HYDROLOGICAL MODELING AND FLOOD INUNDATION MAPPING OF SHABELLE RIVER: A CASE STUDY FROM BELETWEYNE CITY, SOMALIA

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Master's Thesis

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Programme in Hydraulic

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Anadolu University

Institute of Graduate Programs

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ABSTRACT

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Hydrological and hydraulic modeling plays a vital role in water development, planning, flood inundation, early warning and flood mitigation works. Shabelle Basin, a transboundary basin with an approximate area of 297,000 km2 originating from Ethiopian highlands, is a region with limited research and paucity of hydro-meteorological data. This study aims to fill the existing knowledge gap on hydrological modeling and flood inundation mapping of Shabelle Basin, targeting Beletweyne, a flood-prone city and amongst the worst flood-hit areas in the region. Beletweyne city has been experiencing unusual floods with a high frequency for the last two decades, paving way for an increasing interest in the area.

In this study, firstly, basin characteristics of the selected area are delineated using HEC-GeoHMS. Then, hydrological modeling is undertaken with the help of HEC-HMS utilizing a continuous processing method. A five years of calibration (2013-2017) and ten years of validation (2003-2012) resulted in a model Nash-Sutcliffe Efficiency of 0.776 and 0.611 respectively. A statistical flood frequency analysis is then applied to determine runoff values for certain return periods (2, 5, 10, 25, 50, 100 and 500). Finally, hydraulic modeling is carried out using HEC-RAS in order to achieve 2-dimensional flood inundation mapping for the city of Beletweyne for different flood levels. The results show that Beletweyne city is under high risk of flooding even for short return period floods. As a conclusion, a protection plan (construction of flood control structures and setting up an early flood warning system) is recommended to reduce flood damages and protect people's lives and property in the region.

Keywords: HEC-HMS, HEC-RAS, Flood Inundation, Shabelle River.

ÖZET

SHABELLE NEHRİNDE HİDROLOJİK MODELLEME VE TAŞKIN HARİTALAMASI: SOMALİ BELETWEYNE ŞEHRİ ÖRNEĞİ

ABDINOUR ABSHIR HUSSEIN

inşaat mühendislik Anabilim Dalı

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Hidrolojik ve hidrolik modelleme, su geliştirme, planlama, baskın, erken uyarı ve sel azaltma çalışmalarında hayati rol oynar. Etiyopya dağlarından doğan yaklaşık 297,000 km^2 alana sahip sınıraşan bir havza olan Shabelle Havzası, sınırlı araştırma yapılan ve az sayıda hidro-meteorolojik ölçüme sahip bölgelerden biridir. Bu çalışma, Shabelle Havzasında sıkça sellere maruz kalan Beletweyne şehrini örnekleyerek hidrolojik modelleme ve taşkın haritalamasına ilişkin mevcut bilgi boşluğunu doldurmayı amaçlamaktadır. Beletweyne Şehri, son yirmi yıldır sık aralıklarla olağandışı seller yaşamakta olduğundan bölgedeki önemi giderek artmaktadır.

Bu çalışmada, öncelikli olarak ilgili alanın havza karakteristikleri HEC-GeoHMS ile çıkartılmıştır. Ardından HEC-HMS yardımıyla sürekli bazda hidrolojik modelleme uygulaması yapılmıştır. Beş yıllık kalibrasyon (2013-2017) ve on yıllık validasyon (2003-2012) çalışmasında model Nash-Sutcliffe Performansı olarak sırasıyla 0.776 ve 0.611 sonuçlarına ulaşılmıştır. İstatistiksel taşkın frekans analizlerilyle çeşitli tekerrür sürelerindeki (2, 5, 10, 25, 50, 100 and 500) akım değerleri hesaplanmıştır. Sonrasında HEC-RAS hidrolik modeli 2-boyutlu çalıştırılarak Beletweyne Şehrinin farklı akım seviyelerindeki taşkın alanları haritalanmıştır. Sonuçlar Beletweyne Şehrinin kısa tekerrürlü taşkınlarında bile yüksek risk altında olduğunu göstermiştir. Çalışmanın sonucunda bölgedeki sel hasarlarını azaltmak ve insanların canlarını ve mallarını korumak için bir koruma planı (sel kontrol yapılarının inşası ve erken uyarı sisteminin kurulması) önerilmiştir.

Anahtar Sözcükler: HES-HMS, HEC-RAS, Taşkın haritaları, Shabelle Nehri.

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First and foremost, I would like to thank Almighty Allah for helping me throughout my research. Secondly, my thanks go to my supervisor, Assist. Prof. Dr. Ali Arda ŞORMAN for guiding me throughout the thesis duration and his relentless efforts, patience, and guidance. Thanks to my two jury members Assist.Prof.Dr. Gökçen UYSAL and Assist.Prof.Dr. Mustafa Cansaran ERTAŞ for their support. I would also like to thank my parent and sibling for their assistance and backing through the phone call as they are far away from me.

ABDINOUR ABSHIR HUSSEIN

06/11/2020

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Anadolu University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

ABDINOUR ABSHIR HUSSEIN

CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

GLOSSARY OF SYMBOLS AND ABBREVIATIONS

CN	:	Curve Number
DV	:	Diffusion Wave
DEM	:	Digital Elevation Modeling
FOA	:	Food Agricultural Organization
Fr	:	Froude number
GIS	:	Geography Information System
GUI	:	Graphic User Interface
HWSD	:	Harmonized World Soil Data
HECGeoHMS	:	Hydrologic Engineering Center-Geospatial Hydrological Modeling System
HEC-HMS	:	Hydrologic Engineering Center-Hydrological Modeling System
HEC-RAS	:	Hydrologic Engineering Center-River Analysis System
IGBP	:	International Geosphere-Biosphere Program
SCS	:	Soil Conservation Service
SWALIM	:	Somali Water and Land Management
Tc	:	Time of Concentration
UH	:	Unit Hydrograph
UNESCO	:	United Nation Educational, Scientific, and Cultural Organization
USDA	:	United States Department of Agriculture
USGS	:	United States Geological Survey

1. INTRODUCTION

1.1. Background

Flood is a natural hazard that results from a combination of both hydrological and meteorological components. It occurs when normally dry land areas are temporarily inundated due to overflowing of water at the natural or artificial confines of a river resulted from prolonged or heavy rainfall. As reported by World Disasters (2016), seismic catastrophes have claimed the most significant number of lives of around 357,092 people from 2006 to 2015, while flood disasters have hit the highest number of souls, 840 million heads in the midst of 2006 and 2015 and caused $ 342.5 billion damage worldwide.

Floods may lead to extensive destruction, causing casualties and human losses and destroying private resources and significant public infrastructures like hospitals, schools, and governmental buildings. During 1998-2017, floods hit around 2 billion individuals globally. Residents living in lowland and flood plain areas or lack awareness and early warning systems of flooding hazards are at risk and most susceptible people to floods.

Around 82-92% of all recorded and registered catastrophes from natural hazards in the last ten years are caused by severe rainfalls, tropical cyclones, tsunamis, droughts, and floods. Due to extreme precipitation caused by climate change results in the flood with higher intensity and frequency (WHO, 2020).

Even though whole flood prevention is quite impossible, but its consequences might be minimized via proper management and planning. Resulting flood disaster consequences on human lives and their assets might be minimized through control structures (weirs, dams, diversion works) and non-structural (rescue operations, early warning systems, forecasting, public education, and legal instruments) means.

In southern Somalia, particularly cities along the Shabelle River lacks both control structures and non-structural measures. Hence, to minimize the flood consequences on the flood-prone towns along the Shabelle river, proper action should be taken.

Wabi Shebelle is a transboundary river that starts from Ethiopian highlands and ends in Somalia. İts the largest river basin in Ethiopia covering about 19 percent of the total land area of the country. In terms of population, it covers only about 11% of the country’s overall figure. However, the percentage of water resources in the form of surface runoff is very insignificant compared to other river basins; it is only 3% of the average annual runoff of the country. In terms of natural resources, the basin has vast potential in land resources, energy and power, livestock, and human resources. But the shortage of water resources is the biggest stumbling block for the overall development of the basin particularly in the lowlands of the Somali region where the rainfall is scanty and erratic.

In Somalia, Floods usually occur in the Shabelle and Jubba River basin's riverine areas, where both rivers show hydrological seasonal characters with a higher probability of flooding, particularly in the rainy season from (October to November). The most significant flood disasters documented in the last decades in the two rivers happened in 1961, 1977, 1981, 1987, and 2006. The source of these events was due to significant rains contributed by Ethiopian highlands in the upper catchments. Though human activities in the flood-prone areas like cutting and cultivating the riverbanks to let water flow to their farms, also contributed to flooding (Muthusi and Gadain, 2009).

1.2. Problem statement

Since the mid of 1989s, Somalia has been experiencing civil unrest that finally led to the Somali government's fall down and the beginning of the civil war in late 1990. The civil unrest has provoked destabilization and insecurity in the country and throughout the region, the lack of central government power, economic and social infrastructure loss.

The conflict, linked with the lack of reliable water resource administrators' systems and land-use administration institutions, has led to severe flooding along with the riverine and flood-prone areas. Somalia experiences both flash floods and river floods. Due to higher annual precipitation in the Ethiopian highlands, which gets more frequent and high value rainfall than Somalia and lacks proper maintenance and awareness system, it results in human casualties and significant economic damages.

Recent floods in central Somalia, particularly along the Shabelle River has affected nearly one million people displacing and forcing to flee for over 450,000 people. Beletweyne city, this thesis's study target is amongst the worst hit, where the Shabelle river inundated around 85% of the town and nearby villages. Therefore, this matter has necessitated the need for both hydrological and hydraulic modeling of the Shabelle river to identify the source of the problem, and minimize social suffering caused by periodic flooding.

In Somalia, a knowledge gap exists on hydraulic and hydrological modeling, flood hazard mapping, flood inundation mapping, and such water-related problems.

1.3. Objectives

This study's primary objective is to estimate flood inundation extents and hydrological modeling using both hydrologic and hydraulic modeling with the help of HEC-HMS, HEC-RAS, and GIS. This study's other goals include documenting the results of 2D flood modeling using HEC-RAS and recommending a way forward to overcome and minimize the flood reoccurrence of the study area.

Identification of the problems related to flooding in Beletwayne city and developing flood inundation maps as awareness and mitigation measures are among the study's specific objectives.

1.4. Structure of the thesis

Chapter One outlines the research's scope, focusing on the research background, the general description of the study area, research objectives, and the research problems. Chapter Two highlights the study area, methodology, and literature review related to the study dealing with applicability and limitations applied to the research while hydrological modeling using HEC-HMS and some statistical methods are in Chapter Three. Chapter Four deals with the hydraulic modeling used for the research focusing on 2D modeling in HEC-RAS, while Chapters Six Summarizes the results, conclusions, and recommendations.

2. STUDY AREA, METHODOLOGY AND LITERATURE REVIEW

2.1. Study area

The Shebelle river originates at an elevation of about 4000 m.a.s.l. from the Bale mountain ranges of the Galama and the Ahmar in Ethiopia and is located between $0^{o}15'$ and $9^{o}38'$ north of Equator and between $38^{o}40'$ and $46^{o}9'$ east of Prime Meridian. Initially, the river flows in the southern and then in the eastern direction and subsequently changes its course towards the north-eastern direction to East Hararge Zone of Oromiya Region. Thereafter the river course finds its path towards the south and flows into the limestone tablelands situated in the central areas of the basin. This landmass has been deeply eroded by the river waters. The erosion, however, decreases progressively at the beginning of the Somali Region. At this stage, the river takes a turn towards the south – the easterly direction from slightly upstream of Immi and continues flowing towards Somalia via Gode, Mustahil, and Ferfer (MWR, 2004).

Two third of the Shabelle river lies in Ethiopia where the rest lies in Somalia. The total length of the Shebelle River within Ethiopia from the source to the Somali border is about 1300 km. Shabelle River crosses an extra distance of 1,236km of mildly sloping terrain from the border of Somalia directly adds its water to the Indian Ocean.

The river is primarily fed by several tributaries from the left bank originating from Arsi and Chercher's high plateaus. The crucial tributaries are Ulul, Robe, Manya, Ungwata, Ramis, Erer, Dakata, and Fafen. The flow from Fafen and its tributary Jerer are intermittent (MWR, 2004).

The topography of the basin may be broadly categorized into two groups. Highlands and lowlands. Highlands normally covers the western part of the basin between 900m to 4000m elevations whereas the lowlands range between 200m to 900m elevations above mean sea level as mentioned in Figure 2.2. About 50 percent of the basin area has an attitude of less than 550m above sea level and is categorized as the semi-desert zone having a mean annual rainfall ranging between 150 and 500mm and $25^{o}C$ as the annual mean temperature. Sizeable parts of the Somali region is sparsely populated and has no settled farming activity are included in this zone. The area is mainly occupied by semi-nomadic societies with cattle rearing being the main economic activity.

Another zone covering about 15 percent of the basin area and having an altitude between 500m and 1500 m is the tropical zone which is locally termed as Kolla area. It is predominant in the Somali and some part of the Oromiya regions and Harari council. The area included in this zone receives an average annual rainfall between 500 to 1000mm and temperature ranges between 20ºC to 25ºC. Though sparsely populated a sizeable area in this zone is under cultivation. However, due to scarce and unreliable rainfall drought and crop failure frequently occur in this zone.

Sub-Tropical zone locally known as Weina Dega accounts for about 20 to 25 percent of the Basin's total area. This zone is found between an altitude of 1500m and 2500m above sea level in Harari National Regional State and Bale, West Hararge, East Hararge, and Arsi zones of Oromiya region. The zone receives an annual rainfall up to 1200mm and above and the temperature ranges between 16 ºC to 20 ºC. The zone is densely populated and is known for its growing wide variety of crops, agriculture being the predominant economic activity.

About 10 percent of the basin area in the highlands of Arsi and Bale zone is covered in temperate zone locally known as Dega having an altitude between 2500-3200masl. Rainfall ranges between 900 and 1800mm (in very highlands) and the temperature is between 13 ºC to 20 ºC. Settlements are dense and it is the most intensively cultivated area. In these areas, the timely distribution of rainfall is the major factor affecting farming practice.

Wurch and High Wurch zone covering Arsi and Bale highlands occupies the smallest portion of the total area of the basin. For the most part, the year temperature in this zone is below 13oc with the availability of rainfall being almost throughout the year. Cultivation is difficult and confined to growing limited types of crops.

The basin is predominantly rural, with an economy dominated by rainfed subsistence agriculture. The average holding size in the densely populated highlands is about 1.0 ha., barely sufficient to provide subsistence food requirements for one family. Production of cereals and pulses dominates the cropping pattern with Wheat, Barley, and Teff being the short season cereals and Sorghum and maize long season cereals.

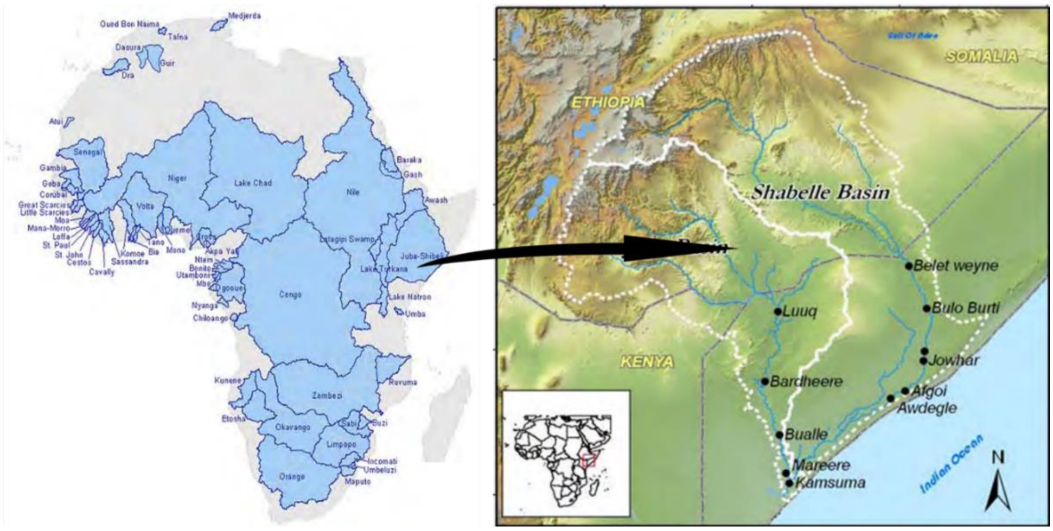

Figure 2-1. *Locations of Shabelle and Juba Rivers*

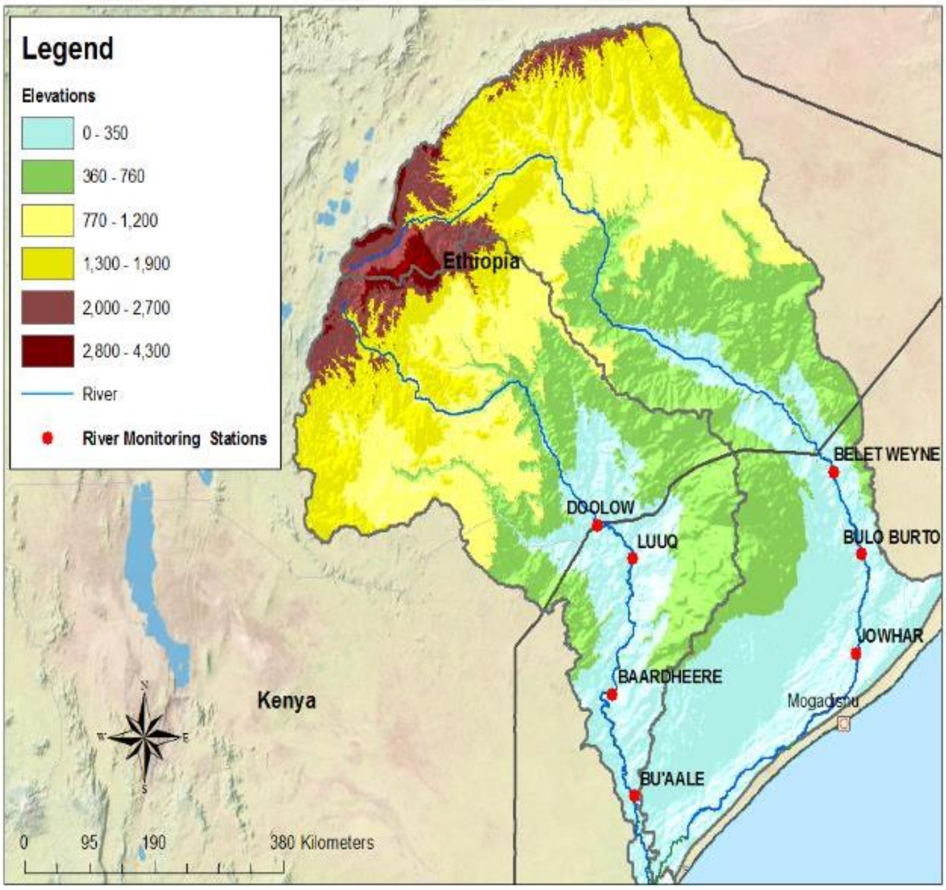

Figure 2-2. *Digital Elevation Model of Shabelle and Juba Rivers*

2.2. HEC (Hydraulic Engineering Centre) Programs

2.2.1. HEC-HMS (Hydrologic Modeling System)

In the recent years, progresses in Geographic Information System (GIS) paved way for hydrological and hydraulic modeling of a watershed system. Since spatial information sharing via the internet from different institutions, agencies, private and public companies become active the integration of GIS with hydraulic and hydrological modeling opens many opportunities and alternatives for studying, analyzing, and understanding the watershed system.

HEC-HMS software was revealed by the Department of the Army Corps of Engineers. It is practiced rainfall-runoff simulations. Generally, HEC-HMS is a rainfall-runoff modeling software with different input parameters representing the software's meteorological components like evapotranspiration, infiltration, precipitation, and snowmelt. It also has additional components for loss determinations, which is called loss transform components. Furthermore, the basin has specific parameters that represent the basin's physical characteristics like the length of the basin, area of the basin, ground properties of the basin, etc (Wałęga, 2013).

HEC-HMS has been practiced effectively for over 30 years and is recognized for many practical purposes, like defining floodways for the U.S. Federal Emergency Management Agency. One of these software's significant gains is the broad selection of different hydrologic models suitable for various environments under other conditions. Moreover, HEC-HMS includes options for the calibration of the chosen models against measured precipitation and runoff data. With HEC-HMS being a widely used, complete, and flexible software solution for modeling the rainfall-runoff process, the applicability rather depends on the hydrologic models' suitability for a given situation rather than on the software itself (Scharffenberg, 2016).

The capacity to conduct spatial analysis for the improvement of lumped and disturbed hydrologic parameters not only spares time and exertion but moreover increases certainty and precision over conventional methods. These progressed modeling strategies have ended up attainable and become feasible since time-devouring data manipulation can presently be produced proficiently utilizing spatial operation in GIS.

HEC-HMS has some basic components that manage the software. Basin and meteorological model manager, control specification, and time-series data manager, paired and grid data manager are among the major components of HEC-HMS. The control specifications manager focuses on the computational time step and the date of the simulation run is defined (US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center 2000).

The main features of the basin model are sub-basins, reaches, and junctions. The modeling results comprise runoff hydrographs for each sub-basin as well as graphical and numerical representations of rainfall, losses, and direct runoff for each sub-basin (Scharffenberg, 2016).

The meteorological model is the representation of the rainfall event that is intended to be modeled where the physical basin model is essentially a simplified physical representation of the watershed which is prepared with HEC-Geo HMS. The control specifications manager focuses on the computational time step and the date of the simulation run is defined.

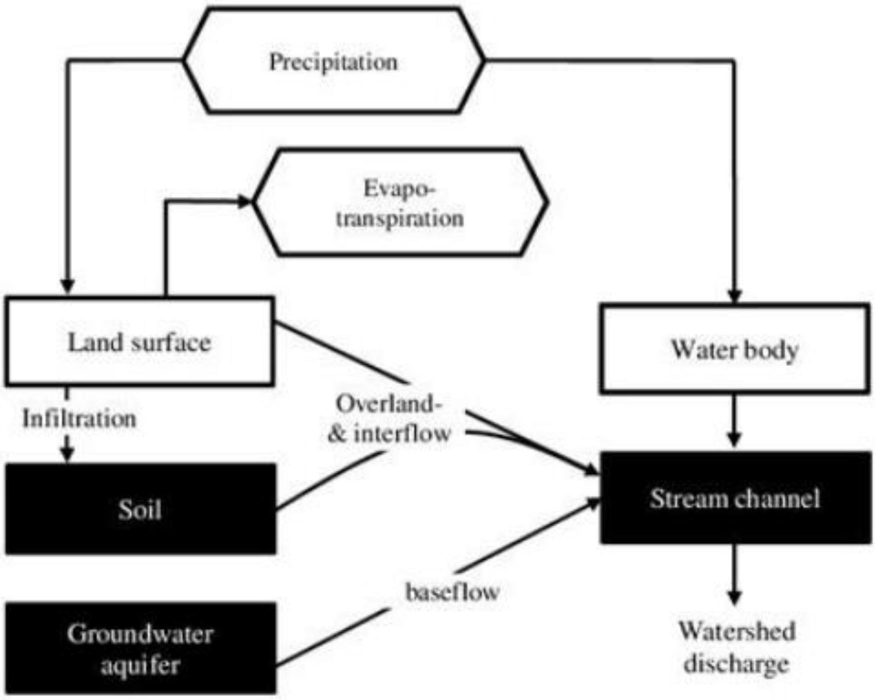

Figure 2-3. *Precipitation-Runoff Process in HEC-HMS (HEC-HMS Manual)*

Generally, the HEC-HMS basin model has three major basin model manager components: the control specification, the basin, and the meteorological model manager.

To create a basin model hydrograph using HEC-HMS, the loss, transform, and base flow method should be determined with specified parameters. Every single loss method has its own parameters. Appropriate methods are chosen according to the purpose of the application, the basin's condition, and the available data. Basin model manager provides physical components of the basin-like reaches, junctions, sinks, reservoirs, etc. The meteorological model is for the precipitation, temperature, evaporation, and discharge values based on time series. Control specifications clearly define and represent the exact starting and end date and time of the run.

Figure 2-4 summarizes the input, process, and output of the HEC-HMS program. It also shows the major components of the program, the model execution and output results.

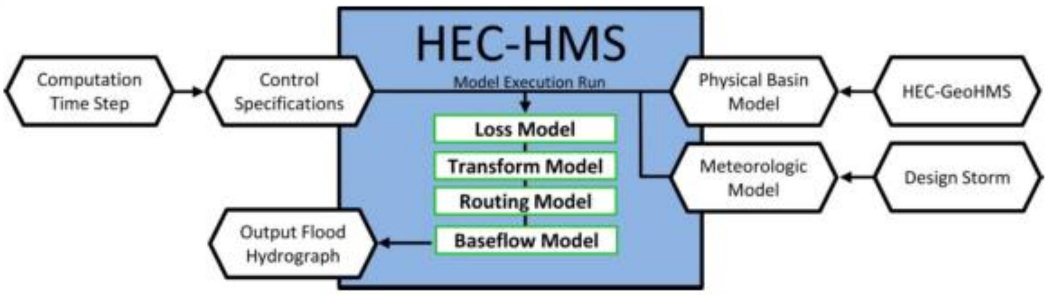

Figure 2-4. *Major Components of HEC-HMS (https://onlinelibrary.wiley.com)*

2.2.1.1. Loss Method

HEC-HMS software recognizes that both water and land in every catchment can be classified as either a porous surface or directly joined impervious surface. The impervious surface, which is directly connected, is the part of the catchment for which all contributing rainfall runoff with no losses (no evaporation and no infiltration, etc.), where there are rainfall-runoff losses in the previous surfaces. In order to account for those losses in a previous-surface HEC-HMS has different alternative loss methods. Infiltration loss, which plays a vital in rainfall-runoff losses, is modeled in the loss method of HEC-HMS. The infiltration rate mainly affects both the peak flow rate and the hydrograph volume.

A model to compute the runoff volume is often referred to as the loss method since it accounts for the losses that occur during a rainfall event as a result of infiltration and evapotranspiration. For each time interval in the modeling process, the loss method calculates the amount of water that contributes to the runoff in the river (effective rainfall).

Available alternative loss model methods in HEC-HMS are Green and Ampt, Deficit and Constant, Soil Moisture Accounting, Smith Parlange, Initial and Constant, SCS Curve Number, Exponential, Gridded Soil Moisture Accounting, Gridded SCS Curve Number, and Gridded Green and Ampt loss method.

Figure 2-5 shows the categorization of loss model methods where Figure 2-6 summarizes the negative and positive aspects of the available loss methods in HEC-HMS.

Model	Categorization
Initial and constant	event, lumped, empirical, fitted parameter
SCS curve number (CN)	event, lumped, empirical, fitted parameter
Gridded SCS CN	event, distributed, empirical, fitted parameter
Green and Ampt	event, distributed, empirical, fitted parameter
Deficit and constant	continuous, lumped, empirical, fitted parameter
Soil moisture accounting (SMA)	continuous, lumped, empirical, fitted parameter
Gridded SMA	continuous, distributed, empirical, fitted parameter

Figure 2-5. *Categorization of Loss model methods (HEC-HMS reference manual)*

The Deficit and Constant Loss method's underlying concept is that it considers a single layer to designate the soil, where rainfall enters the soil layer during rainfall events. Through evapotranspiration, water has been removed from the layer between rainfall events and the excess precipitation becomes direct runoff.

Model	Positive	Negative
Initial and Constant	"Mature" model that has been used successfully in hundreds of studies throughout the US. Easy to set up and use. Model is parsimonious; it includes only a few parameters necessary to explain the variation of runoff volume (see EM 1110-2-1417).	Difficult to apply to ungaged areas due to lack of direct physical relationship of parameters and watershed properties. Model may be too simple to predict losses within event, even if it does predict total losses well.
Deficit and Constant	Similar to above. Can be used for long-term simulations (for example, for period-of-record analyses.)	Similar to above
SCS CN	Simple, predictable, and stable method. Relies on only one parameter, which varies as a function of soil group, land use and treatment, surface condition, and antecedent moisture condition. Features readily grasped and reasonable well-documented environmental inputs. Well established method, widely accepted for use in US and abroad. (From Ponce and Hawkins, 1996)	Predicted values not in accordance with classical unsaturated flow theory. Infiltration rate will approach zero during a storm of long duration, rather than constant rate as expected. Developed with data from small agricultural watersheds in midwestern US, so applicability elsewhere is uncertain. Default initial abstraction (0.2*S*) does not depend upon storm characteristics or timing. Thus, if used with design storm, abstraction will be same with 0.50-AEP storm and 0.01-AEP storm. Rainfall intensity not considered. (Same loss for 25 mm rainfall in 1 hour or 1 day.)
Green and Ampt	Parameters can be estimated for ungaged watersheds from information about soils	Not widely used, so less mature, not as much experience in professional community. Less parsimonious than simple empirical models.

Figure 2-6. *Positive and negative aspects of loss models (HEC-HMS reference manual)*

The Deficit and Constant Loss method considers a single layer of soil with a maximum capacity to retain and keep water. When that soil layer reaches its maximum water holding capacity, the soil gets saturated, and if does not reache the maximum water storage capacity, the soil layer will not get saturated. The deficit can be defined as the amount of water needed anywhere in the soil layer to make the soil layer saturated.

The Deficit and Constant Loss method is a continuous event loss method and as shown in figure2-7 the impervious%, constant rate, maximum deficit, and initial deficit should be specified. This method's difference from the Initial and Constant approach is that the initial loss can be recovered after a long period without precipitation. The current storage can be simply calculated by subtracting the maximum capacity from the deficit amount, and the current storage is considered to be distributed uniformly throughout the soil layer.

Figure 2-7 shows the main input parameters of the Deficit and Constant Loss method.

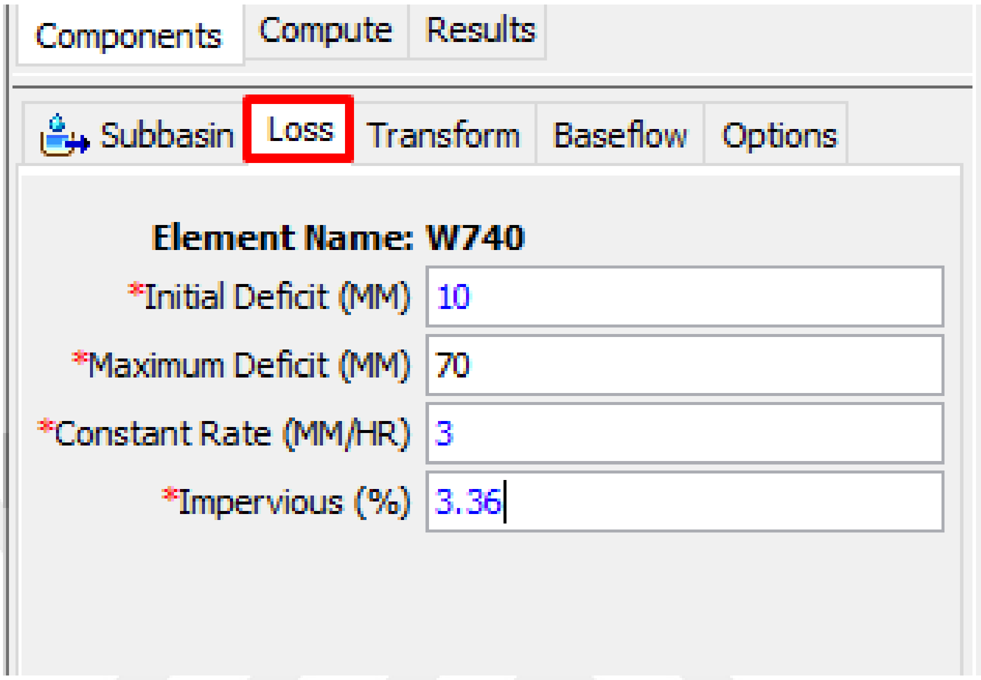

Figure 2-7. *Deficit and Constant Loss Method*

2.2.1.2. Transform Method

Models of direct runoff are also called transform methods since they convert the effective rainfall over a watershed into a hydrograph at the watershed outlet. These models account for the surface roughness and geometry of the watershed.

The excess precipitation turns into direct runoff in a given rainfall event depending on the rainfall event's duration and intensity. Rainfall-runoff transformation in HEC-HMS is done by applying a transform method to the observed precipitation. This transform method provided by the HEC-HMS software includes User-Specified Unit Hydrograph, User-Specified S Graph, Snyder Unit Hydrograph, SCS Unit Hydrograph, Kinematic Wave, ModClark, Clark Unit Hydrograph transform method, Figure 2-8 summerizes categorization of the alternative transform methods in HEC-HMS.

Model	Categorization
User-specified unit hydrograph (UH)	event, lumped, empirical, fitted parameter
Clark’s UH	event, lumped, empirical, fitted parameter
Snyder’s UH	event, lumped, empirical, fitted parameter
SCS UH	event, lumped, empirical, fitted parameter
ModClark	event, distributed, empirical, fitted parameter
Kinematic wave	event, lumped, conceptual, measured parameter
User-specified unit hydrograph (UH)	event, lumped, empirical, fitted parameter

Figure 2-8. *Categorization of Transform method in HEC-HMS*

During excess precipitation to runoff transformation, Clark's transform method considers two critical processes named Attenuation and Translation. Attenuation is change in (flow) or decreased discharge's magnitude as the excess is deposited throughout the catchment due to storage characteristics. Translation (time) or change in time of the excess from its origin within the drainage to the catchment outlet.

This model clearly considers changes in travel time to the catchment outlet from all watershed regions. Clark (1945) stated that a time-field curve could explain the water flow motion over the basin. This is the curve showing that precipitation falling somewhere in the basin to the basin outlet is a function of time. In the HEC-HMS Clark Unit Hydrograph method, tc represents the time of concentration in hours, and R storage coefficient in hrs. Time of concentration tc is the longest travel time in which the most remote reach could contribute its runoff to the outlet.

As shown by Figure 2-9, the time of concentration in hours and storage coefficient in hours are the estimating parameters of Clark’s unit hydrograph transform method in HEC-HMS.

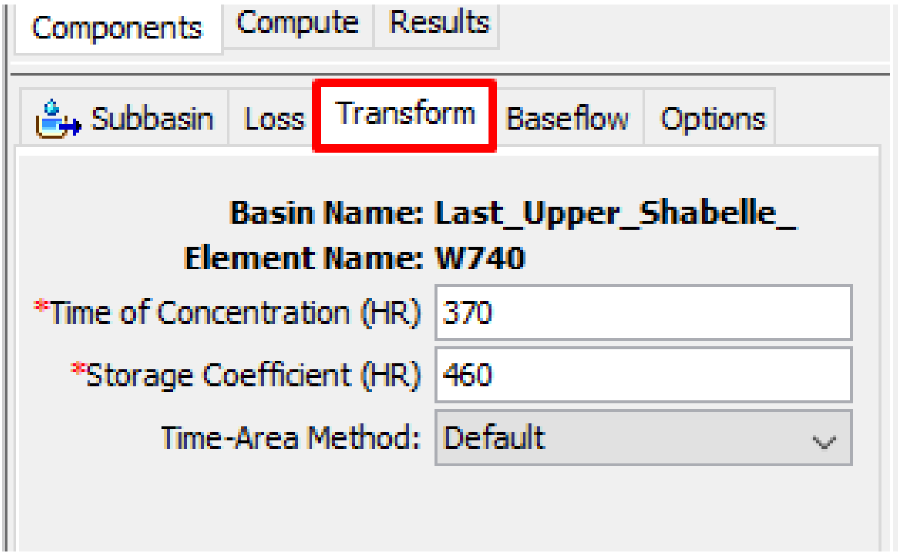

Figure 2-9. *Clark unit hydrograph transform method in HEC-HMS*

2.2.2. HEC-GeoHMS

HEC-GeoHMS is created as a geospatial hydrology toolbox for both hydrologists and other engineers with limited GIS knowledge. The software allows users to imagine spatial data, archive watershed properties, make the spatial analysis, delineate sub-basins and rivers, build inputs data to hydrological models, and help with the preparation of a report. Operating with HEC-GeoHMS by its interfacing, toolboxes, menus, icons, available offline help tools, and advanced online help permits the user to appropriately make hydrological inputs, which might be explicitly utilized with HEC-HMS.

Some of the main HEC-GeoHMS capabilities are basin model files, background map files, a grid cell parameter file, and meteorological model files, which might be utilized by HEC-HMS to create a precise hydrologic model. The basin model file has its hydrologic components and their corresponding hydrologic interface. It incorporates sub-basin zones and other hydrologic parameters, which can be evaluated by utilizing geospatial information. HEC-GeoHMS can produce tables of attributes comprising physical characteristics and features of watersheds and streams.

HEC-GeoHMS aims to process catchment data as soon as the terrain data gets ready, and data preprocessing is done. The gathering of GIS information can be performed by utilizing a standard GIS computer program that backs the Arc Hydro tool. HEC-GeoHMS isn't expected as an apparatus for data or information acquisition. During data collection, it is vital to understand how to utilize and process the data by GIS program to put the data in distinctive sorts and formats into a universal coordinate system. Digital

Elevation Model (DEM), stream orientations, stream, and rain gauge locations are among the primary data to be collected and preprocessed in ArcGIS software.

After the pre-required data is collected, the HEC-GeoHMS program prepares the spatial and terrain data to produce several input data for an HEC-HMS model. Those input data helps the user to start an HEC-HMS model. With the help of the program, the user has the ability to assess hydrological parameters from the catchment, gaged precipitation, streamflow data, sub-basin physical characteristics, etc. Moreover, HEC-HMS lets the user adjust the hydrologic components and their network to represent the site situation or stream network more accurately and precisely.

The connection between HEC-HMS, HEC-GeoHMS, and GIS is outlined in the Figure 2-10, with the bold dashed line isolating the functions of watershed hydrology and GIS. HEC-GeoHMS gives the association for interpreting GIS spatial data into model files for HEC-HMS. GIS ability is utilized for information organizing, preparing, and transformation of the coordinate system. The outcomes of GIS process results can be a spatial hydrology database that comprises the land use data, soil types, digital elevation model (DEM), precipitation, etc.

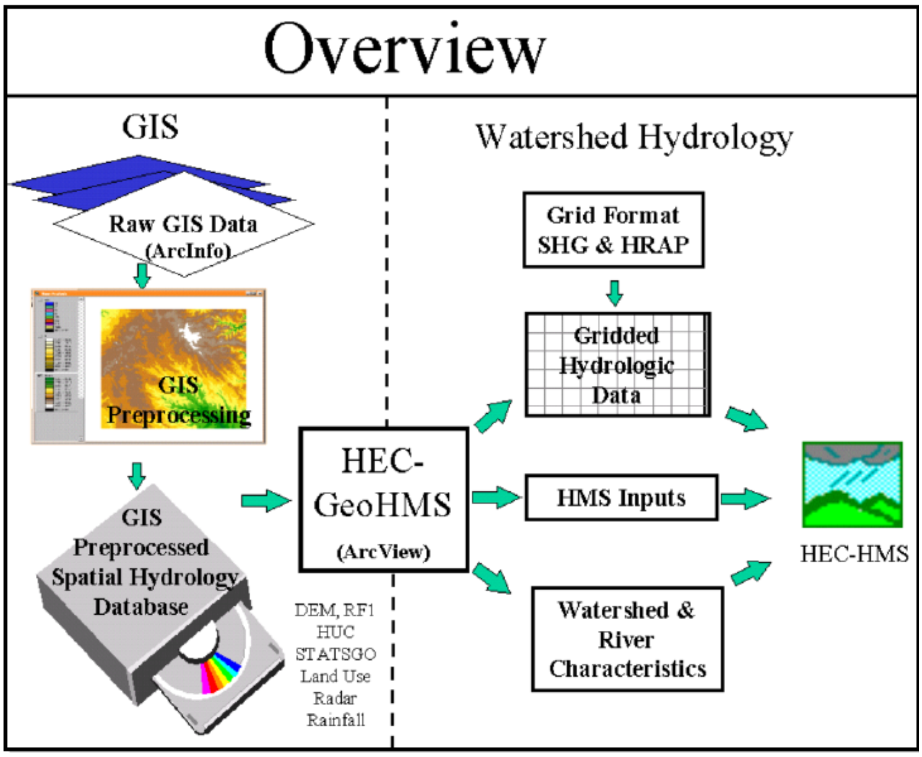

Figure 2-10. *The connection between HEC-HMS, HEC-GeoHMS, and GIS (Bakir and Xingnan, 2008)*

2.2.3. Arc-Hydro tool

Arc Hydro tools utilizes to gather various data collections that describe the drainage shape of a watershed. Raster analysis was carried out to produce data on stream characteristics like stream definition, flow accumulation, flow direction, stream segmentation, and watershed delineation. At that point, this information is utilized to create a vector representation of watershed and drainage lines. Terrain Pre-processing tool in the Arc Hydro tool is used to generate terrain of the study area, and the other process was done using HEC-GeoHMS for HEC-HMS model preparation.

Terrain Preprocessing requires DEM (advanced height show) to distinguish the surface drainage pattern. When terrain preprocessing finishes, the Digital Elevation Model (DEM) and its subordinates may be utilized for stream network creation and effective watershed delineation.

2.3. HEC-RAS

In general, the hydraulic model is a physical or mathematical model of a fluid flow system such water system, sewer system, or storm system and it is used to analyze the system's hydraulic behavior. A hydraulic model is used to create real-world data like GIS data and CAD data and that data is input into a model to create a physical representation of the real-world system. Hydraulic modeling deals with the physical properties of water such as the depth of a flow in a channel and velocity of the flow in the channel.

HEC-RAS is a river analysis system created by the Hydrologic Engineering Center. It is a program that provides an opportunity to carry out one-dimensional steady flow, one and two- dimensional unsteady flow computations, sediment transport, and water quality modeling (Brunner, 2016).

Existing different hydraulic modeling software used to analyze and model the system, HEC-RAS is among the most used river analysis systems.

HEC-RAS is a water surface profile model used to analyze both steady, unsteady flow and quasi-unsteady flow, one-dimensional and two-dimensional flow, gradually varied flow in both natural and made channels. HEC-RAS is an integrated river analysis system software developed for common use in a multitasking environment with a comprised graphical user interface (GIU), different hydraulic analysis components, data storage, and data management capabilities, graphics and reporting facilities (Bentley System, 2003).

HEC-RAS system compromises different river analysis components. HEC-RAS has mainly the four main following components:

- The steady flow of water surface profile computation
- 1D and 2D unsteady flow Simulation
- Computation of sediment transportation/ Movable Boundary Computations
- Analysis of water quality

2.3.1. The steady flow of water surface profiles

HEC-RAS was developed to carry out both one-and two-dimensional water surface profile calculations and other hydraulic calculations for steady and unsteady gradual varied flow for a full network of natural and manmade channels. HEC-RAS is also capable of calculating subcritical, supercritical, and mixed flow regime water surface profiles.

In inundation analysis, flow modeling simulates a flood wave's flow through a river reach and its floodplain areas. In hydraulics, the flow of water in a river is referred to as an open channel or free-surface flow as the water surface is exposed to the atmosphere.

For modeling and design objectives, continuity, momentum, and energy equations have been developed in the past to typify and describe the flow in an open channel mathematically. The three basic laws of physics: the continuity of mass, energy, and momentum are the basis of the mathematical equations. Flow models resemble the flow running into an open channel in a system that meets these basic mathematical equations for open channel flow or simplified versions of it.

The water surface profiles are calculated from a single cross-section to the succeeding cross-section through determining and figuring out the energy equation with an iterative algorithm method termed as the standard step method (Thomas, 2018).

For a particular water surface elevation and corresponding flow at the target cross-section, the aim and objective of the direct step method are to calculate the water surface elevation at the succeeding cross-section. The starting point of the computations, whether from downstream to upstream or vice versa, devolves on the flow regime. The Froude number (Fr), a dimensionless number is used to describe the type flow regime (Tate, 1999).

Another relevant aspect that is important for the modeling of open channel flow is the distinction between the subcritical and supercritical flow. This distinction is due to the fact that for a given discharge, there is a critical flow depth, for which the specific energy of the flow is at its minimum. The specific energy of a flow is described as the flow's energy with reference to the channel bed as the datum and thus only depends on the depth and velocity of the flow. If the specific energy is not at its minimum, there are two likely flow depths for a fixed discharge: the flow regime is subcritical if the flow depth is higher than the critical depth. The flow regime is supercritical if the flow depth is lower than the critical depth. A practical distinction can be made because, in supercritical flow, a wave resulting from any type of disturbance cannot propagate upstream compared to subcritical flow. Consequently, water surface computations from one cross-section to another are done in the upstream direction for subcritical flow and in the downstream direction for supercritical flow. Situations in which both flow types happen in the modeled reach are referred to as mixed-flow regimes.

2.3.2. One-and Two-Dimensional unsteady flow simulation

The unsteady flow simulation component is intended to simulate combined 1D2D, two-dimensional, and one-dimensional unsteady flow in a whole network of humanmade and natural alluvial fans, floodplains, and open channels. The unsteady flow simulation can carry out mixed flow regimes, supercritical, and subcritical computations. Unsteady flow simulation calculates hydraulic jumps, supercritical, subcritical, and drawdowns.

Physical models still have their place. They can capture the stochastic characteristics of dynamic river flow, only in a scaled application. However, nothing beats real experiments on the prototype (full-scale). Today, river modeling is most commonly done with 1-Dimensional models. HEC-RAS is one of the most popular 1D models used today. A 1D model involves laying out cross-sections along the river or channel. Now, HEC-RAS, Version 5.0.7, has the capability to model the fully dynamic St Venant equations in two dimensions.

In one-dimensional flow routing, flow running into the river channel, and the floodplains are treated just in the longitudinal direction parallel to the conduit. Even though, in reality, the flow in a natural channel is not in any circumstance truly 1-D, the flow models are found to deliver acceptable outcomes for predicted hydraulic parameters in many applications (Corkhill, 2001).

In the one-dimensional HEC-RAS flow model, the floodplains and the river channel's geometry are represented by a series of geometry cross-sections on the river reach.

Mostly one-dimensional (1-D) models are subdivided into steady and unsteady-flow models. In the steady flow simulations, a constant inflow is modeled so that the depth of flow at any specified location does not change over time. In comparison to that, a discharge hydrograph is applied as the inflow into the modeled reach in unsteady-flow simulations resulting in changes in depth at specified locations over time. The appropriate choice between these two basic approaches highly depends on the situation that is intended to be modeled. Since the hydrologic modeling is meant to create full flood hydrographs with specified statistical return periods, unsteady-flow modeling was selected to account for the volume and propagation of the flood wave.

In 2D modeling, it numerically solves the vertical integrated momentum and mass continuity equation using different methods. While 2D modeling solves fully dynamic St. Venant equations of conservation of mass and momentum along the two dimensions, the 1D model solves St. Venant equations long one singular dimension (Jesse, 2017).

In HEC-RAS, both 1D and 2D can use the fully dynamic St. Venant equations of Conservation of Mass and Conservation of Momentum. The numerical schemes used are slightly different, but the foundation is the same. In 2D modeling, HEC-RAS, by default, uses the Diffusion Wave simplification of the full conservation of momentum equation, but the user can opt to use the full dynamic conservation of momentum equation. Typical floodplain and overbank 2D modeling work well with the Diffusion Wave simplification- and the model will run faster (Brunner, 2016).

When to prefer and run 1D over 2D

In case the modeler has limited access to high-resolution terrain data, it may be preferable to use a 1D model for the model. Even though 1D and 2D models rely on terrain data, the user can efficiently and quickly remove inconsistencies from 1D cross-sections. More over, rivers, catchments, and channels that move in only one direction with specified over-banks such as mountain streams and canals define the charecteristics that guarantee the 1D hydraulic model.

Another vital thing to be taken into consideration is time. It might take much time (hours) to run a 2D model. If the user requires a model very quickly and running out of time, it might be more preferable to prepare a 1D model (particularly if the modeler or the user has never done a 2D model).

When to prefer and run 2D over 1D

As practically observed, there have been some hydraulic and topographic features that lead and make 1D modeling complicated and sturdy to use. Poorly defined channel or flow direction, the undefined boundary between the riverbanks and the channel, steep slope flow storage and off-channel areas, the considerable changes of the flow direction with different stages, and the channel bends are among the hydraulic and topographic features that made 1D modeling very complicated.

In general, the essential reason for a model approach selection whether 1D or 2D is the objective and outcome of the study. If necessary, it can be also be combined a 1D model with a 2D model and the user can run combined 1D2D modeling. Since each project is distinctly different from other projects, the user will eventually need to use the best engineering judgment to decide what type of modeling approach is most suitable. With a 1D model, the modeler should know the flow path in advance. In some cases, it is challenging, if not unrealistic, to forecast this flow path unless a clearly specified conveyance path exists. In such a case, 2D modeling is the best alternative. In 2D, the modeler will not require pre-determining the flow paths of the floodplain area since they are directly calculated as a function of the applied flow and the model terrain but requires highly detailed and accurate geometry or survey data like LIDAR (Light Detection and Ranging) or ASL (Aerial Laser Survey). 2D modeling also takes longer computational time to run the model.

2.4. Literature Review

2.4.1. Floods

Floods are natural hazards and disasters which happen when a dry area of land gets abruptly submerged underwater. Simply flooding can be clearly defined as the overflow of a large amount of water from streams, rivers, and oceans because of excessive rain onto normally dry land. It is extremely dangerous and has a high potential to damage and demolish entire infrastructures.

Floods can be regarded as the most extremely risky natural disaster with the highest occurrence than any other natural hazard and cause more loss of lives and economics. Recently climate increases the probability of flooding and the magnitude of its effects. Above all flooding results in socio-economic losses, environmental problems, destruction of infrastructures, health effects, and almost lack of human basic needs (Quirogaa et al. 2016).

Flood is a natural hazard that results from a combination of both hydrological and meteorological components. It occurs when normally dry land areas are temporarily inundated due to overflowing of water at the natural or artificial confines of a river resulted from prolonged or heavy rainfall. Hydrologists define flood as a sudden increase in water discharge due to a sudden peak in the water level and exceed the channel's volume causing the stream to overflow onto its surroundings known as flood inundation. Once the flood is over, the water level will drop back to its normal base flow or no flow.

As stated by Abdessamed and Abderrazak (2019), a flood is the highest weather phenomena killer and one of the most occurring hazards with a higher impact such as natural disasters that may cause a loss of lives, economic losses, and destruction of infrastructures. Between 1980 and 2013, flood damages exceeded $1 trillion in economic losses, claimed the lives of over 220,000 people. Flood damage becomes bigger and greater due to steady growth in population and lack of awareness of the economic activities in flood-prone areas (Winsemius et al. 2016).

In 2004, United Nations Development Program (UNDP) estimated that an average of almost over 200 million people in more than 90 countries on the globe faces catastrophic flood events every year (Thiemig and Vera, 2010).

Types of floods

It's not simple to categorize and classify flood types due to its complex inter-related process that can cause flooding. In general, it is recommended to distinguish between two categories of floods according to the magnitude of the affected area and duration of the storm spatial and temporal scale of the flood events (Banach et al. 2009). Moreover, two main classes of floods come forth: extensive, long-lasting floods (plain floods) and local, sudden floods (flash floods).

By focusing on natural disasters, the six types of floods are; coastal floods, river floods, flash floods, drainage problems, tsunamis, and tidal waves. Below is a detail of some flood types (Jonkman, 2005).

Flash flood

Flash floods are the product of heavy rains over a small area with a short period of time commonly less than 6 hours causing the water to rise suddenly and fall rapidly or a sudden release of water from the dam and it always happens in regions with steep geographic slopes and it can happen under various conditions. Due to the geographic formation of the region, stormwater is collected in areas with higher or steep slopes, then flows downstream with speed directing water to the riverbed. As a large amount of water gets collected in the riverbed, the water level rises rapidly flowing over the riverbanks and floods nearby areas.

This type of flood mostly occurs in mountainous and hilly regions with steep slopes and has limited time to predict it in advance. The heavy rainfall on the flood scene can be used as an indicator of this type of flash floods. Nevertheless, this type of floods can also happen in plane areas where the slope is too small and permits quick runoff of flow, rather water may pile up into lower slope areas like drainage, streets, and ditches (Jonkman, 2005).

Flash floods occur mostly in the rainless area that has freshly received heavy rainfall but may reach and be seen anywhere even miles from the source of precipitation. Extensive heavy rainfalls caused by hurricanes and other tropical storms can result in flash floods. Man-made activities can also sometimes result in flash floods like when a dam fails a large amount of water can be suddenly released from the dam and can devastate everything around the downstream. Below are the dramatic examples of flash floods.

Table 2-1. *Dramatic examples of flash floods (Wikipedia)*

Year	Location	Death toll
1889	Pennsylvania, USA	Around 2,200 people dead
1963	Vajont Dam Disaster, Italy	1910 dead
1967	Lisbon	464 dead
2011	Philippines	Around 1200 dead
2013	India	822 dead
2018	France	15 dead and 99 injured
2019	Iran	At least 23 dead

River floods

River or fluvial floods occur when the water in the river or the stream rises, overtops onto its banks, and finally bursts it banks overflowing onto the surrounding areas and nearby inlands. River floods are among the most common types of inland flooding and it is the result of the continuous heavy rainfall for a prolonged period over a large area. Most commonly river floods are the combination of different factors in a specific region like land use, soil type, soil moisture condition, hydrological and meteorological factors.

Seasonal storms are the main source of this type of flood. During heavy rainfall seasons, the soil gets fully saturated, thus exceeding its water absorption capacity permitting a large amount of overland flow as a runoff. In autumn/summer river floods are mostly sparked by regional heavy rainfalls where in winter/spring are sparked by a large scale of precipitation that can be partly linked together with ice melt and snow. A dramatic example of river floods is that of Rhine river in 1995 which caused damage worth 320 million US$ in Germany and another dramatic event hit the same region in 1993 causing huge fatal accidents and losses of 600 million US$ (Barredo, 2007).

River floods are commonly accounted for as an expected event as it always happens seasonally, specifically during the rainy season where extreme stream discharge can be predicted in advance for a period.

Coastal floods

Coastal floods, sometimes called storm surges occurs when a severe storm caused by winds coincides with the high tides and large wave events at sea, resulting in seawater level drop and rise with the tide. Similarly, tropical storms and hurricanes can cause an unusual rise of the seawater level to move towards the land resulting in a coastal flood. Coastal flooding starts when high tide waves move to overtop and breaching the coastal defenses or barrier works which can be both manmade engineered structures or natural barriers such as sand dunes and floods the land behind it. Once it overtops and breaches the barrier works, extreme flooding occurs in areas behind the barriers (Barredo, 2007).

2.4.2. Study area

Shabelle Basin has a total catchment area of about 297,000km^2, where two-third of the basin catchment is in Ethiopia and the rest in Somalia (Muthusi and Gadain, 2009).

The river is around 1536 km long having an altitude of more than 4000m above mean sea level (ASML) in the Eastern Ethiopian highlands to Mogadishu's sea level. The climate is mostly dry and sub-humid caused by the north-easterly winds, with two annual rains seasons: Gu (long rains) from mid-April to June, and Deyr (short rains) from beginning October to November. These rains cause a twice-yearly flooding period of the river (Thiemig and Vera, 2010).

Floods are a regular event in riverine and flood-prone areas near the Shabelle river. The river floods two times: one is during the two main rainy seasons from (April to June) of Somalia Gu season, from (October to December) of Somali Deyr season, second is when there is heavy rainfall in the Ethiopian highland with both higher quantity and frequency than the rainfall in Somalia, which brings extreme runoff flow in the downstream catchment. The lower regions along the Shabelle river commonly face severe flooding with various consequences. These are resulting from both human-made activities in the river banks and weather (Muthusi and Gadain, 2009).

In the dryer season in 2006 (late September- early December), extremely heavy rains rained in both in Ethiopia and Somalia, led the Shabelle river to make massive scale flooding in many areas in Somalia. In some Somalia regions, the Deyr in 2006, the rainfall was estimated to triple the average rainfall in those regions. It was reported the Shabelle river surpassed the mark of the flood at Beledweyne (Guleid et al. 2007).

Somalia has hydro-meteorological data since the 1950s, but due to the prolonged civil war, the hydro-meteorological stations could not collect data and record no data, which led to many gaps in terms of rainfall and flow data. In 2002 SWALIM started reestablishment of the hydro-meteorological station and set up a data collection network (Muthusi and Gadain, 2009).

As stated by Mohamed (2013) areas surrounded the Shabelle river has an average annual rainfall of 425mm, although mountain areas and areas close to the border between Ethiopia and Somalia are about 1500 mm and 200mm, respectively. For example, in the Ethiopian highlands, the city Godey has an average rainfall of $3387mm^3$, while the town Beledweyne in Somalia has about $2384mm^3$, and the difference is lost in the Ogaden desert in Eastern Ethiopia. Mohamed (2013) has also mentioned that the river produces insufficient runoffs due to low rainfall and high evaporation. The river contributes most of Somalia's water, where runoff contribution by catchments is usually minimal.

Michalscheck, Petersen, and Gadain (2016) stated the water is highly saline where the livestock and humans' lives depend on the river's water. Water harvesting is also an alternative resource of water in the wet season, and the source of groundwater recharge is the inflow from the river.

The source of the Shabelle river in Ethiopia has abundant surface water, where in the middle reaches, the river carries considerable volumes of water throughout the year. Although drought is a repeated drought hazard in the region, there have been some recent drought hazards in 1973-76, 1978-80, 1984-89, 2000/01, 2006, and 2008, which let extreme consequences like the loss of lives and properties (Houghton et al. 2011).

Figure 2-11 shows the topographical view of Beletweyne city with normal condition where there is no floods, where Figure 2-12 show the city under flooding situation. Figure 2-13 also shows a rescue team using boats to rescue the local community and vulnerable residents in Beletweyne city during flood events.

Figure 2-11. *Beletweyne City with normal condition (no flood) (www.hiiraan.com)*

Figure 2-12. *Beletwayne city under flood (www.hiiraan.com)*

Figure 2-13. *Rescue team during flooding event at Belet Weyne (Garoweonline.com)*

2.4.3. HEC-HMS

HEC-HMS is open-source software for modeling the rainfall-runoff process developed by the U.S. Army Corps of Engineering´s Hydrologic Engineering Center. The software includes a graphical user interface for the management and analysis of the model data. It is essential to mention that HEC-HMS itself is not an actual hydrological model rather than software that enables the user to perform hydrological modeling based on a wide selection of standard mathematical models used in hydrology (U.S. Army Corps of Engineers, 2013).

There have been numerous studies applying HEC-HMS both for event and continuous simulations.

As mentioned by (Wałęga, 2013), HEC-HMS software has the ability to simulate a rainfall flood event in an ungauged basin, where calculations of flood events are caused by continuous rain in the middle of 1998 was done. The model parameter of four different hydrological models was compared and the best simulation results were found with Synder-regression and Synder-standard methods, but they concluded the direction of further research to verify the applicability of the HEC-HMS software for farther hydrological studies of further comprehensive hydrometric materials and basins with various features and characteristics.

A.Majidi and Shahedi (2012) has simulated rainfall-runoff using HEC-HMS conducting an applying five different precipitation events. Model calibration with both sensitivity analyses and optimization method were carried out and obtained that the lag time is a sensitive parameter where the study finally concludes that hydrologic simulation of Abnama watershed in Iran can be modeled with the use of HEC-HMS software.

Concerning basin modeling, physical circumstances caused by the complexity of hydrological systems on one side, and insufficient data on the other side lead to the unavoidable application of rainfall-runoff simulation models. Considering that all parameters' effects on the catchment's runoff are unrealistic and unfeasible, picking a proper model with reasonable precision, least input data demands, and simple structure is vital and fundamental (Behyan Motlagh et al. 2018).

Yuvacik basin in Turkey, Yener et al. (2012) applied the HEC-HMS model, where parameters (baseflow and infiltration) are calibrated to obtain seasonal average values concluding that the calibrated model can be used as a decision support tool for the management and the operation of the Yuvacik dam reservoir.

In Iran, the yellow river basin was calibrated and validated by Radmanesh et al. (2006) using HEC-HMS for hydrological modeling and found a reliable result with a better fit between peak discharges of simulated and observed hydrographs.

Markus et al. (2007) used the HEC-HMS model and daily rainfall data as an input parameter, analyzed peak discharge changes caused by increased rainfall at 12 different stations and found reliable results.

Bagmaty basin in Vietnam, Kafle et al.(2007) applied the HEC-HMS model to simulate and analyze rainfall-runoff effects on the basin and obtained that simulated peak discharge is broadly similar to the observed discharge.

Şensoy, Uysal, and Şorman (2018) applied HEC-HMS for the simulation of rainfall/snowmelt runoff of the Yuvacik dam basin in order to develop a decision support framework for real-time flood management using integrated models and found convincing hydrological results of around 0.89 Nash-Sutcliffe model efficiency and -2.2% of overall volume difference.

2.4.4. HEC-RAS

HEC-RAS is among the most commonly practiced hydraulic engineers' models in both floodplain delineations and river flow simulations and analysis where it can perform 1D steady flow, 2D unsteady flow simulations, and combined 1D2D flow simulations. Using HEC-RAS, it is feasible to simulate different water surface profiles for various flows and the impacts of many hydraulic structures such as weirs, overbank structures, bridges, and culverts (US Army Corps of Engineers, 2000).

As reported by Solaimani (2011) many applications using the HEC-RAS model were done to discover and find the extent of the inundation caused by different floods with different return periods.

Şensoy, Uysal, and Şorman (2018) used HEC-RAS for unsteady two-dimensional river analysis and flood inundation mapping of Yuvacik dam basin to get better results in terms of detailed flood characteristics like depth/velocity profiles and detailed inundation maps – and found successful results that will promote further water research analysis.

Azouagh (2018) used the HEC-RAS model to estimate water surface profiles corresponding to chosen flood events downstream of Al Wahda Dam in the Sebou basin in Northern Morocco and found good results, where (Abdessamed and Abderrazak 2019) used HEC-RAS coupling with HEC-HMS for the evaluation of floodplain inundation maps in Sefra city of the southwest of Algeria concluding that HEC-RAS giives better inundation maps.

Sihna et.al (2010) used GIS and HEC-RAS for flood hazard mapping in Kayu Ara basin in Malaisia and found that land use and rainfall event's magnitude plays vital role in flood hazard mapping.

Farooq, Shafique, and Khattak (2019) utilized the HEC-RAS 2D model for flood hazard assessment and mapping of Swat river using high-resolution world DEM developing good hazard maps that will help and pave way for hazard assessment, mapping, developing, and planning policymakers.

3. HYDROLOGIC MODELING

3.1. Hydrometeorological Data

3.1.1. Rainfall

The rainfall of the study area was found from the Ethiopian meteorological agency through means of Somali regional water enterprise. Figure 3-1 shows available rain gauge stations with their names and locations. Generally, when making hydrological simulations, rainfall is the significant input data for the catchment, and different methods calculate the areal mean depth of rainfall over the area.

Figure 3-1. *Upper Rain gauge stations for the study area*

For this study, daily areal rainfall distribution estimation was done by using the Thiessen polygon method, where lines are created with the help of ArcGIS software by joining all rain gauge stations in and around the catchment. Triangular edges are created for each perpendicular bisector where these triangular edges make the Thiessen polygon, and whereabouts, where lines intersect, defines the Thiessen area polygon.

Interpolation of the Thiessen polygon was done using a spatial analysis tool in ArcGIS. Comparatively, it is a straightforward method that requires feature coverage considering all the rain gauge stations in the basin based on the direct variations of the rainfall within two gauges and its aerial range.

Average precipitation (Pav) of Thiessen polygon in a basin is calculated as

$$Pave = \frac{P1A1 + P2A2 + P3A3 + PnAn}{A1 + A2 + A3 + An}$$

Where A represents the area of the stations and P represents the precipitation of the stations.

Figure 3-2 depicts the Theissen polygon map of the study area and Table 3-1 illustrates the areal rainfall distribution of the upper catchment of the Shabelle basin using the Thiessen polygon.

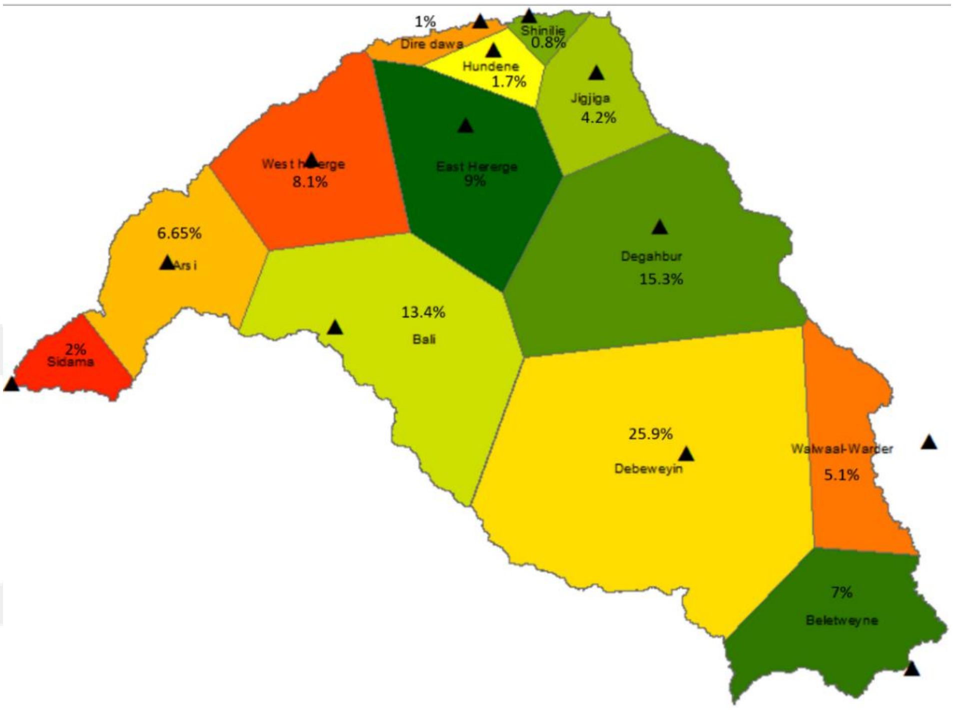

Figure 3-2. *Thiessen Polygon distribution map*

Table 3-1. *Thiessen Polygon Distribution percentage*

Station names	Area (sqkm)	Area(%)
Bali	26301.7	13.38
Debeweyin	50926.7	25.90
Walwaal-Warder	10025	5.10
Jigjiga	8224.25	4.19
West hererge	16019.3	8.15
Sidama	3851.7	1.96
Arsi	13071.9	6.65
Degahbur	30006.4	15.26
Beletweyne	13757.2	7.00
Shinilie	1528.42	0.78
Hundene	3305.3	1.68
East Hererge	17704.9	9.00
Dire dawa	1912.09	0.97

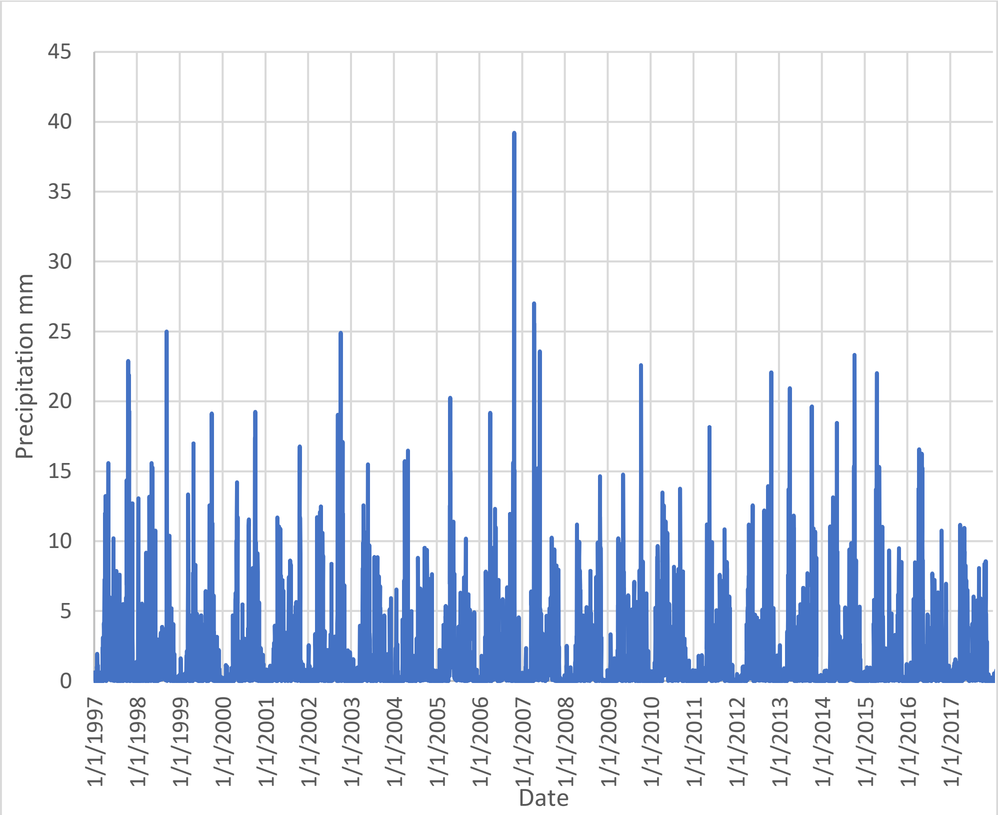

Figure 3-3. *Computed average precipitations of the Shabelle basin*

Somalia has two main rainy season named **Gu'** (April, May, June) and **Deyr** (Oct, Nov, Dec) which are separated by two dry seasons called as **Jiilaal** (Jan-March) and **Xagaa** (July-Sept). Figure 3-4 illustrate monthly average rainfall data at Beletwayne city.

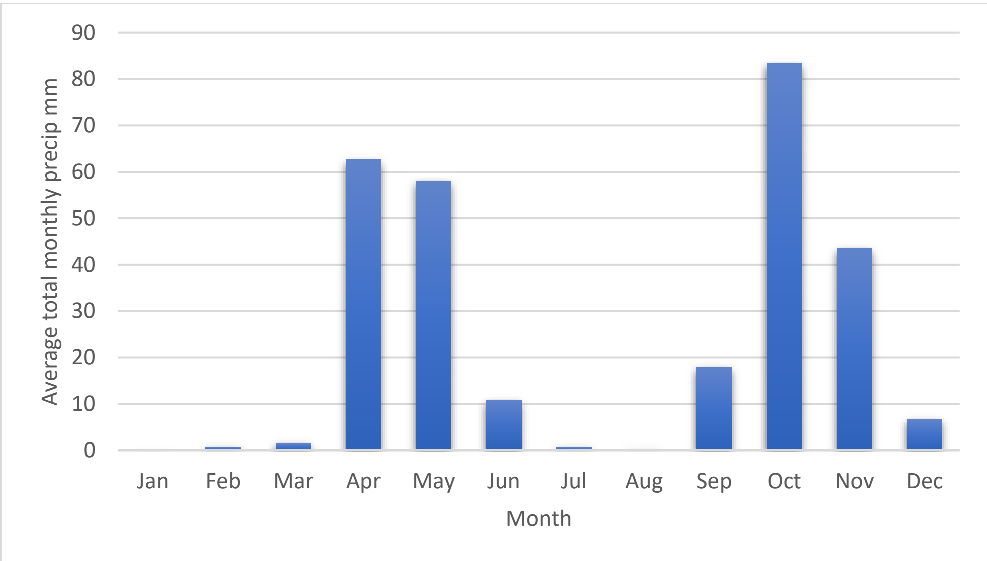

Figure 3-4. *Average total monthly rainfall data at Beletwayne city*

Figure 3-5 shows the highest daily rainfall events of each year recorded at Beletwayne station. From the last 21 years observations (1997-2017), the highest recorded maximum daily rainfall is 188mm which occurred in 2012.

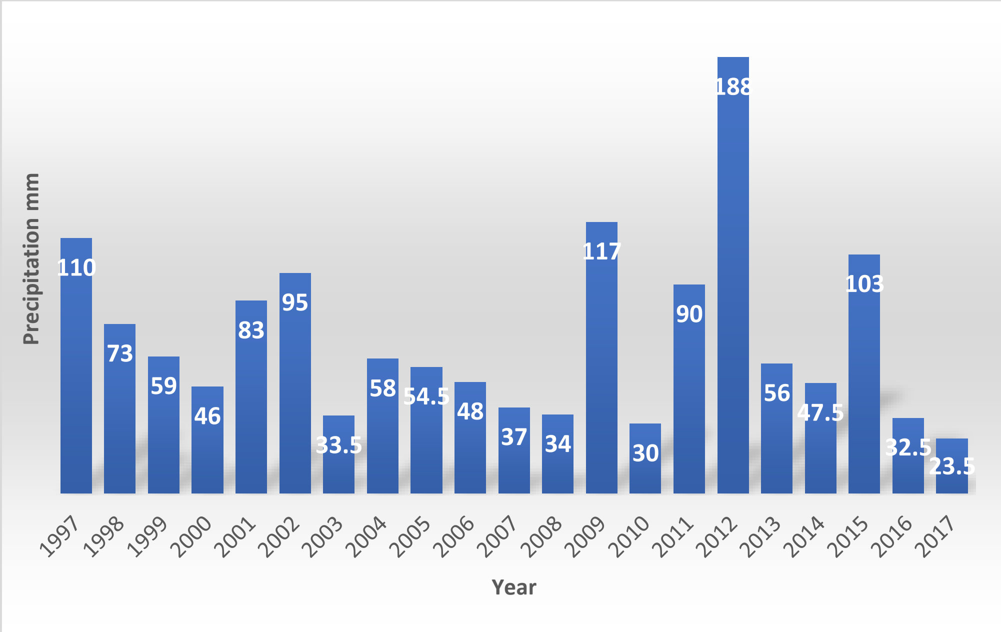

Figure 3-5. *Represents the maximum yearly precipitation of the Beletwayne city*

3.1.2. Discharge

Somalia has started recording its hydro-meteorological data in the early 1950s with numerous breaks in the data. Totally between 1990 and 2000, there was a huge gap due to prolonged civil war and unrest in the country where no data has been recorded. In 2002 SWALIM commenced restoring the data collection and rehabilitation of the existing gauges.

Historically, water institutions managed to collect river flow data for critical stations near the river. Figure 3-6 highlights the stream gauge stations, where Table 3-7 shows long term runoff values.

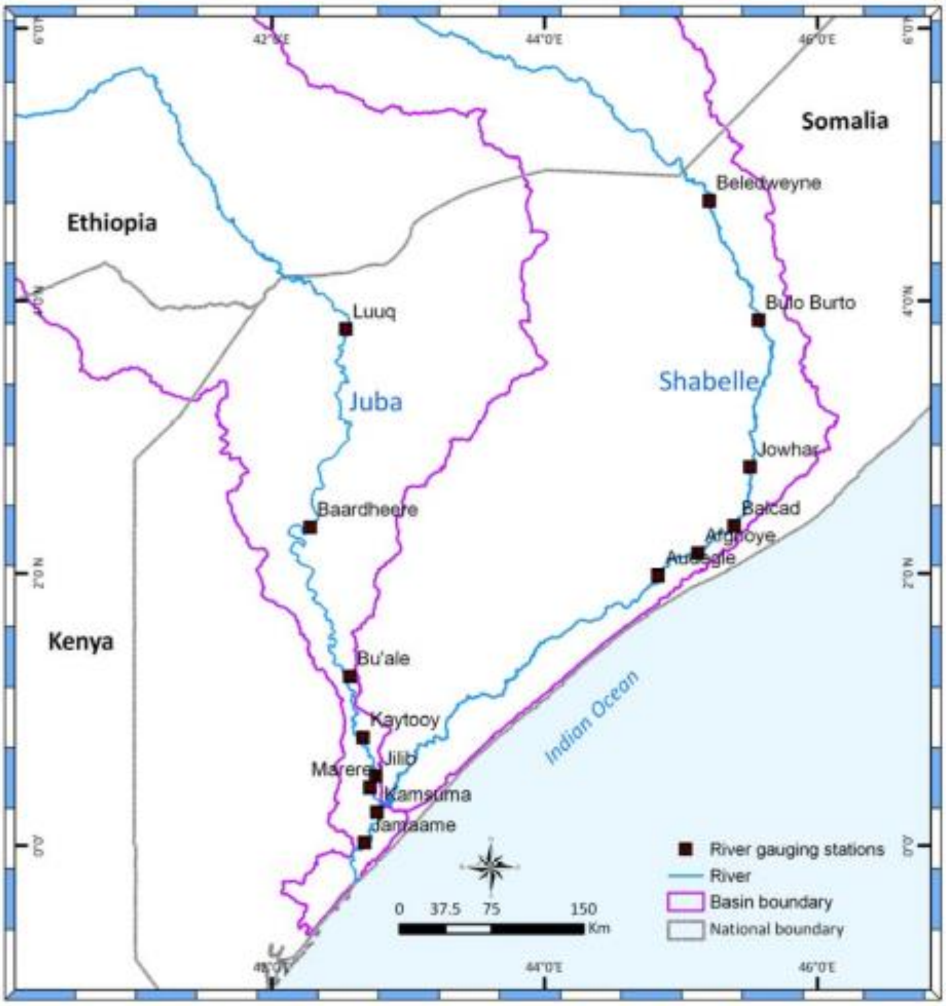

Figure 3-6. *Stream gauge locations of Shabelle river in Somalia (SWALIM, 2009)*

Figure 3-6 shows stream gauge locations of the Shabelle river in Somalia, where the most upper stream gauge is located in Beletwayne city which is 72kms away from the Somali national border. Currently there are eight functioning stream gauges along the Shabelle river in Somalia.

Figure 3-7 depicts long-term mean annual runoff in the Shabelle and Jubba river, where Jubba river has five times more runoff than Shabelle river with less flooding due to topography of the rivers. Luuq is the most upstream city along the Jubba river which is close to Ethiopian border where Jamaame city is located in the downstream of the Jubba river. When comes to Shabelle river, Beletweyne city is the most upstream and Awdegle at the downstream of the river which is 712kms away from the Ethiopian border. Generally, Shabelle has a higher flood frequency than Jubba river with a less runoff.

Table 3-2. *Long term-mean annual runoff in the Shabelle River (m3/s) at Beletwayne and Bulo Burti (SWALIM, 2007)*

Station	Area (km²)	Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Belet	193,288	Mean	19	16	28	75	155	85	55	115	156	136	93	41	81
Weyne		Std.Dv.	16	14	37	62	97	70	25	37	62	61	78	39	29
		C.V.(%)	85	86	133	83	63	83	45	32	40	45	84	96	36
Bulo	207,651	Mean	20	16	29	71	138	84	52	107	147	136	92	43	78
Burti		Std.Dv.	18	17	44	59	87	69	23	37	62	67	72	44	30
		C.V.(%)	92	104	149	83	63	82	45	34	42	49	78	103	39

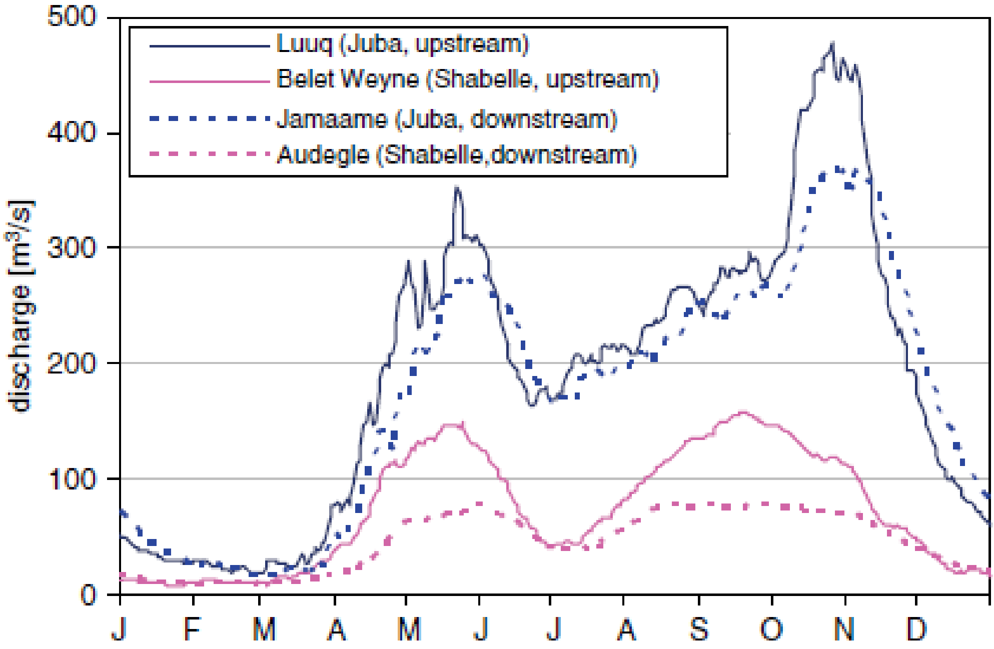

Figure 3-7. *Long term-mean annual runoff in Shabelle and Juba Basin*

Figure 3-8 represents the longitudinal profile of the Shabelle river in Somalia, where the most upstream gauge is located in Beletwayne city which is only 72kms from the Ethiopian border where the last stream gauge is located in Awdegle city. Jamaame is where the Shabelle and Jubba rivers meet and contribute their water into the Indian ocean.

Table 3-2 depicts the long-term mean annual runoff in the Shabelle river in (m3/s) of the upstream gauges of Beletweyne and Bulo Burti. Bulo Burti city is 240kms away from the Ethiopian border and next to Beletwayne city. As Table 3-2 shows, the area of the Shabelle river at Beletwayne is around 193,288km^2 with long-term mean annual runoff of 81m^3/s. At Bulo Burti, the area of the river is around 207,651m^3/s with a mean annual runoff 78m^3/s.

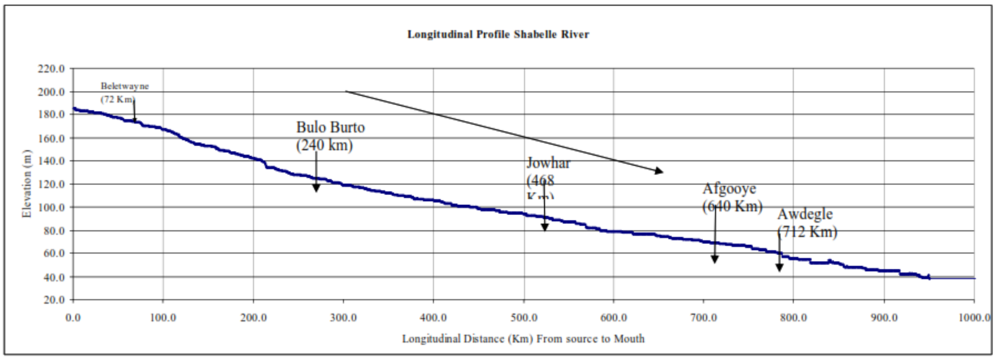

Figure 3-8. *Longitudinal Profile of the Shabelle River in Somalia*

3.1.3. Evaporation

It is clearly seen that evaporation plays vital role in the hydrological cycle. There is scarcity in data availability, and it is hard to fine such accurate data in Africa. SWALIM archived some daily PET data for Somalia since 2000 and has never been enough for more detailed and accurate analysis.

Figure 3-9, shows the mean annual PET for Somalia prepared by SWALIM, where the highest recorded PET occurs in norther-eastern coastline with a range starting from 2751mm/yr. to around 3000mm/yr. where lowest recorded PET occurs southern coastlines of lower Shabelle, lower Jubba and some parts of middle Jubba and Bay regions ranging from 1501mm/yr. to 1750mm/yr.

In Somalia, PET exceeds the rainfall resulting larger water loss in the country. Figure 3-9 clearly depicts the mean monthly rainfall and evaporation of Somalia.

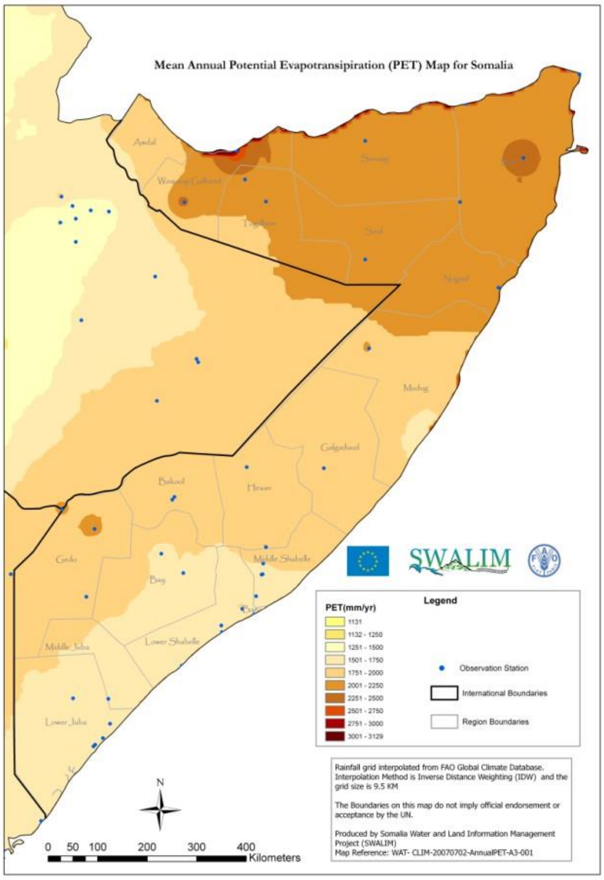

Figure 3-9. *Mean annual PET for Somalia (SWALIM, 2007)*

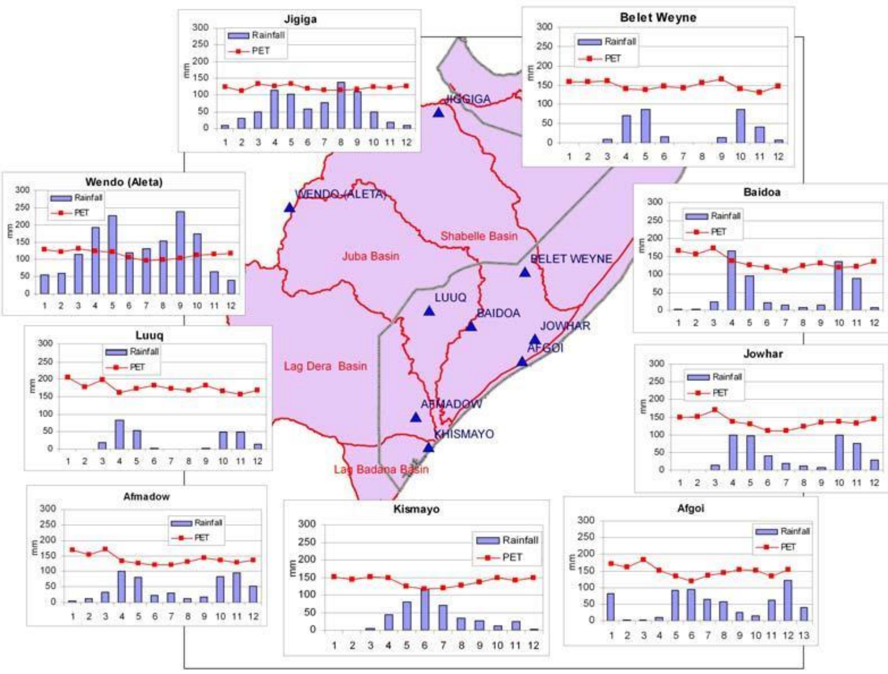

Figure 3-10. *Mean monthly rainfall and evapotranspiration of some selected station along Shabelle and Jubba Basin (Source SWALIM 2007)*

3.2. Basin delineation using GIS

3.2.1. Arc-Hydro Tool

Arc Hydro tools are utilized to gather various data collections that describe the drainage shape of a watershed. Raster analysis is carried out to produce data on stream characteristics like stream definition, flow accumulation, flow direction, stream segmentation, and watershed delineation. At that point, this information is utilized to create a vector representation of watershed and drainage lines. A geometric system is developed using the above-mentioned data. Arc Hydro tool's utility was illustrated by applying to create attributes that are valuable in hydrologic modeling.

Fill sinks

If there are some sinks on the DEM, the Fill Sinks tools fill it. If a cell is surrounded by another cell with a higher elevation, the water will not flow due to elevation difference and is caught in that cell with no flow.

Flow Direction

The Flow Direction tool calculates the direction the water will flow for a given cell. The values within the given cells of the flow direction network show, the direction of the steepest grid from that cell. FdrFilled has eight values, each showing the direction of the water flow (255 demonstrate sinks – since the network has been filled 255 represents none).

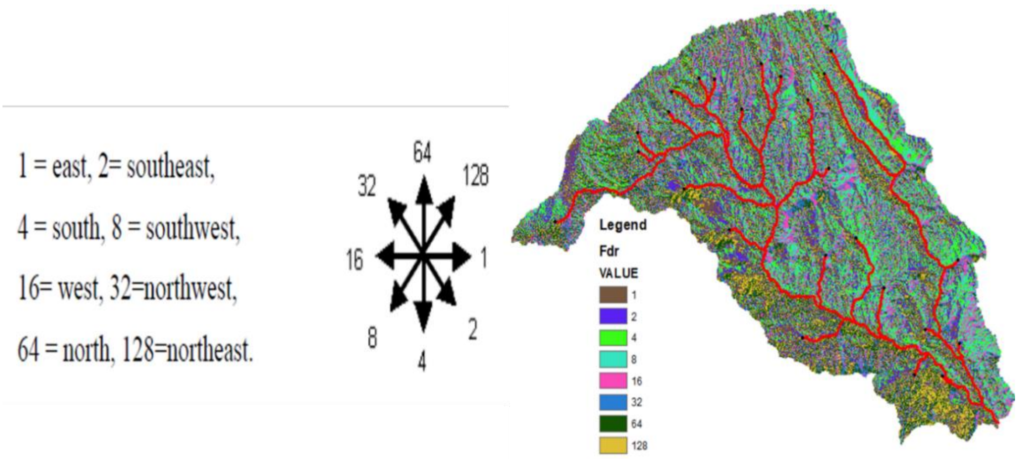

Figure 3-11. *Flow Direction Eight possible routes*

Flow Accumulation

The Flow Accumulation computes the flow collection network that includes the accumulated quantity of the flow from the upstream cells. Filled DEM was used as an input DEM to generate the flow accumulation.

Stream Definition

This tool defines the stream network using the flow accumulation, and a user indicated limit. The smaller the threshold, the denser the stream arrangement and will result in a more prominent number of delineated catchments, which may prevent the performance of the catchment delineation.

Stream Segmentation

Stream Segmentation tool makes a network of stream sections with a unique, recognizable proof. A segment may be ahead portion, or it may be identified as a segment between two segment crossings.

Catchment Grid Delineation

This function makes a grid in which each cell carries esteem (grid code), demonstrating to which catchment the cell has a place. The grid compares the grid given by the stream section or sinks connect that channels that zone, characterized within the input stream section link network (Sink Segmentation) or (Stream Segmentation).

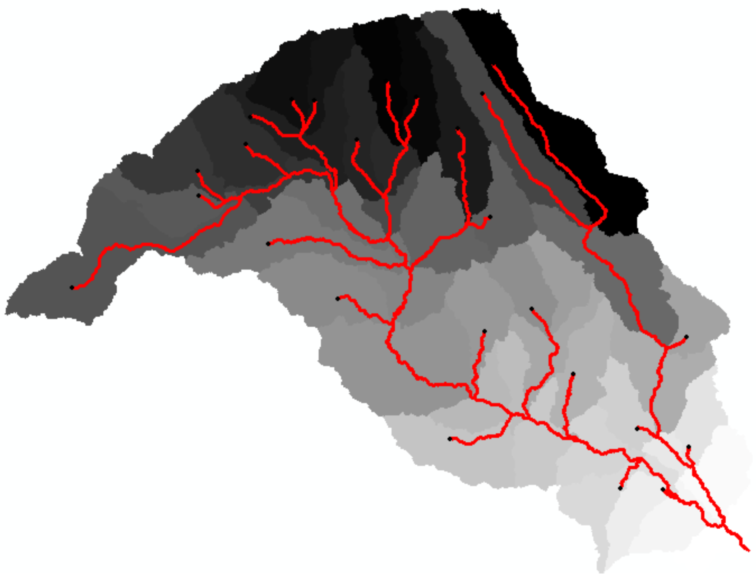

Figure 3-12. *Catchment Grid Delineation*

Catchment Polygon Processing

Catchment Polygon Processing tool changes over the grid catchment into a polygon catchment feature class. This tool is under the Terrain Preprocessing Menu and accepts catchment as an input grid and transforms it into a feature class named catchment polygon. The adjoining cells in the catchment grid with identical grid codes merge into a single cell with a vectorized boundary.

Drainage Line Processing

The Drainage Line Processing function under the Terrain Preprocessing menu transforms the input Stream Link grid into a Drainage Line feature class.

Adjoint Catchment Processing

This function produces the totaled upstream catchments from the "Catchment feature class." For every basin, which is not a head basin, a polygon corresponding to the entire upstream region flowing to its inlet point is built and put away in a feature class with an "Adjoint Catchment" tag.

Drainage Point Processing and Slope

This tool supports creating the drainage points connected with the watershed, where the slope tool helps in creating a slope grid in a degree or percent format for a given DEM. The percentage rise of the slope in the upper Shabelle river is in the range of 0-81.94%.

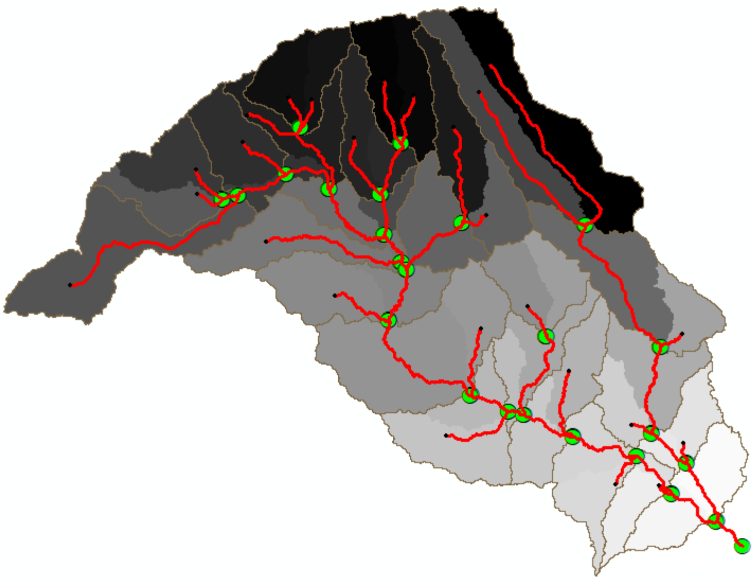

Figure 3-13. *Drainage point processing*

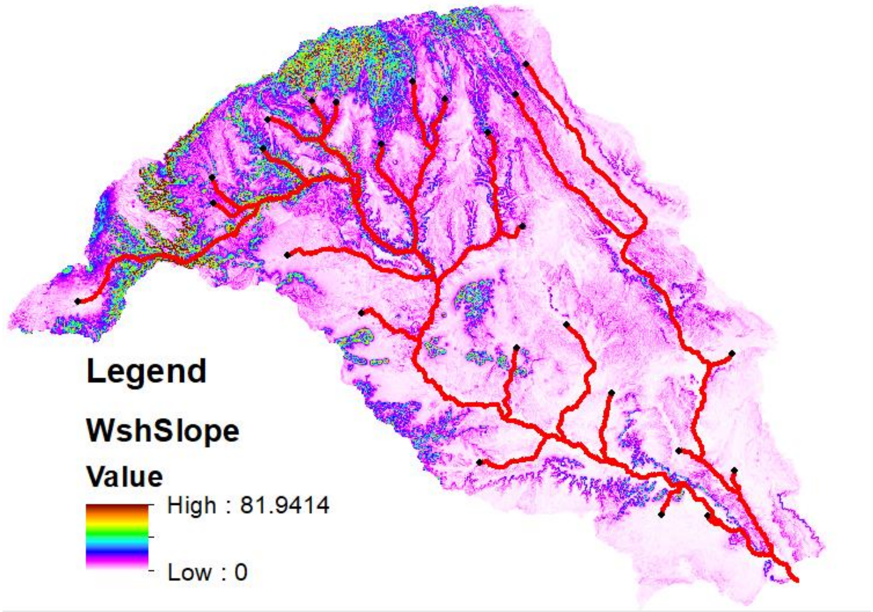

Figure 3-14. *Slope of the study area*

3.2.2. HEC-GeoHMS

The project set up menu can take out information that will be utilized to create the fundamental data to make an HEC-HMS Project. The method and strategy for taking out or extraction includes indicating a control point at the downstream outlet. The marked and pointed control area describes the downstream boundary of the project. After characterizing the catchment outlet, HEC-GeoHMS takes out primary input data from the available data sets made utilizing the "Terrain Preprocessing" tools in the Arc hydro tool.

Each vector data made with GeoHMS will be kept in an unused geodatabase with the same title as the saved project or ArcMap archive (unless named and saved to an existing geodatabase) and within the similar registry (currently working folder) where the project has been saved.

The project setup menu in HEC-GoeHMS has tools for characterizing the watershed boundary and catchment delineation for the HEC-HMS project. Since many HMS basin models could be created by utilizing similar spatial information, they are overseen by characterizing two main feature classes: Project Area and Project Point. Model administration of these main feature classes through the project area and for project point allows the model users understand and recognize zones for which HMS basin models are as of now made, and permit users to revive models with distinctive stream network thresholds. It is additionally helpful to eliminate and cancel projects and related HMS records through Project Area and Project Point alternatives.

Adding the following raster and vector data sets from the arc hydro tool under terrain preprocessing in the ArcMap documents, data management tools can be checked whether it's being set up or not.

Basin parameters

After the physical characteristics of the watershed and sub-basin have been identified and prepared, some hydrological parameters should be estimated. Using the available soil and land use database, parameters like time of concentration tc, SCS curve number CN and channel routing parameters can be found. The above-mentioned hydrological parameters can be obtained from the available digital elevation model, previously surveyed data, recorded discharge, and precipitation data.

The parameter menu in HEC-GeoHMS has tools that will provide and assist the estimation of loss parameters, transform method parameters, channel routing parameters, sub-basin lag time, and sub-basin time of concentrations. Later the computed hydrological parameters should be compared and verified against surveyed or published data.

Computed parameters using HEC-GeoHMS are always considered and processed as initial estimates. HEC-HMS model validation and calibration should be done to improve and reassure the model parameters.

HEC-HMS data check and basin model

In general, when defining the hydrological structure of the model, database checking for consistency should be done. Data checking tools checks whether river reaches, and centroids are contained within the sub-basin. HEC-HMS data checker keeps the relationship between sub-basin, the river reaches, and outlet points. The checks are essential for the connection between hydrological parameters.

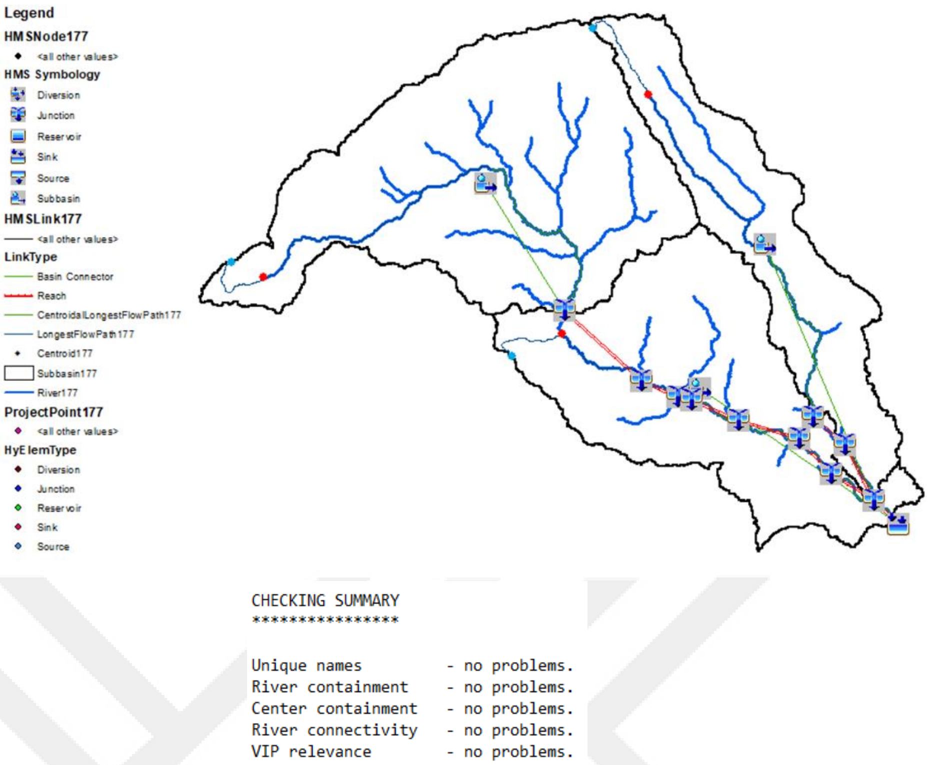

Figure 3-15. *HEC-HMS basin background of the study area*

3.3. SCS CN Grid

3.3.1. Data preprocessing/preparation

To create an SCS Curve number which is an empirical parameter applied to forecast infiltration or direct runoff from the excess rainfall. It's directly related to soil infiltration capacity, land use, soil type, and hydrologic soil group.

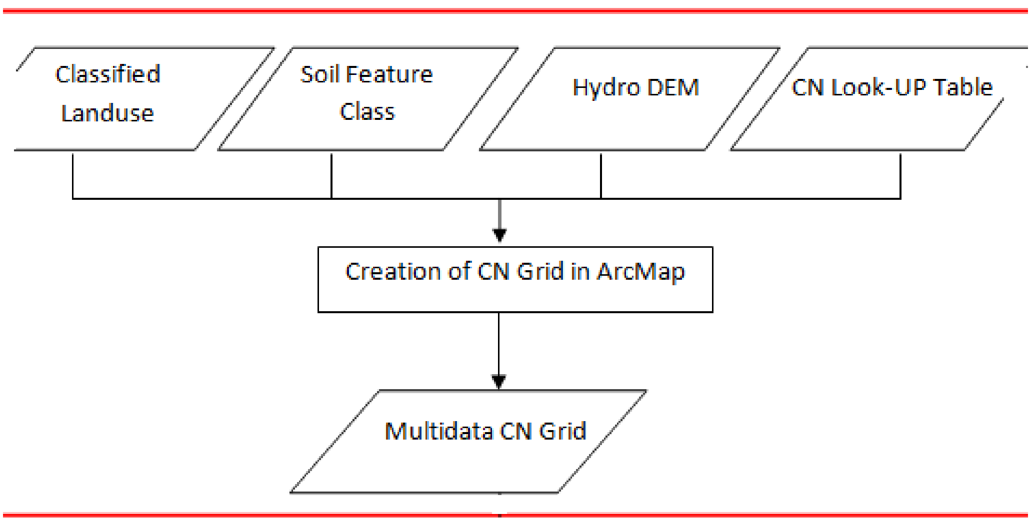

Figure 3-16. *Data preprocessing*

3.3.2. Land use preparation for CN grid

Since the land use data of the study area (Shabelle Basin) is vital for CN grid preparation and was not done before, new land-use data downloaded from the earth explorer under NASA LPDAAC Collections MODIS Land Cover V6 (MODIS MCD12Q1 V6) was used in this study (Yale, 2020). Selecting LC Type1 classification which is in hdf format should be changed into .tif format for further analysis.

The MODIS Land Cover Type product (MODIS MCD12Q1 V6) is a worldwide land cover categorization data layer generated yearly from 2001 to 2013. Research groups develop five land cover schemes yearly.

The MODIS Land Cover Type product (MODIS MCD12Q1 V6) is a worldwide land cover categorization data layer generated yearly from 2001 to 2013. Research groups develop five land cover schemes yearly. Data are dispersed by the USGS at 500m determination in standard MODIS grid tiles. These tiles utilize the sinusoidal projection and cover around 1200 x 1200 km (~10° x 10° at the equator).

The MODIS Terra + Water Arrive Cover Type Yearly L3 Global 500 m SIN Grid product joins the following five different arrive cover classification schemes, each determined through an administered decision-tree classification method:

- Land Cover Type 1: IGBP global vegetation classification scheme
- Land Cover Type 2: University of Maryland (UMD) scheme
- Land Cover Type 3: MODIS-derived LAI/fPAR scheme
- Land Cover Type 4: MODIS-derived Net Primary Production (NPP) scheme
- Land Cover Type 5: Plant Functional Type (PFT) scheme

The above five different research groups generated their own very specific categorization scheme that classifies land cover properties using one year of Terra and Aqua MODIS data .The International Geosphere-Biosphere Program (IGBP) Type 1 land cover scheme recognizes 17 land cover classes (0 – 16) which incorporate 11 natural vegetation classes, 3 created and mosaicked arrive classes, and three non-vegetated land classes. Figure 3-17 shows the common landcover type discriptions.

Overlaying the newly saved tiff image and the study area shapefile, land use of the area of interest can be extracted. Finally shape file of the study area is generated. The grid codes in the attribute table represents to the land cover classification codes as mentioned table below. For instance, Type 1 (IGBP) Grid Code 12 refers to Croplands. Similarly, the other grid codes and types refers to their perspective land uses.

Focusing on the land use attribute table of Shabelle Basin, it can be notified that majority of the cells represents grassland and shrubland with little of agriculture, barren, forest, savannah, urban and built up.

Figure 3-18 represents the classified landcover classification of the study area where the upper stream of the catchment is more of grassland and shrubland dominating the mid and the downstream of the study area.

***Land Cover Types Description (1 through 4 classification schemes)**

Class	IGBP (Type 1)	UMD (Type 2)	LAI/fPAR (Type 3)	NPP (Type 4)
0	Water	Water	Water	Water
1	Evergreen Needleleaf forest	Evergreen Needleleaf forest	Grasses/Cereal crops	Evergreen Needleleaf vegetation
2	Evergreen Broadleaf forest	Evergreen Broadleaf forest	Shrubs	Evergreen Broadleaf vegetation
3	Deciduous Needleleaf forest	Deciduous Needleleaf forest	Broadleaf crops	Deciduous Needleleaf vegetation
4	Deciduous Broadleaf forest	Deciduous Broadleaf forest	Savanna	Deciduous Broadleaf vegetation
5	Mixed forest	Mixed forest	Evergreen Broadleaf forest	Annual Broadleaf vegetation
6	Closed shrublands	Closed shrublands	Deciduous Broadleaf forest	Annual grass vegetation
7	Open shrublands	Open shrublands	Evergreen Needleleaf forest	Non-vegetated land
8	Woody savannas	Woody savannas	Deciduous Needleleaf forest	Urban
9	Savannas	Savannas	Non-vegetated	
10	Grasslands	Grasslands	Urban	
11	Permanent wetlands			
12	Croplands	Croplands		
13	Urban and built-up	Urban and built-up		
14	Cropland/Natural vegetation mosaic			
15	Snow and ice			
16	Barren or sparsely vegetated	Barren or sparsely vegetated		
254	Unclassified	Unclassified	Unclassified	Unclassified
255	Fill Value	Fill Value	Fill Value	Fill Value

Figure 3-17. *Landcover classifications (https://yceo.yale.edu/modis-land-cover-product-mcd12q1)*

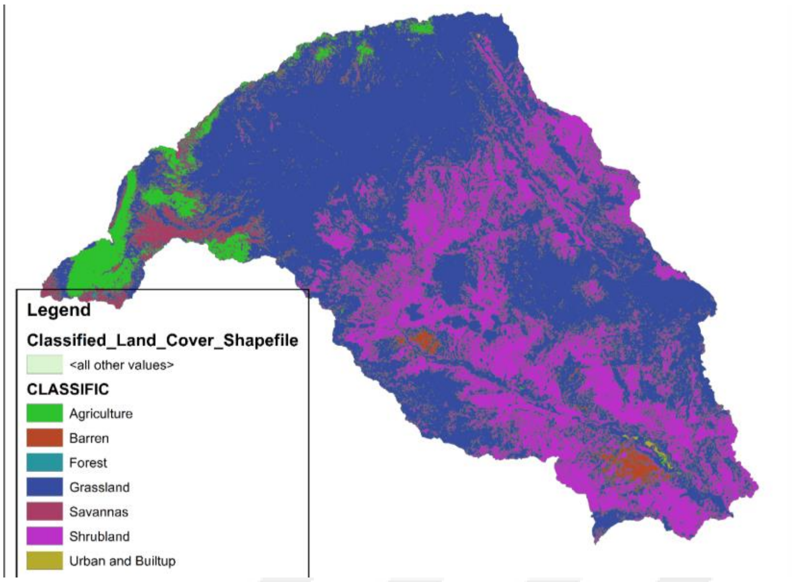

Figure 3-18. *Classified landcover of the study area*

3.3.3. Soil data preparation for CN grid

the CN grid generation requires soil data and land use of the area of interest. Therefore, the soil data of Shabelle Basin is extracted from Harmonized World Soil Database (HWSD) shown in Figure 3-19, which is a global soil database revealed by The Land Use Change and Agricultural Program" (LUC) of the "International Institute for Applied System Analysis" (IIASA) and the "Food and Agricultural Organization of the United Nations" (FOA, 2020).

Moreover, the raster database HWSD comprises a harmonized soil attribute database in Microsoft Access format. Both can effectively be connected in GIS software, permitting the display and query of user-selected soil parameters.

HSWD comprises an attribute database where each mapping unit has detailed information on the dominant soil group, the soil unit composition, elaborated chemical and physical characteristics of the topsoil (0-30 cm), and subsoil (30-100 cm) including sand, silt, clay fraction percentages of each unit, topsoil USDA texture classification, topsoil PH, topsoil salinity, sodicity, gypsum and lime contents, soil depth, granulometry, and sodium exchange percentage.

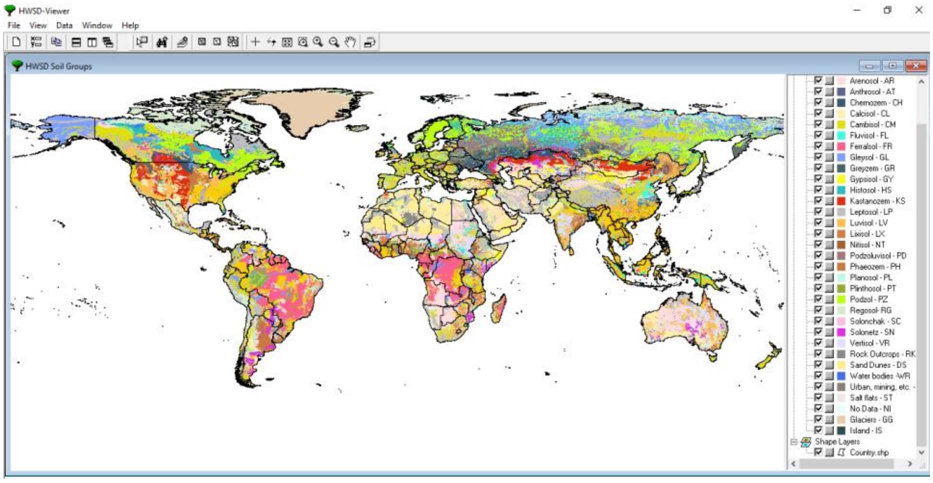

Figure 3-19. *Harmonized World Soil Data*

After downloading global soil raster data and converting it into a shapefile and it can be simply extracted the shape of the area of interest and can be manually filled the physical and chemical characteristics of the soil based on the shapefile extracted from global soil raster data. After detailed mapping based on the global soil data and harmonized world soil database, it can be noted that vertisols, yermosols, nitosols are the three most dominant soil groups of the Shabelle basin with limited soil group of luvisols, fluvisols, leptosols, and regosols.

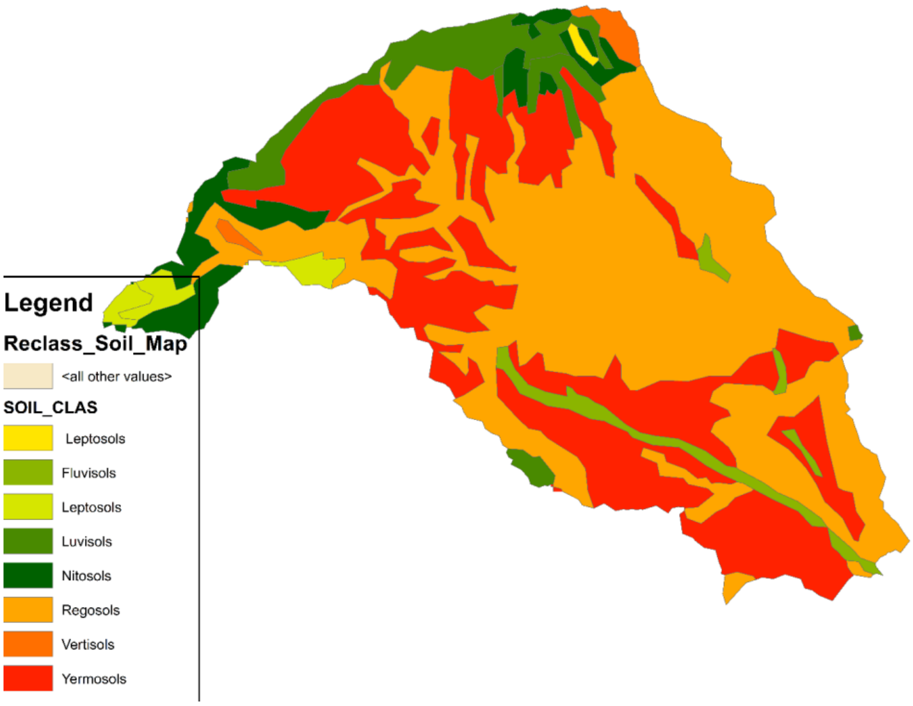

Figure 3-20. *Classified soil map of the study area*

After preparing the soil vector data of the study area, the attribute table of soil shapefile data should be edited in order to add detailed descriptions and more fields relating to the physical and chemical characteristics of the soil, including soil group, sand percentage, silt percentage, clay percentage, soil unit name, pH, salinity, sodicity, soil texture USDA, hydrologic soil group HSG and percentage of the HSG (PctA, PctB, PctC, PctD).

All the above-mentioned detailed information is obtained from "The Harmonized World Soil Database HWSD " except the hydrological soil group and their corresponding percentages. For each polygon in the soil vector data defines the specific hydrological group it belongs (A, B, C, D) and PctA represents what amount of area in percentage within the polygon belongs to soil group A, the same PctC defines what percentage of the area within the polygon that belongs to the soil group of C, and so on.

After defining clearly how much area of a polygon belongs to every soil group (A, B, C, D) it will be simple to create the amount of the hydrological soil group in percentage. For instance, in soil group A, the percentage of the hydrological soil group PctA equals 100, where the three remaining HSG remains zero likewise, for a polygon feature class with soil group D, only PctD= 100, and the three remaining soil groups percentages are zero.

Table 3-3. *Hydrological Soil Group HSG with soil texture*

HSG	Soil textures
A	Sand, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty sandy, or clay

When the soil and land use data of the study area gets prepared the next move is to combine and merge both soil and land use data to generate a polygon feature that has both soil information and land use.

In order to create the Curve Number Grid, the land use feature class and the soil group feature will be combined and will overlayer. The SCS CN table is a table which represents CN for different combinations of land use and soil group.

3.3.4. Merging land use and soil data

Prepared soil and land use data are merged and joined to create a merged shapefile with both soil and land use attribute table. The result of the merged polygon inherits attributes from both feature classes that are used as an input. In any case, the outer boundaries of input polygon don't resemble precisely, the resulting merged polygon ordinarily will have features with attributes from just one feature class since the other feature do not exist in this boundary.

Merge or union process was done using in ArcToolbox under Analysis Tools - *Overlay*, selecting soil data, and land use as the input feature and leaving all the other as default options. The merged output features are usually referred to as "slivers." When the merged new feature is opened, it will be found that there are different sliver polygons within the feature that have attributes only from land-use polygon, leaving the soil attributes empty or vice versa.

Fundamentally, the feature polygon that has -1 value FID is referred to as a sliver polygon and it can be simply verified by checking the attribute table of the merged soil and land use feature polygon. There are two ways to deal with sliver polygons: one is to assign missing values to all features and the other is to delete all negative values. For this study, all negative values are deleted.

Merging soil and land use feature polygon finalizes the spatial data processing for developing curve number CN grid. The next move is to set up a CN Lookup table with different curve numbers for the various combinations of soil groups, and land uses. SCS curve number is a straightforward, broadly utilized, and productive approach for defining the approximate amount of runoff from a rainfall even in a specific zone. The spatial feature with the curve number lookup (CN Lookup) table can be used to generate the CN grid.

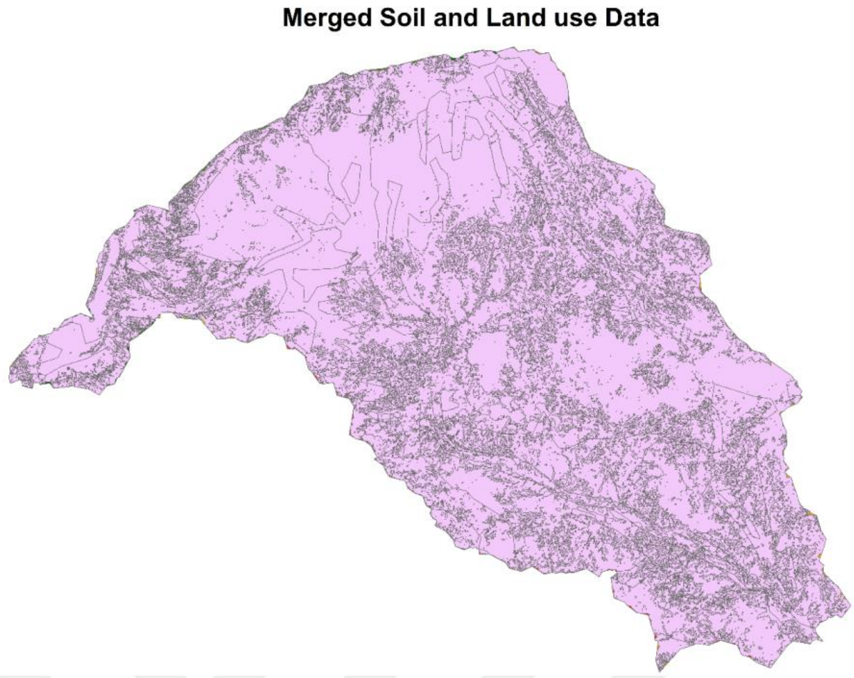

Figure 3-21. *Merged land use and soil data*

3.3.5. Creating CN lookup table

Curve number CN Look up table is a table that will define cover description and curve number for hydrologic soil group. After creating the table, the following fields should be created:

- LUValue (Type: short integer)
- Description (Type: text)
- A (Type: short integer)
- B (Type: short integer)
- C (Type: short integer)
- D (Type: short integer)

3.3.6. Creating CN grid

After all required data including land use data, soil data, Raw DEM and CN Lookup gets prepared, the next step will be creation of curve number CN grid in ArcMap with the help of HEC-GeoHMS. Using merged feature class of soil and land use and the look up table (CN Look up) HEC-GeoHMS will automatically generate curve number CN grid.

The formats and field names used when generating the look up (CN look up) table are compatible to HEC-GeoHMS. The last move is to add new field name LandUse to the merged feature polygon of the combined soil and land use data. This new field will have land use category information that connects it into look up (CN Look up) table.

Finally clicking Generate CN grid under the Utility on the HEC-GeoHMS project view toolbar and choosing the look up parameter as Curve Number will help to create the curve number CN grid.

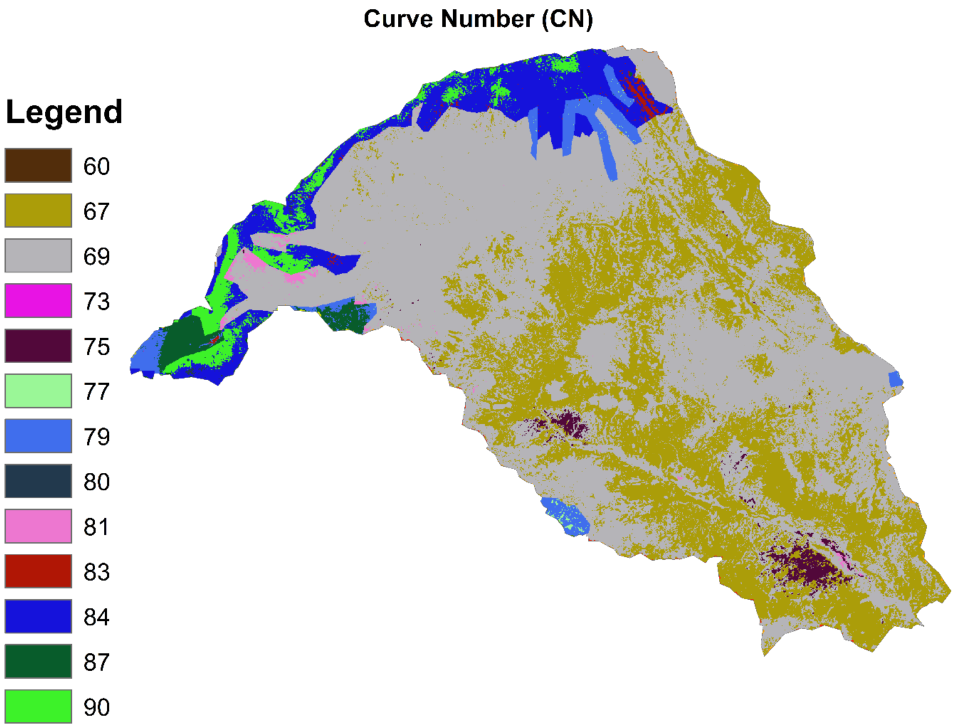

Figure 3-22. *Curve Number CN*

3.4. HEC-HMS modeling

In general, getting better data is quite challenging, where data availabailty in some parts of the world is scarcy and hard to find the needed data. Daily ainfall data of the study were obtained from Ethiopian meteorological agency through means of Somali regional water enterprise for the upper catchment in Ethiopia and SWALIM which is Somali land and water management agency in Somalia. The available data in hand from both countries is in between 01 Jan 2003 to 31 Dec 2017. Using the available 15 years of daily rainfall data, data is divided into two parts: one part for calibration and other for validation. Considering 01 Jan 2003 to 31 Dec 2012 as validation years and 01 Jan 2013 to 31 Dec 2017 as a validation the model was set.

Table 3-4 clearly depicts the calibration and validation years of the rainfall data.

Table 3-4 *Calibration and validation years*

Calibration years	Validation years
01 Jan 2013-31 Dec 2017	01Jan2003-31Dec2017

HEC-HMS has different methods used for both loss and transforms process, where some of the methods are event-based methods, and some are continuous event-based. In this study, the Deficit and Constant Loss methods is used as loss methods during the rainfall-runoff process where Clark unit hydrograph was used as a transform method Detailed results of the Deficit and Constant Los model with its calibration and validation are presented as follows.

During the complicated rainfall-runoff modeling process, this model considers only two parameters: evaporation between rainfall events and infiltration amount during a rainfall event. The deficit and constant model is applied for continuous simulations.

Since the Deficit and Constant Loss model is a continuous model, it was applied daily rainfall data in hand to this study.

HEC-HMS model validation and calibration should be done to improve and reassure the model parameters. The parameters to be calibrated during the simulations were the time of concentration tc in hours, the storage coefficient in hours, the percentage of the imperviousness, the initial deficit, the maximum deficit, and constant rate.

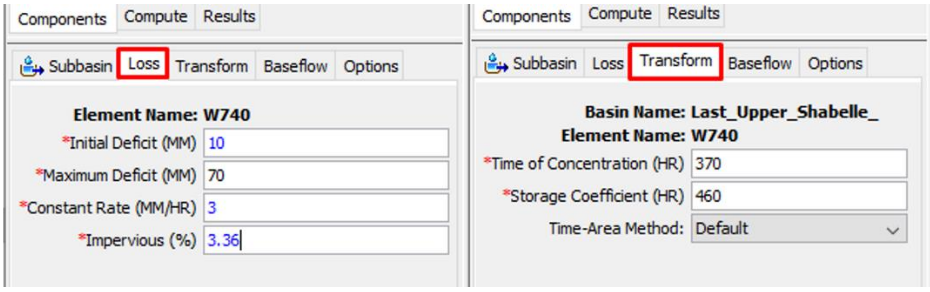

Figure 3-23. *Parameters to be calibrated*

Considering rainfall data from 01 Jan 2013 to 31 Dec 2018 as calibration years and usinng the Deficit and Constant Loss as a loss method, and Clark unit hydrograph as a transform method, the HEC-HMS program was run and found better matching graphs of observed and computed hydrographs with a Nash-Sutcliffe Efficiency of 0.776 using 5 years of calibration data were done.

Nash-Sutcliffe Efficiency is a model performance that is a broadly used and certain statistic for estimating the goodness of fit and predictive skill of the hydrological model. NSE indicates how well the simulated data fits the observed data. NSE is computed as one minus the ratio of the residual variance of the modeled time-series data divided by the measured data variance.

Model validation should be done using the calibrated parameters to evualate wether the calibrated parameters are valid. Considering data from 01Jan2003 to 31Dec2012 as a validation years, the model was validated and found a Nash-Sutcliffe Efficiency of 0.611 for 10 years data.

Figures 3-24 and Figure 3-25 depicts the calibration and the validation results.

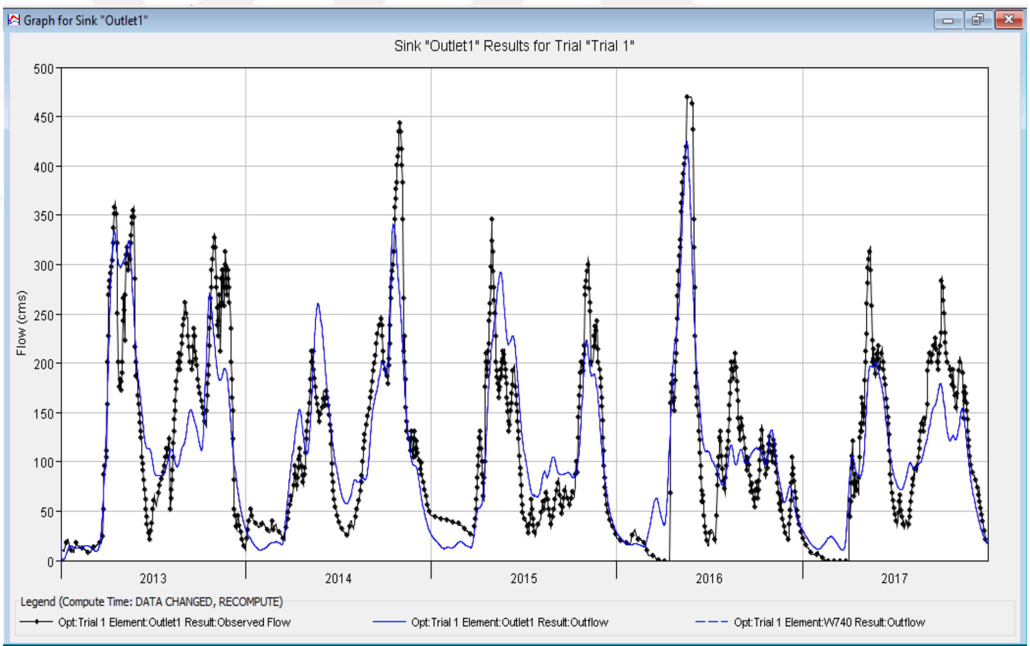

Figure 3-24. *Summary results graph of the observed and computed results of the calibration using the deficit and constant loss method*

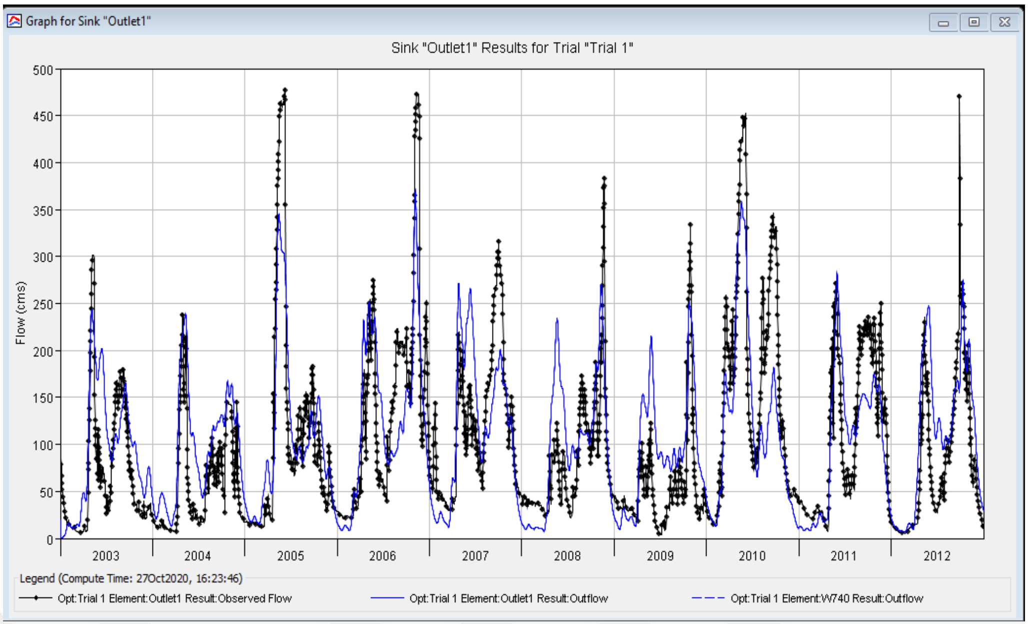

Figure 3-25. *Summary graph of observed and computed results of the validation (01jan2003-31Dec2012)*

Table 3-5 Summerizes the perfomance of the model results. According to the calibration and validation results of the model, it can be concluded that the model is good and give better model evaluation results.

Table 3-5. *Calibration and validation summery results*

	Years	NASH	Volume(MM)
Calibration	01 Jan 2013-31 Dec 2017	0.771	90.35
Validation	01 Jan 2003-31 Dec 2012	0.611	158.29

3.5. Statistical flood frequency analysis

3.5.1. Introduction

In general, during extreme rainfall events floods occur due to the excess rainfall that transforms into direct runoff. During rainfall-runoff transformation many parameters and variables combine; thus, analyzing these using any conventional model like a rational method for peak runoff in a catchment or unit hydrograph method yields good results.

The primary variables that are always involved are the characteristics of the basin, duration, and intensity of the soil's rainfall and antecedent moisture conditions. Each of these parameters depends on a host of other secondary parameters; for instance, the soil's antecedent moisture conditions depend on the characteristics of the soil (whether its sandy, silty, and clay).

In general, a statistical approach to hydrology is used for flood flow and rainfall event predictions. For instance, having limited data of 30 years it can be predicted what will happen after a certain period like 10, 50, or 100 years. The defining characteristics of statistics take into consideration sample characteristics from the population. This is often the mean/median of the population under observation, where the population can be defined as a collection of objects whose measurable properties area of interest.

Statistics is the process of drawing inferences based on the same characteristics while probability gives a certain idea of outcomes based on the characteristics of such a population.

A statistical approach for flood frequency analysis estimates the design flood by using past streamflow data of maximum annual flood flow which may be taken from direct observations or estimated by using suitable methods.

Flood frequency analysis is conducted using an available record of the maximum annual rainfall event in that region.

The analysis of flood frequency events forecasts how usually a predetermined and particularized flood event will happen. Ahead every step related to the estimation is to analyze in detail the available river flow data to get the flood distribution events probability. Among the biggest and critical challenges hydrologists face is to obtain more solid and reliable knowledge of flood regimes.

To pass the challenges mentioned above and achieve a better understanding of flood regimes, hydrologists and civil engineers developed a flood frequency distribution method that focuses on flood peak estimations. one of the most commonly used flood frequency distribution methods for extreme flood prediction is Gumbel's extreme value distribution.

3.5.2. Flood Estimation result comparison using

Using the limited available flow data of the study are, flood frequency estimation of the study area for a return period of 2, 5, 10, 25, 50, 100, and 500 years is calculated using three different statistical frequency estimation methods-Gumbel's extreme value type 1 distribution, Log Pearson type III distribution and Lognormal distribution methods.

Table 3-6. *Calculated flood frequency results using different methods*

Station	Beletweyne						
Return Period (T)	2	5	10	25	50	100	500
Gumbel's EV1	390	444	509	592	653	714	855
Logpearson III	389	444	497	566	605	647	745
Lognormal	390	444	499	559	614	660	765

Customary flood frequency analysis, including Log Pearson type III distribution, Gumbel's Extreme Value type I distribution, and log-normal distributions, was applied to simulate extreme floods with different return periods (2,5,10,25, 50, 100, and 500 years). Gumbel's extreme value type 1 results higher peaks than the other methods. Logpearson type III and Lognormal both shows quite close results having only 1m^3/s difference in 2 years return period and 20m^3/s differences in 500 years return period.

Gumbel's distribution which is extreme value type 1 distribution is the most commonly used distribution for flood frequency events. This type of flood frequency distribution method is used to model the maximum distribution of the sample. Gamble's described a flood as the maximum of the 365-daily flow, and the annual series of flood flows that create a series of most massive flows.

Gumbel's Extreme value type was used as the input peak floods into the HEC-RAS model to determine the corresponding flood levels expected along the river.

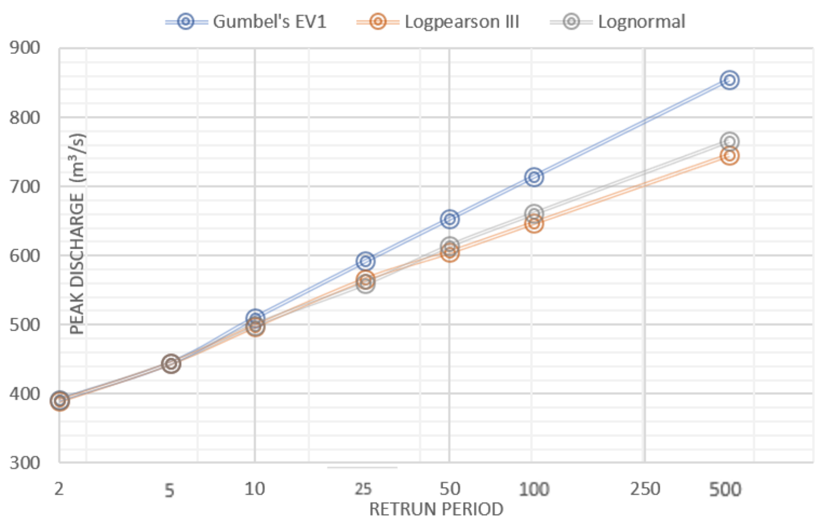

Figure 3-26. *Calculated flood frequency for different flood estimation methods*

4. HYDRAULIC MODELING

4.1. Steps for creating HEC-RAS 2D model

The aim of this part (flood inundation mapping) is to assess the feasible inundation extent of a stream reach using one of the basic and updated components of HEC-RAS Mapper to create a two-dimensional model of a river system. Mapping the outcomes of a hydrodynamic-model to discover the flooded or inundated zones is vital for classifying and recognizing the critical zones that are flooded to assist and aid decision-makers reach decisions and take measures that would moderate and mitigate the impact and consequence of floods. Or to achieve adaptation actions to prevent analogous floods in the coming years. It also plays a vital role in assessing the degree of model results.

The latest version of HEC-RAS (5.0.7) is used for this study with no necessity for using HEC-GeoRAS and ArcMap because it has a RASMapper that performs all geometry preparations.

To set up the HEC-RAS model or a project, the primary data, which is the input of the model, should be prepared and pre-processed. A specific folder for the study must be created to save all the data into that folder. The system international (metric system) is selected as the working units of the study.

The geometry component in HEC-RAS includes data about hydraulic structures, cross-sections, Manning roughness coefficient, riverbanks, etc. The Geometry data is stored in a user-specified geometry file with the extension (. g0*). Back to the old version of HEC-RAS, it was essential to carry out pre-processing of accessible data applying HEC-GeoRAS in ArcGIS. Currently, the RAS mapper in HEC-RAS can create all the pre-processing activities of the available data.

The first step for creating geometry in RAS Mapper is to specify the coordinate system of the study area. RAS Mapper is a devoted component for viewing, processing, and handling geospatial data. Before geometry formation, it is essential to perform the necessary conditions to generate geospatial features (i.e., defining a coordinate system). The coordinate system assigned by the projection file must be a coordinate system that has been projected.

The next step is to add terrain data. 10m satellite digital elevation model of the study area prepared by SWALIM is added to RAS Mapper under tools. After creating new geometry in RAS Mapper, river attribute data was added. River centerline defines the river network of the model and they are aligned in the flow direction from upstream to downstream.

Riverbank lines that separate the main channel from the embankments and riverbanks are created under geometry. Information associated with riverbank positions is needed to specify various characteristics of the cross-sections. Drawing bank lines is the same as drawing the channel centerline.

After setting up all the necessary data, the next move is to run the model to see and interpret the results. Every catchment or watershed has its specific site information. Pay much attention for model selection which model approach applicable to that river system over the other (i.e., unsteady over steady flow area and two-dimensional over one-dimensional).

RAS Mapper has additional capabilities and options to help the modeler. The data in RAS Mapper can be exported in different ways and can be used in different programs for further visualization. RAS Mapper can export both raster data and vector but in a different way. The two figures showed below describes the export option of vector and raster data in RAS Mapper.

HEC-RAS Mapper can export RAS Mapper results for further visualization and rendering through online web-based mapping.

Manning’s Coefficient

Manning's coefficient of roughness n represents the friction or roughness resisted to the flow by the river channels. This coefficient characterizes the channel's resistance to the flow. Manning’s coefficient is among the prerequired input parameters to the HEC-RAS software to map the inundation extent, computation of depths, water surface elevation, and flow velocity. SWALIM proposed the manning coefficient n values of Belet Wayne city as 0.025 and 0.02 for the bank and the channel, respectively. For this study, a manning coefficient value of 0.025 for the bed and 0.02 for the channel was applied to computation.

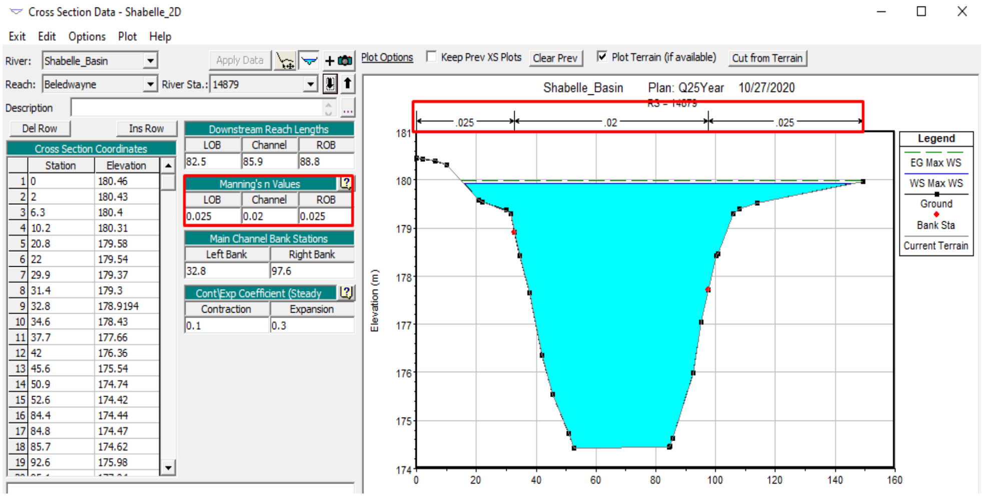

Figure 4-1. *Manning's coefficient of the study area*

Courant number

Courant number is the number of grid sizes per computation, so the number of grid cells that water will travel between time intervals computations. If the courant number is one means, there is one grid cell per computation, and if it is much greater than one, it means that the user is skipping grid cells with the computation, which finally results in instabilities of times. The courant number range is between 0.5 to 0.99.

Under unsteady simulation, courant no can be adjusted the computation time step. Instead of using computational interval in unsteady flow as a fixed interval, it can be taken advantage of the new feature, which is a variable time step control. Instead of selecting the basic fixed time-step method, adjust time-based on the courant might be chosen.

Adjusting time-based based on the courant sometimes improves the model's speed; sometimes, it will slow it down, but it should make it more stable and more efficient in focusing on the computation where the user needs them most. In the study, both basic fixed time-step and adjusted time based on courant were done; both methods almost result in the same inundation maps but took different running time.

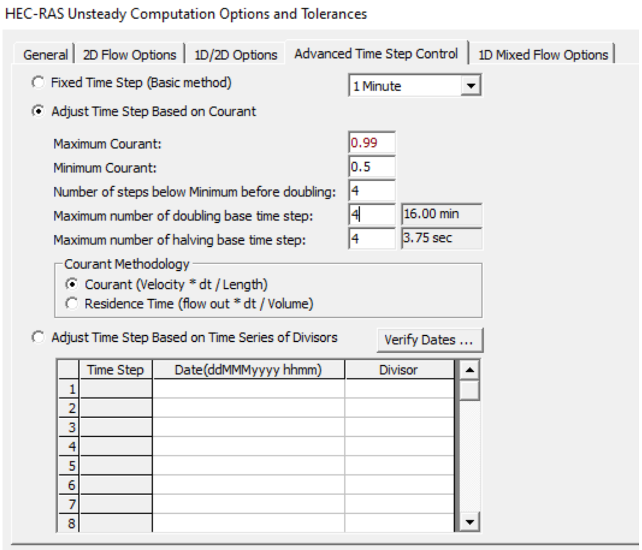

Figure 4-2. *Courant number*

4.2. Mapping Inundated areas in HEC-RAS

HEC-RAS Mapper can map and render in a dynamic format the inundated or flooded area for both unsteady and steady flow models. Figure 4-3 represents the digital elevation mapping of Beletwayne city. An illustration Shabelle river geometry at Beletwayne city generated with HEC-RAS Mapper is presented in Figure 4-4. Only urban boundary was considered when creating the 2D mesh to map urban flood inundation of Beletwayne city.

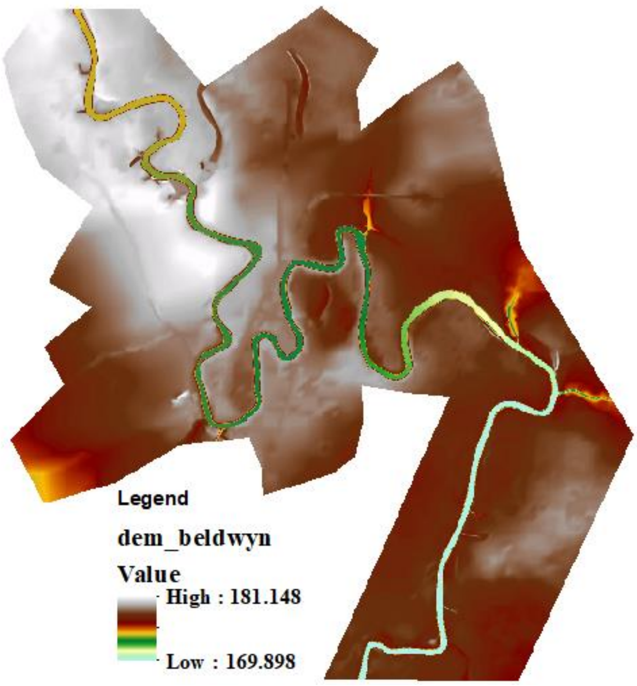

Figure 4-3 *Digital Elevation Model (DEM) of the area of interest*

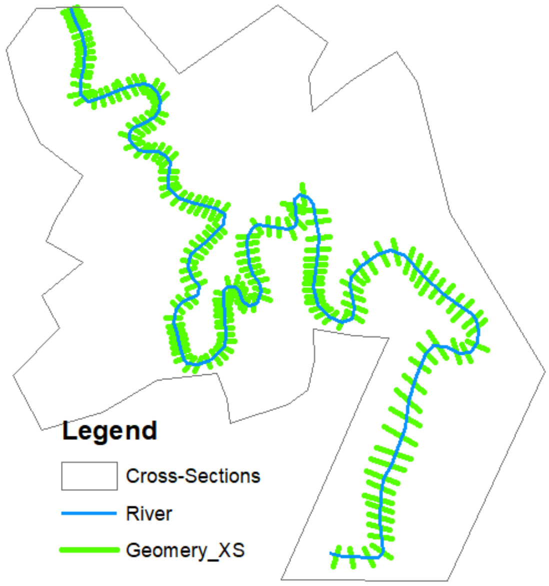

Figure 4-4. *River Geometry at Beletwayne City*

Figure 4-5. *2D Mesh Diagram*

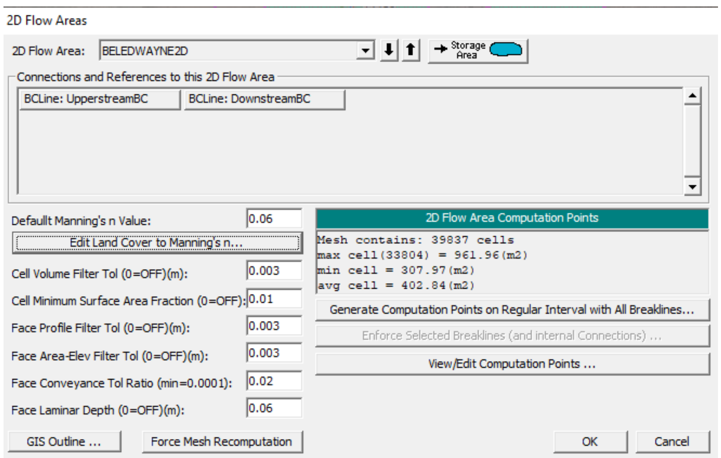

Figure 4-6. *2D Flow Areas Computational Mesh*

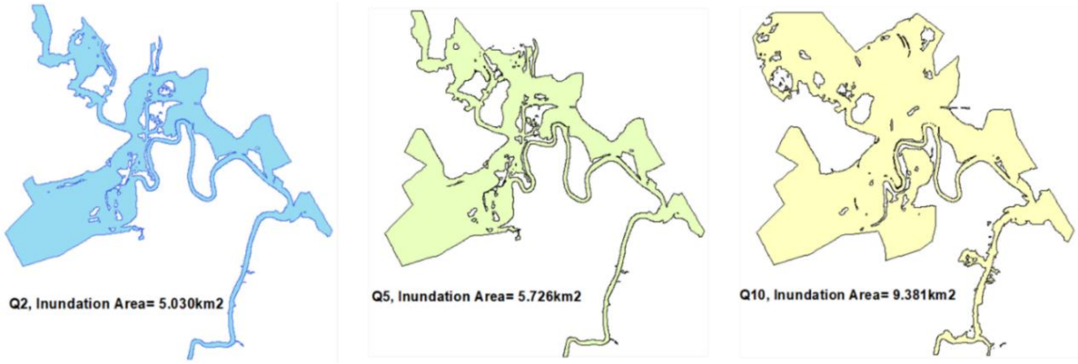

Figure 4-7. *Flood inundation extent of Q2, Q5, and Q10 discharges*

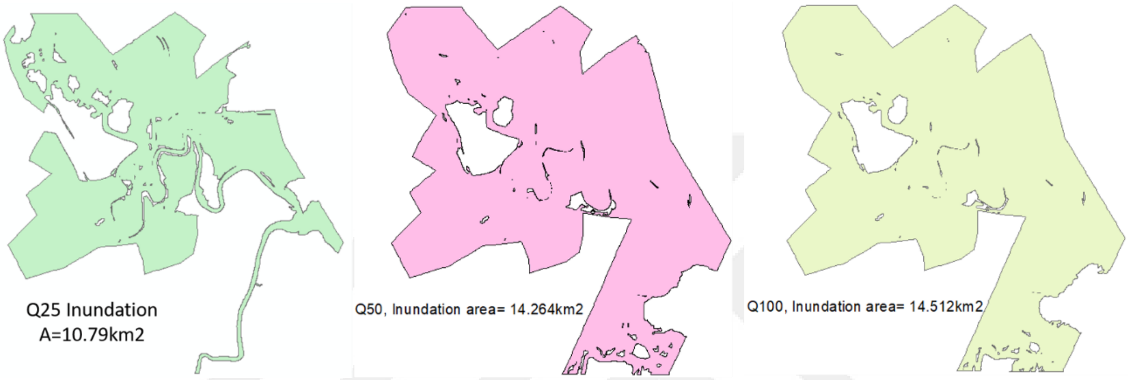

Figure 4-8. *Flood inundation extent of Q25, Q50, and Q100 discharges*

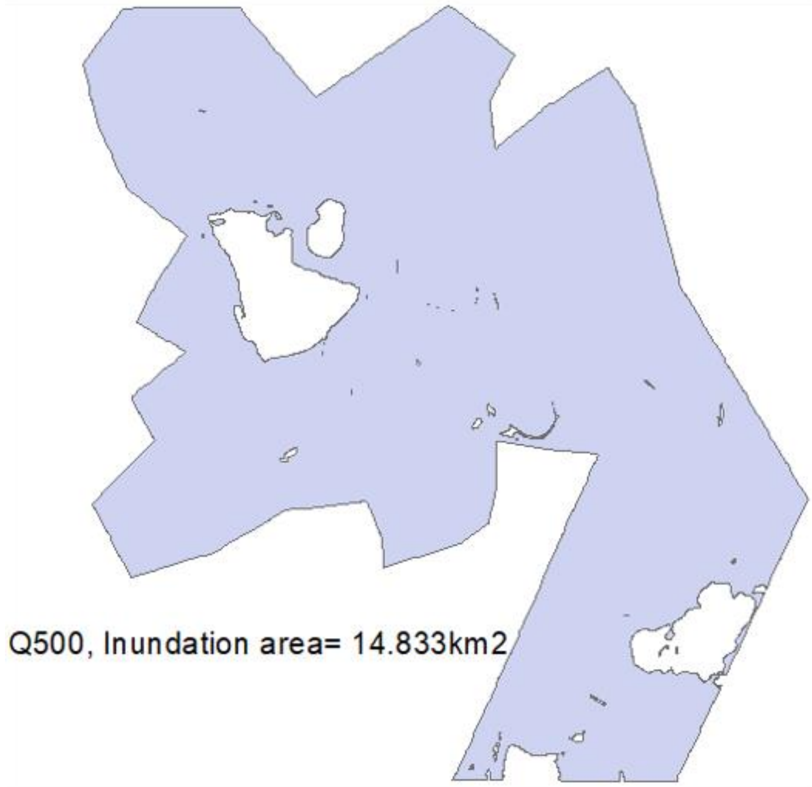

Figure 4-9. *Flood inundation extent of Q500*

Table 4-1 Summerizes the inundation area of Beledwayne city for different return periods. It can be seen clearly that flood extent increases from 2 years return period but somehow reaches 50 years return period the flood inundation extent does not show any signifant differences, though the discharge increases but the depth changes and increases. For instance, Q50 (653.7m^3/s) inundates an area of around 14.26km^2 where Q500 (855.27m^3/s) inundates a very close area of 14.833km^2, which means a big difference in flooding extent may not be seen after flooding extent reaches around 14km^2 but the depth changes.

Table 4-1. *Inundation area for a different return period*

Discharge m^3/s	Q2	Q5	Q10	Q25	Q50	Q100	Q500
Inundated Area (km^2)	5.03	5.73	9.38	10.79	14.26	14.51	14.83

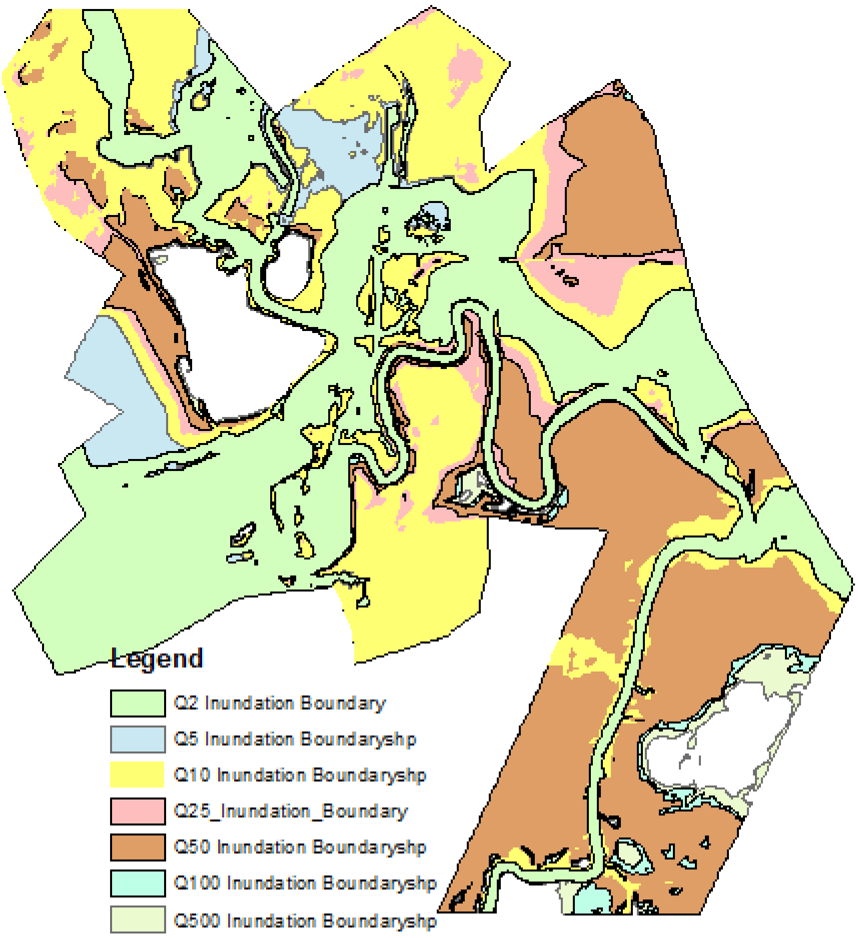

Figure 4-10. *Comparison of Q2, Q5, Q10, Q50, Q100, and Q500 inundation boundaries*

Flood inundation map result shows that Beletwayne city is vulnerable city to flooding and every 2-year return period around 5km^2 area inundates. Inundation extent ranges from 5.03km^2 with a corresponding 2-year return period to 14.83 km^2 with a corresponding of 500-year return period. Apart from the rainfall frequency increase in the Ethiopian highlands there are also other contribution factor that takes part the flood frequency increase at Beletwayne city. Among those are lack of regular riverbed rehabilitation and maintenance. Moreover, there is also an increase in erosion rates, causing sedimentations in the river channels and shallowing the channel depths which causes an increase in water depth.

Figure 4-11 depicts satellite observed flood event at Beletwayne by SWALIM and 2-year return period inundation extent. The main aim here is to company the observed satellite flood event in 2019 to the modeled Q2 and found that there is a quite match between the two events. Thought it's not clearly written the flood extent area of the observed satellite event but there can be seen there is a close matching in terms of flooded extent.

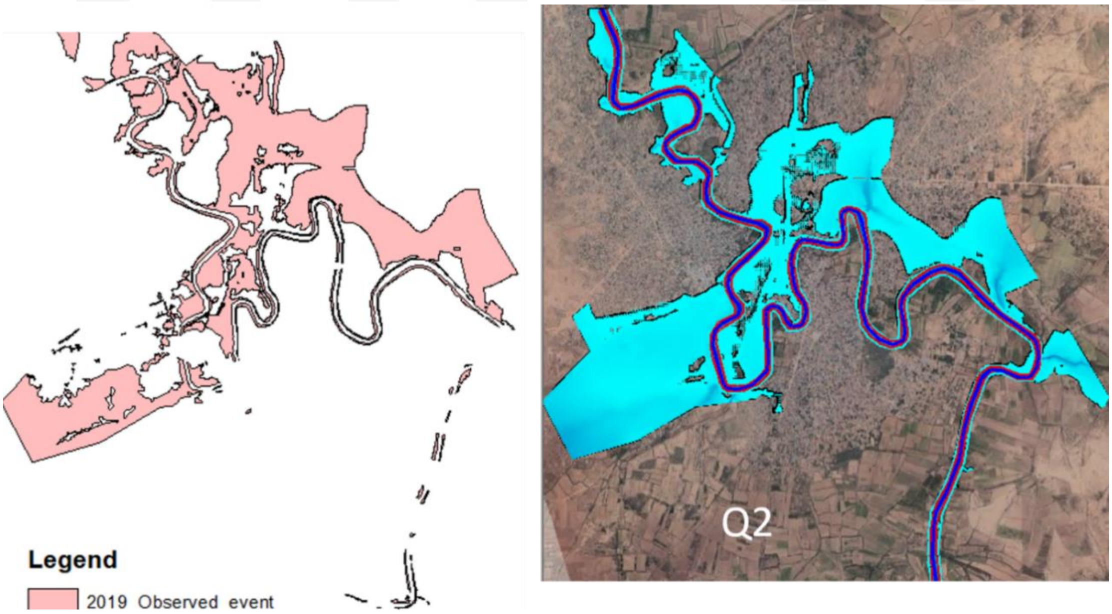

Figure 4-11. *Comparison of Q2 flood inundation extent to the Satellite observed 2019 event*

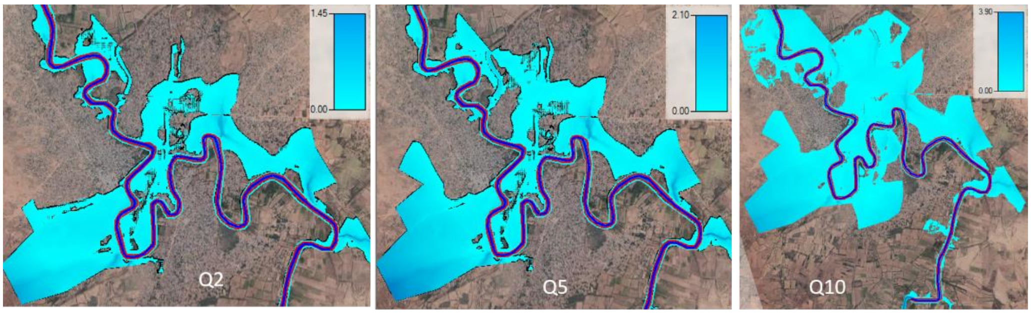

Figure 4-12. *Depths of Q2, Q5, and Q10 discharges*

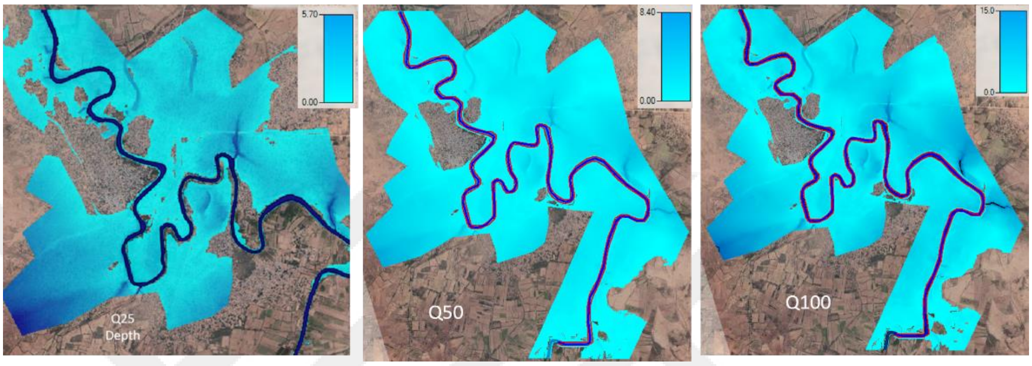

Figure 4-13. *Depths of Q25, Q50, and Q100 discharges*

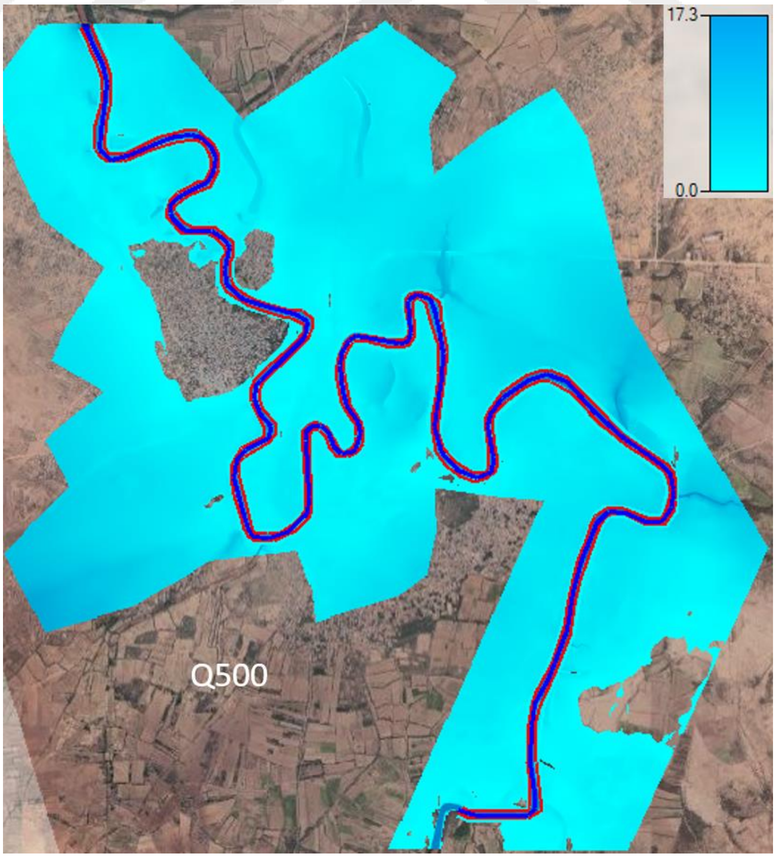

Figure 4-14. *Depths of Q500*

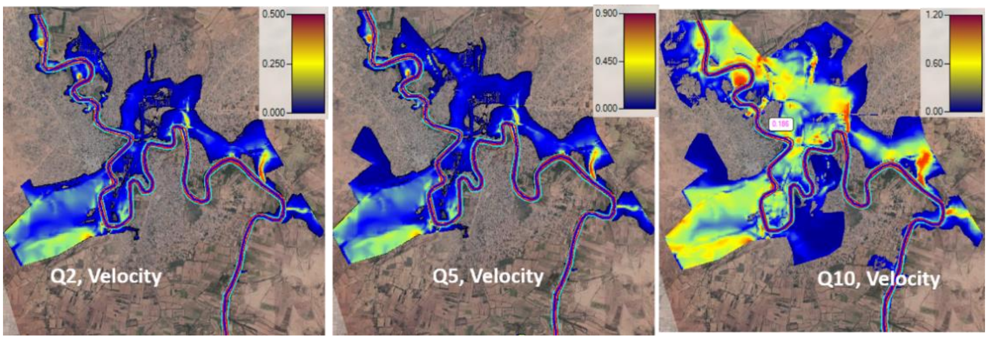

Figure 4-15. *Velocity of Q2, Q5, and Q10 discharges*

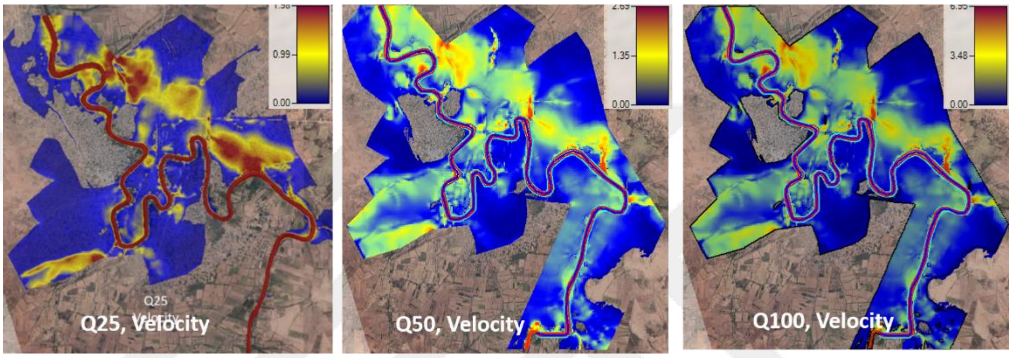

Figure 4-16. *Velocity of Q25, Q50, and Q100 discharges*

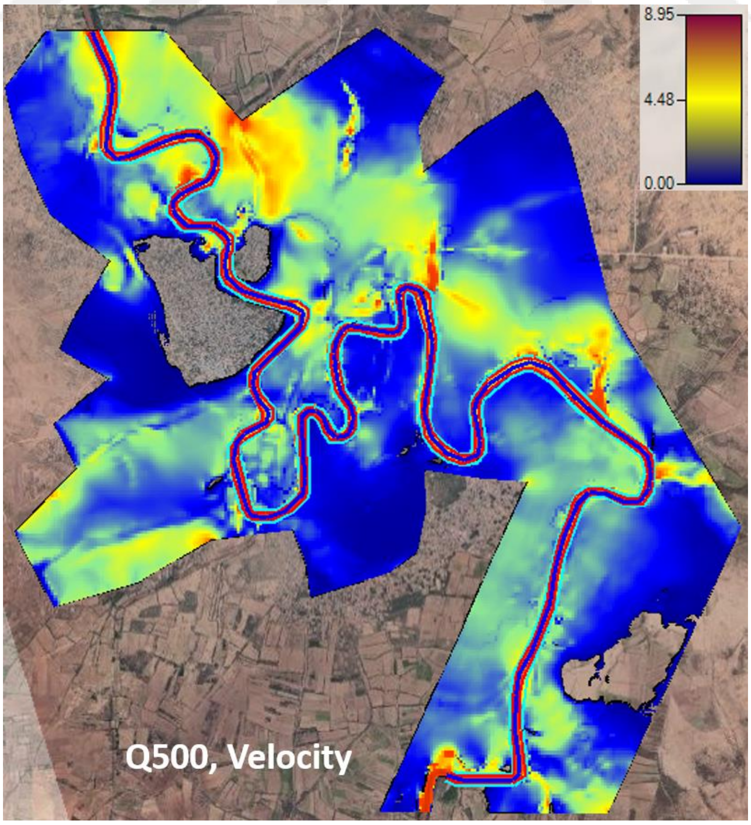

Figure 4-17. *Q500 velocity*

The results of flood inundation boundaries that there is only slight change in the flood extent in from 50-year return period to 500-year return where there is a big difference in their corresponding discharges, but there is a change in both depth and velocity. The depth corresponding to the 50-year return period is 8.4m where the depth corresponding to the 500-year return period of the study area is around 18.83m.

Figures from 4-12 to 4-14 clearly show the corresponding depths of the different return periods of 2, 5, 10, 25, 50, 100 and 500 years, where Figures form 4-15 to 4-17 depicts the corresponding velocities of the different return periods.

Figure 4-18 compares the flood inundation boundaries of 2-year return period and 500-year return period. It can be seen clearly from the map how flood extent increases from Q2 to Q500. Figure 4-19 also compares the difference of Q2 and Q500 in terms of water depth. The corresponding depth of 2-year return period is 1.45m, where the corresponding depth of 500-year return period is 17.28m. These results demonstrate how Beletwayne city is vulnerable to the floods where every 2 year 1.45m water might flood to the city.

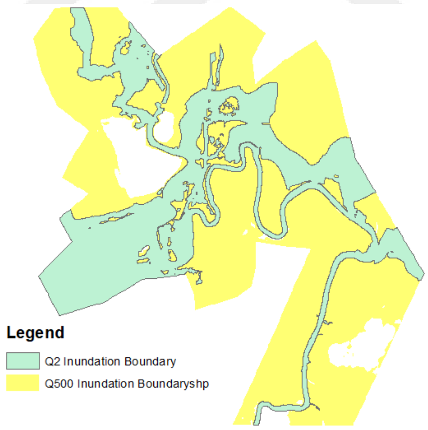

Figure 4-18. *Flood inundation boundary comparison of Q2 and Q500*

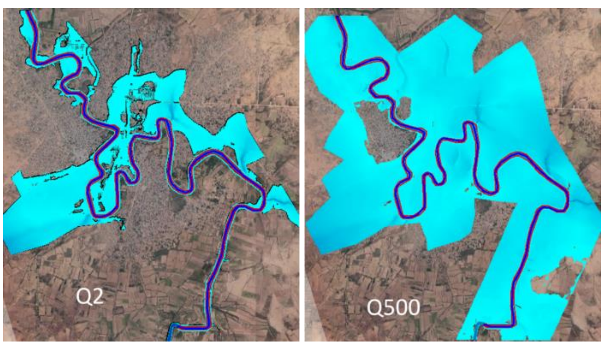

Figure 4-19. *Depth comparison of Q2 and Q500.*

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Beletwayne town in southern Somalia is regularly hit by multiple types of natural and human-made hazards. Floods are prominently among the most disastrous and destructive natural hazards in Beletwayne town, causing massive death and severe damage to human, infrastructure, agriculture, and local economies. Therefore, this study is aimed to map the flood inundation area of Beletwayne city using GIS, hydrological and hydraulic modeling.

HEC-HMS software was used to model rainfall-runoff simulation for this study. Using loss method as deficit and constant loss model found that the deficit and constant technique is applicable with a NASH of 0.776 for calibration of five years and 0.611 for validation of 10 years.

The years of 01Jan2013-31Dec2017 were considered as the calibration year for the loss methods, where 01Jan2003-31Dec2012 were considered validation. Clark unit hydrograph was used as a transform method for the deficit and constant loss model.

The conventional flood frequency analysis like log Pearson type III distribution and Gumbel's extreme value distribution was used to calculate the extreme flood flow of different return periods of the study area and used an input flow for HEC-RAS.

This study's primary objective is to assess the HEC-RAS model's suitability in simulating water surface profiles and defining the extent of inundation under different return-period floods for the Shabelle river in Beletwayne city. It included routing the flood by using RAS-Mapper for channel geometry generations and 10m resolution DEM from SWALIM as an input.

Using Gumbel's extreme value type 1 distribution the peak discharge corresponding values of 2, 5, 25, 10, 50,100, and 500 years return period floods at Beletwayne city were found to be 390.804m^3/s, 444.261 m^3/s, 509.695 m^3/s, 592.370 m^3/s, 653.704 m^3/s, 714.584 m^3/s, and 855.270 m^3/s respectively. Combination of ArcGIS and RAS-Mapper in HEC-RAS model mapping the extent of flood-prone areas in Beletwayne city expected to be flooded under different return-period floods was done.

Analysis of the flood plain map results certainly showing that Q50 at Beletweyne city (653.704m^3/s) would inundate the whole city and totally flooded except very few areas with a higher elevation with is partially flooded area.

This case study concludes that HEC-RAS models can be efficiently and productively used to improve and analyze the predictions of regions and areas expected to be flooded under a given flood flow.

Apart from the weather, other essential factors that increase flood frequency in flood-prone areas are natural environment changes, which increases erosion rates, causing sedimentations in the river channels and shallowing the channel depths. Lack of river maintenance, river embankment failures, and human activities for cultivation during dry seasons also contribute to increased flood frequency.

5.2. Recommendations

As the results of the flood inundated map show extreme flooding over the whole of Beletweyne city. Consequently, it is imperative and crucial to implement protection measures to Beletweyne city and its environs on riverbank embankments. Flood damages could be reduced by different measures like continuous riverbed maintenance, river reach de-silting, construction of flood protection structures, etc.

Maintenance and rehabilitation of existing riverbanks must be done regularly, and the local municipality of Beletweyne city should make this at the top of their list. Furthermore, a flood warning system should be made at Beletweyne city to make early evacuation during extreme flood events.

An extra relevant difficulty that contributes to extreme flooding is its invasion by the local people. Recently, there was increased intrusion to riverbanks and floodplain areas due to growth and population increase pressures in the riverine areas. To protect people's lives and property and minimize the extent of the inundated areas, the riverbed and embankments should remain conserved and maintained. Keeping riverbanks preserved and relieving people encroachment can minimize flood consequences and render advantages through parks and other entertainment tools.

Flood forecasting, monitoring, and transmission system with automated real-time hydrometeorological data collection should be implemented at the upper catchment of the basin. A functional forecasting center (FFC) with both hydrological and hydraulic modeling capacity should also be implemented. Establish a plan of educating vulnerable local communities in Beletweyne city on the actions needed to do and advice to follow during and after the warning system is released.

Digital Elevation Model (DEM) data with a high-resolution for Shabelle Basin, particularly flood-prone areas like Beletwayne city, should be acquired. New real-time gauges should be also be established.

Beletwayne city has a very flat topography; therefore, the construction of flood control structures on the upstream would be recommended to minimize the flood extent on the downstream and flood-prone areas.

Some general recommendations for flood protection area listed below:

- Flood control structure like dikes, retaining walls, and other barriers
- Regular rehabilitation and maintenance of both the river channel and riverbed
- Flood diversion structures
- Changing in channel conveyance properties

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