



HYDRAULIC MODELING AND FLOOD MAPPING OF HAROSHA RIVER  
WITH HEC-RAS AND HEC-GeoRAS MODELS IN TIGRAY, ETHIOPIA

MASTER OF SCIENCE THESIS

MULUGETA TAREKE ABEBE

HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

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WITH HEC-RAS AND HEC-GeoRAS MODELS IN TIGRAY, ETHIOPIA

MULUGETA TAREKE ABEBE

A THESIS SUBMITTED TO THE  
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MAJOR ADVISOR: SHEMELIES ASSEFFA (PhD)

CO - ADVISOR: SIRAK TEKLEAB (PhD)

NOVEMBER, 2017

SCHOOL OF GRADUATE STUDIES  
HAWASSA UNIVERSITY  
ADVISOR'S APPROVAL SHEET

(Submission sheet)

This is to certify that the thesis entitled “**HYDRAULIC MODELING AND FLOOD MAPPING OF HAROSHA RIVER WITH HEC-RAS AND HEC-GeoRAS MODELS IN TIGRAY, ETHIOPIA**” submitted in partial fulfillment of the requirements for the degree of **Masters’** with specialization in **Irrigation and Drainage Engineering**, the Graduate program of **School of Water Resource Engineering**, and has been carried out by **Mulugeta Tareke Abebe I.D.No PGIDE/023/08**, under our supervision. Therefore, we recommended that the student has fulfilled the requirements and hence hereby can submit the thesis to the school.

Approved by Advisors:

Shemeleis Asseffa (PhD) \_\_\_\_\_

Name of Major advisor                      Signature                                      Date

Sirak Tekleab (PhD) \_\_\_\_\_

Name of co-advisor                              Signature                                      Date

SCHOOL OF GRADUATE STUDIES  
HAWASA UNIVERSITY  
EXAMINERS APPROVAL SHEET  
(Submission Sheet)

We, the undersigned, members of the Board of Examiners of the final open defense by **MULUGETA TAREKE ABEBE** have read and evaluated his/her thesis entitled **“HYDRAULIC MODELING AND FLOOD MAPPING OF HAROSHA RIVER WITH HEC-RAS AND HEC-GeoRAS MODELS IN TIGRAY, ETHIOPIA”** and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement for the Degree of **Master’s of Science in Water Resource Engineering with Specialization in Irrigation and Drainage Engineering.**

**Mr. Ayalew Shura**

Name of the Chairperson

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

**Dr. Shemelies Asseffa**

Name of Major Advisor

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

**Dr. Mulugeta Dadi**

Name of Internal Examiner

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

**Dr. Adane Abebe**

Name of External Examiner

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
SGS Approval

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

**Stamp of SGS**

**Date** \_\_\_\_\_

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## **DECLARATION**

I certify that this thesis submitted for the degree of Master of Science is the result of my own original research, except all the sources of material used for this thesis where otherwise acknowledges, and that this thesis (or any part of the same) has not been submitted for a higher degree to any other University or Institute.

Full Name \_\_\_\_\_

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## LIST OF ACRONYMS AND SYMBOLS

AMC	Antecedent soil Moisture Condition
CN	Curve Number
DEM	Digital Elevation Model
DTM	Digital Triangular Model
ERADDM	Ethiopian Road Authority Drainage Design Manual
FAO	Food Agricultural Organization
FDREMWR	Federal Democratic Republic of Ethiopia Ministry of Water Resources
FRMCPAE	Flood Risk Mapping Consultancy for Pilot Areas in Ethiopia
HEC-GeoRAS	Hydrologic Engineering Center's GeoRiver Analysis System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
Km <sup>2</sup>	Square Kilometer
LU/LC	Land use/ land cover
M	Meter
m a.s.l	meter above sea level
m <sup>3</sup> /s	Cubic meter per second
NRCS	Natural Resource Conservation Service
OHWM	Ordinary High Water Mark
Pf <sub>1</sub> , Pf <sub>2</sub> , Pf <sub>3</sub> , Pf <sub>4</sub> , Pf <sub>5</sub>	Water surface Profiles for 5, 10, 25, 50, and return periods respectively
REST	Relief society of Tigray
SCS	Soil Conservation Service
TIN	Triangular Irregular Network
UNDP	United Nation Department of Program
USACE	Unites State Army Crop of Engineers
USDA	Unites State Department of Agriculture
USSCS	Unites State Soil Conservation Service
WRB-FAO	World Reference Base -Food and Agriculture Organization

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## **ABSTRACT**

*The Harosha river catchment is found in Tigray region in Raya Valley. This study area is surrounded by Waja and Tumuga catchment in the south and Harosha, Limeat and Harle catchment in the North and also it is the upper south part of the Raya valley catchment. The area is also dominated by undulating terrain with relatively steep to moderately steep and flatter slopes in the downstream of the catchment. Harosha flood plain has been vulnerable to high flooding from rainfall during rainy season. Also the main causes of these damages are land use changes from years to years and the main objective of this study is to estimate peak flood for various return period and prepare flood inundation mapping that can be used as decision support system for future intervention. The data used for this study was annual daily maximum rainfall, DEM, land use land cover map, and soil map and the flood frequency analysis of annual maximum daily rainfall was analyzed. The SCS rain fall-runoff method, HEC-RAS, HEC-GeoRAS and ArcGIS environment are used to determine the peak flood for different return periods. The simulation result for return period of 5, 10, 25, 50 and 100 year floods magnitude are 347.4, 383.7, 420.8, 443.6 and 463.1m<sup>3</sup>/s respectively. The maximum flood hazard and flow depth maps for a return periods of 5, 10, 25, 50 and 100 year are 84.6 and 3.36; 86.1 and 3.84; 86.9 and 4.35; 87.1 and 4.91; and 87.7 hectare and 5.89 m respectively with a maximum velocity of 4.6 m/s.*

*Key Words: SCS, GIS, HEC-GeoRAS, HEC-RAS, Flood modeling*

## **1. INTRODUCTION**

### **1.1. Background**

Floods are the most common natural disasters that affect societies, many countries or regions year after year around the world (Dilley et al., 2005). The flooding can be caused by, for instance, heavy rain, land subsidence, and dam failures. The natural disaster related to the weather system variability, climate change, and environmental degradation have been frequently influencing human beings and their impacts seem to have greatly increased in recent decades (Vincent, 1997); they estimated that more than one-third of the world's land area is flood prone affecting some 82% of the world's population. About 196 million people in more than 90 countries are exposed to catastrophic flooding, and that some 170,000 deaths were associated with floods worldwide between 1980 and 2000 (UNDP, 2004). These figures show or indicate that flooding is a major concern in many regions of the world.

Globally, the economic cost of extreme weather events and flood catastrophes is severe, and if it rises owing to climate change, it will hit poorest nations the hardest consequently, and the poorest section of people will bear the brunt of it. The number of major flood disasters in the world has risen relentlessly over recent time. There were six in the 1950s; seven in the 1960s; eight in 1970s; eighteen in the 1980s; and twenty six in the 1990s (UNDP, 2004).

According to Aris (2003) in Getahun and Gebre (2015) flood can be explained as excess flows exceeding the transporting capacity of river channel, lakes, ponds, reservoirs, drainage system, dam and any other water bodies, whereby water inundates outside water bodies. Flood is a continuous natural and recurring event in floodplains of monsoon rainfall areas like Ethiopia, where over 80% of annual precipitation falls in the four wet months (Sanyal and LU, 2005).

Guilio Castelli (2014) indicated that floods are one of the most common and widely distributed natural risks to human lives, destroy properties, damage economies, make fertile land unusable and damage the environment. Some of Alamata Wereda villages and very wide farm and irrigation area are located in a low-lying area of Harosha river basin surrounded by range of mountains from the north and west of the outlet of the river; The steep slope of the mountain range and the highly erosive seasonal rainfall of the area have made it vulnerable to

problems related to flooding; Many fertile croplands, village settlers and the existing and newly built roads and bridges are suffering the consequences of flood coming from high mountains. Having problem in the study are the people and the government has been taking different flood mitigation measures like gabion dykes unfortunately the above actions were not enough to completely stop the flooding problem and it is obvious to have a detail flood study that will help to take the appropriate action for the flooding hazard. As a result there is a need to identify the risk of flood of the city and nearby villages to support decisions making process for risk management, and for high-level planning and detailed design for having appropriate flood mitigation measures in order to reduce these negative effects of flooding.

Harosha River catchment is suffering the consequences of flood coming from the high mountains during the main rainy season. By generating the peak discharge for different return period related to the hydro metrological data of past events, and geometrical characteristics of the river channel and the reach boundary conditions and using SCS method, HEC-RAS and HEC-GeoRAS models water surface profile and flood mapping has been done for Harosha watershed.

## **1.2. Statement of the problem**

Harosha is one of the ungauged catchment with no water level management in Raya Valley and prediction in ungauged place is the most challenge in hydrology. From downstream to upstream about six and half kilometer long is affected by flooding problems were observed on the Harosha river basin that risks human lives, destroy properties, damage economies, make fertile land unusable and damage the environment on villages and agricultural lands including the irrigation area as well as diversion irrigation projects.

In addition the area located in left and right side and also the lower part of Harosha River flood plain are at risk due to high flooding and they are highly affected. For more understanding of this problem different land uses which are damaged by flooding are listed in the figure 4 and 5 in appendix 2.

In the study area the previous studies was not the extent of flood so this study is expected to produce a flood hazard map that will show the predicted flooding magnitude and extent to help the planning and construction of flood management practices.

### **1.3. General Objective**

The general objective of this study is to develop hydraulic modeling and flood mapping of Harosha river catchment by defining the possible flood water level by applying SCS method, HEC-RAS and HEC-GeoRAS.

#### **1.3.1. Specific Objectives**

The specific objectives are:

- To estimate the amounts of peak flood for various return periods.
- To map flood inundation water surface profile for Harosha river catchment.
- To prepare flood hazard map of the study area.

### **1.4. Research questions**

The research questions related for identifying the problem of the study area are:

- What is the amount of flood in Harosha River for different return period?
- How is the inundation water surface profile of the study area?
- Where about is the effect of flooding in the study area?

### **1.5. Research Hypothesis**

- Flood damage in Harosha river doses not varies with return periods;
- Water surface profile of Harosha river is similar at all time; and
- Harosha watershed is not affected and will not be affected in the future.

### **1.6. Scope of the study**

The study focuses on flood mapping of the study area to indicate commonly inundated area and flood water surface profile.

### **1.7. Significance of the study**

After mapping of the flood susceptible area in this location the mitigation measures recommended that is to be used as decision supporting tool to safeguard the agricultural lands, irrigation projects and the community living in the study area.

## **2. LITERATURE REVIEW**

### **2.1. Global Flood Modeling and Flood Hazard**

According to Khan et al. (2011), floods are among the most recurring and devastating natural hazards, impacting upon human lives and causing severe economic damage throughout the world. Floods occur because of the rapid accumulation and release of runoff waters from upstream to downstream, which is caused by very heavy rainfall. Discharges quickly reach a maximum and diminish almost as rapidly. The occurrence of flooding is concern in hydrologic and natural hazards science due to the top ranking of such events among natural disasters in terms of both the number of people affected globally and the proportion of individual fatalities (Borga et al., 2011). The potential for flood casualties and damages is also increasing in many regions due to the social and economic development, which imply pressure on land-use, e.g., through urbanization. Flood hazard is expected to increase in frequency and severity, through the impacts of global change on climate, severe weather in the form of heavy rains and river discharge conditions (Dihn et al., 2012). The current trend and future scenarios of flood risks therefore demand for accurate spatial and temporal information on the potential hazards and risks of floods.

The HEC-GeoRAS or HEC-RAS has been used worldwide for inundation mapping, such as in Euro [Dragan and Slobodan (2009) and Panagoulia et al. (2013)], in the USA [Brunner (2013), Yongping and Kamal (2011) and Keren et al. (2008)], in Africa [Botes and Smith (2010), Fosu et al. (2010) and Okirya et al. (2012)], in Asia [Menon and Ajin (2014)] and also in Ethiopia [Getahun and Gebre (2015), Brhane (2011), and Tesema (2009)].

### **2.2. Flooding and flood modeling in Ethiopia**

According to Brhane (2011) flood is defined as a great flow of water, especially, a body of water, rising, swelling and overflowing over land surface and also flood control implies all measures taken to reduce the detrimental effect of flood. In addition to this flooding over the world is one of the worst natural disasters, in terms of economic losses and number of water born deaths. Accurate and current floodplain maps can be the most valuable tools for avoiding severe social and economic losses from floods. This updated floodplain maps also improve public safety and property. Early identification of flood-prone properties during emergencies

allows public safety organizations to establish warning and evacuation priorities. Flooding occurs due to high stages in the river, which can be caused by the following reasons that are too high discharges, backing up of the water and increase in bed levels, human intervention in the highlands areas at an ever increasing scale.

Flooding is inevitable in some areas of Ethiopia during the main rainy season, which extends from June to September; the season is characterized by high volumes of rain fall. Flooding is normally expected in some areas of Tigray, around Lake Tana and Oromia zone of Amhara, Zones 1 and 3 of Afar, Gode, Afder and Liben zones of Somalia, east and southwest Shoa of Oromia Region, South Omo zone, Gambela, Itang and Jikawo woredas of Gambela Region (FRMCPAE, 2010).

Flood study can be done by using different models like approximate methods which simply determination of flood way, two dimensional modeling and the back water modeling which is based on the measurement of energy loss along flood plain mostly the back water modeling is used for river line flooding conditions with HEC-RAS which is the most common computer application (Tesema, 2009).

The above modeling is also been widely used for river flood mapping purpose in Ethiopia and it is checked its applicability in different catchments like hydraulic modeling and flood mapping of Fogera flood plain a case study of Gumera river, Dechatu catchment Dire Dawa town flood study. In addition ERADDM (2002) recommended using SCS method for the peak discharge estimation and most the consultants in the country uses the ERA drainage design manuals for the hydrology and hydraulic analysis of bridges.

The peak flood for different return periods was determined using stream flow recorded data and the results of peak discharge estimation for 100 years return period is  $319.60 \text{ m}^3/\text{s}$ , and by using 30 m resolution DEM, HEC-HMS, HEC-GeoHMS, HEC-RAS and HEC-GeoRAS the value of flood hazard map were prepared and the potential damage of the study area is  $31.36 \text{ km}^2$  with the model output a maximum depth of 7.94 m in the flood plain of Fogera a case study of Gumera river in Amhara region (Brhane, 2011). The person was determining the maximum flood using Rainfall recorded data for hydrologic estimations.

The result for precipitation modeling flood analysis methods was used as a key input for determination flood frequency and magnitude. By using 57 m resolution DEM, HEC-HMS, HEC-GeoHMS, HEC-RAS and HEC-GeoRAS and magnitude and for 50 year return period is found to be 1187 m<sup>3</sup>/s. In this case even if the flood inundated area was delineated the area affected by flood in hectare determined is not clear in the Dechatu Catchment (Dire Dawa Town) Flood Study (Tesema, 2009).

According to Haftom (2015), the results of peak discharge estimation using SCS method for 100 years return period is 99.37 m<sup>3</sup>/s, and by using 90 m resolution DEM, HEC-RAS and HEC-GeoRAS the value of flood hazard map were prepared and the potential damage of the study area is 5.76 hectare with the model output a maximum depth of 2.21 m in the flood plain of ETU river in Tigray Alamata.

### **2.3. Spatial Information and Multi-Criteria Evaluation for Flood Vulnerability Mapping**

Flooding risk consists of hazard and vulnerability. Hazards can be defined as threatening events, or the probability of occurrence of a potentially damaging phenomena within a given time period and area. When a hazardous event occurs, the damage depends on the elements at risk. The elements at risk are the population, hydraulic structures and economic activities, public services and infrastructure (Barroca et al., 2006). Vulnerability on the other hand is the most crucial component of risk in that it determines whether or not exposure to a hazard constitutes a risk that may actually result in a disaster. If the potential exposure to floods becomes a reality, i.e., when floodwaters physically encroach on hydraulic structures, then the vulnerability of people and infrastructure is decisive for the degree of harm and damage.

### **2.4. Peak Flood Estimation methods**

Designing maximum flood is the flood magnitude, which is expected to occur with a certain return period during the design period for different purpose. In every case, the design period can be established through rigorous analysis of the available data. Maximum flood is the peak river discharge that corresponds to a certain return period. Many hydrologic methods are available to estimate peak flood (ERADDM, 2002).

### 2.4.1 Attributes for Flood Estimation and Mapping

**Catchment Area or Watershed** is a topographically delineated area drained through a common confluence point on a stream or river; an area that drains rainfall runoff water to a common outlet. It is also Drainage system (The area upon which water fall & the network through which it travels to an outlet); and also Pour Point – (A location at which the rainfall runoff contributing area can be determined) (Mekelle University, 2016).

**Surface runoff or overland flow** occurs when the rainfall rate is greater than the infiltration rate. The runoff equation was developed for this condition. The runoff flows on the surface of the watershed and through channels to the point of reference. This type of runoff appears in the hydrograph after the initial demands of interception, infiltration, and surface storage have been satisfied. It varies during the storm and ends during or soon after the storm. The volume of surface runoff flowing down dry channels of watersheds in arid, semiarid, or sub humid climates may be reduced by transmission losses, which could be large enough to eliminate the runoff (Chow, 1959).

**Base Flow** occurs when there is a fairly steady flow from natural storage. The flow comes from an aquifer that is replenished by infiltrated rainfall or surface runoff. Changes in this type of runoff seldom appears soon enough after a storm to have an influence on the hydrograph for that storm, but an increase in base flow from a previous storm increases the stream flow rate. In flood hydrology base flow is generally dealt with separately, and all other types are combined in to direct runoff, which consists of channel runoff, surface runoff, and subsurface flow in unknown proportions (Mockus, 1949).

**The CN** is an index developed by the Natural Resource Conservation Service, to represent the potential for storm water runoff within a drainage area; The CN for a drainage basin is estimated using a combination of land use/land cover, soil type, and AMC; There are four hydrologic soil groups: A, B, C and D in addition to these Group A have comparatively high infiltration rates and group D have low infiltration rates (ERADDM, 2002).

**Soil Conservation Service** is the method used to estimate surface runoff discharge from the rainfall depth and area of the catchment. This method takes into account the land use,

hydrological soil cover and antecedent moisture conditions for predicting the yield from the basin (ERADDM, 2002 and USACE, 2002).

**Time of Concentration** is defined as the time it takes a drop of water falling on the most remote point hydraulically in the catchment area to travel through the catchment area to the outlet; it is the time required for surface runoff water to flow hydraulically from the remotest point of the catchment to the point of exit (ERADDM, 2002; USACE, 2002; and Chow et al., 1988).

**Antecedent Moisture Contents (AMC):** The soil moisture conditions of the catchment area at the beginning of a storm. These conditions affect the volume of runoff generated by a particular storm event. Notably they affect the peak discharge only in the lower range of flood magnitudes – approx. As floods become rarer, antecedent moisture has a rapidly decreasing influence on runoff (ERADDM, 2002 and Chow et al., 1988).

#### **2.4.2. Rational Method**

ERADDM (2002) indicated that Rational Method was originally developed for urban catchments for which the basic assumptions of the method hold. The Method can be applied to small rural catchments if they do not exceed 0.5 km<sup>2</sup>. In this case, the consequences of applying the Rational Method to larger catchments is to produce an over estimate of discharge and conservative design. The Rational Method of estimating design flood on small watershed is conceptually based on the criterion that storms of uniform intensity distributed evenly over the basin, maximum rate of runoff equal to a certain percentage of rainfall intensity occurs when the entire basin area is contributing at the outlet. This condition is met after the elapsed time T<sub>c</sub>, time of concentration. The equation in the Rational Formula is function of catchment area, runoff coefficient, and frequency factor and rainfall intensity.

##### **A) Runoff Coefficient (C)**

Values shown in Table 2.1 below are stipulated in ERADDM (2002) for determination of C (for non-urban catchments), depending on terrain type and hydrologic soil grouping.

Table 2.1: Recommended Runoff Coefficient, C

Terrain Type	Soil Type			
	A	B	C	D
Flat < 2%	0.04 - 0.09	0.07 - 0.12	0.11 - 0.16	0.15 - 0.20
Rolling 2 - 6%	0.09 - 0.14	0.12 - 0.17	0.16 - 0.21	0.20 - 0.25
Mountain 6 - 15%	0.13 - 0.18	0.18 - 0.24	0.23 - 0.31	0.28 - 0.38
Escarpment > 15%	0.18 - 0.22	0.24 - 0.30	0.30 - 0.40	0.38 - 0.48

**B) Time of Concentration ( $T_c$ ):** The rainfall intensity used in the Rational Method is determined from the time of concentration ( $T_c$ ).  $T_c$  comprises of summation of flow durations in sheet flow, shallow concentrated flow and open channels.

As per ERADDM (2002), the methods adopted to determine  $T_c$ : sheet flow condition is limited to a maximum of 100 m and flow duration is computed using the simplified Manning kinematic solution. For shallow concentrated flow, the velocity method is used. For flow in open channels, the Manning' equation is used; in using the above procedures for determination of  $T_c$ , the following difficulties may be encountered:

- In sheet flow computation, although a maximum limit of 100m is stated, an accurate demarcation of flow length is somehow difficult and may not be accurate.
- For shallow concentrated flow, the stretch (length) of the flow is not readily determined from topographical maps or as aerial photos.
- Use of Manning's equation for open channel flows is dependent on availability of channel geometric section properties, which once again is difficult to determine from topographic maps and aerial photos. This may require conducting channel cross section surveys at various locations along the stream which is practically difficult especially on large catchment areas. Hence, due to the above conditions, Kiprich's equation employed, noting the caution stated in the ERADDM (2002). In order to minimize in estimating too short  $T_c$ , in using this equation, the channel is subdivided

in to a number of stretches with similar slopes and Tc for each stretch is calculated and summed up to obtain the final Tc.

### **C) Frequency Factor ( $C_f$ )**

As per ERADDM (2002), the frequency factor shown in table 2.2 below is used to magnify the less frequent storms, i.e. storms with recurrence interval greater than 10 year. The table 2.2 below shows the frequency factor values.

Table 2.2: Frequency Factors for Rational Method

Return Period (year)	5	10	25	50	100
Frequency Factor ( $C_f$ )	1.0	1.0	1.1	1.2	1.25

Those rational formula used for estimation of flood peak are essentially regional formula based on statistical correlation of the observed peak and observed catchments parameters.

#### **2.4.3. Soil Conservation Service (SCS)**

ERADDM (2002) indicated that The USSCS (1972) has developed a synthetic unit hydrograph procedure that has been used widely for developing rural and urban hydrographs. The unit hydrograph used by the SCS method is based upon an analysis of a large number of natural unit hydrographs from a broad cross section of geographic locations and hydrologic regions. This method can be used for catchment areas greater than 50 hectares (0.5 km<sup>2</sup>). This technique requires the same basic data as the Rational Method: catchment area, a runoff factor, time of concentration and rainfall. The SCS approach, however, is more sophisticated in that it considers also the time distribution of the rainfall, the initial rainfall losses to interception and depression storage, and an infiltration rate that decreases during the course of a storm. With SCS method, the direct runoff can be calculated for any storm either real or generating scientifically, by subtracting infiltration and other losses from the rainfall to obtain the precipitation excess.

According to ERADDM (2002) and FDREMWR (2002) a relationship between accumulated rainfall and accumulated runoff was derived by SCS from experimental plots for numerous hydrologic and vegetative cover conditions. Data for land- treatment measures, such as

contouring and terracing, from experimental catchment areas were included. The equation was developed mainly for small catchment areas for which daily rainfall and catchment area data are ordinarily available. It was developed from recorded storm data that included total amount of rainfall in a calendar day but not its distribution with respect to time. The SCS runoff equation is therefore a method of estimating direct runoff from 24-hours or 1-day storm rainfall.

## **2.5. HEC-RAS modeling**

### **2.5.1. Theory and Concept used in HEC-RAS**

The computer program HEC-RAS is used to determine stream widths, elevations and flows. This section has an introduction where the basic elements of HEC-RAS are given, with a description of the mathematical and physical principles used and the special features of the program. The HEC-RAS computer model has a large number of options, such as mixed flow regime analysis, allowing analysis of both sub- and supercritical flow regimes in a single computer run, culvert and bridge routines allowing for multiple openings of different types and sizes, quasi 2-D velocity distributions, and x-y-z graphics of the river channel system (Davis 1995).

HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. HEC-RAS system can ultimately contain three one-dimensional hydraulic analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; and (3) movable boundary sediment transport computations. A key element is that all three components can use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the three hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed. In addition to these by importing the peak discharge for different return period related to the hydro meteorological data of past events, the geometrical characteristics of the river channel and the reach boundary conditions

with the help of ArcGIS and HEC-GeoRAS HEC-RAS will calculate the water surface profile in steady flow analysis (USACE, 2010).

The development of HEC-RAS projects requires geometric data, flow data and plan files to delineate flooding extents. The large amount of time taken to produce complex river geometries within HEC-RAS prompted HEC to develop the software HEC-GeoRAS. HEC-GeoRAS handles geometries digitized by users within geographic information systems (GIS), located in layers, to create geometric input files which are imported into HEC-RAS to create a HEC-RAS geometry file. HEC-GeoRAS also handles output data from HEC-RAS to map flooding extents, depth and velocity (USACE, 2010; Brunner, 2010a).

HEC-RAS can assist in Ordinary High Water Mark (OHWM) delineation in numerous ways. The modeling can simulate the water surface elevation for a given discharge or can allow a user to find the discharge that matches a given elevation. Once a model is set up for a given river reach, water surface profiles can be quickly modeled for a range of flows. In this way, a user can determine, for instance, the flow rate that would reach the level of field indicators or potential OHWM locations. The user can then combine these results with hydrologic information (e.g., stream-gage information or modeled stream flow estimates) to determine the recurrence interval of a given discharge and to test if these flows are reasonable for the OHWM (Brunner, 2010a).

According to Brunner (2010a and 2010b) the required inputs for a HEC-RAS model for steady state flow are:

- channel geometry in the form of a series of cross sections;
- Manning's roughness coefficient,  $n$ ;
- flow rates;
- flow change locations (longitudinally along a river reach); and
- Boundary conditions, which are often the water surface slope or elevation at the downstream-most cross section.

In the process of building a HEC-RAS model, users must depend on professional judgment in making many choices about the data collection and analysis at each site. There is no set prescription for every location and training and experience are required to properly simulate

the flows at a site, even when making use of the HEC-RAS user manuals and program documentation.

### **2.5.2. Model assumptions and other considerations**

HEC-RAS steady-flow analysis has the following assumptions (Brunner 2010a):

- Flow is steady (i.e., constant over time at any given location).
- Flow is gradually varied, meaning the depth or width does not change abruptly over a short distance. (An exception is at hydraulic structures such as bridges, culverts, and weirs. At these locations, where the flow can vary abruptly, the momentum equation or other empirical equations are used.)
- Flow is 1-D (i.e., velocity components in directions other than a single, principal direction of flow are not accounted for).
- River channels have small slopes, generally less than 1:10.
- If a study site violates these assumptions, the model can still produce an output; but it could be erroneous.

The model inputs and assumptions described in this document are not an exhaustive list of all the elements of a HEC-RAS model, but they do cover many of the issues that a user or reviewer should reflect on when creating or assessing HEC-RAS models. The HEC-RAS reference guide (Brunner 2010a) and users' manual (Brunner 2010b) provide a complete list of the potential inputs. Professional judgment, based on training in hydraulic analysis and experience with HEC-RAS and other models, is required for a thorough review of all the considerations in a HEC-RAS model of a study area. As with the Manning equation, HEC-RAS models never yield an exact or complete answer; but the quantitative results improve understanding of the system being investigated. Typically the model results must be contextualized with the flow recurrence intervals of the simulated flows. And, as stressed throughout this document, the modeling results can enhance, but typically not replace, field observations in the process of OHWM delineation.

### **2.5.3. HEC-RAS Model inputs for Curving out the output uncertainty**

According to Brunner (2010a and 2010b) and ERADDM (2002) the following sections lay out the essential considerations in making a HEC-RAS model and provide how different decisions affect the modeling results in case studies on rivers in semi-arid, and in temperate locations:

#### **A. Cross-Section data**

The geometry of the waterway is one of the most important inputs of a HEC-RAS model, so surveys of the geometry require careful consideration. The extent and resolution of cross-section measurements determine the extent and resolution of the HEC-RAS simulation. The surveys must span the entire reach in question, and the cross sections must extend laterally far enough to capture the elevation of the OHWM and any other features of interest. It is desirable to have additional cross sections beyond the reach in question, especially on the downstream end, to minimize the effect of user-defined boundary conditions on the results at the area of interest.

The resolution of survey points along a cross section must be sufficient to capture the transitions in topography, especially in the vicinity of the OHWM elevation. It is generally preferable to have variable spacing of the survey points to characterize breakpoints rather than an even spacing of survey points. Users should recognize that the variations in topography between survey points are not incorporated into the model. The exact number of survey points appropriate for a given cross section is a balance between the desire to have the most accurate model possible and the time and cost to survey many points.

#### **B. Roughness**

HEC-RAS requires the user to define the roughness of channels and floodplain surfaces. Different values can be input for the channel and overbank areas, which often have very different roughness values because of the abundance of vegetation on the overbank areas and the lack of vegetation in the main channel. Users generally input  $n$ , Manning's roughness coefficient. As with the Manning equation, HEC-RAS models are sensitive to the  $n$  value, especially for fine-tuning the models. However, given the relatively narrow range of  $n$  values in natural channels, entering incorrect  $n$  values, does not typically lead to extreme errors in the model because errors are generally less than 20%. Although this error is not extreme, it can have an important effect in OHWM-related modeling in some circumstances. This roughness

coefficient can be calibrated based on field evidence of high water marks, surveys during flow events, and knowledge of stage–discharge relationships at stream gages.

The chosen roughness value,  $n$ , can affect the modeled water surface elevation. Higher roughness impedes the flow more; so with the higher  $n$  value, the water elevations are higher than the other model runs to convey the same discharge amount. At most, the use of different  $n$  values changed the flow depth by approximately 20%.

### **C. Boundary conditions**

HEC-RAS requires only a downstream boundary condition in subcritical flow simulations, only an upstream boundary condition in supercritical flow simulations, and both downstream and upstream boundary conditions in mixed subcritical–supercritical flow simulations. The boundary condition can be based on a known water surface elevation, the critical water elevation for the modeled discharge, or a known slope. If a known slope is used, the energy gradient slope is the proper input although the water surface slope is often entered as an approximation of the energy gradient slope because the water surface slope can be measured in the field. In any case, the user-defined boundary condition has the greatest effect at the cross section where it is set; and the effect typically attenuates with distance from the cross section. For this reason, it is desirable to have additional cross sections downstream of the reach of interest to minimize the effect of user-defined boundary conditions on this reaches. Boundary conditions can affect modeled water surface elevations in HEC-RAS but generally only in the most downstream of the modeled cross sections.

### **D. Discharge**

The flow to be modeled is also user defined; and, logically, higher flows typically equate to higher water surface elevations. The flow input into the model depends on the question at hand. For this thesis the elevation and extent of the water surface at the 5, 10, 25, 50, and 100-year recurrence-interval flow, was estimated their flow value and to use it as input.

The hydraulic modeling of flow elevations provides context to the field observations, especially when compared with flow recurrence intervals derived from flow frequency analysis. In a steady-flow simulation, HEC-RAS computes the hydraulics of a single flow value. Multiple flow values can be entered at once, and HEC-RAS will calculate the water surface of each flow independently. Many users will specify steady flow if the simplification

can be made because adding variation in flow over time greatly increases the complexity of the computations (Brunner 2010a).

### **E. Steady Flow Water Surface Profiles**

This component of the modeling system is intended for calculating water surface profiles for steady gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. The steady flow component is capable of modeling subcritical, supercritical or mixed flow regime water surface profiles. The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations where the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e., hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions). The effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain may be considered in the computations. The steady flow system is designed for application in flood plain management and flood insurance studies to evaluate floodway encroachments. Also capabilities are available for assessing the change in water surface profiles due to channel improvements, and levees. Special features of the steady flow component include: multiple plan analyses; multiple profile computations; and multiple bridge and/or culvert opening analysis.

### **2.6. HEC-GeoRAS**

HEC-GeoRAS is an ArcMap GIS (geographic information system) extension that incorporates the power of GIS analysis and visualization into HEC-RAS model input and output. This has several advantages, the foremost being the integrated use of remotely sensed imagery and DEMs. HEC-GeoRAS helps with deriving the input data and visualizing the output data, but the hydraulic computations are undertaken in a standard HEC-RAS model (Brunner 2010a).

HEC-GeoRAS is set of ArcGIS tools specifically designed to process geospatial data for use with HEC-RAS. The extension allows users with limited GIS experience to create an HEC-RAS import file containing geometric data from existing DTM and complementary data sets. Results exported from HEC-RAS may also be processed (USACE, 2010).

HEC-Geo RAS extension allows users to create Ras layers an HEC-RAS import file containing geometric attribute data from an existing DTM and complementary data sets; Water surface profile results may also be processed to visualize inundation depths and boundaries; HEC-Geo RAS extension for ArcGIS will use an interface method to provide a direct link to transfer information between the Arc GIS and the HEC-RAS; The model uses the geometric attribute data from an existing digital terrain model (DTM) in TIN format and exported results from HEC-RAS model [Ackerman CT (2005) and Zelda Els (2011)].

HEC-GeoRAS creates a file of geometric data for import into HEC-RAS and enables viewing of exported results from RAS. The import file is created from data extracted from data sets (ArcGIS Layers) and from a DTM. HEC-GeoRAS requires a DTM represented by a TIN or a GRID. The layers and the DTM are referred to collectively as the RAS Layers. Geometric data are developed based on the intersection of the RAS layers. Prior to performing hydraulic computations in HEC-RAS the geometric data must be imported and completed and flow data must be entered. Once the hydraulic computations are performed, exported water surface and velocity results from HEC-RAS may be imported back to the GIS using HEC-GeoRAS (USACE, 2010).

The HEC-GeoRAS assists the ArcGIS in providing pre-processing, direct support, and post-processing functionality before and after the hydraulic analysis. For pre-processing, both HEC-GeoRAS and ArcGIS packages should preprocess data, but HEC-GeoRAS provides the extra capability to capture the geometric data according to the HEC-RAS format required for the hydraulic modeling. The HEC-GeoRAS exports and imports the spatial data to different formats between ArcGIS and HEC-RAS by using a data exchange format called a RAS GIS File [Ackerman (2005) and Zelda (2011)].

Brunner (2010a) indicates that the primary considerations in a setting up a hydraulic model in HEC-GeoRAS are fundamentally the same as in a HEC-RAS model, namely:

- cross-section data must be appropriately spaced and have adequate resolution,
- roughness values should be chosen carefully and should vary between the channel and the vegetated overbank areas,

- boundary conditions need to be established and should be set at cross sections suitably downstream so that they have minimal effect on the reach of interest,
- ineffective and disconnected flow areas need to be considered carefully by examining levees and other obstructions between channels that may exist between cross sections, and
- Modeled discharge should be appropriate for the question at hand.

HEC-RAS does not account for the topography between cross sections, and water extent is interpreted linearly between cross sections. However, HEC-GeoRAS will interpolate the areas of inundation between cross sections based on the simulated water surface elevation and a DEM of the study area. The output from HEC-GeoRAS can look fantastic and be highly beneficial for OHWM delineation purposes, but the modeling is still subject to all of the considerations of a reliable HEC-RAS model. The results need to be field-verified; and the modeled water extents can be used to inform, but typically not replace, a field-based OHWM delineation (Brunner 2010a and Brunner 2010b).

## **2.7. Geographic Information Systems (GIS)**

GIS stands for geographic information system; an information system is a computer program that manages data; A GIS, then, is a type of information system that deals specifically with geographic, or spatial, information. Like other information systems, a GIS requires lots of data that it can access, manipulate, and use to produce a product. Geographic information describes the spatial (locational) factors of an object or area. This can be simply latitude and longitude coordinates, but in most cases more complex factors are included. GIS is a computer-based information system that enables capture, modeling, manipulation, retrieval, analysis and presentation of geographically referenced data. Geographic elements in a GIS are typically described by one of three data models: vector, raster, TIN. Vector objects include three types of elements: points, lines, and polygons. A point is defined by a single set of Cartesian coordinates [easting(x), northing(y)]. A line is defined by a string of points in which the beginning and end points are called nodes, and intermediate points are called vertices. A straight line consists of two nodes and no vertices whereas a curved line consists of two nodes and a varying number of vertices. Three or more lines that connect to form an enclosed area define a polygon. Vector feature representation is typically used for linear feature modeling

(roads, lakes, etc.), cartographic base maps, and time-varying process modeling (Ackerman, 2005).

The raster data structure consists of a rectangular mesh of points joined with lines, creating a grid of uniformly sized square cells. Each cell is assigned a numerical value that defines the condition of any desired spatially varied quantity. Grids are the basis of analysis in raster GIS, and are typically used for steady-state spatial modeling and two-dimensional surface representation and the land surface representation in the raster domain is called a DEM (Ackerman, 2005).

A TIN is a triangulated mesh constructed on the (x, y) locations of a set of data points. To form the TIN, a perimeter around the data points is first established, called the convex hull. To connect the interior points, triangles are created with all internal angles as nearly equiangular as possible. This procedure is called Delaunay triangulation. By including the dimension of height (z) for each triangle vertex, the triangles can be raised and tilted to form a plane. The collection of all such triangular planes forms a representation of the land surface terrain in a considerable degree of detail. The TIN triangles are small where the land surface is complex and detailed, such as river channels, and larger in flat or gently sloping areas. Additional elevation data, such as spot elevations at summits and depressions and break lines, can also be included in the TIN model. TIN triangles do not cross break line (Ackerman, 2005).

GIS is a tool that can assist floodplain managers in identifying flood prone areas in their community. GIS manages spatial data such as DEMs, land cover, land use, rainfall and slopes. With GIS, geographical information is stored in a database that can be queried and graphically displayed for analysis. By overlaying or intersecting different geographical layers, flood prone areas can be identified and targeted for mitigation or stricter floodplain management practices. It provides graphical output that can be put off great use to developers and authority on the floodplain management (Ackerman, 2005).

## **2.8. HEC-RAS, HEC-GeoRAS and GIS integration**

To facilitate the creation of geometric files for use by and the viewing of output from HEC-RAS the software package HEC-GeoRAS was created to manage the passage of geographic information between the GIS environment and HEC-RAS. HEC-GeoRAS facilitates the

development of geographic features to be stored in GIS layers. Users edit the layers by digitizing or loading pre-existing data into these layers in preparation to developing a geometric file for use by HEC-RAS. The basic data HEC-GeoRAS utilizes in developing geometry files include a DTM, in the form of a GRID or TIN, and geographic features located in GIS layers. HEC-GeoRAS handles these layers and by utilizing the digital terrain model creates an input file, which HEC-RAS accepts as an input for the creation of a geometry file. Upon completion of hydraulic computations HEC-RAS allows for the export of water surface profile data into an output file. With the output file HEC-GeoRAS creates new GIS layers representing water surface extents, velocity grids, and depth grids which can be viewed and analyzed within GIS (USACE, 2010).

Brunner (2010a) indicates that the descriptions of HEC-RAS, HEC-GeoRAS and Arc-GIS as a whole indicated in figure 2.1 constitutes therefore a coherent computation tool that allows primarily to prepare the geometric data (preprocessing) then, to make the necessary calculations (simulation) and finally, to exploit the results (post-processing).

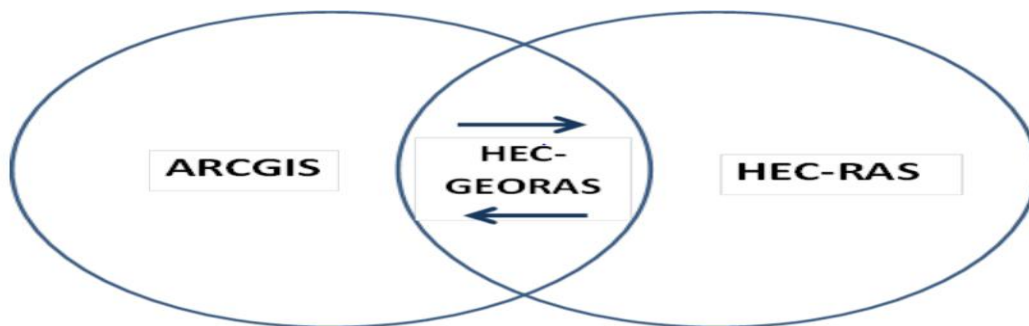


Figure 2.1: Schematic representation of HEC-RAS, HEC-GeoRAS and GIS environment

### 3 MATERIALS AND METHODS

#### 3.1. Description of the Study area

##### 3.1.1. Location

Harosha River catchment indicating in figure 3.1 is located in the distance of approximately 570 km north direction of the capital city of Ethiopia, Addis Ababa, as well as 190 km from the regional capital Mekelle. The Harosha River is bounded by the Waja and Tumuga catchment in the south and Harosha, Limeat and Harle catchment in the North and also it is the upper south part of the Raya valley catchment. Harosha River catchment is also located between coordinate 541563 m and 563043 m Easting, and 1357632 m and 1368729 m Northing in UTM 37-WGS84 Projected coordinates system.

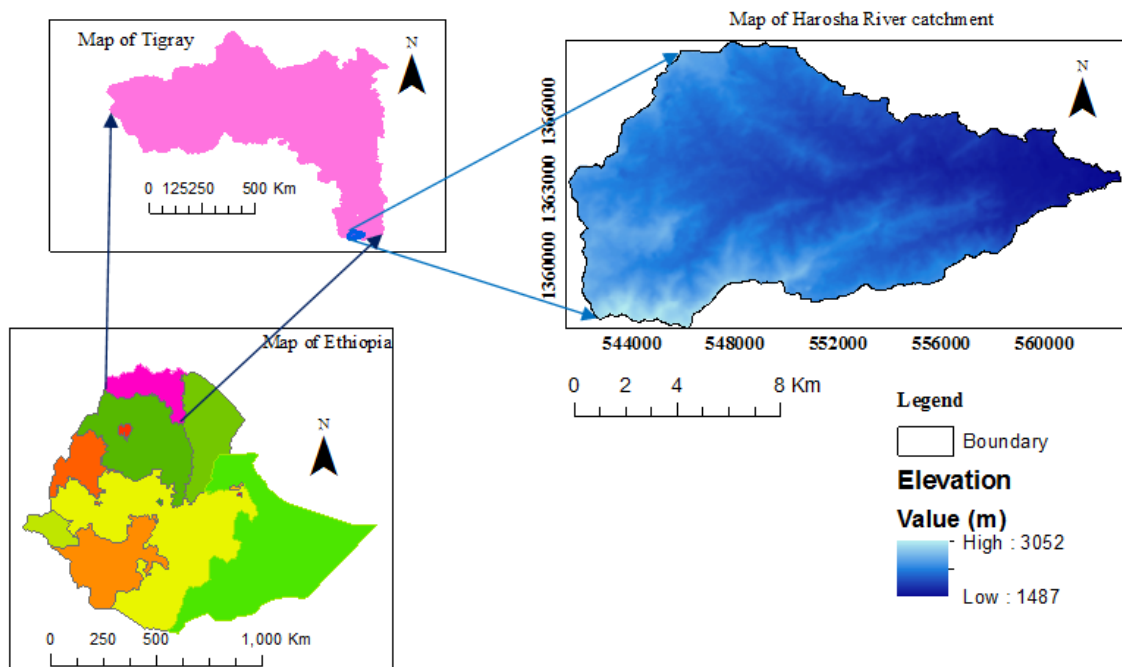


Figure 3.1: Location Map of the Harosha River Catchment

##### 3.1.2. Climate

In Ethiopia, the climate is varies with regard to its high extent of altitude and topographical features. The amount of rain fall increases with rise in altitude (WRB – FAO, 1998). The same is true for this study area. The main rainy season, starts from June and ends in mid of October.

According to the moisture index criteria, provided by REST (1996), the Raya Valley area is classified as dry climates of semi-arid and arid environment; and Harosha river catchment area is parts of in the Raya Valley which is the same climate environment.

Average weather data estimated for Harosha river catchment such as annual maximum, minimum and average/ or mean rainfall and temperature are 930 mm and 29<sup>o</sup>c; 347 mm and 13<sup>o</sup>c and 692 mm and 19<sup>o</sup>c respectively.

### 3.2. Data Sources and availability

The sources of data used for the study was collected from different sectors as shown in the table 3.1 below. DEM 30m resolution were used for the extraction of catchment boundary, elevation, slope, drainage lines or streams and soil map; land use land cover image, and soil data of the study area were used for determination of CN. In general, the primary data derived were outlet location, land use/cover, drainage line and topography, the areas affected by floods and slope measurement using clinometers in the field visit. Whilst secondary data, used were rainfall, DEM, soil class and LU/LC data.

Table 3.1: Data collected types and sources

Data type	Source
Weather	National Meteorological Agency
DEM 30 m x 30 m resolution	National Mapping Agency
LU/LC 30 m x 30 m resolution updated in the year of 2016	Google Earth and USGS land satellite with combination of practical field observation
Soil	FAO soil classification, Mekelle University, and TBWR

### 3.3. Materials and models used

Generally, to process the overall required parameters, the following materials and GIS packages were used:

- ARCMAP 10.1 was used for GIS Analysis;

- Arc-Hydro module ArcGIS 10.1 extension was used for catchment delineation and drainage extraction; used for creating, managing and generation of different layer and maps;
- Land satellite image or map of the study area from <http://www.USGS.gov> which is the united state geological survey with combination of Google Earth and USGS land satellite with practical field observation and GIS was used for generation of Land use / land cover map in GIS;
- HEC-RAS 4.1 was used for flood inundation mapping;
- HEC-GeoRAS 10.1 was used for integration of GIS and HEC-RAS;
- GPS for taking geographic-coordinate values in (altitude, latitude and longitude);
- Digital camera for field photographs during the study; and
- Clinometer is used for verifying the slope generated from DEM.

### **3.4. Data Collection and Analysis**

#### **3.4.1. Topography**

The Harosha river catchment indicated in figure 3.2 is divided into three major zones: low land areas with an altitude less than 1660.8 m.a.s.l which mostly covers large part of the lower to central part of the catchment; middle land areas with an altitude of ranging from 1660.8 to 2008 m.a.s.l which mostly covers the central part of the catchment; and the high land areas having altitude above 2008 m.a.s.l which covers the from southern to northern and from western to middle eastern edges of the study area. In addition in this study area the minimum altitude is 1487 m.a.s.l which is the outlet of the catchment and a maximum altitude of 3052 m.a.s.l as shown in the figure 3.2 below.

The Harosha river catchment topography is highly exposed to soil erosion by high flood due to very steep land features. It is characterized by undulating terrain and steep slopes, erratic rainfall and sparse vegetation coverage which in turn facilitate soil erosion by flood.

According to FAO (2006) guideline for soil description, the general shape of slope in both horizontal and vertical directions of this catchment ranged from 0 up to > 60 % which is from flat area to very steep slope. The slope of the study area is ranging from 0 to 66 % and based

on the FAO classification the catchment is more dominated by moderately sloping to very steep slope as shown in figure 3.3 below.

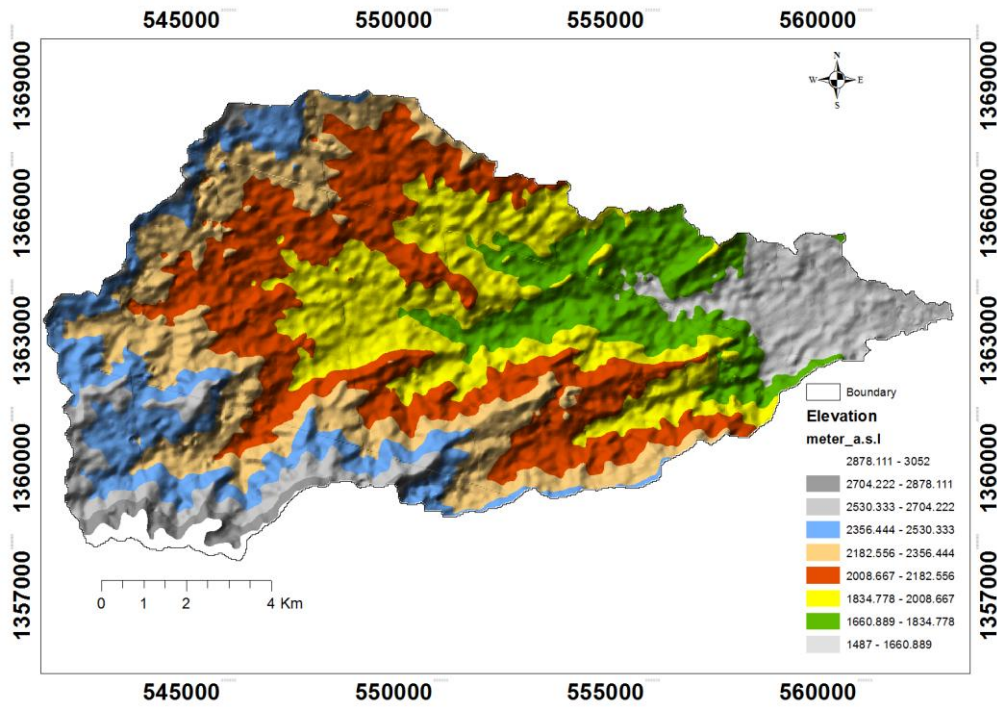


Figure 3.2: Topographic/Elevation map of the study area in m.a.s.l

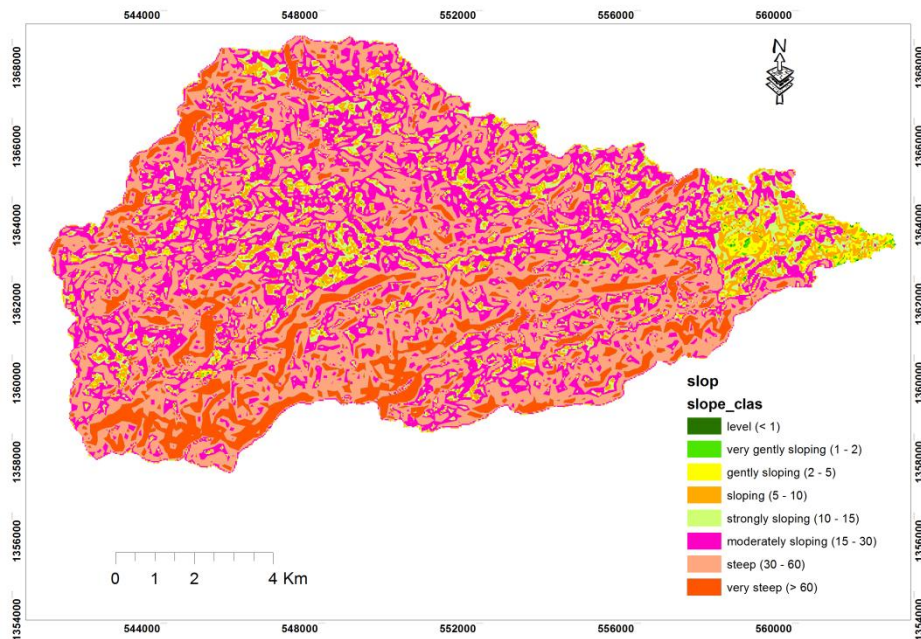


Figure 3.3: Slope map of the study area (%)

Table 3.2: Slope range and area coverage of the study area

S.No	Description	Area coverage (km <sup>2</sup> )
1	Level	0.156
2	Very gently slopping	0.570
3	Gently slopping	3.713
4	Slopping	10.119
5	Strongly slopping	12.284
6	Moderately slopping	43.383
7	Steep slopping	51.417
8	Very steep slopping	15.870

According to FAO (2006) guideline for slope description as shown in table 3.3 and as the above figure 3.3 indicated that the topography of the catchment is from very steep in the upper (comparatively very red color) to the flat in the lower part (yellow to green color) which the river has carved through the surrounding plateau. The river is located in an undulating terrains, begins from the upper Catchment Mountain to the lower part of the villages and agricultural lands. In addition to the map indicates us the upper catchment is very Steep Mountain which is high flood intensity; whereas the lower catchment is very flat area and comparatively almost similar slope which is exposed to soil erosion and degradation due to high intensity of flooding.

### 3.4.2. Drainage Networks

The study area is consists of separate drainage units emerging from the western highlands to eastern lowlands of the catchment, which have a sub-parallel flow path in east-west directions. The southern, western and northern margin of the catchment is a source of the rivers in the study area and the south west of the study area is the most source of the main river line or stream line of the catchment. Most of the streams that originate in the catchment highlands flow west-easterly are following the dip direction at the middle of the catchment and join the major river system of the Harosha River as shown in figure 3.4.

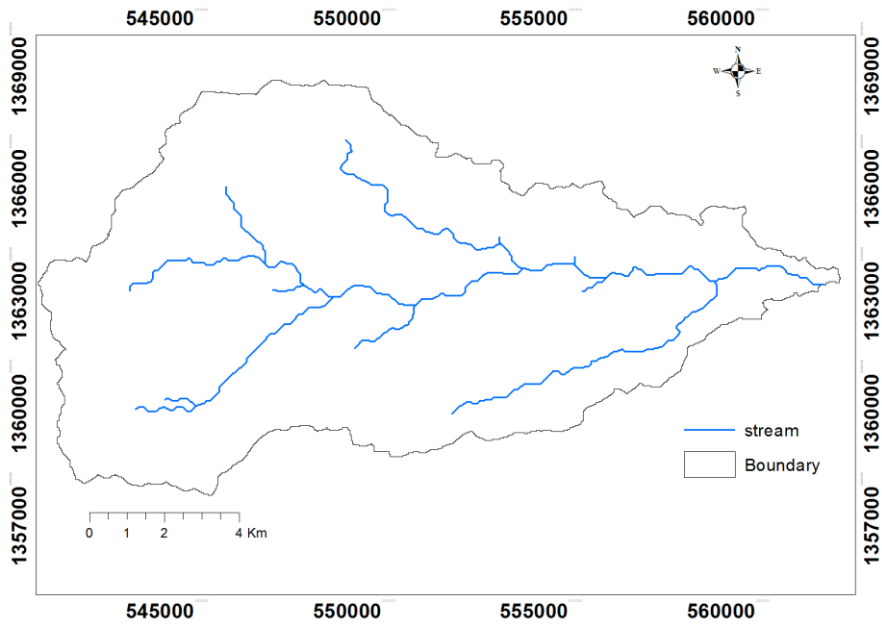


Figure 3.4: Map of Catchment Boundary and Drainage Network of the study area

### 3.4.3. Soil Type

As indicated in figure 3.5 and table 3.3 below the soil of the study area classified as FAO soil classification is classified in to three, namely chromic vertisols (Vc), Lithosols (I) and Eutric Cambisols (Be). The most widely covered soil of the study area is Lithosols (76.6%) followed by Eutric Cambisols (20.8%) and the less dominant soil type of the study area is Chromic vertisols (2.7%) which is the downstream around at the outlet of the study area.

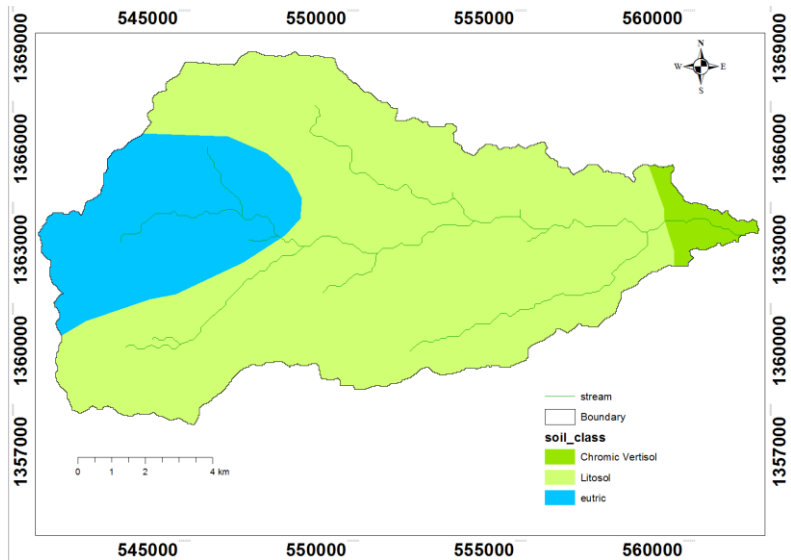


Figure 3.5: Soil Map and Drainage Network of the study area

Table 3.3: Soil Type and Coverage of the study area

Symbol	Soil Type	Area Coverage (Km <sup>2</sup> )	Percentage (%)
Vc	Chromic vertisols	3.6	2.7
Be	Eutric Cambisols	28.6	20.8
I	Lithosols	105.3	76.6

### 3.4.4. Land use and cover

Land use and land cover is one of the most important factors that affect runoff in a watershed (ERADDM, 2002). Using GIS and Google Earth the reclassifications of the land use were done to represent the land use according to the specific land cover types. In addition the map indicated in figure 3.6 below is the LU/LC of the study area updated in the year of 2016.

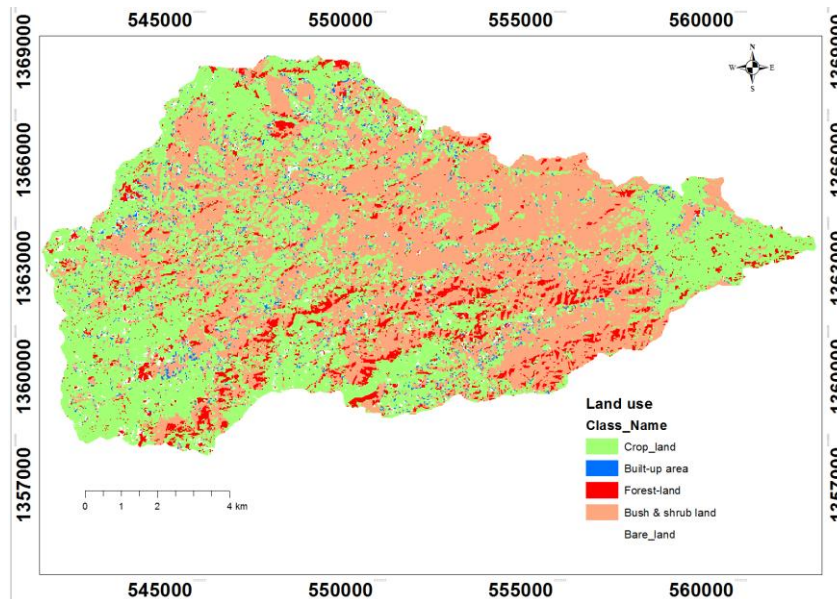


Figure 3.6: Land use/land cover of study area

There are five LU/LC types recognized from the land use map of Harosha river catchment or watershed as indicating figure 3.6 above.

The crop land which is used for agriculture purpose and Bushes and shrubs which are the most dominant land use types while in smaller coverage land use such as forest, Built-up area and bare lands are found.

### **3.4.5. Data Input Preparation for HEC-RAS**

#### **Pre field work**

This stage included collection of necessary information about the area, collecting available secondary data from different sources, preparing base map and preparation for field work including acquisition of field equipments. Among the activities are reviewing the Raya valley feasibility study to have good understanding about the problem and to define the approach to the research and flood peak discharge estimation using SCS method for generating flood inundation and flood hazard mapping.

#### **Field work and Post field work**

A field trip was made to collect primary data from the study area and secondary data from different sources. The primary data collection included, taking readings of outlet location and elevation of the study area using GPS, collection of soil samples based on soil type and land cover of the study area for runoff curve number analysis and different part of the study area damaged by flood for flood inundation mapping and to see the effect of flood hazard on different land use. The ground truth field observations were focused on the description of the location, topography, main drainage networks, land use and location of damaged land uses areas by flood.

Data processing was the main activity of this stage. The data collected during pre-fieldwork and during fieldwork were processed and analyzed. The main activities here are organizing the collected data, preparing the database for the recharge calculation, and peak flood estimation for different return periods and flood inundation and flood mapping using SCS method and HEC-RAS software.

### **3.4.6. Rainfall Data**

The rainfall data from two rain gauge stations as indicated in table 3.5 which have been considered to describe the rainfall regime using thiesen polygon areal ratio were collected and analysed. The available data for twenty five years (1992 to 2016) have relatively consistent data, by using adequacy completeness and homogeneity methods; that can be used for the purpose of this study are listed in table 4.1. In this case the annual daily maximum rainfall data

was taken for analyses. Since there is no stream flow data the peak flood was estimated from the recorded rainfall data using SCS rainfall – runoff model.

Data was analyzed for Adequacy Completeness and Homogeneity by:

1. Extracting the daily annual extreme series.
2. Identifying and estimating the missed year's data.
3. Testing the consistency of record and finally reconstructing the data for any gaps and inconsistency of records.

A criterion for extraction of daily annual maximum series was:

- At least 50% of the month's data present.
- if more than 15 days were missing and the maximum for the month was less than 30% of average I consider it as missing.
- 10 days of the month were missing and the maximum precipitation for that month was 0.00 is consider it as missing.

The years of 2013 and 2016 for Alamata Station and the years of 1992 and 1993 for Waja station are missed data and it was calculated using normal ratio method as indicated in equation 3.1, this is due to the annual maximum rainfall at each of the index station is outside 10% of that for the stations with a missing record; and also the daily maximum rainfall (P) was calculated using equation 3.2 [(ERADDM, 2002) and (FDREMWR, 2002)].

$$P_A = \frac{1}{n} \left[ \frac{N_A}{N_B} P_B + \frac{N_A}{N_C} P_C + \dots + \frac{N_A}{N_N} P_N \right] \dots\dots\dots (3.1)$$

Where;  $P_A = P_{max}$  = an estimated value for missing record at station A;

n = number of stations;

$P_B, P_C, \dots P_N$  = rainfall records at index stations at a time of missing records,

$N_A, N_B, N_C,$  and  $N_N$  = Normal annual maximum rainfall values at stations A, B, C, ...N.

To use the stations climatic data to the watershed area coverage ratio modeling process a Thiessen polygon method was developed and used accordingly. This method was used in the ArcGIS to determine how much part of the watershed is covered by each of the meteorological

stations as shown in figure 3.8. Thiessen polygon method was applied to estimate the mean annual rainfall for the entire watershed. In the Thiessen polygon method, the study area is divided into two polygons with the rain gauge in the middle of each polygon assumed to be representative for the rainfall on the area of land included in its polygon. These polygons are made by drawing lines between gauges, and then making perpendicular bisectors of those lines form the polygons (ERADDM, 2002). The weighted mean of the precipitation was calculated using equation 3.2 which resulted in 72.44 mm/day of mean annual daily maximum rainfall for the entire Harosha river catchment.

$$P = \frac{A_1P_1 + A_2P_2 + A_3P_3 + \dots + A_iP_i \dots A_nP_n}{A_t} \dots\dots\dots (3.2)$$

Where: P = Mean annual maximum rainfall on the entire catchment whose area is A<sub>t</sub> [mm],

A<sub>1</sub>, A<sub>2</sub>, A<sub>3</sub>, ... A<sub>n</sub> = Area of enclosed polygons [km<sup>2</sup>]

P<sub>1</sub>, P<sub>2m</sub> P<sub>3m</sub>, ... P<sub>nm</sub> = daily annual maximum rainfall of each stations [mm]

A<sub>t</sub> = Total area of the catchment [km<sup>2</sup>]

The geographical coordinates of each meteorological stations and the delineated watershed boundary through use of the application of Thiessen polygon in ArcGIS (table 3.4) helps to capture the grids for annual maximum daily precipitation for use for ungauging stream flow using SCS method for peak flood estimation.

Table 3.4: Location of Metrological stations for thiesen polygon application

Station Name	Northing (m) UTM-WGS84	Easting (m) UTM-WGS84	Altitude (m)
Alamata	560502	1372456	1547
Waja	565315	1357995	1446
Korem	556673	1382295	2466
Kobo	568641	1343604	1524
Muja	531341	1326927	2749

(Source: Ethiopian Meteorological Agency)

As indicated in figure 3.7 the locations of Korem, Kobo and Muja Metrological stations are do not share boundary with study area but they are used for preparation of thiesen polygon given for better representation .

Areal Ratio Preparation of Metrological Stations for Harosha River Catchment Using Thiesen Polygon Method

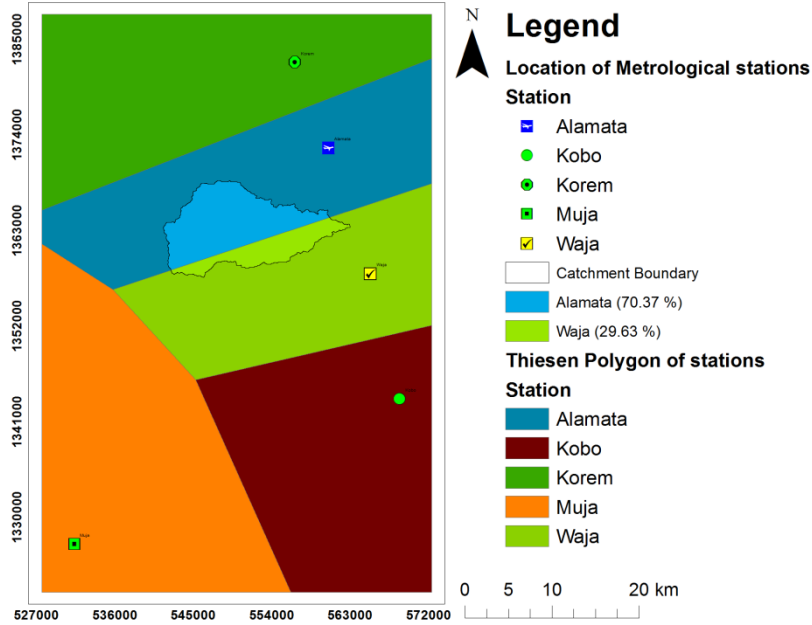


Figure 3.7: Spatial distribution of rainfall stations for generating thiesen polygon map

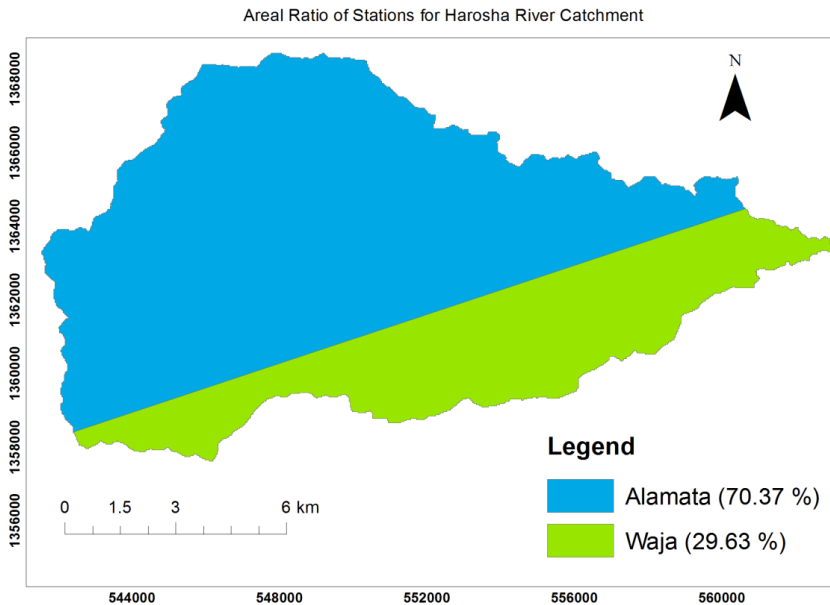


Figure 3.8: Available Spatial distribution of rainfall stations from thiesen polygon map representing study area.

As indicated in figure of 3.7 and 3.8 the stations Alamata and Waja are found in the lowlands of Raya valley and comparatively, Alamata station is located at higher land than Waja station.

The Thiessen polygon generated grid clearly identifies areal weight of each meteorological station, and accordingly, the percentage of areal coverage of Alamata is 70.4% and Waja is 29.6%. Alamata has covered more than half of the watershed area whereas Waja has covered only one third part of the watershed area (Table 3.5).

Table 3.5: Metrological stations based area coverage of the study area

S.No	Shape type	Station name	Area (km <sup>2</sup> )	Area Coverage
1	Polygon	Alamata	96.78	70.37%
2	Polygon	Waja	40.74	29.63%

**3.4.7. Data adequacy, Goodness of fit and consistency checking**

As per ERADDM (2002) and FDREMWR (2002) the following different equations for the purpose of testing the consistency of record and finally reconstructing the data for any gaps and inconsistency of records are used:

**A) Data adequacy**

The adequacy of rainfall data in research will be made by using outlier which is given as “higher outlier” and “lower outlier” and can be expressed by the following formulas.

$$\text{Higher outlier} = \hat{Y} + Kn\sigma \dots\dots\dots (3.3)$$

$$\text{Lower outlier} = \hat{Y} - Kn\sigma \dots\dots\dots (34)$$

$$\text{Standard error} = \frac{\sigma^2}{\sqrt{N*100}} \dots\dots\dots (3.5)$$

Where; n = total number of rainfall data,  $\hat{Y}$  = mean rain fall of the given data,  $\sigma$  = standard deviation of the given data, and  $\sigma^2$  = variance of the given data. In addition to this test for adequacy will be made and if the standard error is < 10%, the data is adequate but if it precedes 10% the data could not be adequate.

**B) Goodness of fit**

The goodness of fit can be checked by after the frequency distribution analysis is done using the methods described in the topic of flood frequency distribution analysis and observed which

distribution fits the given data. After observing and choosing which method can fit the data given, we can conclude that that distribution analysis fits the data and the goodness of fit is good and better as that frequency distribution analysis method.

**C) Data consistency**

The consistency (K) is given by the following equation:

$$K = \frac{\sigma}{\hat{Y}_m * N^{0.5}} \dots\dots\dots (3.6)$$

Where: N = total number of rainfall data,  $\sigma$  = standard variation of the given data, and  $\hat{Y}_m$  = mean rain fall of the given data.

**3.4.8. Methods of Flood Frequency Analysis**

As per Chow et al. (1988), ERADDM (2002) and FDREMWR (2002) the following different equations for different flood frequency analysis methods are used for determination of peak flood.

When there is stream flow data arranged in the descending order of magnitude, they constitute statically array whose distribution can be expected in terms of frequency of occurrence. The probability ‘p’ of each event being equal to or exceeded (plotting position) formula using Weibull.

$$P = \frac{m}{N + 1} \dots\dots\dots (3.7)$$

Where; m = order number of the events and N = Total number of events in the data.

The recurrence interval (T) return interval is calculated as:

$$T = \frac{1}{P} \dots\dots\dots (3.8)$$

But in our case there is no measured flow data instead it is possible to determine the probability of occurrence of daily maximum rainfall (rain fall frequency analysis).

The general equation for flood frequency analysis is:

$$X_T = \mu + K \times \sigma \dots\dots\dots (3.9)$$

Where;  $X_T$  = Value of variant (X) of random hydrologic series with return period (T),

$\mu$  = Mean value of variant,  $K$  = frequency factor which depends up on the return period (t) and assumed frequency distribution, and  $\sigma$  = standard deviation of variate.

The most frequency-distribution functions in the hydrologic studies can be expressed by the general equation of hydrologic frequency analysis:

$$X_T = X_m + K_T \times \sigma \dots\dots\dots (3.10)$$

Where;  $X_T$  = value of the variation X of a random hydrologic series with a return period T,

$X_m$  = mean of the variate,  $\sigma$  = standard deviation, and  $K_T$  = frequency factor which depends up on the return period T and the assumed frequency distribution.

**A. Normal distribution Method of Analysis:** if the distributions of the rain fall data is normally distributed.

$$K_T = \frac{X_T - X_m}{\sigma} \dots\dots\dots (3.11)$$

Where;  $K_T$  = frequency factor,  $X_T$  = value of the variate  $X_m$  = mean of the variate, and  $\sigma$  = standard deviation of sample data.

**B. Log Normal distribution Method of Analysis:** if the distributions of the rain fall data is log-normal and the following formula can be used for determining the frequency factor ( $K_T$ ).

$$U = w - \frac{c_0 + c_1 w + c_2 w^2}{1 + d_1 w + d_2 w^2 + d_3 w^3} + \varepsilon(p) \dots\dots\dots (3.12)$$

Where;  $C_0 = 2.515517$ ,  $C_1 = 0.802853$ ,  $C_2 = 0.010328$ ,

$d_1 = 1.432788$ ,  $d_2 = 0.189269$ ,  $d_3 = 0.001308$ ,  $\varepsilon(p)$  = error, it is less than  $4.5 \times 10^{-4}$

$$\text{Or, } K_T = Z = W - \left[ \frac{(2.516 + 0.8028W + 0.0103W^2)}{(1 + 1.4328W + 0.1893W^2 + 0.0013W^2)} \right] \dots\dots\dots (3.13)$$

Where; W is intermediate variable calculating from the formula of:

$$W = \left[ \ln \frac{1}{P^2} \right]^{\frac{1}{2}} \text{ Where; } (0 < P < 0.5) \dots \dots \dots (3.14)$$

Where; p is the probability of exceedance. When  $p > 0.5$ ,  $1 - p$  is substituted for p and the value of Z which is computed is given a negative sign.

**C. Log Pearson Type III distribution Method of Analysis:** if of the rain fall data is fitted by this distribution. The frequency factor of this distribution depends on return period T and coefficient of skewness ( $C_s$ ). when  $C_s$  was zero then  $K_T = Z$ , if not  $K_T$  would be approximated by:

$$K_T = Z + (Z^2 - 1)K + \frac{1}{3} (Z^3 - 6Z)K^2 + ZK^4 + \frac{1}{3}K^5 \text{ Where; } K = \frac{C_s}{6} \dots \dots \dots (3.15)$$

**D. Gumbel (EVI) distribution Method of Analysis:** Gumbel distribution is a member of family of Extreme Value distributions with the value of parameter  $k = 0$ . It is a two parameter distribution and is widely used in hydrology. The frequency factor of this distribution is given by:

$$K_T = \frac{Y_T - Y_n}{S_n} \dots \dots \dots (3.16)$$

Where;  $Y_T$  is the reduced variation which is given by:

$$Y_T = -\ln \left[ \ln \left( \frac{T}{T-1} \right) \right] \dots \dots \dots (3.17)$$

**3.4.9. The SCS method of Runoff Estimation**

Runoff was estimated with the aid of hydrological model using USDA (1985) for estimation of surface runoff using SCS-CN model. According to USDA (1985) figure 3.9 below shows the methodology followed to estimate runoff using SCS-CN model to achieve the first objective of the thesis research.

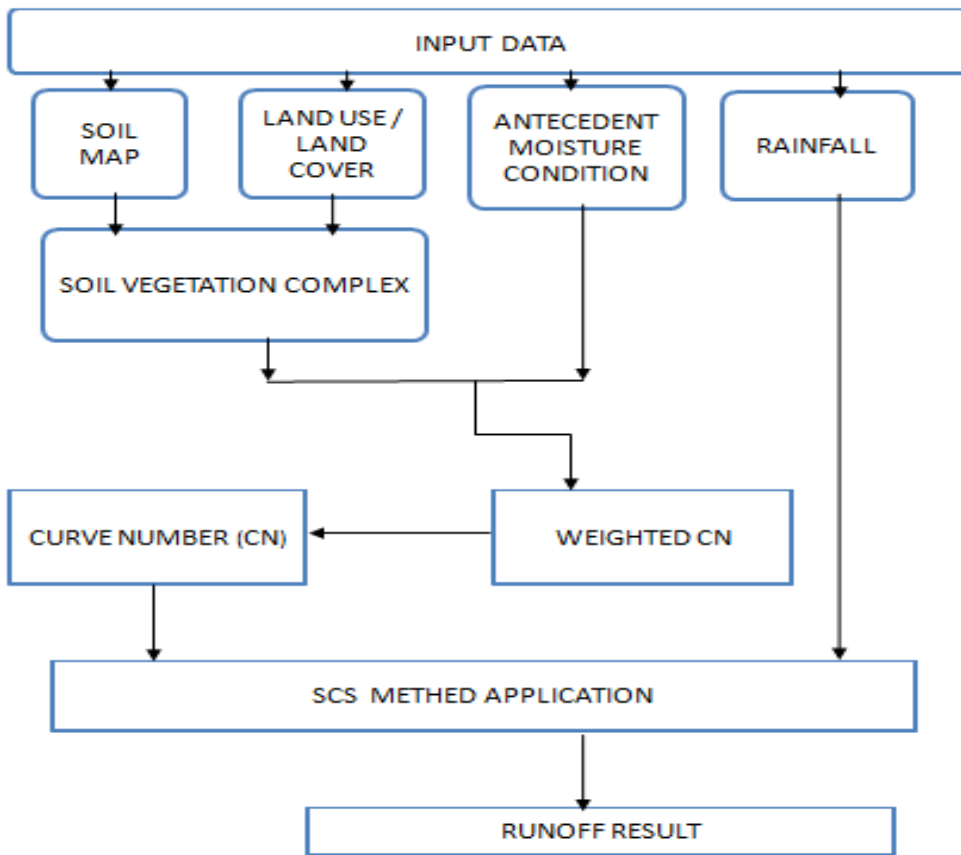


Figure 3.9: methodology to estimate surface runoff by SCS-CN method

**Curve number model**

The CN values documented for the case of AMC-II (USDA, 1985) and to adjust the CN for the cases of AMC-III, the following equations are used:

$$CN(III) = \frac{23 \times CN(II)}{10 + (0.13 \times CN(II))} \dots\dots\dots (3.18)$$

Where, CN (II) is the curve number for normal condition, and CN (III) is the curve number for wet condition.

**Runoff estimation**

Surface runoff is mainly controlled by the amount of rainfall, initial abstraction and moisture retention of the soil. The SCS curve number method is based on the water balance equation and two fundamental hypotheses which are stated as, ratio of the actual direct runoff to the

potential runoff is equal to the ratio of the actual infiltration to the potential infiltration and the amount of initial abstraction is some fraction of the potential infiltration.

$$\frac{Q}{P - I_a} = \frac{F}{S} \dots\dots\dots (3.19)$$

$$F = (P - I_a) - Q \dots\dots\dots (3.20)$$

Substituting equation (3.4) in to equation (3.5) and solving results:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \dots\dots\dots (3.21)$$

Where,  $Q$  is the actual direct runoff (mm),  $P$  is the total rainfall (mm),  $I_a$  is initial abstraction which represents all the losses before the runoff begins and is given by the empirical equations:

$$I_a = 0.2S \dots\dots\dots (3.22)$$

Substituting equation (3.7) in equation (3.6) and it becomes:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}; \text{ For } (P > 0.2S) \dots\dots\dots (3.23)$$

Where,  $S$  is the watershed storage or the potential infiltration after the runoff begins (mm);  $S$  is related to CN and given by the following equation:

$$S = \frac{25400}{CN} - 254 \dots\dots\dots (3.24)$$

Where, CN is a dimensionless parameter and its value range from 1 (minimum runoff) to 100 (maximum runoff). It is determined based on hydrologic soil group, land use, land treatment, and hydrologic conditions depending on the study area criteria.

Land Use / Land Cover of study area has been classified in five classes which are crop land, forest, bushes and shrubs, built-up area and bare land. Area under each class has been calculated from the attribute table and given in Table 4.2. The Land Use/ Land Cover thematic map and soil map are interpreted.

Once the data has been gathered, the typical process for results and discussion of estimating the curve number for the catchment is summarized as follows (ERADDM, 2002):

- a. Define and map the boundaries of the drainage basin for which curve number to be calculated. Determine the area of the catchment or drainage basin.
- b. Map the soil types and land use for the Harosha river catchment of interest;
- c. Converts the soil types to hydrologic soil groups based on their FAO Soil map descriptions;
- d. Overlay the land use and hydrologic soil group maps, identify each unique land use soil group polygon, and determine the area of each polygon;
- e. Overlay the catchment map on the land use soil group polygons;
- f. Assign a curve number to each land use classes, based on standard SCS curve number tables; and finally
- g. Calculate the curve number for drainage basin by area-weighting the land use-soil group polygons within the catchment boundary.

According to FDREMWR (2002) the following equations of 3.25 to 3.31 are recommended to be used in our country for determination of Peak rate of discharge created by 1mm run off depth (excess rain fall).

Weighted CN for each sub area is worked out using the following equation:

$$\text{Weighted CN (II)} = \frac{\sum (CN_i \times A_i)}{A_t} \dots\dots\dots (3.25)$$

Where,  $CN_i$  = Curve number for watershed uniform land use and soil types,  $A_i$  = sub area with curve number  $CN_i$ , and  $A_t$  = Total area of the catchment.

$$\text{Slope of the main water course: } S = \frac{H_1 - H_2}{L} \dots\dots\dots (3.26)$$

Where;  $H_1$  = maximum elevation of the catchment (topographic map), m

$H_2$  = lower elevation of the catchment (topographic map), m

$L$  = length of water course (the longest flow path of the stream), m

$$\text{Time to concentration: } T_c = \frac{1}{3000} \left[ \frac{L}{S^{0.5}} \right]^{0.77} \dots\dots\dots (3.27)$$

Where;  $T_c$  = time to concentration (hr) and  $S$  = slope of the main water course (m/m)

Rainfall excess duration is given as:

$$D = 1 \text{ hr if } T_c > 3 \text{ hrs; } D = \frac{T_c}{6} \text{ if } T_c < 3 \text{ hrs} \dots\dots\dots (3.28)$$

Where, D = rainfall excess duration (hr) and T<sub>c</sub> = time to concentration (hr)

Time to peak is given as:

$$T_p = 0.5D + 0.6T_c \dots\dots\dots (3.29)$$

Where; T<sub>p</sub> = time to peak (hr), D = rainfall excess duration (hr)

T<sub>c</sub> = time to concentration (hr)

$$\text{Time to base of hydrograph is given as: } T_b = 2.67 \times T_p \dots\dots\dots (3.30)$$

Where; T<sub>p</sub> = time to peak (hr), T<sub>b</sub> = time to base of hydrograph (hr).

Peak rate of discharge created by 1mm run off depth on whole of the catchment (excess rain fall) (q<sub>p</sub>) is given as follows:

$$q_p = \frac{0.208 \times A}{T_p} \dots\dots\dots (3.31)$$

Where: q<sub>p</sub> = is peak rate of discharge (m<sup>3</sup>/s), A = area of catchment (km<sup>2</sup>), and

T<sub>p</sub> = time to peak (hr)

### **Hydrologic Soil Group Classification**

According to the ERADDM (2002) HSG for Ethiopia, as indicated in table 3.6 below the two HSG types of the study area are hydrologic soil groups of B and D. HSG - B are soils which have soils primarily consist moderate infiltration rates when thoroughly wetted and these soils have a moderate rate of water transmission. They are Silt loam, or loam, due to moderately infiltration rates Soils having a moderately low runoff potential. HSG - D are soils have a high runoff potential (very slow infiltration rates) when thoroughly wetted. These soils consist chiefly of clay soils with high swelling potential. These soils have a very slow rate of water transmission which are clay loam, silt clay loam, sandy clay, silt clay or clay; Soils having a high runoff potential due to very slow infiltration rates (ERADDM, 2002).

Table 3.6: Types of Hydrologic Soil Group for Harosha River Catchment

Symbol	Soil Type	Hydrologic soil group	Area Coverage (Km <sup>2</sup> )	Area Ratio (%)
Vc	Chromic vertisols	D	3.653	2.656
Be	Eutric Cambisols	B	28.558	20.766
I	Lithosols	D	105.313	76.578

### 3.5. General HEC-GeoRAS and HEC-RAS Model Description

The HEC-GeoRAS or HEC-RAS has been developed by USACE Hydrologic Engineering Center and it is a free downloadable with other supportive documents about how to use the model for flooded area mapping. The HEC-GeoRAS is a GIS extension with a set of procedures, tools and utilities for the preparation of river geometry GIS data to import into HECRAS and it is used to generate the final inundation map. The input data required for the River geometry preparation using the HEC-GeoRAS model are TIN, DEM, and land use. The river geometry file and stream flow data are the input files for HEC-RAS to generate the water surface level along the River (USACE, 2002).

HEC-GeoRAS is a data management interface between ArcGIS and HEC-RAS. This tool provides or creates the river geometric file to be analyzed in HEC-RAS model. The river stream centerline, bank lines, flow path centerlines, and XS cut lines should be digitized from a previous river file, aerial photographs, or topographical data sets using HEC-GeoRAS interface. The river reach (river segment between junctions), cross-section and other related data like flowpaths and banks are stored in the geo data base file of HEC-GeoRAS. The river and cross-section data layers are created with predefined attribute tables that are manually populated in the case of the river and reach names, while all other attributes such as flood inundation are automatically calculated by the HEC-GeoRAS (Botes ZA and Smith, 2010).

It is possible to edit the exported GIS geometric data in the HEC-RAS model using the HEC-RAS editor tools. The HEC-RAS consists of a number of editors tools to deal with different functions in the modeling process. For this study only the geometric, steady flow data, cross-section, and steady flow simulation editors are used. The .xml file exported from the HEC-

GeoRAS is imported into the Geometric Editor, which is a Graphical User Interface (GUI) that is used to manage the geographic data. In this editor, the Manning friction values of left and right overbanks and channel were entered for the cross sections in each reach. The stream flow data is entered into the steady flow data editor. This editor extracts the river and data for the reaches from the geometric editor. To compute the water surface level, the model needs to know the starting water level at the start and end of reaches that are not connected and at junctions to other reaches (boundary conditions). For a steady flow analysis, four types of boundary conditions are available, namely known water surface level, critical depth, normal depth, and rating curve [(Brunner, 2013) and (Botes and Smith, 2010)].

### **3.6. Hydrological and hydraulic Model application for flood mapping**

Flood mapping models using GIS for hydrologic/hydraulic modeling usually involves three steps: 1) preprocessing of data, 2) model execution, and 3) post-processing/visualization of results. Pre RAS, post RAS and GeoRAS menus of HEC-GeoRAS extension in ArcGIS were used for creating required data sets, making import file for model simulation in HEC-RAS.

**Pre GeoRAS application:** The pre RAS menu option was used for creating required data sets for creating import file to HEC-RAS such as Stream centerline, main channel banks (left and right), flow paths, and cross sections were created. Also 3D layer of stream centerline and cross section were also created for RAS GIS import file.

**HEC RAS application:** This is the major part of the model where simulation is done. The import files created by HEC-GeoRAS will import in Geometric Data Editor interface within HEC-RAS. All the required modification and editing were done at this stage. The flood discharge for different return periods were entered as steady flow data. Reach boundary conditions were also entered in this window. Then, the water surface profiles were calculated in steady flow analysis window. After finishing the simulation the RAS GIS export file were created.

### **3.7. Flood Inundation and Flood Hazard data analysis**

According to USACE (2002), the general method adopted for hydraulic modeling and flood hazard and flood inundation basically consists of different steps as indicated in the figure 3.10.

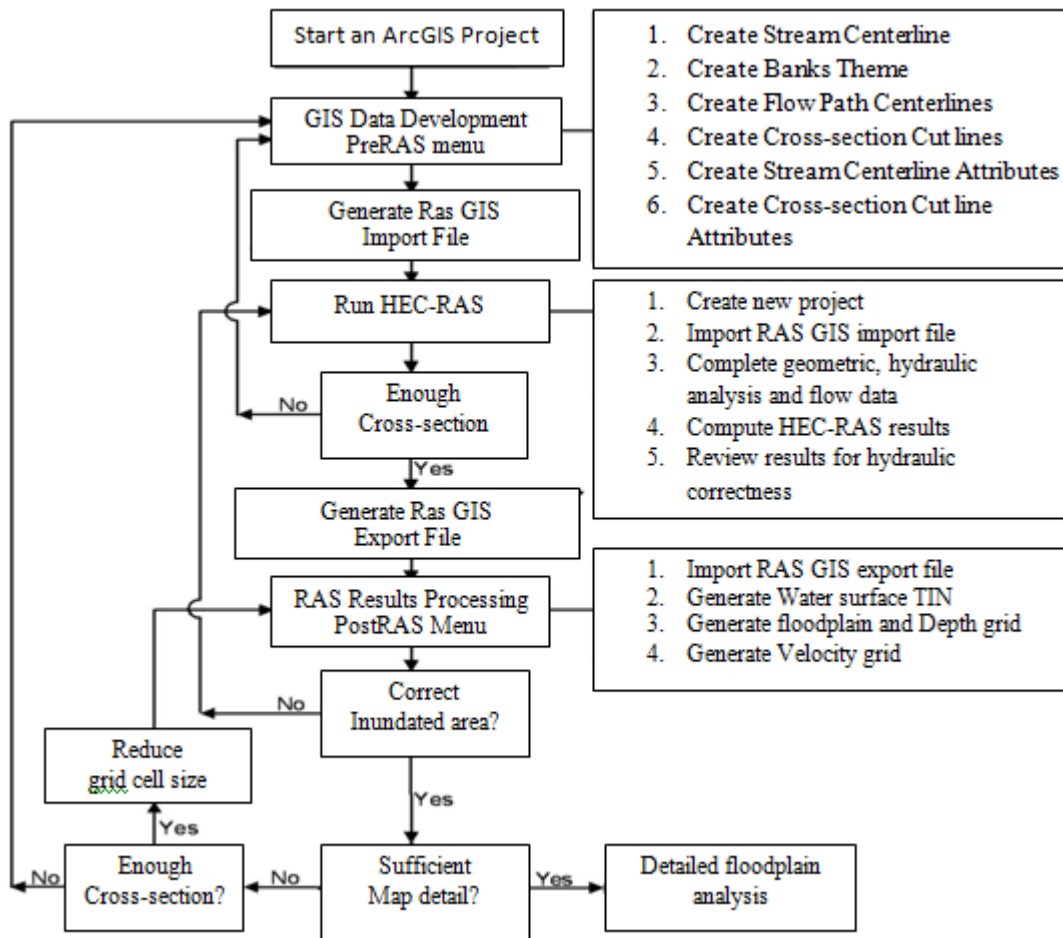


Figure 3.10: The scheme showing data assimilation for flooding mapping

### 3.7.1. Pre-processing of Geometric Data

#### A) Generating DTM from DEM

The beginning step in the pre-processing stage was to create a Digital Terrain Model (DTM) of the river system in a TIN format. The TIN must be constructed with a special care in order to provide for accurate analyses. Elevation data for each cross section is extracted from the TIN. The objective of this part is to form the spatial data required to generate a HEC-RAS import file with a 3-D stream network and 3-D cross sections defined. Watershed and stream delineation developed in this step is preliminary and they are used for stream delineation (USACE, 2002).

## B) Creating RAS Layers

According to USACE (2002) this is the main objective of the pre-processing HEC-GeoRAS for creating physical attributes in Arc-GIS and then exporting them to the HEC-RAS geometry file. The geometry file for HEC-RAS contains information on cross-sections, hydraulic structures, river banks and other physical attributes of river channels.

In HEC-GeoRAS, each attribute is stored in a separate feature class called as RAS Layer. The RAS layers were created in one step and stored collectively in a Geo-Database. By default, this Geo Database is saved under the same name and at the same location as the ArcMap project. The RAS layers are created by selecting from the HEC-GeoRAS toolbar and individual RAS layer created (digitized) after the creation and digitizing layers was done for the first four parts as in figure 3.11 which are river, flow paths, banks and XsCutLines. Based on this, the next step to populate the remaining attributes of the river layer.

After creating RAS layers, these are added to the map document with pre-assigned symbols. Since these layers are empty, the task is to populate some of these layers depending on the project needs, and then create a HEC-RAS geometry file.

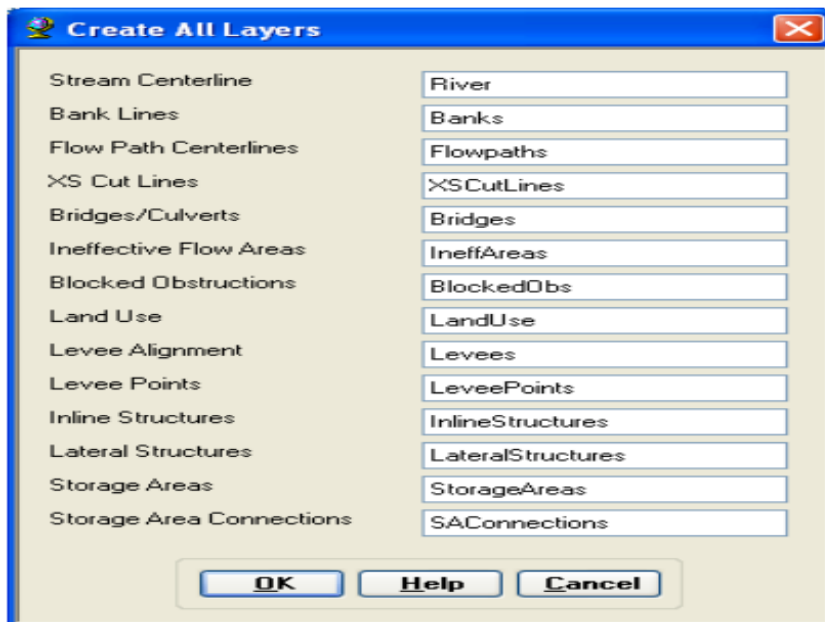


Figure 3.11: Window for Creating Ras layer

### C) HEC-GeoRAS pre-processing to generate HEC-RAS import data file

According to USACE (2002) HEC-GeoRAS is an extension specifically designed to process geospatial data for use with the HEC-RAS. This extension allows us to create an HEC-RAS import file containing geometric attribute data from an existing DTM and complementary data sets, and also to process results exported from HEC-RAS. It creates an import file, referred as the RAS GIS Import File, containing river, flow paths, banks and XsCutLines. Prior to performing hydraulic computations in HEC-RAS, the geometric data must be imported and completed and flow data must be entered. Once the hydraulic computations are performed, exported results from HEC-RAS can be imported back to the GIS using HEC-GeoRAS for spatial analysis.

### D) Exporting GIS Data to HEC-RAS

The last step is to create a GIS import file for HEC-RAS so that it could export the GIS data to create the geometry file. First, it is necessary to define which layers would be exported to HEC-RAS. The Required Layers option is used for entering the River Layer, XSCutLines Layer and XSCutLines 3D Layer. The Optional Layers option is used for entering other RAS layers. Figure 3.12 below shows a typical RAS Layers definition at Optional Layers tab. Export of GIS Data is performed in this way.

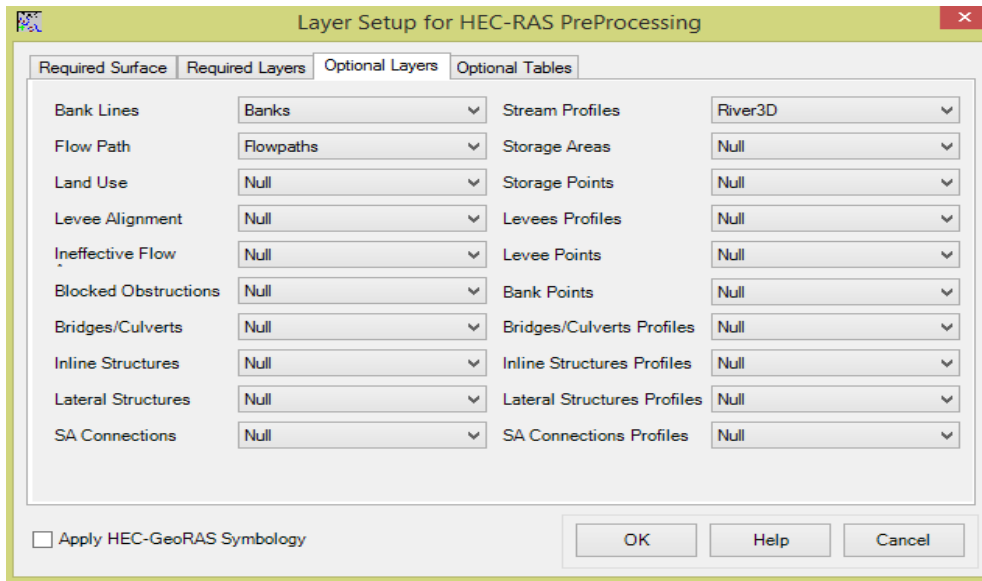


Figure 3.12: Optional layer setup Definition window

### E) Creating Cross-sections in the Imported Geometric data:

Cross-sections are one of the key inputs to HEC-RAS. Cross-section Cutlines are used to extract the elevation data from the terrain to create a ground profile across channel flow as indicated in figure 3.13 below. The intersection of Cutlines with other RAS layers such as centerline and flow path lines are used to compute HEC-RAS attributes such as bank stations (locations that separate main channel from the floodplain), downstream reach lengths (distance between cross-sections) and Manning's n. Therefore, creating adequate number of cross-sections to produce a good representation of channel bed and floodplain is critical. Certain guidelines must be followed in creating cross-section Cutlines: (1) they are digitized perpendicular to the direction of flow; (2) must span over the entire flood extent to be modeled; and (3) always digitized from left to right (looking downstream) (USACE, 2010).

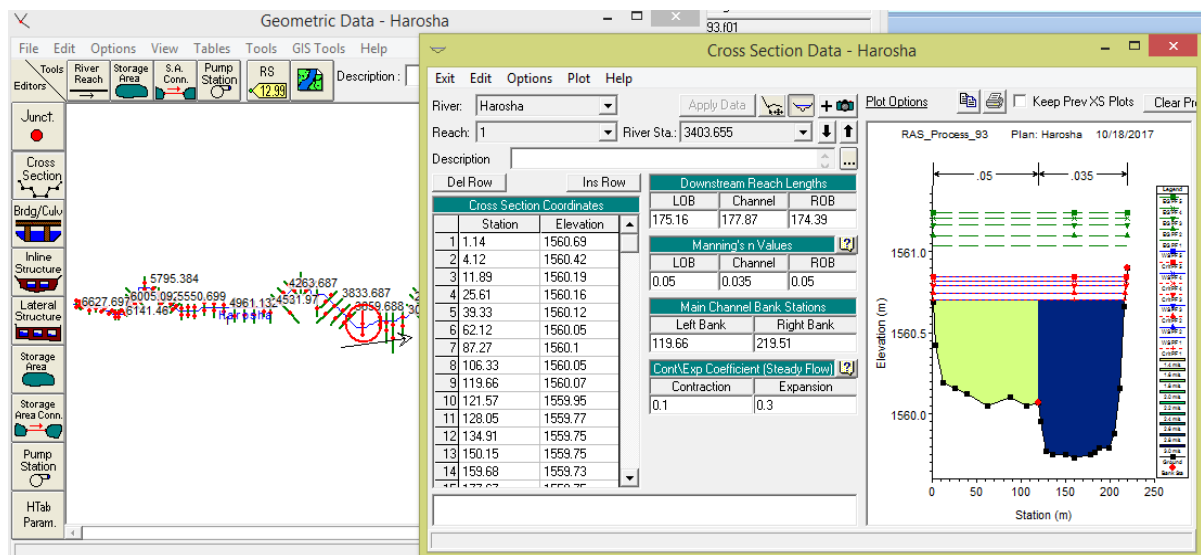


Figure 3.13: Output of River Cross-section window profile

### Manning's Roughness Coefficient for flow data:

Manning's n values were used in the model to define roughness for each cross section. The "n" values were assigned in two steps: The first step involved defining land-use characteristics for common areas throughout the watershed and flood plain. Each land-use characteristic was given n-value based on published values for similar conditions (Chow, 1959) and on engineering judgment and experience. Once the land-use was defined for the entire watershed, the representative n-values were assigned to the portion of each cross section that intersects

the respective land-use area. These n-values were then exported to the HEC-RAS model using HEC-GeoRAS.

For the study area the typical manning's coefficient is determined by using field visit or survey and compared it with the standard “n” values of different land use depending on the ERDDM (2002) shown in table 3 of appendix 1.

### Flow Data to GIS Export

After the geometric data is completed and the steady flow data and new boundary conditions are entered, the HEC-RAS system is executed for the subcritical flow profile. The output results are checked for hydraulic correctness.

The next or final step involves export of the computation results (water surface elevation) back to GIS. In the GIS export window, all five profile results (for the five flow scenarios) are selected and exported using the default format “RASexport.sdf”. The figure 3.14 below shows the GIS Export window and the selected profiles used for export. Then, now return to ArcMap to create a flood inundation map.

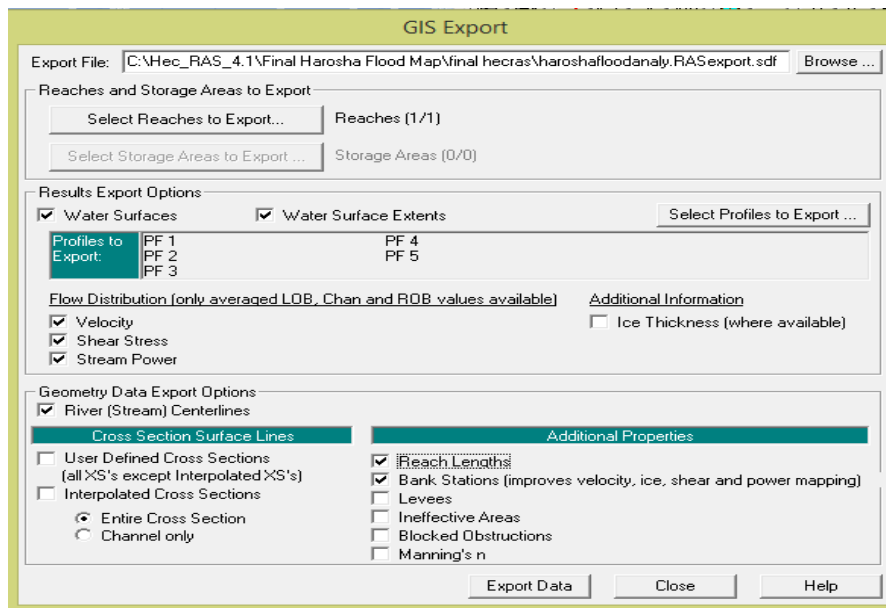


Figure 3.14: GIS export window in HEC-RAS

### 3.7.2. Post processing of HEC-RAS results for floodplain mapping

With the development of a GIS Import File from HEC-RAS, we can begin the last portion of the model application. Post-processing using GeoRAS incorporates the water surface

profiles derived from the HEC-RAS model into the spatial environment of GIS. The water surface profile data is used to develop a water surface TIN, and the intersection of the water surface TIN with the terrain model TIN provides flood visualization (USACE, 2002).

The post-processing of computation results is performed using the same maps which were used for the pre- processing of geometry data. The only additions to these maps are new map layers. Detailed explanation of the data post-processing as follows:

The process starts with opening a desired ArcMap for post-processing. Since the HEC-GeoRAS cannot read the proprietary spatial data format (.RASExport.sdf) file created in the HEC-RAS, It is necessary to convert into the XML file format, supported by HEC-GeoRAS. This is achieved by selecting the “Import RAS SDF File” option from the HEC-Geo RAS Toolbar.

Creating the Layer Setup is a necessary step for processing the HEC-RAS results. In the Layer Setup window, the type of analysis and the input and output data are identified. Now click on RAS Mapping → Layer Setup to open the post processing layer menu as figure3.15 below shows a typical Layer Setup window from the data post-processing.

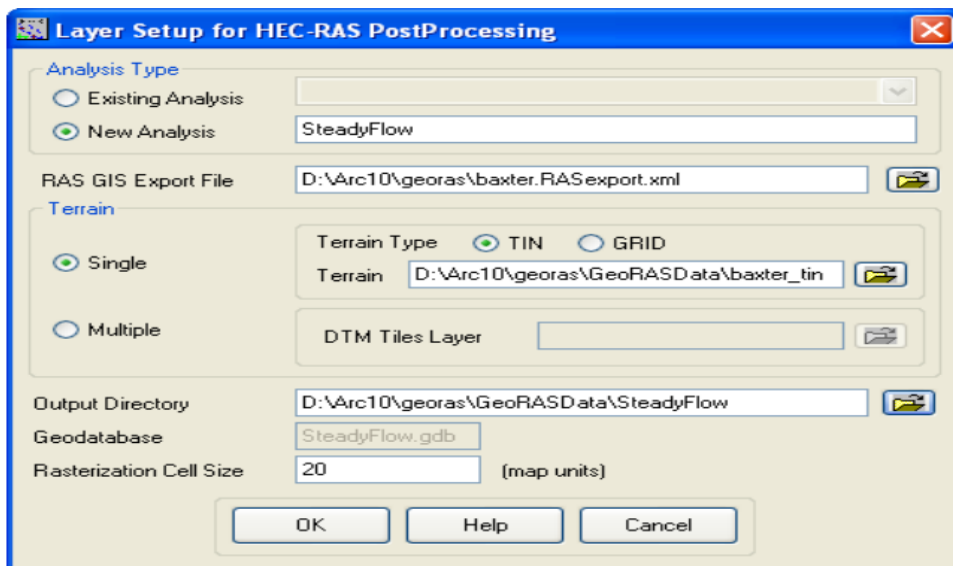


Figure 3.15: Layer setup for HEC-RAS Post processing

### **A) Hydraulic analysis Water Surface Profiles Using HEC-RAS**

The HEC-RAS program, like the HEC-GeoRAS software, it can be downloaded free of charge from the Hydrologic Engineering Center's. The model is used for determination of water surface profiles for different flow scenarios. The peak discharge generated by the SCS method is used to determine the flow profiles and flood plain profiles for the selected return periods. The key data's used in this model are field observation, cross sectional survey works using DEM and the peak flow resulted from simulation of the SCS method.

### **B) Flood Inundation mapping**

Flood hazard maps for the 5, 10, 25, 50, and 100 year floods were generated. Floodplain mapping is performed using the water surface elevations on the XS cut lines, within the limits of the bounding polygon. Flood plain mapping was completed in two steps, which are explained as water surface TIN and flood plain delineation.

#### **Water surface TIN**

The first step is to create a water surface TIN from the cross section water surface elevations. After the analysis extent is defined, we are ready to map the inundation extent. This can create a surface with water surface elevation for the selected profile which is all five flow data.

Water surface profiles are selected from the window. The TIN that is created in this step were defining a zone that was connect the outer points of the bounding polygon, which means the TIN can include area outside the possible inundation. At this point we have a water surface and we have an underlying terrain.

Now we can subtract the terrain from the water surface which is included in the water surface TIN. These areas are removed in the process of delineation with the bounding polygon was created that represents the flooded area.

#### **Flood inundation mapping**

We select Ras mapping in order to do inundation map with select the profiles with highest flow data. The area with positive results (meaning water surface is higher than the terrain) is flood area, and the area with negative results is dry. All the cells in water surface grid that

result in positive values after subtraction are converted to a polygon, which is the final flood inundation polygon (USACE, 2002).

After the inundation map is created, we must check the inundation polygon for its quality. We had to look at the inundation map and the underlying terrain to correct errors in the flood inundation polygon. This is an iterative process requiring several iterations between GIS and HEC-RAS. The ability to judge the quality of terrain and flood inundation polygon comes with the knowledge of the study area and experience.

## 4. RESULTS AND DISCUSSION

### 4.1. Estimation of peak flood

#### 4.1.1. Rainfall Data

The 25 years annual daily maximum rainfalls in mm are tabulated in the table 4.1 and figure 4.1 below from two meteorological stations that are Alamata and Waja. Also missed rainfall was calculated using equation of 3.1, and the actual rainfall of the catchment (P) is determined by equation 3.2.

Table 4.1: Annual maximum daily Rainfall (mm/day)

Year	1992	1993	1994	1995	1996	1997	1998	1999	2000
Alamata	55.4	39	50	46	62	58.5	66.2	44.5	64.7
Waja	44.8	32.01	44.5	71.1	37.5	42	66.6	31.6	30.3
P	52.25	36.93	48.37	53.44	5474	53.61	66.32	40.68	54.51
Year	2001	2002	2003	2004	2005	2006	2007	2008	2009
Alamata	53.1	55.2	48	58	37.3	62	33.3	27.7	47.8
Waja	23.9	27.5	50.2	42.5	43.1	36.8	45.7	29.2	43.2
P	44.45	46.99	48.65	53.41	39.02	54.53	36.97	28.14	46.44
Year	2010	2011	2012	2013	2014	2015	2016		
Alamata	80.2	45.3	73.7	61.25	32.5	34.5	61.74		
Waja	54	51	50	50	48.5	32.5	51.8		
P	72.44	46.99	66.68	57.92	37.24	33.91	58.80		

The rainfall data indicated in table 4.1 was analyzed for Adequacy, Completeness and Homogeneity by:

- Choosing of the daily annual maximum rainfall series.
- Finding and estimating the missed daily annual maximum of four different year's data (missed two daily annual maximum for each station).
- Higher and lower out layer checking and testing the consistency of record using the equations of 3.3, 3.4, 3.5 and 3.6.

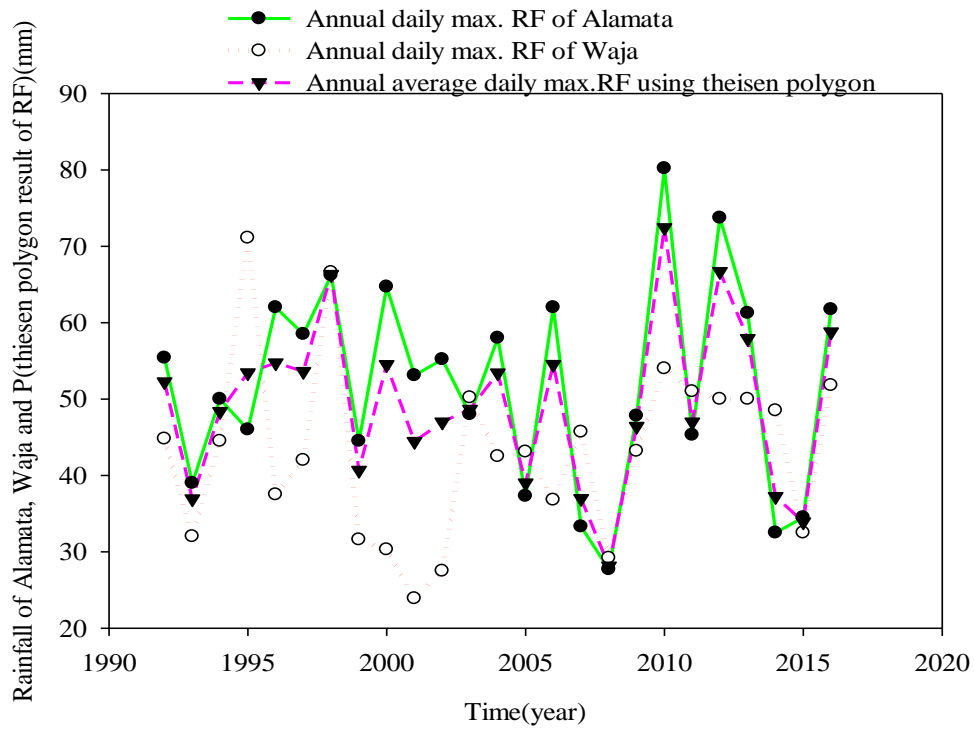


Figure 4.1: Annual maximum daily rainfall data stations near to study area

#### 4.1.2. Land Use and Land Cover

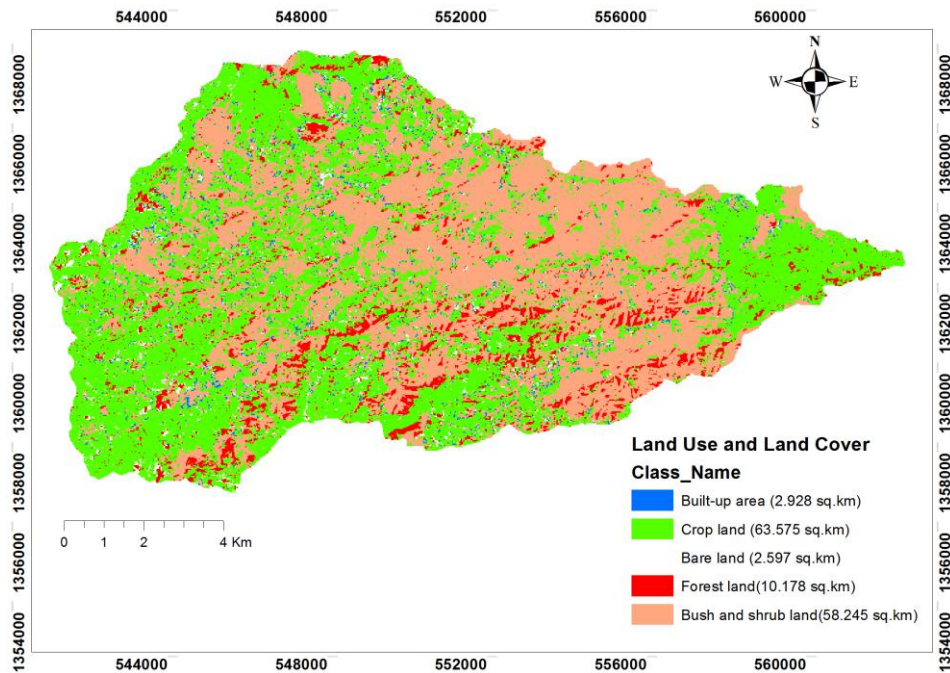


Figure 4.2: Land use/land cover of the study area

As indicated in figure 4.2 above the land use and land cover classes were categorized in the watershed as given in table 4.2 below. The crop types of the study area are namely Teff, Maize and Sorghum.

Table 4.2: Land use/cover Classes for Harosha River Catchment

Land use	Area coverage (km <sup>2</sup> )	Ratio (%)
Built- up area	2.9	2.1
Crop land (sorghum, teff and maize)	63.6	46.2
Bare land	2.6	1.9
Forest land	10.2	7.4
Bush and Shrub land	58.2	42.4
Total	137.5	100

#### 4.1.3. Hydrologic Soil Group (HSG) Classification

According to the ERADDM (2002) hydrological Soil Groups for Ethiopia are Groups of A, B, C, and D. According to soil map of the study area result, the soil of Harosha river catchment can be classified into three types; chromic vertisols, Eutric Cambisols and Lithosols.

Table 4.3: Land Class based Hydrologic Soil Group coverage

Land Use	HSG	Area Coverage (Km <sup>2</sup> )	
Built- up area	D	2.13	2.93
	B	0.8	
Crop land	D	47.5	63.58
	B	16.1	
Bare land	D	1.91	2.6
	B	0.7	
Forest land	D	8.82	10.2
	B	1.4	
Bush and shrub land	D	48.64	58.3
	B	9.61	
Total		137.523	137.523

Based on this code the chromic vertisols and Lithosols are hydrologic soil groups D and Eutric Cambisols is hydrologic soil groups B. In addition to this the most dominant hydrological Soil Groups for the study area is group D (109 km<sup>2</sup> or 79.2 %) from the total catchment area of 137.523 km<sup>2</sup> as shown in table 4.3 above and figure 4.3 below.

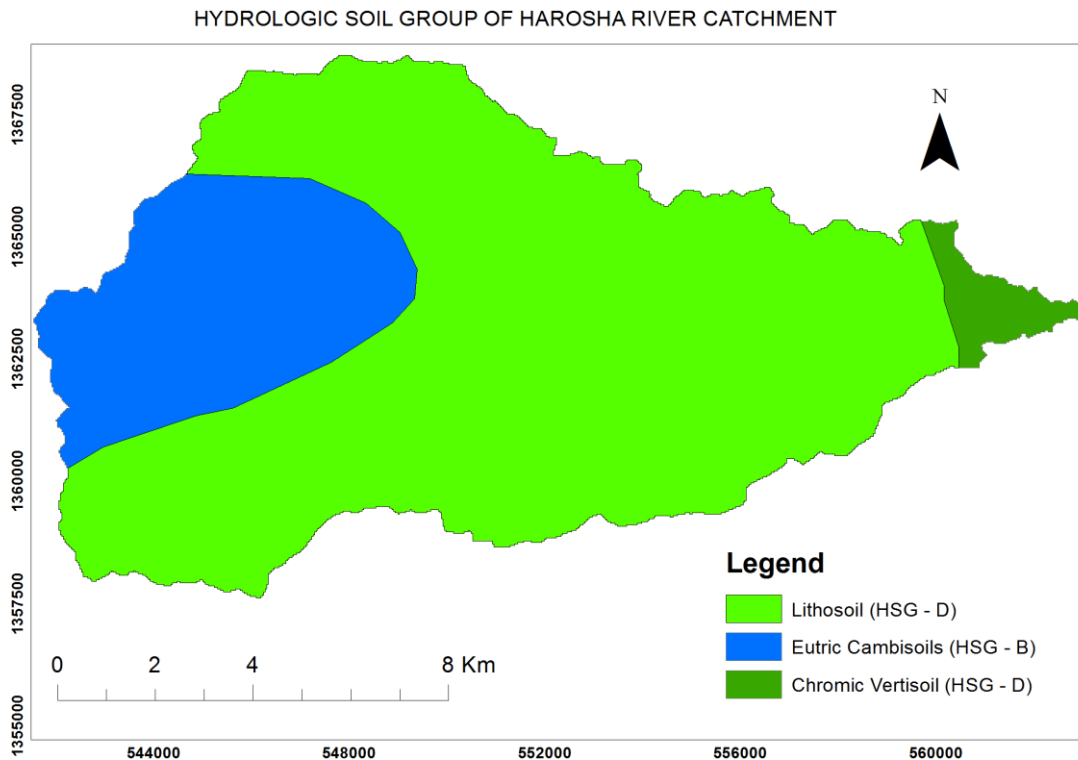


Figure 4.3: Hydrologic Soil Group Classification Map of the study area

#### 4.1.4. Runoff Curve Number

The Runoff Curve number value for each soil hydrologic group and corresponding land use classes are presented based on the processes the result of the CN for antecedent moisture conditions of II and III are as shown in the table 4.4 below. Based on the data given in the table, the composite curve number was found by using the equation of 3.25 and the value are 89.7 for curve number values of AMC II and 95.3 for curve number values of AMC III by using the equation of 3.18. The hydrologic soil group D is the most dominant than hydrologic soil group B with the total CN values of 72.7 and 17.0 respectively.

Table 4.4: CN Values for Harosha River Catchment

Land Use	Soil Type	HSG	Area coverage		CN	Weighted CN (II)	CN (III)
			km <sup>2</sup>	Ratio (%)			
Built-Up area	Lithosols and Chromic vertisols	D	2.131	1.549	86	1.333	95.26
	Eutric Cambisols	B	0.797	0.579	74	0.429	
Crop land	Lithosols and Chromic vertisols	D	47.475	34.522	93	32.105	
	Eutric Cambisols	B	16.100	11.707	85	9.951	
Bare land	Lithosols and Chromic vertisols	D	1.909	1.388	94	1.305	
	Eutric Cambisols	B	0.688	0.500	86	0.430	
Forest land	Lithosols and Chromic vertisols	D	8.815	6.410	79	5.064	
	Eutric Cambisols	B	1.363	0.991	65	0.644	
Bushes and shrubs land	Lithosols and Chromic vertisols	D	48.637	35.366	93	32.891	
	Eutric Cambisols	B	9.609	6.987	80	5.590	
Total			137.523	100		89.74	

The catchment area is dominated by the weighted CN value of crop land 42.1 and followed by bushes and shrubs 38.5. And the less dominant soil type of the study area forest land, built-up area and bare land come to be 5.7, 1.8 and 1.7 respectively.

#### 4.1.5. Results of Peak Flood for different Recurrence Periods

Time of concentration and the slope has been determined using equation 3.27 and 3.26 and respectively.

The flood frequency analysis for 5, 10, 25, 50 and 100 years return period was determined using different methods and some of them are Normal distribution, Log normal distribution, Log Pearson type III distribution and Gumbel EVI distribution. The Log Pearson Type III distribution method was selected as a best fit due to the least value as compared to other

methods. The results of flood frequency analysis for 24 hour rainfall depth for the different recurrence period are listed in the table of 4.5 below.

To determine the peak discharge (Runoff estimation) it has been used the SCS method developed by the U.S soil conservation service (1972) because of the catchment area is greater than 50 hectares, applicable for areas which do not have stream flow records, it is also approved by the ERADDM and FDREMWR in 2002 for maximum flood estimation.

Peak runoff potential has been estimated using SCS method using equations of 3.18, 3.23, 3.31, and using the detail procedure equations of hydrograph. Maps and SCS method for various parameters have been generated and finally a map and SCS method showing the runoff potential has been prepared.

Using SCS method calibration was performed for a period of twenty five years (1992 to 2016) Harosha Watershed using thiesen polygon method of annual daily maximum rainfall. The mean daily annual rainfall of the study area for the period between 1992 and 2016 is 49.34 mm with annual daily maximum rainfall of 72.44 mm in 2010 and annual daily minimum of 28.14 mm in 2008.

The weighted curve number for AMC II and III for the catchment is estimated as per the SCS methodology and results are 89.7 and 95.3, and also Potential maximum retention is calculated (12.6mm) using the equation 3.24.

The Rainfall data and the result of the calibrations for the five different return periods in the study area were obtained, and the result of the 24 hrs rainfall, runoff depth and maximum peak flow is presented in table 4.5 as shown below. The maximum peak discharge was determined using ordinate hydrograph for 6 hour time duration.

Table 4.5: Results of peak discharge for different return periods

Return Period	24 hours rainfall Depth	Direct surface Runoff Depth	Maximum peak discharge
Years	P (mm)	Q (mm)	Qp (m <sup>3</sup> /s)
5	58.69	45.85	347.38
10	63.05	50.07	383.74
25	67.68	54.57	420.84
50	70.52	57.34	443.6
100	72.94	59.70	463.13

## 4.2. Results of Hydraulic analysis and Flood Mapping

### 4.2.1. Pre-processing of Geometric Data

Hydraulic modeling in this pre-processing research was conducted for the last 6.66 km of main Harosha River line downstream from the total of 24 km. 74 cross sections at different suitable intervals are created the extent average of 94 m. The cross sections distance restriction is do not have rule due to differences in direction, size, and depth of the river. It was done by taking many sections in the curve and downstream part for reduction of errors, using assumptions of cross sections Cutline rules such as the crossing always from left to write, no cross each other, the crossed line should be perpendicular to the river line and should extent to the flood plain. Based on this the results of pre processing developed map including DTM, river lines, banks, flowpaths and cross-section Cutlines with 3-Dimensions are shown in the figure 4.4 below.

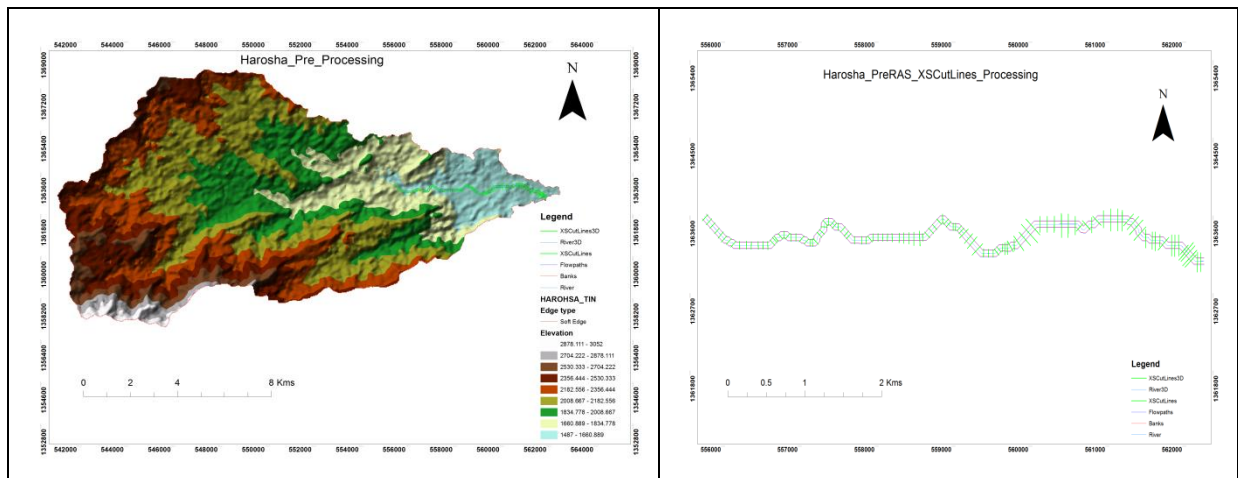


Figure 4.4: Pre-processing and Cross-section Cutlines Map of the study area

### 4.2.2. Hydraulic Results in HEC-RAS

After finishing the cross sections of Harosha River and importing the pre-processed Geometric data shown in figure 4.5 below, the maximum flood discharge with different return periods, and other information such as the coefficient of roughness of the main channel and normal depth, modeling was performed. Therefore, the roughness value was determined by comparing the manning's value for different land uses recommended for our country approved by ERADDM with that of Harosha River catchment and found to be 0.035 and 0.05 for main channel and overbanks respectively. The flow regime was considered as steady one and

boundary conditions for downstream river flow a downstream normal depth 0.065 slope of Harosha River using downstream reach elevation difference and length were introduced.

After stimulating the flow in HEC-RAS Model, its many characteristics such as cross sectional profile as shown in figure 4.5 below can be observed and based on their result of river and flood control option can be provided and also these areas show the level and depth of flooding.

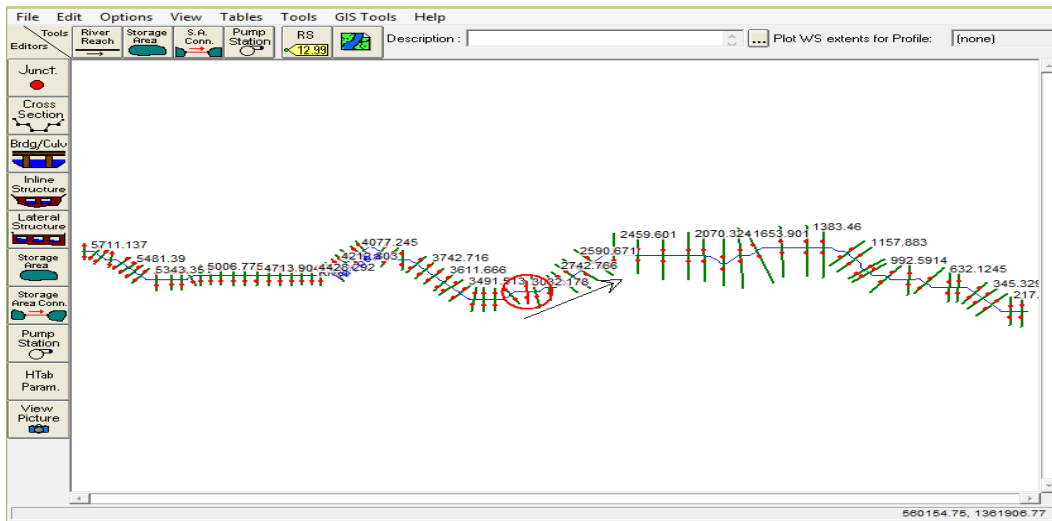


Figure 4.5: Locations of cross sections on the Harosha River

The simulation results were shown the flood levels in different cross sections, as a result Profile plot views of flood levels and X-Y-Z Perspective views of flood plain in a part of the study reaches as shown in figure 4.6 and rating curve as indicated in figure 4.8 flood area was performed.

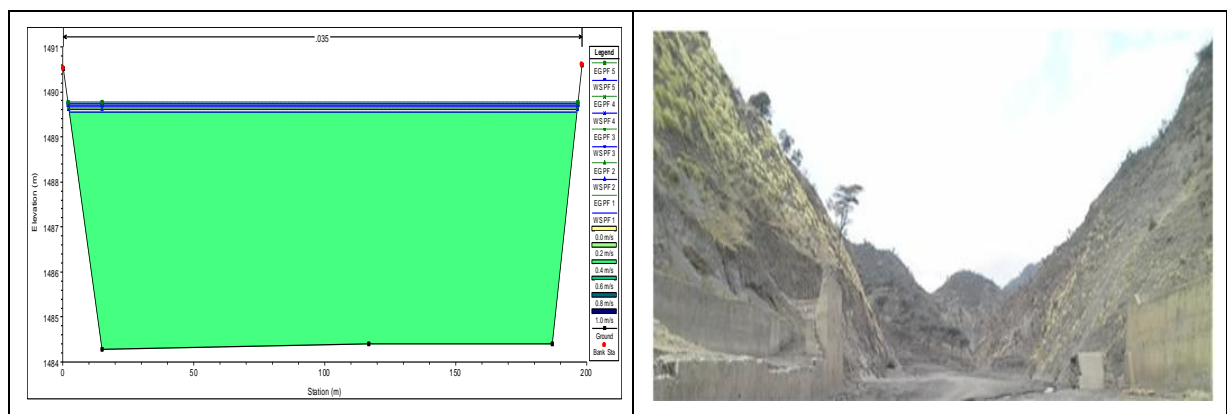


Figure 4.6: Profile plot views result of flood level with specific area on the study area

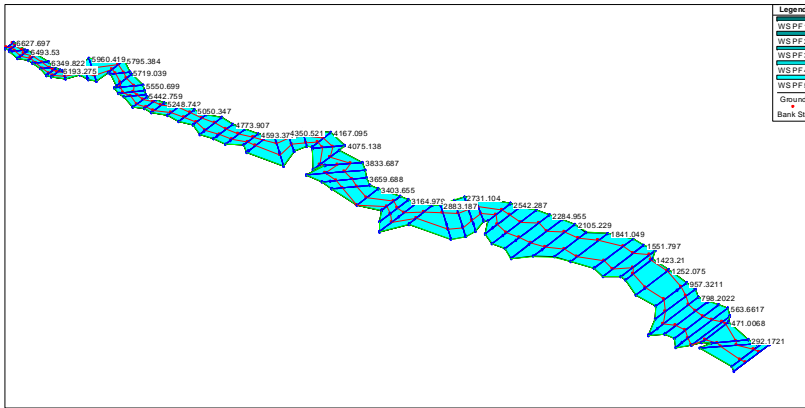


Figure 4.7: X-Y-Z Perspective views result of flood plain for the study area

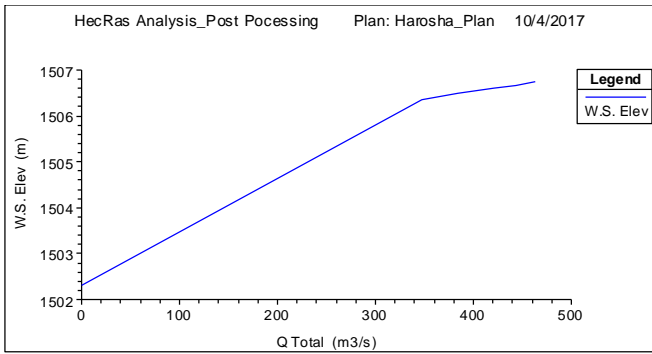


Figure 4.8: Rating curve result of the study area

#### 4.2.3. Post-processing of Hydraulic Results and Flood Plain Mapping

After running HEC-RAS for water flows of 5, 10, 25, 50 and 100 year return periods, water surface profiles, and other hydraulic parameters such as flows, minimal and maximum channel profiles, channel velocity, flow area, and critical water surface are available for each cross section from HEC-RAS outputs.

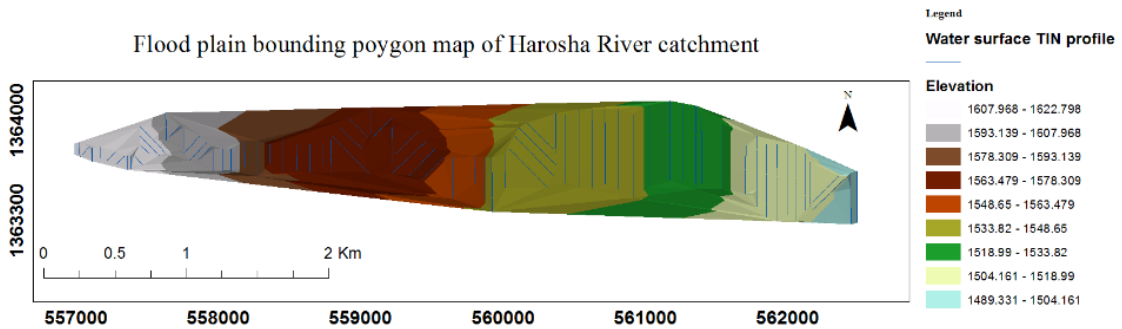


Figure 4.9: Water surface TIN of the study area

After simulation the hydraulic analysis in HEC-RAS the water surface TIN result as shown in figure 4.9 above is delineated by ArcGIS with combination of HEC-GeoRAS from bounding polygon for flood plain inundation boundaries calibration.

After preparing the flooding map areas in GIS with different return periods, it shows the level and depth of flood areas. Flood inundation area in figures of 4.10, 4.11, 4.12, 4.13 and 4.14 for the return periods of 5, 10, 25, 50, and 100 years flood maps below shows that by increasing the discharge of longer return periods, flood covers more surface flooding. Expansion of flood zoning affected by topographical features of the Harosha River, human intervention in river channel and river banks such as agriculture and irrigation structures. Anywhere in the valley the widths of channel have increased, the width of the flood area has increased and flood water has expanded.

The most flood prone area in the Harosha river catchment is at the middle and lower reach. Also the flood plain would be affected more especially with the 25, 50 and 100 year floods. The results of the whole return periods flood mapping are summarized as shown in the figures and in table 4.6 below one to another.

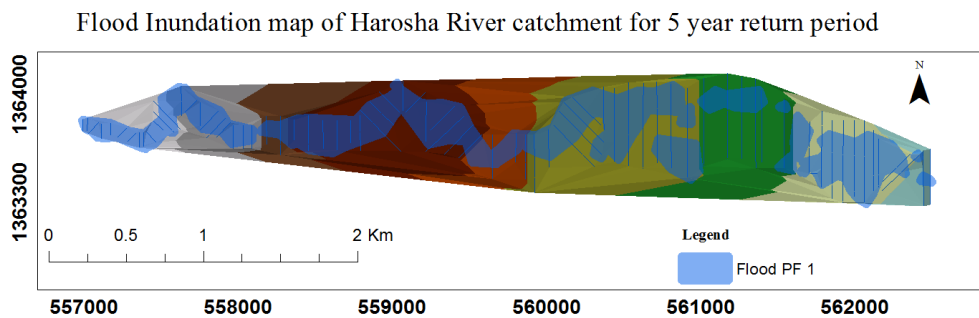


Figure 4.10: Floodplain inundation map for 5 years return period

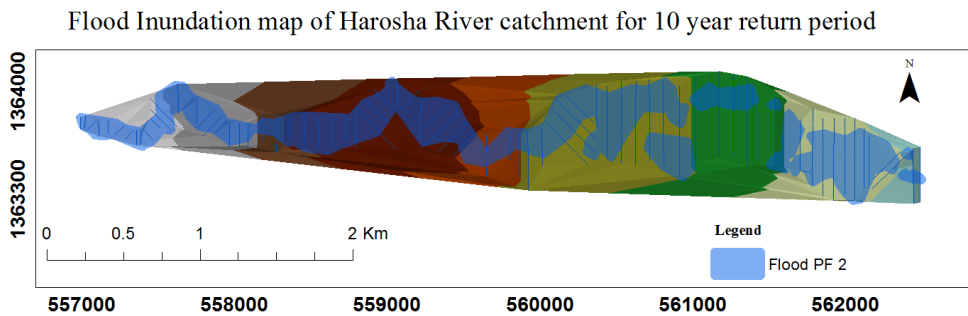


Figure 4.11: Floodplain inundation map for 10 years return period

Flood Inundation map of Harosha River catchment for 25 year return period

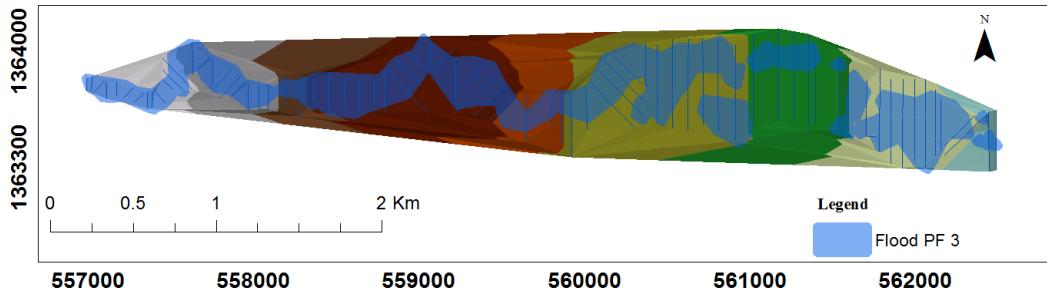


Figure 4.12: Floodplain inundation map for 25 years return period

Flood Inundation map of Harosha River catchment for 50 year return period

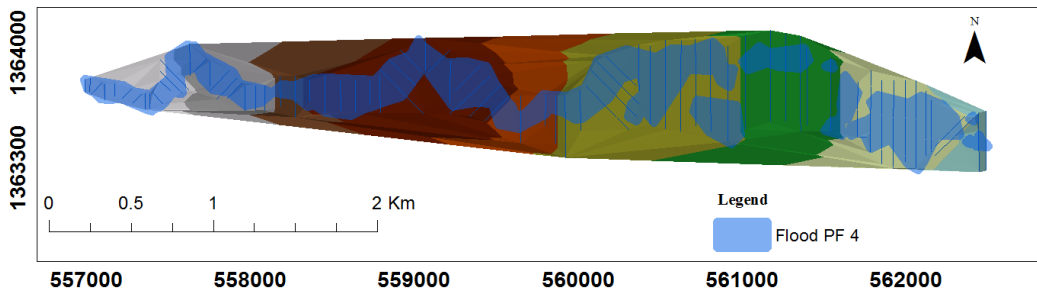


Figure 4.13: Floodplain inundation map for 50 years return period

Flood Inundation map of Harosha River catchment for 100 year return period

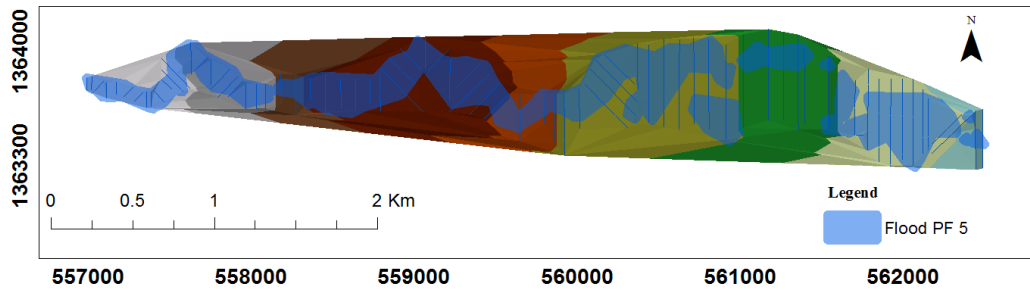


Figure 4.14: Floodplain inundation map for 100 years return period

The effect of flood on the river flood hazard maps is the factor that can be assessed based on the generated flood map for the Harosha river basin. The results show that an increase of the runoff or flood magnitude leads to an increase in the extent of the flood hazard as indicated in table 4.6. For example, in existing river basin development condition, the area of high hazard

class changes from 84.6 to 87.7 for 5 years to 100 years. This means that, increases of high hazard class can be observed by increase of flood event magnitude from 5 years to 100 years.

Table 4.6: Table of flow data and Floodplain inundation coverage

Profile	Return period	Flow data	Flood inundation area	
	year	m <sup>3</sup> /sec	m <sup>2</sup>	hectare
Pf1	5	347.38	845894.3	84.6
Pf2	10	383.74	860735.2	86.1
Pf3	25	420.84	868527.9	86.9
Pf4	50	443.60	870976.9	87.1
Pf5	100	463.13	877134.7	87.9

#### **Depth of Flood inundation and Flow Velocity**

The HEC-RAS simulation produced and depths flow velocities in the main channel and flood inundated areas. The maximum depth of flood inundations are 3.36 m, 3.84 m, 4.35 m, 4.91 and 5.89 m, for simulated of 5, 10, 25, 50 and 100 recurrence years respectively. All of the depths flood inundations for recurrence period are done and for return periods of 5 and 100 depth of flood inundations map are considered for mapping can be seen in the figures of 4.15 and 4.16 below and the rest depth of flood inundation map for 10, 25, and 50 year return period are considered in the figure 1, 2 and 3 of appendix 2 and also the different land uses which are damaged by flood are listed in the figure 4 and 5 in appendix 2. The figures indicate the maximum depth of flood inundation occurs at the middle of the reaches. In addition to this the return period of 100 year maximum depth is greater than return period of 5 year maximum depth of flood inundations map. This indicates as recurrence period increases the depth of flood inundation also increase.

Flood inundation depth map of Harosha River catchment for 5 year return period

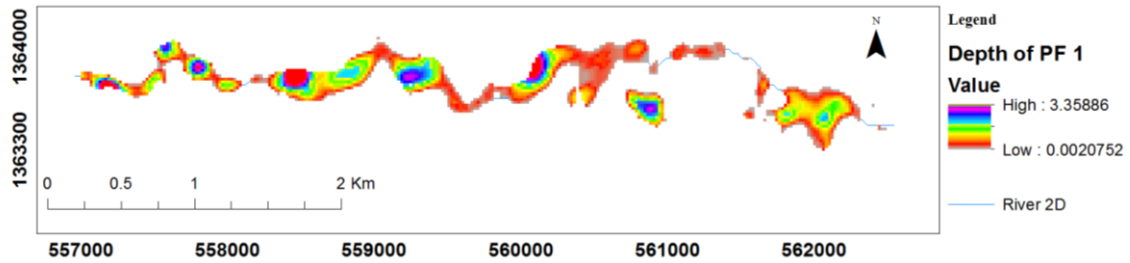


Figure 4.15: Depth of flood plain map for 5 year return period

Flood inundation depth map of Harosha River catchment for 100 year return period

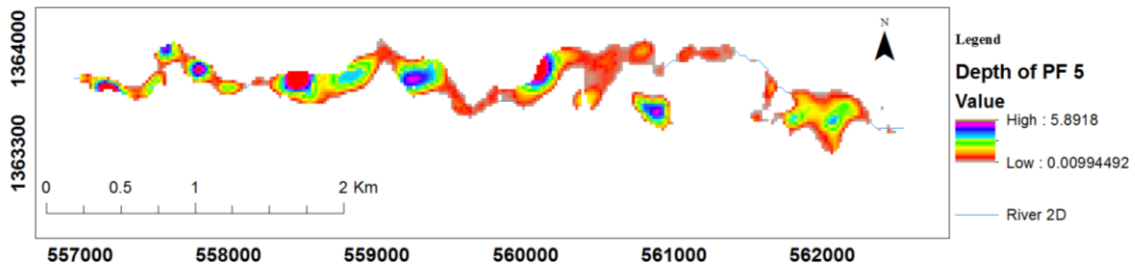


Figure 4.16: Depth of flood plain map for 100 year return period

The high velocity is occurring mostly in the main channel. The maximum velocity of the catchment is 4.6 m/s. The spatial distribution of inundation flow velocity of the catchment shows a correlation with the spatial distribution of the elevation as high values flow velocities are observed at upstream and low values at downstream. The high values at the upstream can be accepted to the steep slope of the terrain whilst the low velocity at the downstream is attributed to the flatness of the terrain. Generally, high velocities were recorded in the main channel than the floodplains and also at the upstream than downstream.

Flow velocity map of Harosha River catchment

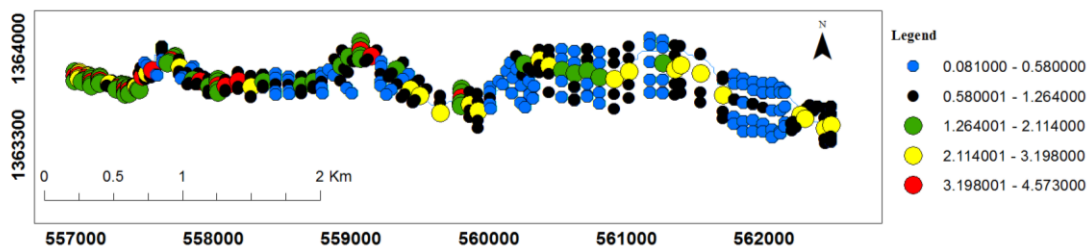


Figure 4.17: Velocity of flood plain map of Harosha River reaches.

This over all study result is good as compared with the results of Haftom (2015) in the flood plain of ETU river study area in Tigray Alamata. This is due to the different use in method of CN determination; the person uses the graphical method of ERADDM manual and I was used by preparing the updated LU/LC of the study area and determining the Areal weighted ratio to determine the actual CN value. In addition the person was used DEM of 90 m by 90 m as compared the DEM 30 m by 30 m resolution I used and this indicates the acceptance of my study is comparatively best.

## **5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS**

### **5.1. Summary and Conclusions**

Different methodologies have been applied to fulfill the objective of this study. These methodologies of this research comprise data and models used. The data used are 25 years of annual daily maximum rain fall, DEM 30 m resolution, land use land cover map, and soil map. In addition to this the modeling used for the success of this research objective are consists of river flood model i.e. SCS rainfall - runoff method model, HEC-RAS 4.1, and HEC-GeoRAS 10.1 and ArcGIS 10.1 environment.

Hydrological modeling (rainfall – runoff analysis) was successfully performed using SCS method. The model output results were the quantified runoff floods that resulted from input rainfall data. Together with a detailed analysis of the hydrological characteristics of the study area, the hydraulic modeling results were incorporated into a representative flood hazard map of the study area.

Harosha RAS hydraulic model was calibrated and then used to simulate the 5, 10, 25, 50 and 100 year floods of 347.4, 383.7, 420.8, 443.6 and 463.1 in m<sup>3</sup>/s magnitude respectively.

The flood hazard maps for the 5, 10, 25, 50 and 100 year maximum floods were generated and the total area affected by flood inundation is 84.6, 86.1, 86.9, 87.1, and 87.7 hectare respectively and gave the maximum flood depth of 3.36, 3.84, 4.35, 4.91 and 5.89 m respectively and also the maximum velocity for Harosha river catchment is 4.6 m/s.

The study area especially at the middle and downstream is more unusable due to more flooding especially the agricultural lands, downstream of settlements and irrigation projects such as diversion head works and spate irrigations.

The area of flood hazard maps developed indicated that the most flood prone area is located around and below the flood plain this is true especially for flood with return periods of 25, 50 and 100 year.

## **5.2. Recommendations**

- Based on this result encroaching agricultural practices and settlement in and around the reach of flood plain should be avoided or stopped in order to avert the risk especially for flood with return period of 100 year.
- Terrain data with good resolution is needed to properly and accurately to determine the flood hazard.
- Flow measuring station of Harosha outlet is needed for accurately estimate flood event.

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## LIST OF TABLES IN APPENDICES

Table 1 Appendix 1: hydrologic soil Group classification

Soil Group	Description	Minimum Infiltration rate (mm/hr)
A	Soils in this group have a low runoff potential (high-infiltration rates) even when thoroughly wetted. They consist of deep, well to excessively well drained sands or gravels. These soils have a high rate of water transmissions.	7.62 - 11.43
B	Soils in this group have moderate infiltration rates when thoroughly wetted and consists chiefly of moderately deep to deep, well-drained to moderately well-drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.	3.81 - 7.62
C	Soils have slow infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes the downward movement of water, or soils with moderately fine-to fine texture. These soils have a slow rate of water transmission.	1.27 - 3.81
D	Soils have a high runoff potential (very slow infiltration rates) when thoroughly wetted. These soils consist chiefly of clay soils with high swelling potential, soils with a permanent high-water table, soils with a clay layer near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission	0 - 1.27

(Source: ERADDM, 2002 and Mc. Cuen, 1982)

Table 2 Appendix 1: Runoff curve numbers (AMC-II) for hydrologic soil cover complex

S.NO	Land Use	Hydrologic Soil Group			
		A	B	C	D
1	Bare crop residue soil cover of agricultural lands	77	86	91	94
2	Contoured & Terraced soil cover of agricultural lands	70	79	84	88
3	Brush -weed – Grass mixture with brush the major element cover of agricultural lands	48	67	77	83
4	Farms-buildings, lanes, drive ways and surrounding lots	59	74	82	86
5	Mountain brushes with mixture of small trees and brushes	-	66	74	79
6	Desert shrubs and brushes	63	77	85	88
7	Mixture of grass, weeds, and low growing brush, with brush the minor element	-	80	87	93
8	Forest (degraded)	45	66	77	83
9	Forest (plantation)	25	55	70	77

(Source: ERADDM, 2002 and Chow et al., 2002)

Table 3 Appendix 1: manning's value for different land uses

S.No	Type of Channel and Description	Manning's Roughness (n) Values		
		Minimum	Normal	Maximum
	NATURAL STREAMS			
A	Minor channels or streams (top width at flood stage < 30 m)			
A.1	Clean ,straight ,full ,no rifts or deep pools	0.025	0.030	0.033
A.2	Same as above ,but more stones and weeds	0.030	0.035	0.040
A.3	Clean ,winding ,some pools and shoals	0.033	0.040	0.045
A.4	Same as above ,but some weeds and stones	0.035	0.045	0.050
A.5	Same as above ,lower stage ,more ineffective slopes and sections	0.040	0.048	0.055
A.6	Same as "4" but more stones	0.045	0.050	0.060
A.7	Sluggish reaches ,weedy ,deep pools	0.050	0.070	0.080
A.8	Very weedy reaches ,deep pools or floodways with heavy stands of timber and brush	0.070	0.100	0.150
B	Mountain streams ,no vegetation in channel banks usually steep ,with trees and brush on banks submerged			
B.1	Bottom : gravels ,cobbles ,and few boulders	0.030	0.040	0.050
B.2	Bottom : cobbles with large boulders	0.040	0.050	0.070
C	Flood plains			
C.1	Pasture no brush			
C.1.1	Short grass	0.025	0.030	0.035
C.1.2	High grass	0.030	0.035	0.050
C.2	Cultivated areas			
C.2.1	No crop	0.020	0.030	0.040
C.2.2	Mature row crops	0.025	0.035	0.045
C.2.3	Mature field crops	0.030	0.040	0.050
C.3	Brush			
C.3.1	Scattered brush ,heavy weeds	0.035	0.050	0.070
C.3.2	Light brush and trees ,in winter	0.035	0.050	0.060
C.3.3	Light brush and trees ,in summer	0.040	0.060	0.080
C.3.4	Medium to dense brush, in winter	0.045	0.070	0.110
C.3.5	Medium to dense brush, in summer	0.070	0.100	0.160
C.4	Trees			
C.4.1	Cleared land with tree stumps ,no sprouts	0.030	0.040	0.050
C.4.2	Same as above ,but heavy sprouts	0.050	0.060	0.080
C.4.3	Heavy stands of timber ,few down trees ,little under growth ,flow below branches	0.080	0.100	0.120
C.4.4	Same as above , but with flow into branches	0.100	0.120	0.160
C.4.5	Dense willows , ,straight ,straight	0.110	0.150	0.200

(Source: ERADDM, 2002)

Table 4 Appendix 1: Hydrologic Soil Group for Ethiopia

**Table 5-7 Typical Hydrologic Soils Groups for Ethiopia**

	Soil Types	Hydrologic Soil Group
Ao	Orthic Acrisols	B
Bc	Chromic Cambisols	B
Bd	Dystric Cambisols	B
Be	Eutric Cambisols	B
Bh	Humic Cambisols	C
Bk	Calcic Cambisols	B
Bv	Vertic Cambisols	B
Ck	Calcic Chernozems	B
E	Rendzinas	D
Hh	Haplic Phaeozems	C
Hi	Luvic Phaeozems	C
I	Lithosols	D
Jc	Calcaric Fluvisols	B
Je	Eutric Fluvisols	B
Lc	Chromic Luvisols	B
Lo	Orthic Luvisols	B
Lv	Vertic Luvisols	C
Nd	Dystric Nitosols	B
Ne	Eutric Nitosols	B
Od	Dystric Histosols	D
Oe	Eutric Histosols	D
Qc	Cambric Arenosols	A
Rc	Calcaric Regosols	A
Re	Eutric Regosols	A
Th	Humic Andosols	B
Tm	Mollic Andosols	B
Tv	Vitric Andosols	B
Vc	Chromic Vertisols	D
Vp	Pellic Vertisols	D
Xh	Haplic Xerosols	B
Xk	Caloic Xerosols	B
Xl	Luvic Xerosols	C
Yy	Gypsic Yermosols	B
Zg	Gleyic Solonchaks	D
Zo	Orthic Solonchaks	B

Source: Ministry of Agriculture

## LIST OF FIGURES IN APPENDICES

Flood inundation depth map of Harosha River catchment for 10 year return period

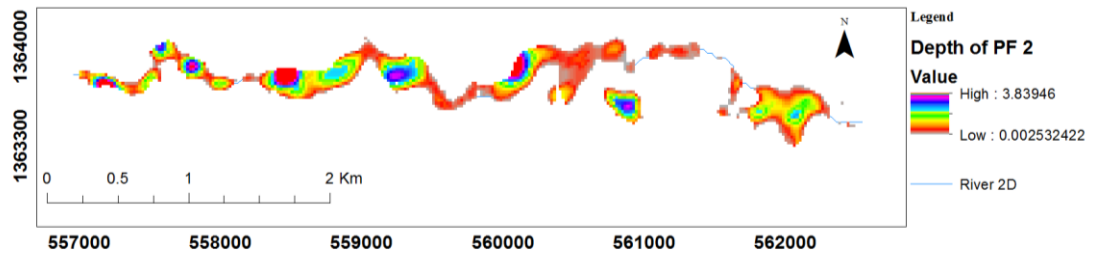


Figure 1 Appendix 2: Depth of flood plain map for 10 year return period

Flood inundation depth map of Harosha River catchment for 25 year return period

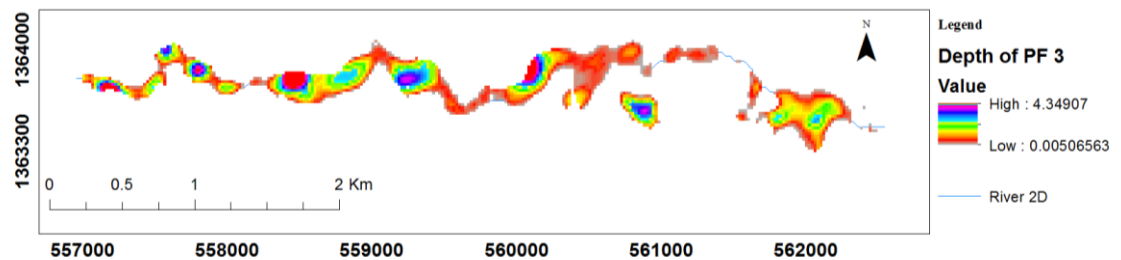


Figure 2 Appendix 2: Depth of flood plain map for 25 year return period

Flood inundation depth map of Harosha River catchment for 50 year return period

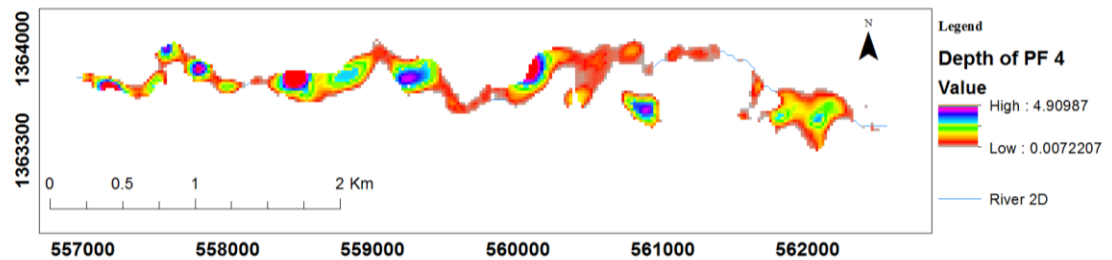


Figure 3 Appendix 2: Depth of flood plain map for 50 year return period



Figure 4 Appendix 2: Depth of River with agricultural land map



Figure 5 Appendix 2: Diversion Headwork damaged by flood