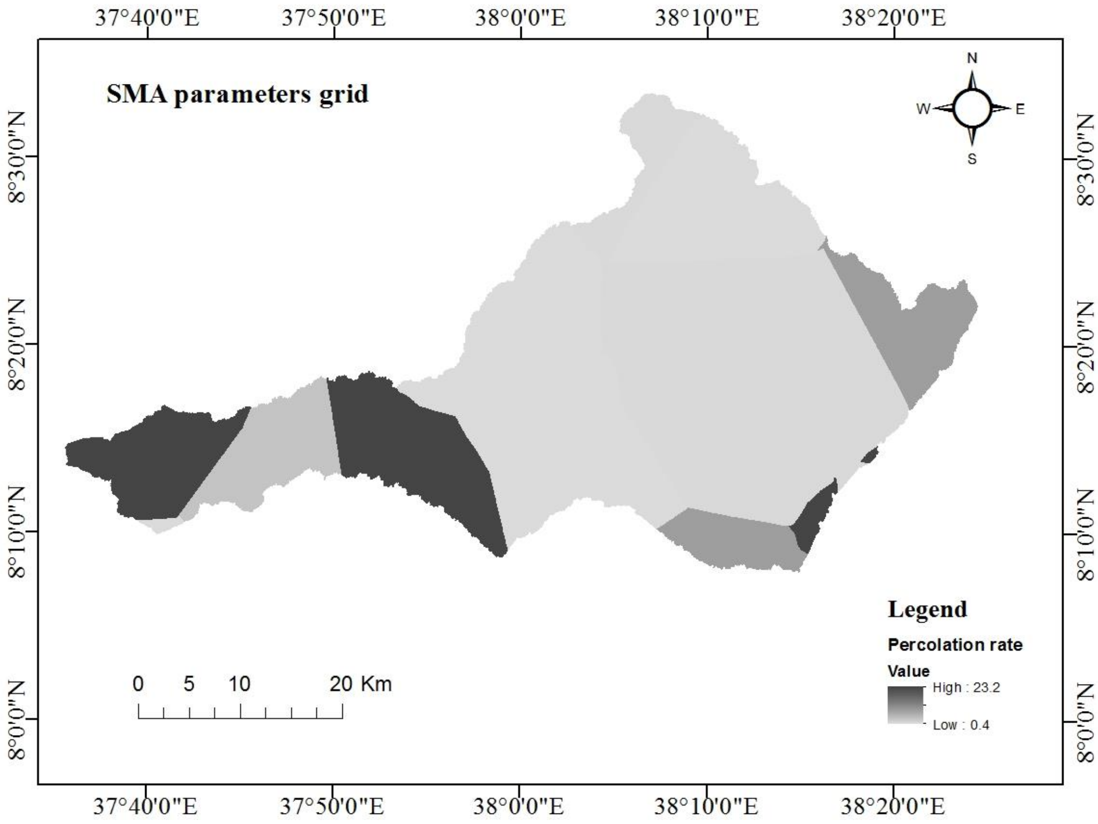


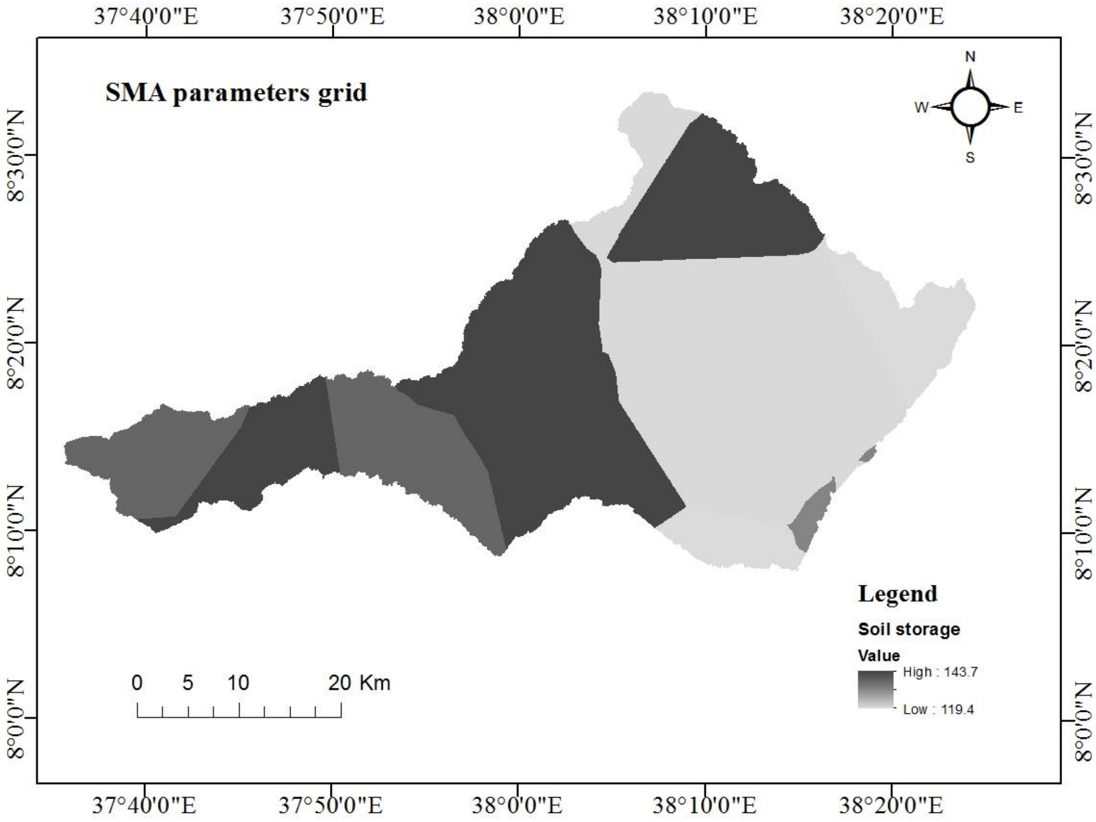


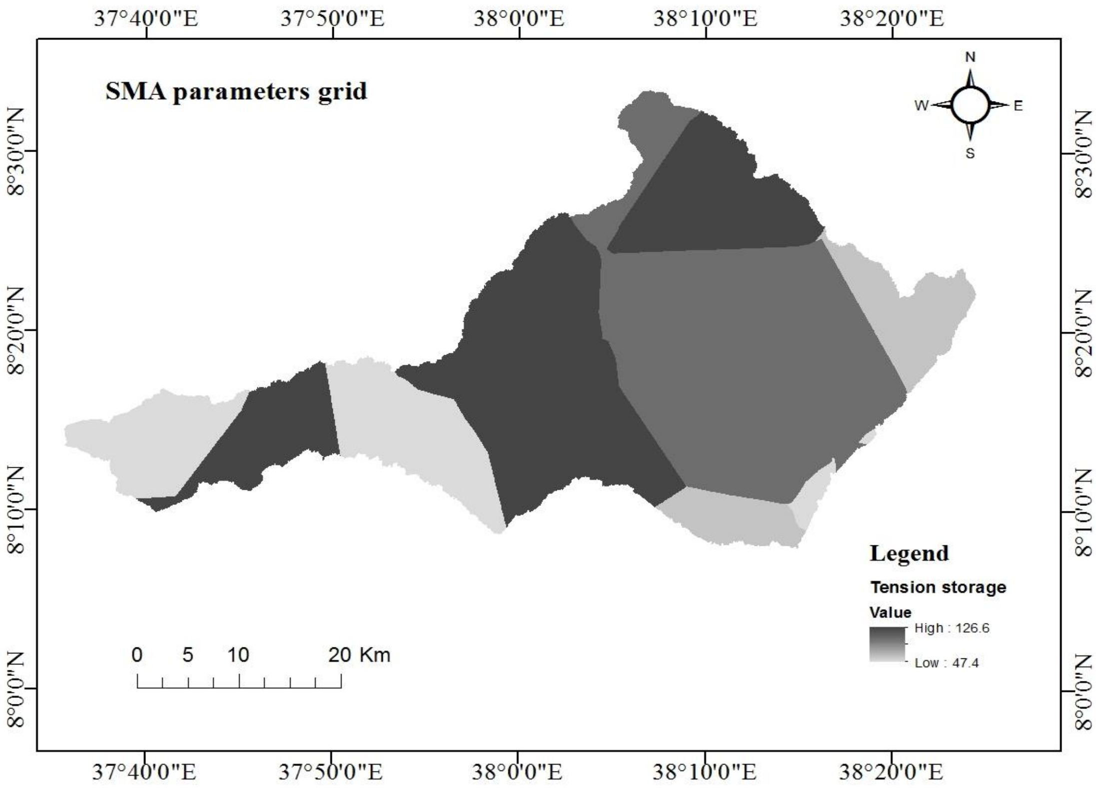
APPENDIX-B: SMA Parameters Grids



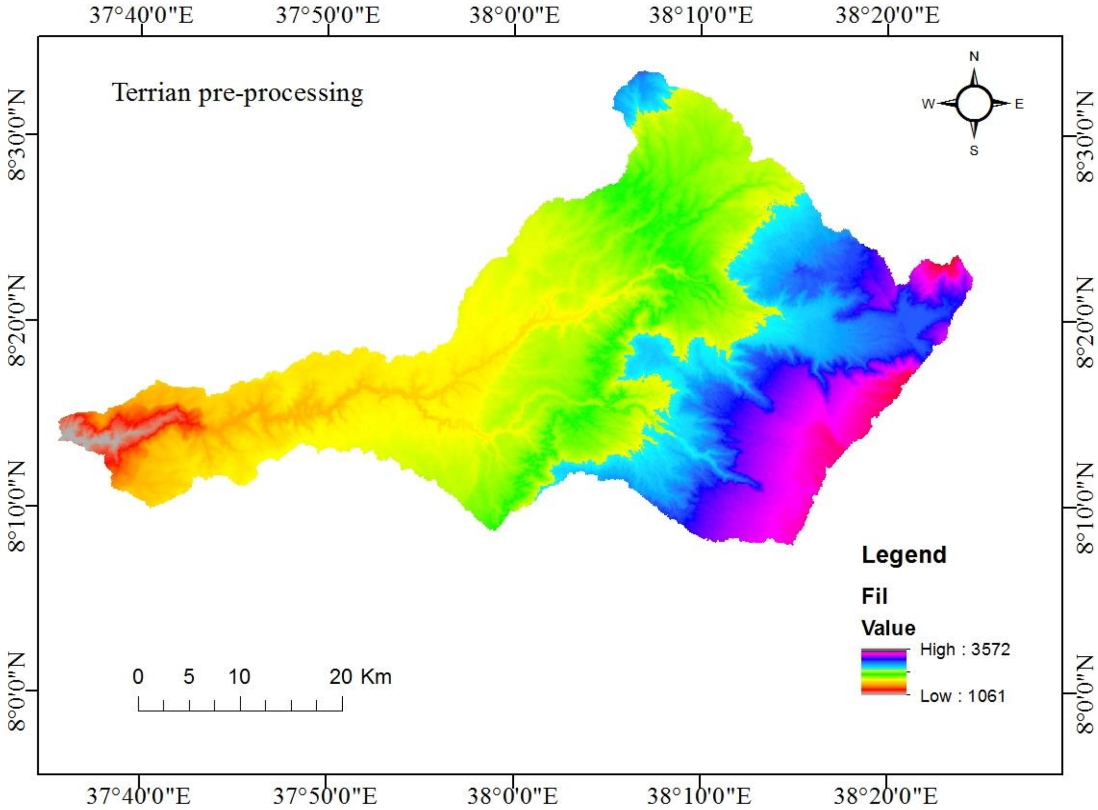

SMA parameters grid
Legend
Max infiltration rate
Value
High : 25.9
Low : 0.6
0 5 10 20 Km
37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N

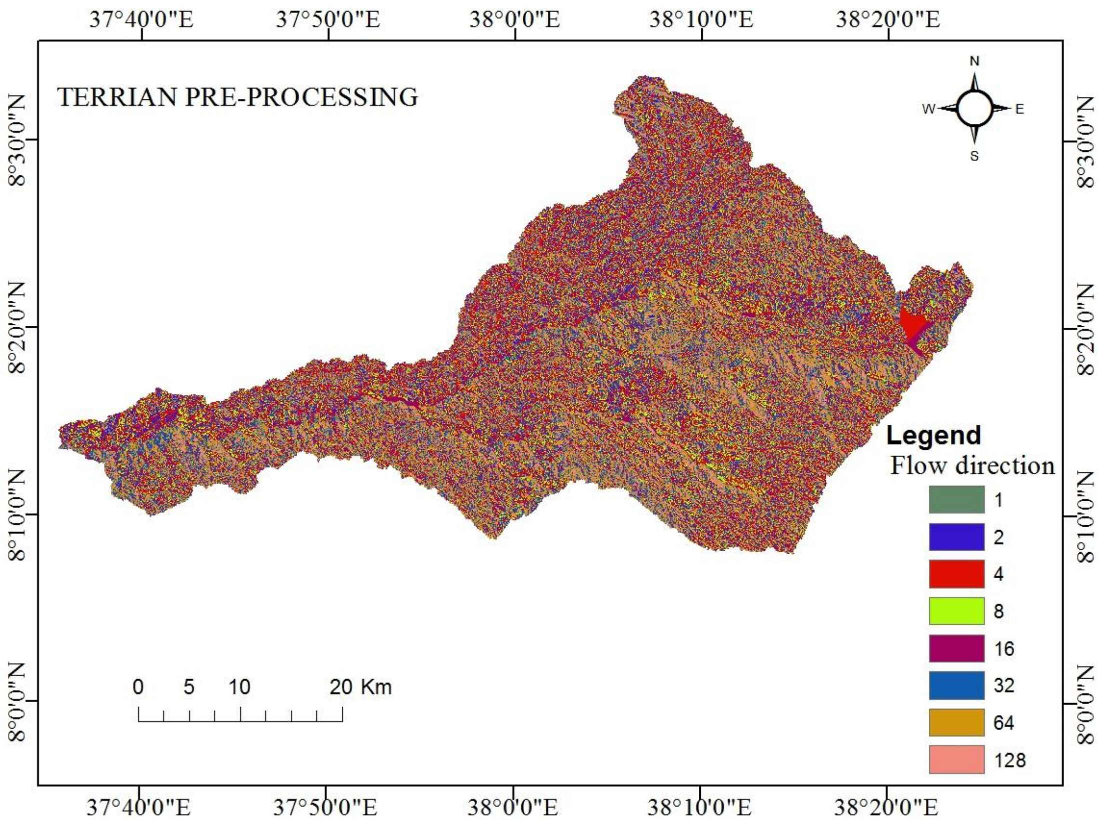

SMA parameters grid
Legend
Percolation rate
Value
High : 23.2
Low : 0.4
0 5 10 20 Km
37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N

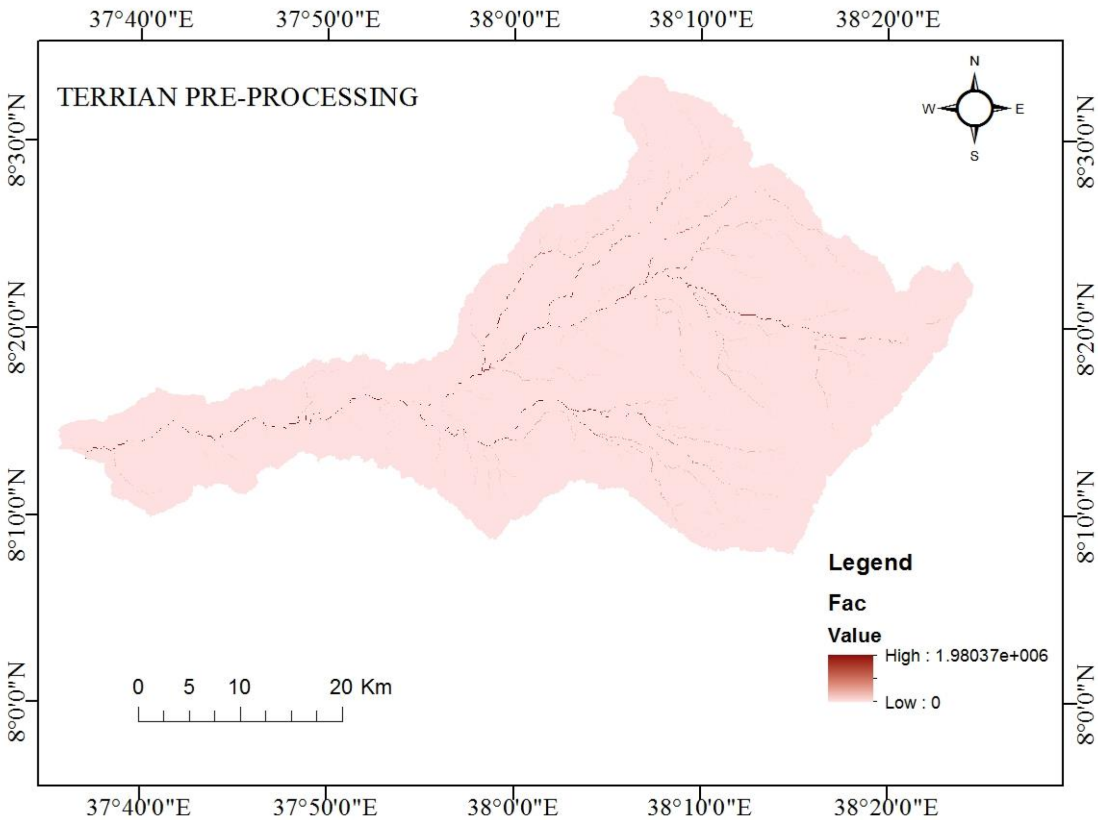

37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N
SMA parameters grid
N
W
E
S
Legend
Soil storage
Value
High : 143.7
Low : 119.4
0 5 10 20 Km

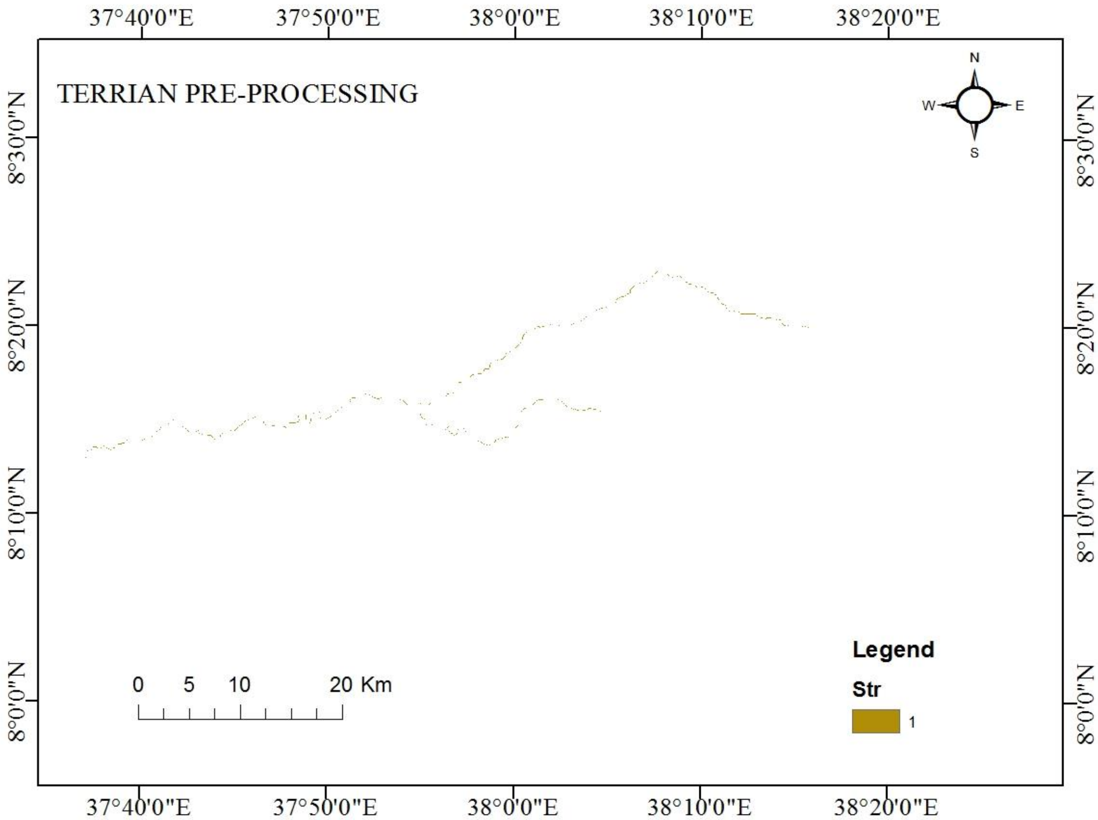

37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N
SMA parameters grid
N
W
E
S
Legend
Tension storage
Value
High : 126.6
Low : 47.4
0 5 10 20 Km

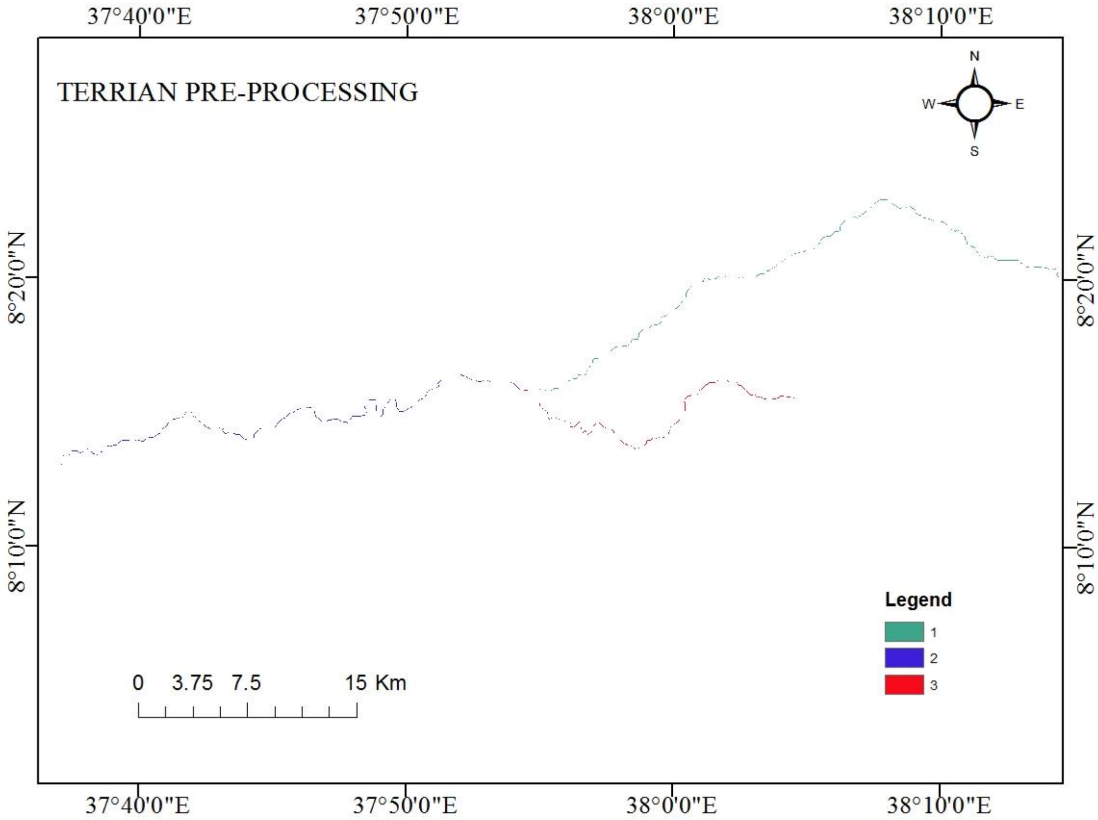
APPENDIX-C: Terrain preprocessing Results

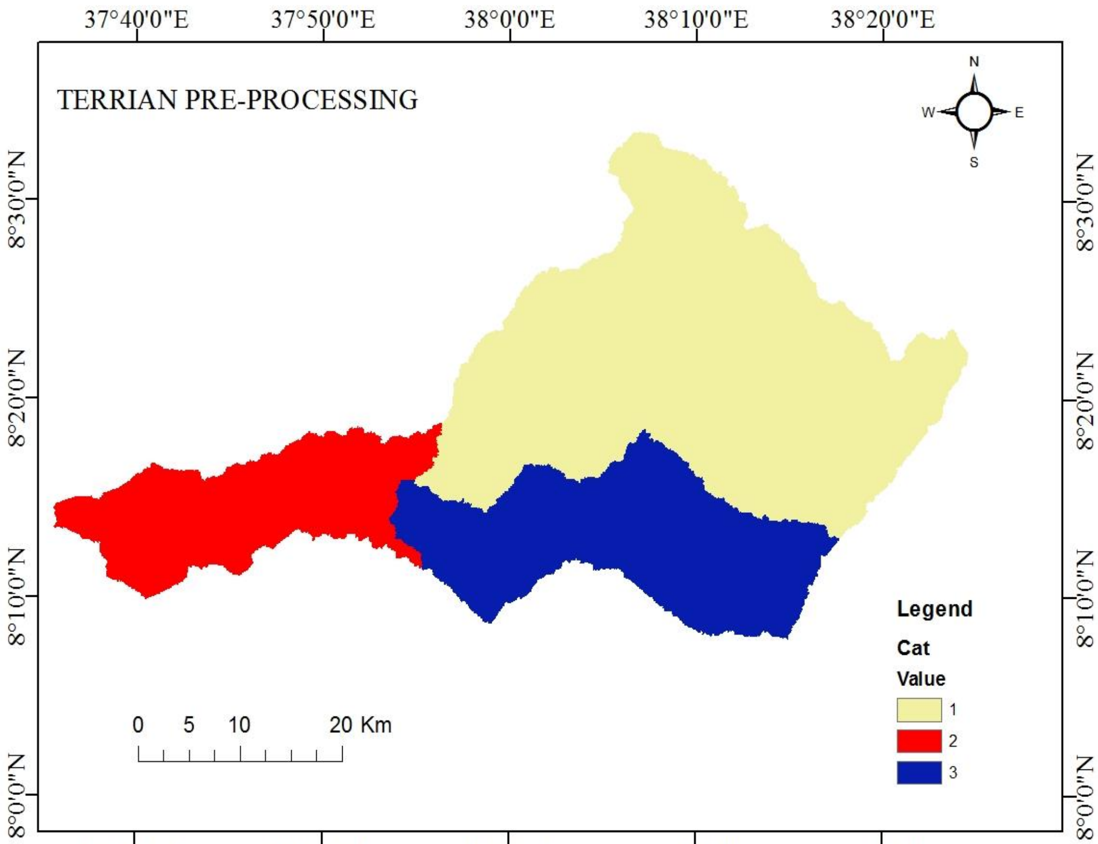


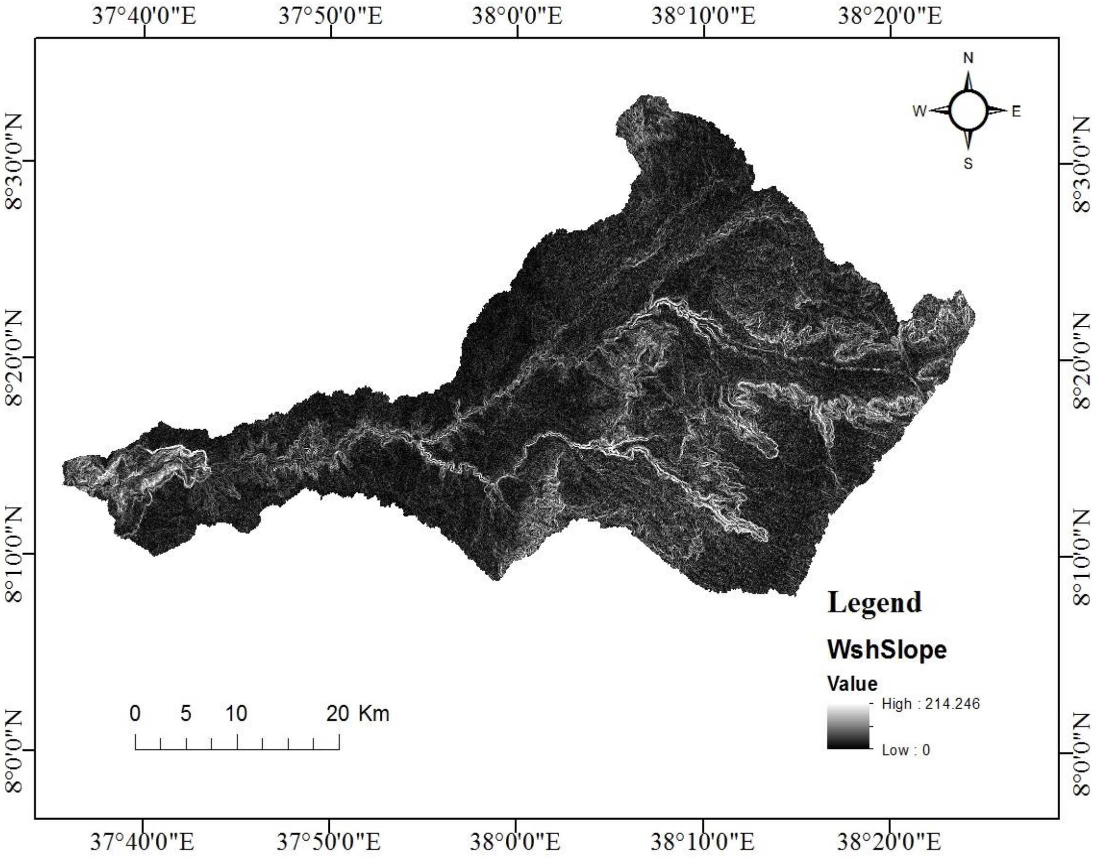



37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N
TERRIAN PRE-PROCESSING
N
W
E
S
Legend
Fac
Value
High : 1.98037e+006
Low : 0
0 5 10 20 Km


37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N
TERRIAN PRE-PROCESSING
N
W
E
S
Legend
Str
1
0 5 10 20 Km


37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
TERRIAN PRE-PROCESSING
N
W
E
S
8°20'0"N
8°10'0"N
Legend
1
2
3
0 3.75 7.5 15 Km


37°40'0"E
37°50'0"E
38°0'0"E
38°10'0"E
38°20'0"E
TERRIAN PRE-PROCESSING
N
W
E
S
8°30'0"N
8°20'0"N
8°10'0"N
8°0'0"N
Legend
Cat
Value
1
2
3
0 5 10 20 Km



APPENDIX-D: HEC-HMS Model Output

Global Summary Results for Run "Calibration"

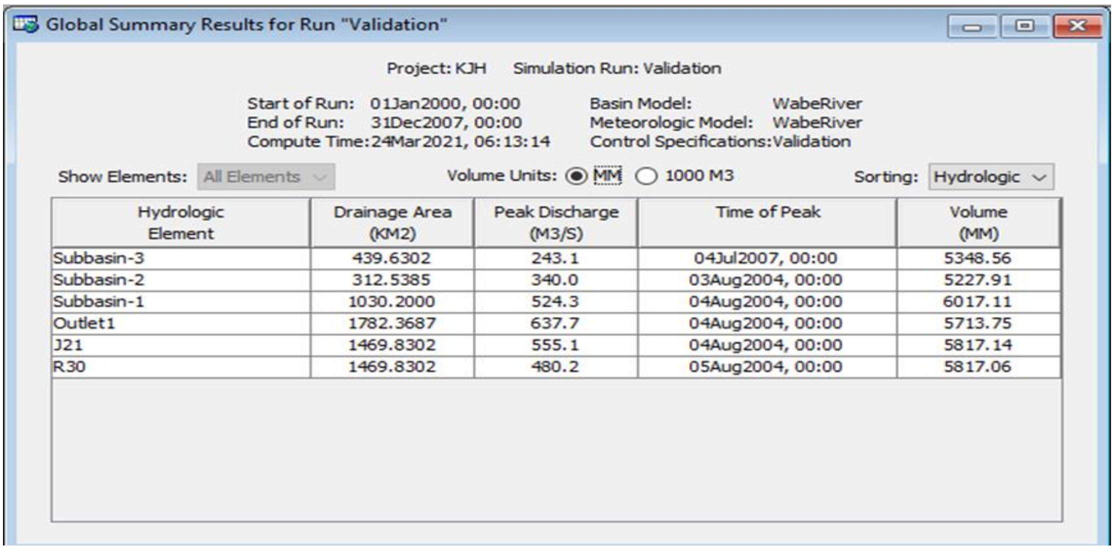
Project: KJH Simulation Run: Calibration

Start of Run: 01Jan1987, 00:00
End of Run: 31Dec1999, 00:00
Compute Time: DATA CHANGED, RECOMPUTE

Basin Model: WabeRiver
Meteorologic Model: WabeRiver
Control Specifications: Calibration

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)
Subbasin-3	439.6302	81.1	17Aug1992, 00:00	8037.59
Subbasin-2	312.5385	169.0	23Aug1988, 00:00	10413.78
Subbasin-1	1030.2000	635.2	23Aug1992, 00:00	12718.59
Outlet1	1782.3687	698.4	23Aug1992, 00:00	11159.67
J21	1469.8302	672.1	23Aug1996, 00:00	11318.49
R30	1469.8302	574.0	24Aug1996, 00:00	11318.27



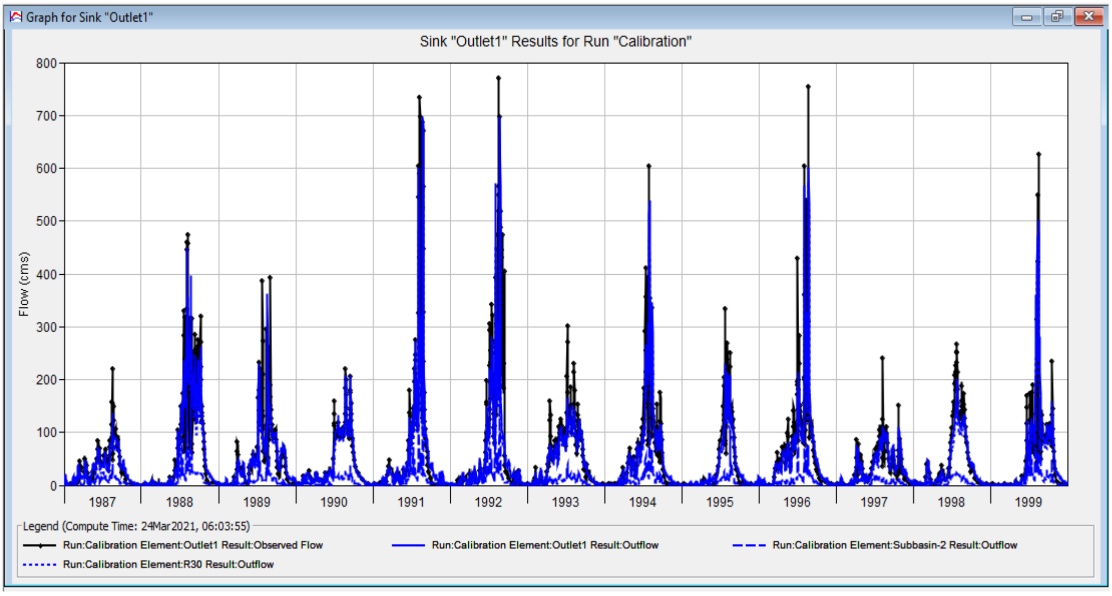
Global Summary Results for Run "Validation"

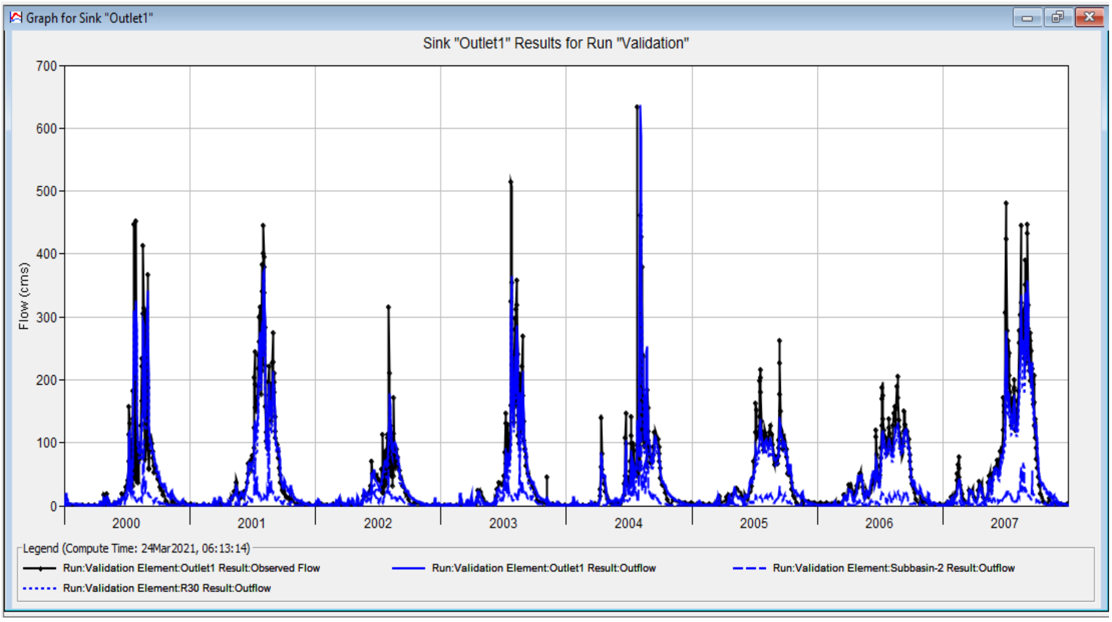
Project: KJH Simulation Run: Validation

Start of Run: 01Jan2000, 00:00 Basin Model: WabeRiver
End of Run: 31Dec2007, 00:00 Meteorologic Model: WabeRiver
Compute Time: 24Mar2021, 06:13:14 Control Specifications: Validation

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)
Subbasin-3	439.6302	243.1	04Jul2007, 00:00	5348.56
Subbasin-2	312.5385	340.0	03Aug2004, 00:00	5227.91
Subbasin-1	1030.2000	524.3	04Aug2004, 00:00	6017.11
Outlet1	1782.3687	637.7	04Aug2004, 00:00	5713.75
J21	1469.8302	555.1	04Aug2004, 00:00	5817.14
R30	1469.8302	480.2	05Aug2004, 00:00	5817.06





Summary Results for Sink "Outlet1"

Project: KJH Simulation Run: Calibration
Sink: Outlet1

Start of Run:	01Jan1987, 00:00	Basin Model:	WabeRiver
End of Run:	31Dec1999, 00:00	Meteorologic Model:	WabeRiver
Compute Time:	05Apr2021, 08:06:48	Control Specifications:	Calibration

Volume Units: (●) MM ( ) 1000 M3

Computed Results

Peak Discharge:	721.6 (M3/S)	Date/Time of Peak Discharge	23Aug1992, 00:00
Volume:	11159.67 (MM)		

Observed Flow Gage Wabi

Peak Discharge:	769.7 (M3/S)	Date/Time of Peak Discharge:	18Aug1992, 00:00
Volume:	10902.89 (MM)		
RMSE Std Dev:	0.5	Nash-Sutcliffe:	0.711
Percent Bias:	2.35 %		

Summary Results for Sink "Outlet1"

Project: KJH Simulation Run: Validation
Sink: Outlet1

Start of Run:	01Jan2000, 00:00	Basin Model:	WabeRiver
End of Run:	31Dec2007, 00:00	Meteorologic Model:	WabeRiver
Compute Time:	05Apr2021, 08:11:24	Control Specifications:	Validation

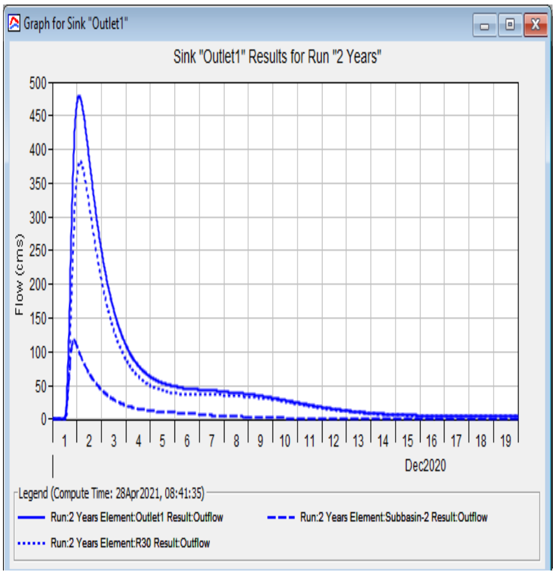
Volume Units: (●) MM ( ) 1000 M3

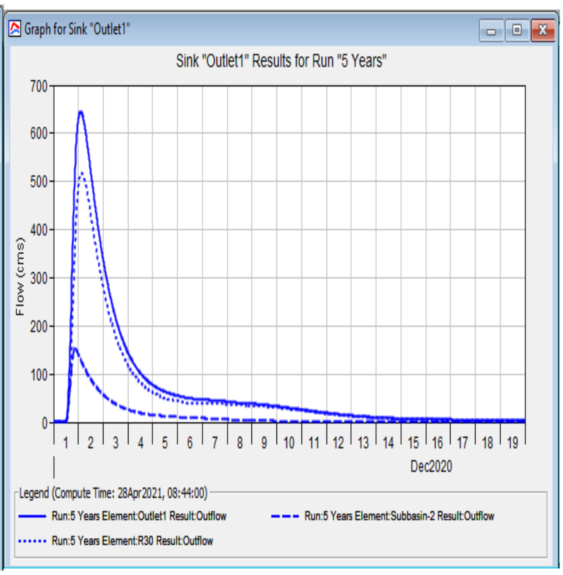
Computed Results

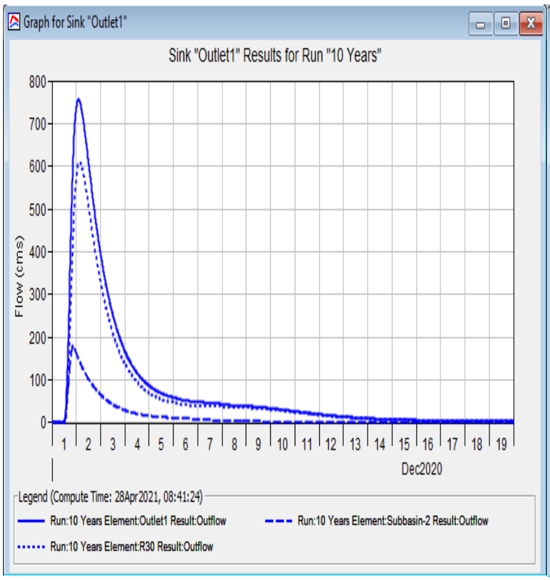
Peak Discharge:	651.3 (M3/S)	Date/Time of Peak Discharge	04Aug2004, 00:00
Volume:	5713.75 (MM)		

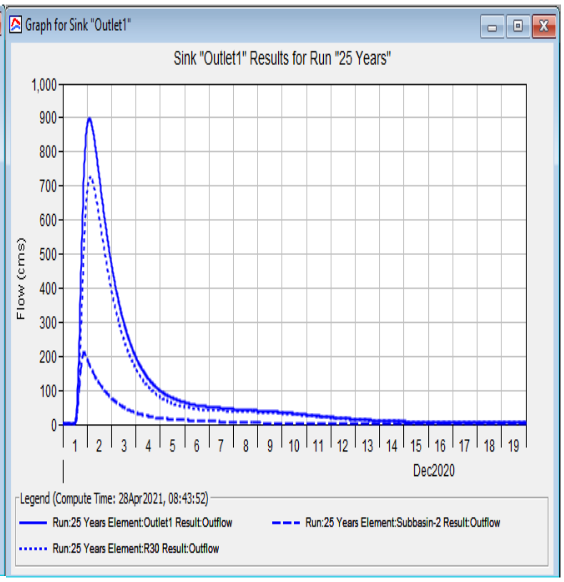
Observed Flow Gage Wabi

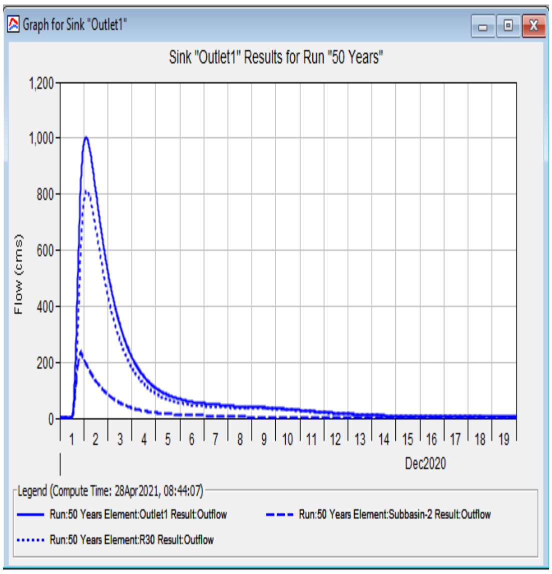
Peak Discharge:	632.9 (M3/S)	Date/Time of Peak Discharge:	26Jul2004, 00:00
Volume:	5737.67 (MM)		
RMSE Std Dev:	0.4	Nash-Sutcliffe:	0.807
Percent Bias:	-0.42 %		

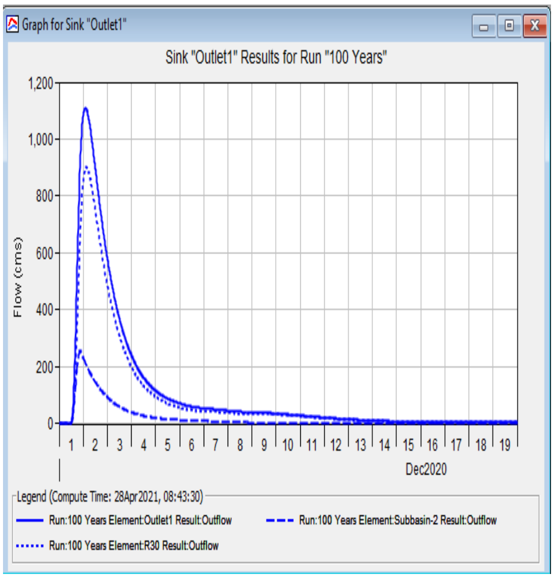


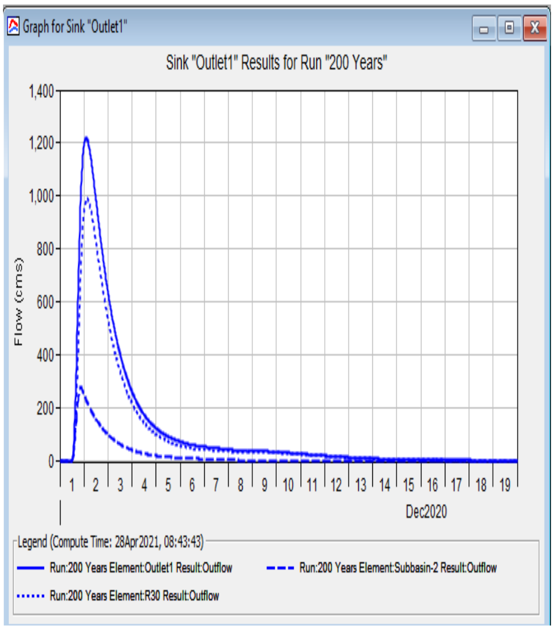


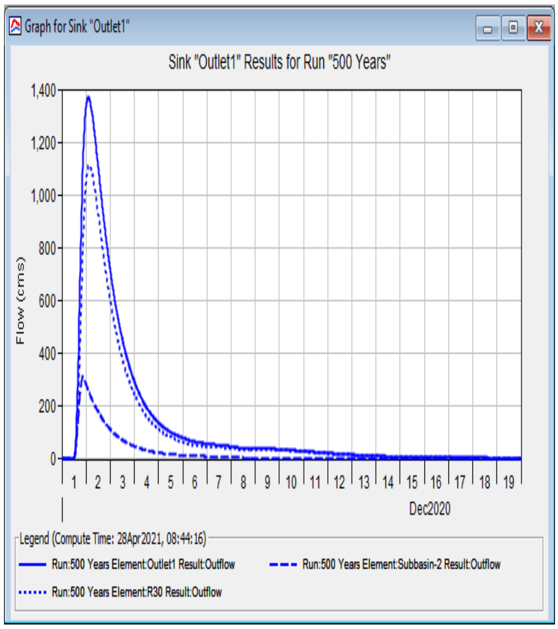

Graph for Sink "Outlet1"
Sink "Outlet1" Results for Run "10 Years"
Flow (cms)
Dec2020
Legend (Compute Time: 28Apr2021, 08:41:24)
Run:10 Years Element:Outlet1 Result:Outflow
Run:10 Years Element:Subbasin-2 Result:Outflow
Run:10 Years Element:R30 Result:Outflow


Graph for Sink "Outlet1"
Sink "Outlet1" Results for Run "25 Years"
Flow (cms)
Dec2020
Legend (Compute Time: 28Apr2021, 08:43:52)
Run:25 Years Element:Outlet1 Result:Outflow
Run:25 Years Element:Subbasin-2 Result:Outflow
Run:25 Years Element:R30 Result:Outflow


Graph for Sink "Outlet1"
Sink "Outlet1" Results for Run "50 Years"
Flow (cms)
Dec2020
Legend (Compute Time: 28Apr2021, 08:44:07)
Run:50 Years Element:Outlet1 Result:Outflow
Run:50 Years Element:Subbasin-2 Result:Outflow
Run:50 Years Element:R30 Result:Outflow


Graph for Sink "Outlet1"
Sink "Outlet1" Results for Run "100 Years"
Flow (cms)
Dec2020
Legend (Compute Time: 28Apr2021, 08:43:30)
Run:100 Years Element:Outlet1 Result:Outflow
Run:100 Years Element:Subbasin-2 Result:Outflow
Run:100 Years Element:R30 Result:Outflow


Graph for Sink "Outlet1"
Sink "Outlet1" Results for Run "200 Years"
Flow (cms)
Dec2020
Legend (Compute Time: 28Apr2021, 08:43:43)
Run:200 Years Element:Outlet1 Result:Outflow
Run:200 Years Element:Subbasin-2 Result:Outflow
Run:200 Years Element:R30 Result:Outflow


Graph for Sink "Outlet1"
Sink "Outlet1" Results for Run "500 Years"
Flow (cms)
Dec2020
Legend (Compute Time: 28Apr2021, 08:44:16)
Run:500 Years Element:Outlet1 Result:Outflow
Run:500 Years Element:Subbasin-2 Result:Outflow
Run:500 Years Element:R30 Result:Outflow