ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

Urbanization and Its Effect on Surface Runoff

(A Case Study on Great Akaki River, Addis Ababa, Ethiopia)

By: Misganaw Nega Beyene

June, 2016

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BY

MISGANAW NEGA BEYENE

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(A Case Study on Great Akaki River, Addis Ababa, Ethiopia)

A Thesis Submitted to School of Civil & Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Hydraulic Engineering

Addis Ababa University

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DECLARATION

I, the undersigned, declare that the thesis entitled "Urbanization and Its Effect on Surface Runoff (A Case Study on Great Akaki River, Addis Ababa, Ethiopia)"comprises my own work. In compliance with internationally accepted practices, I have duly acknowledged and referred all materials used in this work. I understand that non-adherence to the principle of academic honesty and integrity, misrepresentation/fabrication of any idea/data/fact/source/ will constitute sufficient ground for disciplinary action by the university.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge

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ABSTRACT

On this study the effect of high urbanization rate of Addis Ababa City in general the study area on the Great Akaki River is assessed. The surface runoff generated from the catchment is estimated based on the rainfall intensity and major characteristics of the catchment area which are the major factors for designing urban storm water drainage facilities and structures. Satellite image for 1989, 2000 and 2010 of the catchment area is taken based on the quality of data and the available resolution. ArcGIS and GIS extension tools are used to extract hydrological characteristics of the catchment; HEC-RAS for hydraulic modeling, and HEC – HEC-HMS to simulate rainfall - runoff process on Great Akaki watershed which is the major watershed located at the center of Addis Ababa.

The hydrological and hydraulic modelings are accomplished by dividing the watershed in to different sub-catchments. To compute infiltration loss SCS CN method; converting excess rainfall to runoff model SCS unit hydrograph, and channel flow routing accomplished by using Muskingum routing method of HEC-HMS model. To evaluate the accuracy of the simulation model calibration and validation was conducted.

The hydrological modeling classified in to two: the first simulation shows the effect of high urbanization growth on the basin. Accordingly, the peak discharge for 1989, 2000 and 2010 at the Bridge outlet along Addis Ababa Bishoftu Road is 131, 153.4 and 188.1m^3/s respectively. To avoid the effect of rain fall variation on the generated peak discharge similar hourly rainfall of 18 July 2010 was used for each respective year.

The second simulation uses frequency storm method for 10, 50 and 100 return periods and peak discharge of 403.80, 546.50 and 634.70m^3/s for each respective return period was obtained. The result found from HEC-HMS frequency storm method used for hydraulic analysis and flood map hazard generation. Flood inundation maps produced using ArcGIS to visualize flood depth and extent for each return period. Accordingly, maximum flood depth of 7.86, 9.07 and 9.82m for 10, 50, and 100 year return periods respectively was found with flood extent of 82.34 for 10 return period and 100.15 for both 50 and 100 year return periods at the middle of the final reach of the study area.

Keywords: DEM, TIN, flood modeling; HEC-HMS/RAS; HEC- GeoHMS/RAS

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Table of Contents

Pages

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

A	: Cross Sectional Area
ASTER	: Advanced Space borne Thermal Emission and Reflection Radiometer
CN	: Curve Number
CSA	: Central Statistics Agency
DEM	: Digital Elevation Model
DFID	: Department for International Development
ECA	: Economic Commission for Africa
ERA	: Ethiopian Road Authority
FAO	: Food and Agricultural Organization
GDEM	: Global Digital Elevation Model
GIS	: Geographical Information System
IDF	: Intensity-Duration-Frequency
HEC-HMS	: Hydrologic Engineering Center Hydrologic Modeling System
HEC-GeoHMS	: Hydrologic Engineering Center Geospatial Hydrologic Modeling System
HEC-RAS	: Hydrologic Engineering Center River Analysis System
HEC-GeoRAS	: Hydrologic Engineering Center Geospatial River Analysis System
HSG	: Hydrological Soil Groups
Ia	: Initial Abstraction
K	: Travel Time
KML	: Keyhole Markhole Language
L	: Length
LIDAR	: Light Detection And Ranging
LULC	: land Use/Land Cover
NEH	: National Engineering Handbook
NRCS	: Natural Resources Conservation Service
NSE	: Nash-Sutcliffe Efficiency
P	: Rainfall
Q	: Flood Discharge
R^2	: Coefficient of Determination
RGB	: Red, Green, Blue
RS	: River station
S	: Potential Maximum Retention
SCS	: Soil Conservation system
SMA	: Soil Moisture Accounting
STRM	: Shuttle Radar Topography Mission
TIN	: Triangulated Irregular Network
TR55	: Technical Release 55
UH	: Unit Hydrograph
UNEP	: United Nations Environment Programme
UNESCO	: United Nations Educational, Scientific and Cultural Organization

UN-HABITAT	: United Nations Human Settlements Programme
USDA	: United States Department of Agriculture
USGS	: United States Geological Survey
USACE	: United States Army's of corps of Engineers
UTM	: Universal Transverse Mercator
V	: Velocity
WGS	: World Geodetic System
X	: weighting between inflow and out flow

CHAPTER 1: INTRODUCTION

1.1. Background

Nowadays there is a great need to detect spatial patterns of land use/land cover (LULC) change at local, regional and global scales. Understanding LULC change is of fundamental importance for environmental monitoring, urban planning, and governmental decision making around the world. One particular consequence of LULC change is its considerable impacts on hydrological processes by affecting the nature of surface runoff and water quality, hence further impact on ecosystems, biotic systems, and even on human health (Chunhao Zhu, 2011).

Land-use and land-cover changes may have four major direct impacts on the hydrological cycle and water quality: they can cause floods, droughts, changes in river and groundwater regimes, and they can affect water quality (Qihao Weng, 2001). Globally floods are most devastating natural disasters affecting human life than any other natural disasters (Okirya Martin, Albert Rugumayo & Janka Ovcharovichova, 2012). In 2010 alone, 178 million people were affected by floods and the total financial losses in the exceptional years such as 1998 and 2010 exceeded $40 billion (Okirya Martin, Albert Rugumayo & Janka Ovcharovichova, 2012). It is also reported that one sixth of the global population (one billion people); the majority of them among the world's being low income earners live in the potential path of a 1 in 100 year flood according to Department for International Development (DFID). Ethiopia is facing the same global challenges of climate change effects such as droughts and floods. The country experiences two types of floods: flash floods and river floods. Flash floods are the ones formed from excess rains falling on upstream watersheds and gush downstream with massive concentration, speed and force. Often, they are sudden and appear unnoticed (Joint Government and Humanitarian Partners, 2006 Ethiopia report). Therefore, damage caused by such kind of floods becomes pronounced and devastating when they pass across or along human settlements and infrastructures. For example in the recent incident, that the Dire Dawa City experienced is typical of flash flood. On the other hand, much of the flood disasters in Ethiopia are attributed to rivers that overflow or burst their banks and inundate downstream plain lands (Joint Government and Humanitarian Partners, 2006 Ethiopia report). The flood that has been happened in Southern Omo Zone and Awash River is a typical manifestation of river floods (Joint Government and Humanitarian Partners, 2006 Ethiopia report).

On the other hand, population growth is increasing; runoff of rainwater's is expected to increase due to the decrease of the permeability of the urban environment. For example, Addis Ababa had a population of 65,000 in 1912, which grew to 100,000 in 1935; 443,728 in 1961; 1,167,315 in 1978 and 2,112,737 in 1994 (UNEP, UNESCO, UN-HABITAT and ECA, 2003) and 3,195,000 in 2014(CSA, 2013b). This shows that the population increase is dynamic. The foundation and expansion of Addis Ababa was associated with the rapid conversion of land from rural to urban uses more than anywhere else was in the country (UNEP, UNESCO, UN-HABITAT and ECA, 2003). For the last one hundred seventeen years it has been noticed that there is an intensive conversion of rural land to urban development like buildings, transportation networks and facilities (airports and highways), recreation areas, reservoirs and other manmade structures(UNEP, UNESCO, UN-HABITAT and ECA, 2003). During the last three decades as shown from different landsat images of Addis Ababa city the city has been expanded laterally. This dynamic change directly or indirectly has huge impact on the increase of flood in the city from year to year. Especially, the problem is very visible on different parts of the city. Roads and bridges are destroyed, overtopped and washed away.

Therefore, to reduce the impact of flood, during design of roads, bridges, culvers, etc, estimation of flood magnitudes using the appropriate parameters is very essential. If different models support this estimation, the result will be satisfactory. Currently many models are developed to solve these problems. Especially models like HEC-HMS, HEC-RAS and GIS tools have been tested and widely used globally in flood modeling for several years (Okirya Martin, Albert Rugumayo & Janka Ovcharovichova, 2012). In addition to this, these models are readily available and if the result of the models calibrated well, it can be used during design and decision making for both local and national level.

In this research, geographic information system (GIS) software and GIS extension tools are used in combination with hydrologic and hydraulic modeling software's to estimate the generated flood and its effect on Great Akaki River.

1.2. STATEMENT OF THE PROBLEM

Generally, floods are the causes of major destruction of property, buildings and infrastructures in Ethiopia and this problem is getting worse and worse in urban areas due to high rate of urbanization in the country. This has led to deforestation, use of high quality corrugated roofs and paved surfaces or asphalts and its effect is high with the higher raindrop intensity on the city. As we know, urbanization has different stages and various effects can be noticed through those stages. At early, removal of vegetation and trees may decrease evapotranspiration and interception, which increase stream sedimentation. When construction of streets or roads, bridges, houses and culverts begins, infiltration will decrease and stream flow will increase. In addition to this when the development of residential and commercial buildings has been completed imperviousness increase consequently; the time needed for runoff will reduce; concentration will be peak with higher discharges and occur sooner after rainfall starts in basins. The volume of runoff and flood damage potential will greatly increase. As a result, the rainfall–runoff process in an urban area tends to be quite different from that in natural conditions.

The impacts of high rate of growth of Addis Ababa city particularly in the study area reflected through street flooding and over topping as well as bridge, road, culvert materials are washed way. On the other hand, many river flood plains in the city have not yet been delineated considering the land use change and most of small tributary rivers in the city are ungauged. It is obvious, hydrological alterations and channel disturbances along streams because of changes in inputs like; slope, vegetation cover, geology, stream geomorphology and hydrologic processes from year to year as shown on figures 1.1, 1.2 and 1.3.

Therefore, we need to see carefully hydrologic responses to urbanization to improve the understanding of stream response to land use change for rivers found in cities. This study tries to show the effect of high rate of growth of the Addis Ababa city in general the project area on the amount runoff generated at Great Akaki River by using the satellite image of the catchment for the years of 1989, 2000 and 2010.

Figure1.1: Houses in bad conditions which are affected by the flood

Figure 1.2: The relationship of houses found on the boarder of the river and the river

Figure 1.3: Over flood on roads around Bole, 2015

1.3. RESEARCH OBJECTIVES

This study has the following general and specific objectives.

1.3.1. General Objective

The main goal of this study is to show the effect of high rate of growth of the Addis Ababa city on the amount of runoff generated at Great Akaki River for different selected years by considering catchment characteristics and rainfall intensity of the area which are the major factors for designing urban storm water drainage facilities and structures.

1.3.2. Specific Objectives

The study includes the following specific goals:

1. Perform hydrological modeling (rainfall - runoff analysis) for Great Akaki River basin for different selected years of the catchment.
2. Perform hydraulic modeling for Great Akaki River
3. Risk assessment and flood hazard map generation.

1.4. PAPER OUTLINE

This research paper is arranged in 7 chapters. Chapter 2 tries to include the views of different literatures on key point of the study especially the theories behind the software's and models applied in this research and major factors considered on hydrological and hydraulic modeling are presented. In Chapter 3, the study area and the modeling input datasets described briefly. In Chapter 4 the methodologies and procedures used for the development of hydrologic and hydraulic modeling are presented in detail. In Chapter 5 both the hydrological & hydraulic modeling as well as flood hazard map results are presented and discussed. In Chapter 6 the study results summarized and implications associated with results as well as recommendations and limitations of the study described in detail. On the final chapter, which is chapter 7 referenses used for this study mentioned orderly.

CHAPTER 2: LITERATURE REVIEW

2.1. Hydrological Processing and Components

The land surface, the underground and the atmosphere are the three principal elements involved in that continuous water exchange through vertical and horizontal mass fluxes which is termed hydrological cycle (Figure4). Precipitation and runoff are only the visible components of this process. Other components such as evaporation, infiltration, transpiration, percolation, ground water recharge and discharge are other important mechanisms of this cycle. The water exchange between land surface and atmosphere is based on the continuous evaporation of water from the Earth, the temporary storage of water in the form of water vapour in the atmosphere and the return of water to the land surface through several forms of precipitation such as rain, snow, sleet or hail.

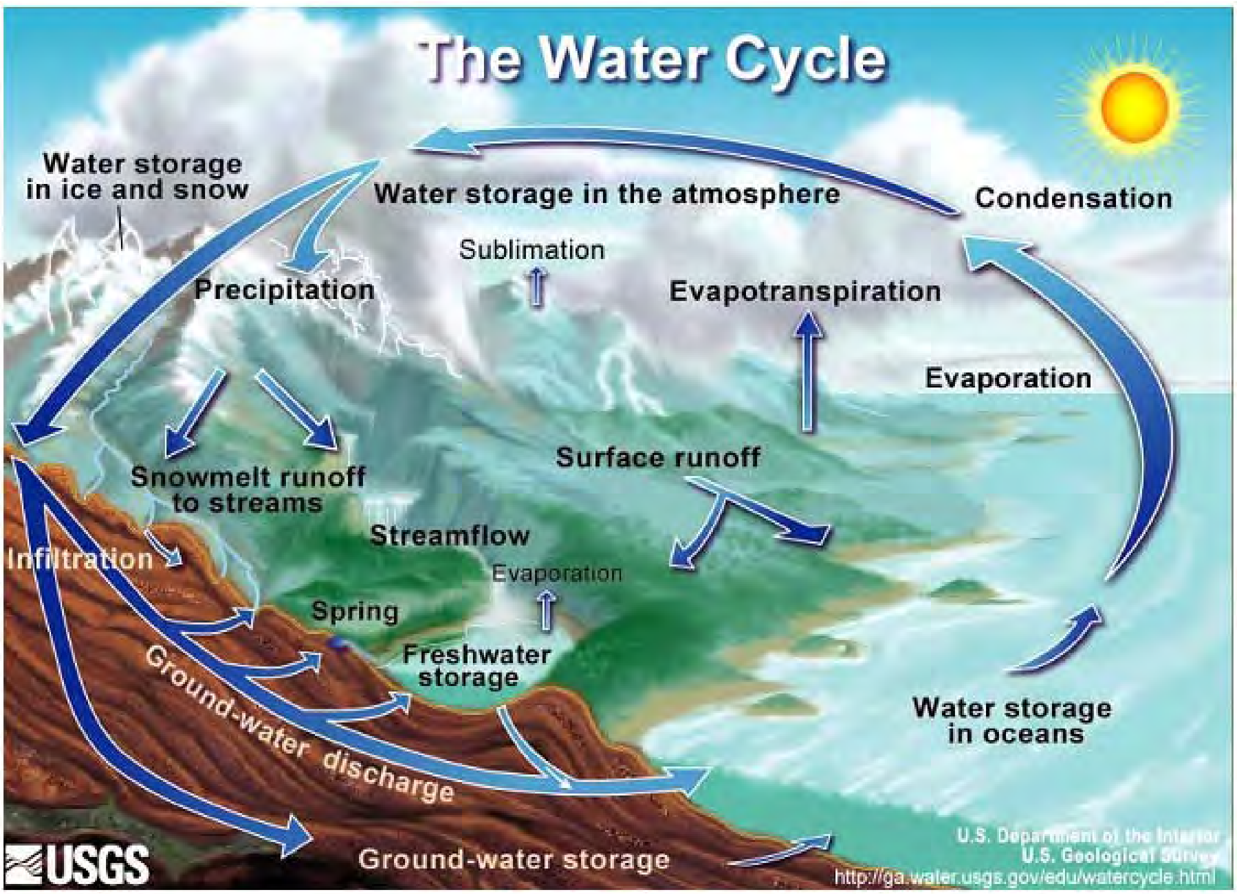


Figure 2.1: Hydrological cycle

Precipitation that reaches the land surface is partially intercepted by vegetation. The amount of water intercepted by a plant, termed interception, largely depends on plant form. Water held on the leaf surface can trickle down reaching the ground or evaporate. Another part of water falls directly on the ground. Here water can evaporate with a rate that depends on wind speed, solar radiation, heat and humidity in the air, or enter into the soil, or flow down t h e land surface as runoff. The amount of water that penetrates into the surface of soil through the infiltration process is related to soil properties such as texture, structure, moisture content and in particular to soil permeability and porosity. Conditions at the soil's surface also influence infiltration. For example, a compacted soil surface or frozen soil conditions reduce the infiltration rate. Vegetation canopy protects the soil surface from comp action by heavy raindrops, slows down water that flows over the soil surface, and plant roots help to create openings in the soil. In filtration n rate is also related to the intensity and duration of precipitation.

Generally, the rate at which water enters the soil from the surface is a function of water-input rate (snow melt and rain fall) and soil infiltration capacity (the maximum rate at which soil will accept incoming water) (Barbara LASTORIA, 2008).

2.2. Run off Modeling and Factors

2.2.1. General

Flood modeling is the processes of transformation of rainfall (Hydrology) into a flood hydrograph and to the translation of that hydrograph throughout a watershed or any other hydrologic system (hydraulics). In this manner, the flooding processes, which consist of upstream watershed hydrological processes and river and floodplain hydraulic processes and approximated either physically or mathematically (through the use mathematical equations) where the relationships between system state, input and output are represented (J. A. Ramirez, 2000).

Recent advances in computer technology have provided a means to rapidly process large arrays of spectral data for remote sensing and to combine these data with other geographical information, such as topography (including slope classes and aspect), vegetation types, soil types and geology. The most important contribution made from the processing of spatial data is the assessment of hydrologically based indices estimated from digital terrain analysis with digital elevation models. Assumptions regarding the effects of topography and related features, such as slope, aspect and indices of soil wetness, on hydrologic processes can be evaluated using digital elevation data. The topography now can be used directly in more physically realistic structures for hydrologic modeling, such as in predicting hill slope flow paths using digital terrain models. The topography is a dominant control on how the energy is distributed, particularly in complex terrain (Normal E. Peters, 1994).

According to Ethiopian Road Authority drainage design manual 2002, for hydrologic analyses, the following factors shall be evaluated and included: drainage basin characteristics including : size, shape, slope, land use, geology, soil type and surface infiltration; stream channel geometry; flood plain characteristics and precipitation amounts.

2.2.2. SCS Curve Number (CN) Method

One of empirical methods that is widely and global used by hydrologists, water project planners and water engineering, is the curve numbers method that has been suggested and supported by the department of agriculture natural resources conservation service of USA. Some applications of GIS are mapping curve number (CN) of catchment by using the digital data analysis, vegetation cover, land using and hydrologic soil groups (Abouzar Nasiri and Hamid Alipur, 2014). This method is a versatile and widely used approach for quick runoff estimation and also relatively easy to use with minimum data and give adequate results (P. K. Gupta[a] and S. Panigrahy[a], 2008)

The SCS Runoff Curve Number (CN) method developed by Natural Resources Conservation Service (NRCS) used for estimating direct runoff from storm rain fall described on the following equation;

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad 2.1$$

where

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in) and

I_a = initial abstraction (in)

Initial abstraction (Ia) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Ia is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, Ia was found to be approximated by the following empirical equation:

$$Ia = 0.2S \qquad 2.2$$

By removing Ia as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount. Substituting equation 2.2 into equation 2.1 gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad 2.3$$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \qquad 2.4$$

The major factors that determine CN are the hydrologic soil group (HSG), cover type, treatment, hydrologic condition, antecedent runoff condition, and impervious areas. On the other hand, infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. Soils are classified into four HSG's (A, B, C, and according to their minimum infiltration rate (TR55, 1986).

According to the USDA Natural Resources Conservation Service of National Engineering Handbook the four hydrologic soil groups (HSGs) are described as:

Group A: soils in this group have low runoff potential when thoroughly wet. Water is transmitted freely through the soil. Group A soils typically have less than 10 percent clay and more than 90 percent sand or gravel and have gravel or sand textures. Some soils having loamy sand, sandy loam loam or silt loam textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments.

Group B: soils in this group have moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded. Group B soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand and have loamy sand or sandy loam textures. Some soils having loam, silt loam, silt, or sandy clay loam textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments.

Group C: soils in this group have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted. Group C soils typically have between 20 percent and 40 percent clay and less than 50 percent sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures. Some soils having clay, silty clay, or sandy clay textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments.

Group D: soils in this group have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted. Group D soils typically have greater than 40 percent clay, less than 50 percent sand, and have clayey textures. In some areas, they also have high shrink-swell potential. All soils with a depth to a water impermeable layer less than 50 centimeters and all soils with a water table within 60 centimeters of the surface are in this group (NEH, 2009).

2.2.2.1. Hydrological Soil Group of Ethiopian Soils

With regard to Hydrological Soil Group (HSG) of Ethiopia most of the hydrological studies in the country used the FAO soil database. Based on FOA, HSG classification in Ethiopia has HSG-A dominates with 48.2% areal coverage followed by HSG-B (30%) and HSG-D with areal coverage of 21.6% and the remaining area is covered by HSG – C which is very small (Belete Berhanu, Melesse and Yilma Seleshi, 2012) and the area coverage clearly seen on figure 2.2.

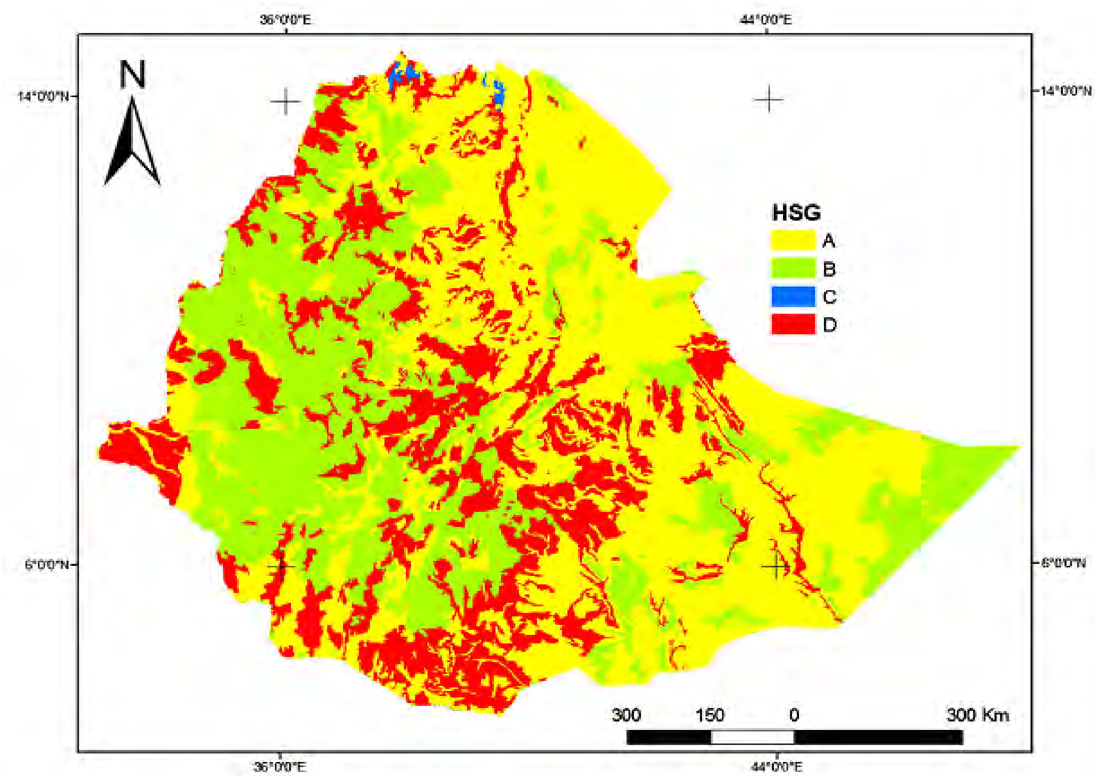


Figure 2.2: Hydrological soil group (HSG) classification of Ethiopian soils

2.2.3. Impervious Area and Urban Watersheds

Impervious surfaces have been identified as an indicator of the impacts of urbanization on water resources. Some of the affected characteristics of a watershed include hydrological impacts (the amount of runoff and peak discharge rates, and base flow are altered), physical impacts (stream morphology and temperature are changed), water quality impacts (nutrient and pollutant loads increase), and biological impacts (stream biodiversity decreases (John S. Gulliver, 2015).

2.3. Geographical Information System (GIS) and Runoff Models

Geographic information system (GIS) technology was developed by Environmental Systems Research Institute, Inc. (Esri) established in1969. Esri developers began formulating the concepts that ultimately led to the release in 1982 of ARC/INFO, the first commercial GIS. From this the fist ARC software other multiple versions have been developed up to the ArcGIS 10 used today (Walter McDonald, 2010).

The uses of geographic information systems (GIS) to facilitate the estimation of runoff from watershed have gained increasing attention in recent years. This is mainly due to the fact that rainfall runoff models include both spatial and geomorphologic variation (Jeongwoo Han, 2010).

Run off modeling needs integration of GIS and remote sensing (RS) and has two processes: (1) hydrological parameter determination using GIS, and (2) hydrological modeling within GIS. Hydrological parameter determination using GIS entails preparing land cover, soil, and precipitation data that go into the SCS model, while hydrological modeling within GIS automates the SCS modeling process using generic GIS functions. Remote sensing is used for obtaining land cover data each year and for obtaining information about the nature, rate, and location of land use and land cover changes (Qihao Weng, 2001).

2.4. GIS Extension Tools

The hydrologic Engineering Centers Geospatial Hydrologic Modeling Extension, HEC-GeoHMS, is a public domain extension to ESRI's ArcGIS software and the spatial analyst extension. It is hydrology toolkit for engineers and hydrologists. The user can visualize information, document watershed characteristics, perform spatial analysis, and delineate sub basins and streams, construct inputs hydrologic models, and assist with report preparation. Therefore use of HEC-GeoHMS can easily and efficiently create hydrologic inputs that can be used directly for HEC-HMS (HEC-GeoHMS, 2013). HE-GeoRAS also an ArcGIS extension specifically designed to process geospatial data for use with the hydrologic Engineering Center's River Analysis System (HEC-RAS). This tool used to create an HEC-RAS import file containing geometric attribute data from an existing digital terrain model (DTM) and complementary data sets. Water surface profile results may also be processed to visualize inundation depths and boundaries. A result created by HEC-RAS can be processed and used an input for Arc GIS (HEC-GeoRAS, 2012).

2.5. HEC-HMS Model

HEC-HMS /Hydrologic Engineering Center Hydrologic Modeling System is designed to simulate the precipitation-runoff process and developed by the Hydrologic Engineering Center under the U.S. Army Corps of Engineers. The first version of HEC-HMS developed in 1968 as HEC-1 and through a lot of efforts now version 4.0 is released which is used in this study. For flood simulation HEC-HMS model has three major parts these are infiltration loss simulation, converting excess rainfall to runoff and channel flow routing.

Infiltration loss simulation of HEC-HMS uses initial and constant rate, SCS CN, Gridded SCS CN, green and ampt, deficit and constant rate, soil moisture accounting (SMA) and gridded SMA. Converting excess rainfall to runoff model or modeling runoff into Hydrograph of HEC-HMS model uses seven methods theses are: user-specified unit hydrograph (UH), Clark's UH, Synder's UN, SCS UH, ModClark, kinematic wave and S-graph.

The third part is modeling one dimensional open channel flow routing and HEC-HMS model uses standard methods such as Kinematic wave, lag time, modified puls, Muskingum, Muskingum cunge standard section; Muskingum cunge eight point section(HEC-HMS, 2013).

2.6. HEC-RAS Model

HEC-RAS/River Analysis System is developed by developed by U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC). This software allows for us to perform one dimensional steady and unsteady flow river hydraulics calculation. The first version of HEC-RAS (version 1.0) was released in July of 1995. Since that time there have been several major releases including version: 1.1; 1.2; 2.0; 2.1; 2.2; 3.0; 3.1; 4.0 and now version 4.1 which is used for this study and released in January 2010.

The HEC-RAS model can handle a full network of natural and constructed channels. In this section the model has two very important river analysis components these are steady and unsteady flow. The steady flow component is used for calculating water surface profiles for steady gradually varied flow as well as capable of modeling subcritical, supercritical and mixed flow regime water surface profiles. The basic computational procedure is based on the one dimensional energy equation and the effect of various obstructions such as bridges, culverts dam, weirs, and other structures can be considered in flood plain computations. It is also, capable for assessing the change in water surface profile due to channel modifications, and levees. On the other hand, HEC-RAS modeling system is capable of simulating one-dimensional unsteady flow through a full network of open channels. Unsteady flow component was developed primarily for subcritical flow regime calculations. However, with release of version 3.1, the model can perform mixed flow regime (subcritical, supercritical, hydraulic jumps, and draw downs) calculation. Then hydraulic calculations for cross-sections, bridges, culverts, and other hydraulic structures that were developed for the steady flow component were incorporated into the unsteady flow component (HEC-RAS, 2010).

CHAPTER 3: STUDY AREA AND MODELING DATASETS

3.1. General Overview of the Study Area

Akaki River is one of the tributaries of the Awash River. The Awash River Basin is the most important river basin in Ethiopia, and covers a total land area of 110,000 km^2 and serves as home to 10.5 million inhabitants according to International Livestock Research Institute (ILRI). The river rises on the High plateau near Ginchi town west of Addis Ababa and Entoto maintain Addis Ababa in Ethiopia and flows along the rift valley into the Afar triangle, and terminates in salty Lake Abbe on the border with Djibouti. The city Addis Ababa is located at the center of the Akaki River catchment and this catchment geographically bounded between 8°46′–9°14′N and 38°34′–39°04′E with an area of about 1500 km^2 (Ferezer, 2012). Generally, the mean water bodies found in the Addis Ababa city are Akaki River and a four-water reservoir namely Legedadi, Geferssa, Dire, and Aba-Samuel. Akaki River has two main branches: the Great Akaki and Little Akaki. The Little Akaki river basin covers the western part of the city. The main tributaries of the Big Akaki River are Kebena, Kechene, Ginfle, Kurtume and Yeka all of these rivers are found within the eastern part of the city (Tamru Alemayehu, 2001).

In addition to this, reservoirs like Legedadi and Dire are found in this basin and they are the major water supply to Addis Ababa city.

The Great Akaki River is gauged since 1981 at the Addis Ababa- Bishhoftu road bridge and the station is equipped with an automatic water level recorder and a cable for discharge measurements (Feyera Asfaw, 2007). According to area delineation of this study the size of the watershed up to the bridge is 884.63km^2 and geographically bounded between $8^0$52’34’’- $9^0$14’N and $38^0$43’18”- $39^0$04’07”E.

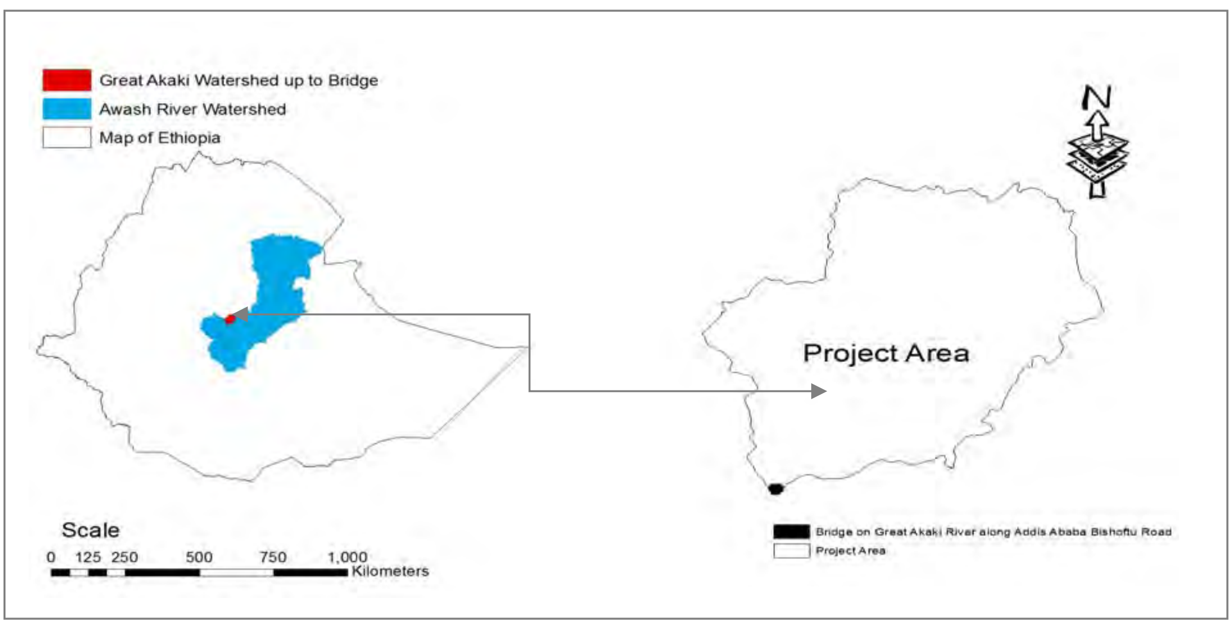


Figure 3.1: Location of the project area

3.2. Climate

Great Akaki river watershed has a subtropical highland climate (Köppen). Geographically, the study area found near to the equator due to this temperature is very constant from month to month. It is difficult to find climate data for specific to the project area, but Addis Ababa is found at the center of the catchment most of published and collected data's found and used for this project area climate data of Addis Ababa. Based on monthly averages for the 30-year period 1981-2010 as shown from table the mean monthly minimum and maximum temperatures varies from 7-11 ^{0}C and 21-25 ^{0}C respectively. The lowest temperature of the project area is 7^{0}C which is registered in November and December, and the maximum temperature is 25^{0}C registered in March and May. The main rainy season for Great Akaki watershed is late June to early September also characterized by dry a winter which is the dry season of the area. Generally the project area has annual perception of 1165mm/year.

Table 3.1: Climate of Addis Ababa based on monthly averages for the 30-year period 1981-2010

Month	Mean Daily Minimum Temperature (°C)	Mean Daily Maximum Temperature (°C)	Mean Total Rainfall (mm)	Mean Number of Rain Days
Jan	8	24	13	3
Feb	9	24	30	5
Mar	10	25	58	7
Apr	11	24	82	10
May	11	25	84	10
Jun	10	23	138	20
Jul	10	21	280	27
Aug	10	21	290	26
Sep	10	22	149	18
Oct	9	23	27	4
Nov	7	23	7	1
Dec	7	23	7	1
Total mean rain fall or rain days per year			**1165**	**132**

Source: World Weather Information Service

3.3. Topography

The topography of a watershed like elevation, slope, aspect, etc. has an important contribution for the amount of surface runoff generated from it. The typography of Great Akaki River basin is rugged and steep mostly between Entoto and Filwoha but it is gentle and flat lying in south and southwest parts of the basin (Feyera Asfaw, 2007). According to the extracted elevation of the project area from DEM, the watershed is located along elevation range from 2060 masl around Addis Ababa Bishoft Road Bridge to 3227 masl on Entoto Mountain.

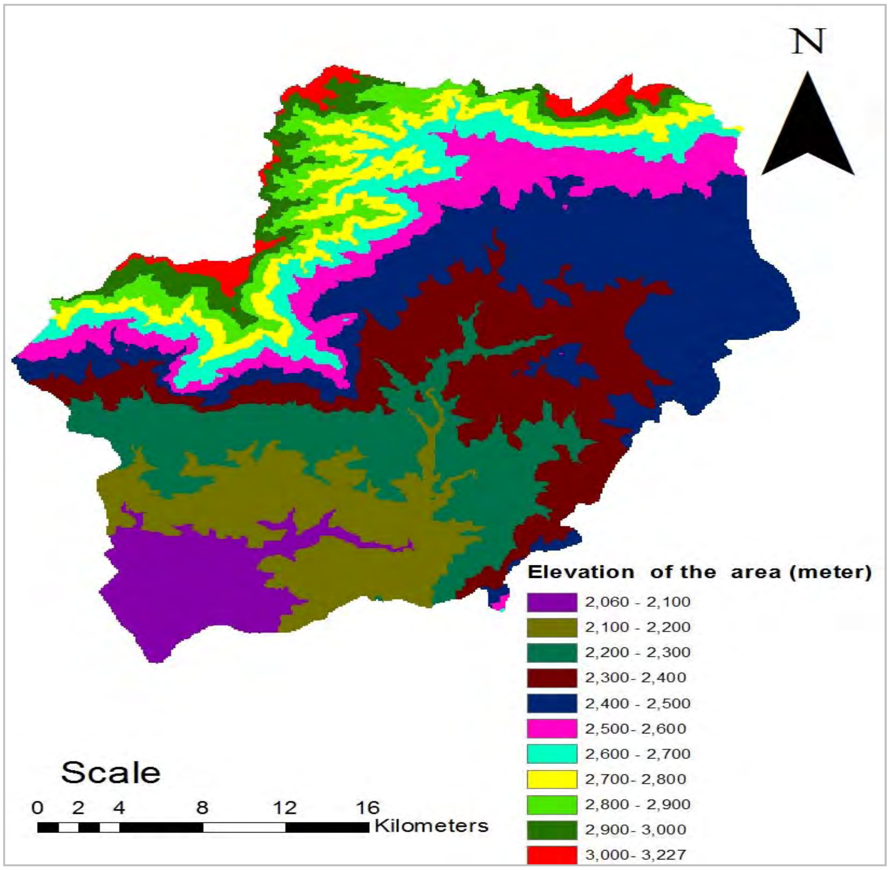


Figure 3.2: Elevation of the project area extracted from DEM

3.4. Soil Type of the Project Area

The soil development in the study area is mostly due to the physical disintegration and chemical decomposition of volcanic rocks. The weathering products are either remain in places and form residual soils or transported and deposited in the areas of Addis Ababa (Tsegaye, 2006). The soil data used for this research is obtained from ministry of agriculture and developed by Ministry of water resource in vector form. Based on this data the study area has a total of nine soil classes namely, Calcic Xerosols, Chromic Cambisols, Chromic Luvisols, Chromic Vertisols, Eutric Nitisols, Leptosols, Orthic Solonchaks, Pellic Vertisols, and Vertic Cambisols. As shown from table 3.2 and figure 3.3 soil class type Pellic Vertisols is the dominant type with 65.74% and Orthic Solonchaks, Calcic Xerosols, Eutric Nitisols and Chromic Luvisols are second, third, fourth and fifth with 11.14%, 7.96%, 5.68% and 5.26% respectively.

According to the world reference base for soil resources FAO which is updated on 2015 the major soil types of the study area defined as follows:

Chromic and Vertic Cambisols: medium and fine textured materials derived from a wide range of rocks have a property of increasing clay percentage which is the parent material of the soil is still young.

Chromic Luvisols: soils with a pedogenetic clay differentiation (especially clay migration) between topsoil with a lower and subsoil with higher clay content, high-activity clays and a high base saturation at some depth. In subtropical and tropical regions, Luvisols occur mainly on young land surfaces. Luvisols (many with the Chromic, Calcic or Vertic qualifier) are common in colluvial deposits of limestone weathering, the lower slopes are widely sown with wheat and/or sugar beet while the often eroded upper slopes are used for extensive grazing or planted with tree crops.

Eutric Nitisols: Deep, well-drained, red tropical soils with a clayey nitic horizon that has typical angular blocky structure breaking into polyhedral or flat-edged or nut-shaped elements with, in moist state, shiny aggregate faces.

Leptosols: comprise very thin soils over continuous rock and soils that are extremely rich in coarse fragments and particularly common in mountainous regions. Continuous rock at less than 10 cm depth in mountain regions are the most extensive Leptosols Such kind of soils has a resource potential for wet-season grazing and as forest land. The excessive internal drainage and the shallow depth of many Leptosols can cause drought even in a humid environment.

Orthic Solonchaks: such kind of soils have a high concentration of soluble salts and found in arid and semi-arid regions, notably in areas where ascending groundwater reaches the upper soil or where some surface water is present, with vegetation of grasses and/or halophytic herbs, and in inadequately managed irrigation areas.

Pellic and chromic Vertisols: heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out are medium.

Calcic Xerosols: These Soils occurring under an aridic moisture regime soils with accumulation of calcium carbonate (FAO – Unesco, 1974).

Table 3.2: Soil classes of the project area

Soil class type	Surface Area Coverage	
	KM^2	%
Calcic Xerosols	70.45	7.96
Chromic Cambisols	4.76	0.54
Chromic Luvisols	46.56	5.26
Chromic Vertisols	19.13	2.16
Eutric Nitisols	50.21	5.68
Leptosols	12.16	1.37
Orthic Solonchaks	98.59	11.14
Pellic Vertisols	581.57	65.74
Vertic Cambisols	1.21	0.14
Total	**884.63**	**100**

Source: Ministry of Agriculture

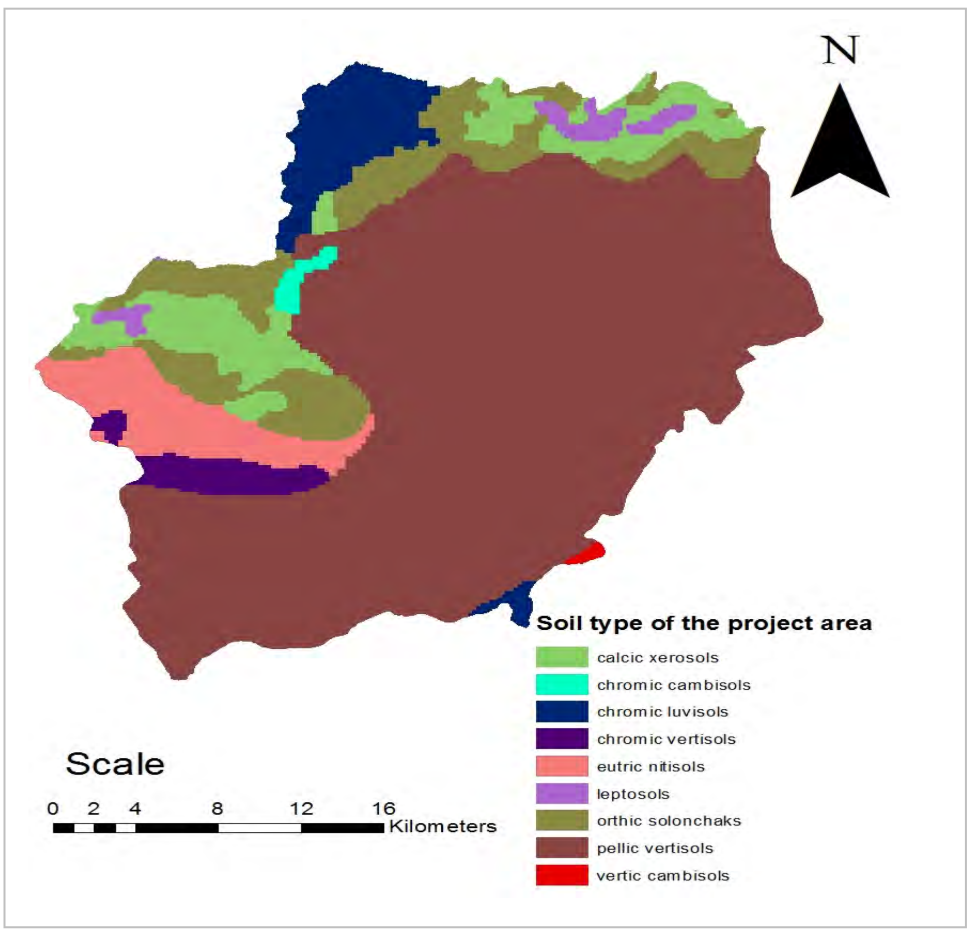


Figure 3.3: Soil type of the project area

3.5. Land Use

The land cover types of Great Akaki watershed classified in to six major classes these are water body, residential, commercial/industry/transport, open spaces, mixed forest and agriculture.

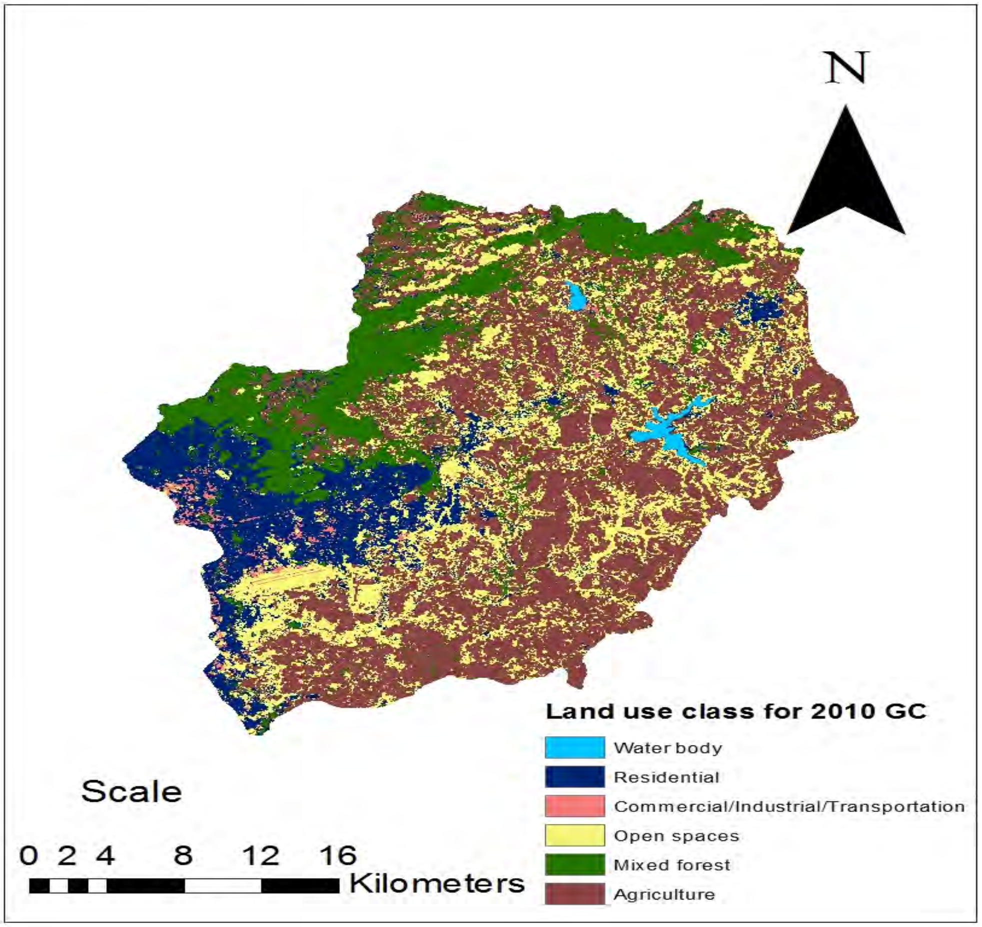


Figure 3.4: Land use map of the study area

3.6. Description of the Datasets and Model Used

In the hydrologic analysis for a watershed, it must be recognized that many variable factors affect output of floods from a watershed. Some of the factors, which are recognized and considered on this study, are rainfall amount and intensity, drainage area size, slope, elevation, ground cover or land use with percentage of impervious area, type of soil, and distance from the farthest point of the drainage area to the point of discharge. The digital elevation model is the basic dataset used in this study for basin delineation and for extracting the above characteristics of the study area. The DEM used in this study has a resolution size of 90mX90m.

For DEM extraction and to integrate the result with soil, rainfall and land use data's ArcGIS 10.1 packages, HEC-HMS 4.0, HEC-RAS 4.1, and GIS extension tools (HEC-GeoRAS 10.1 and HEC-GeoHMS 10.1) are utilized and installed which are compatible each other. HEC- GeoRAS and HEC-GeoHMS models are GIS extensions, which provide a set of procedures, tools, and utilities for the preparation of GIS data for import into HEC-RAS and HEC-HMS and generation of GIS data from HEC-RAS and HEC-HMS outputs respectively (HEC-GeoHMS, 2013 and HEC-GeoRAS, 2012).

All the maps and datasets used in this study projected in to coordinate system: WGS_1984_UTM_Zone_37N which is the zone of the study area.

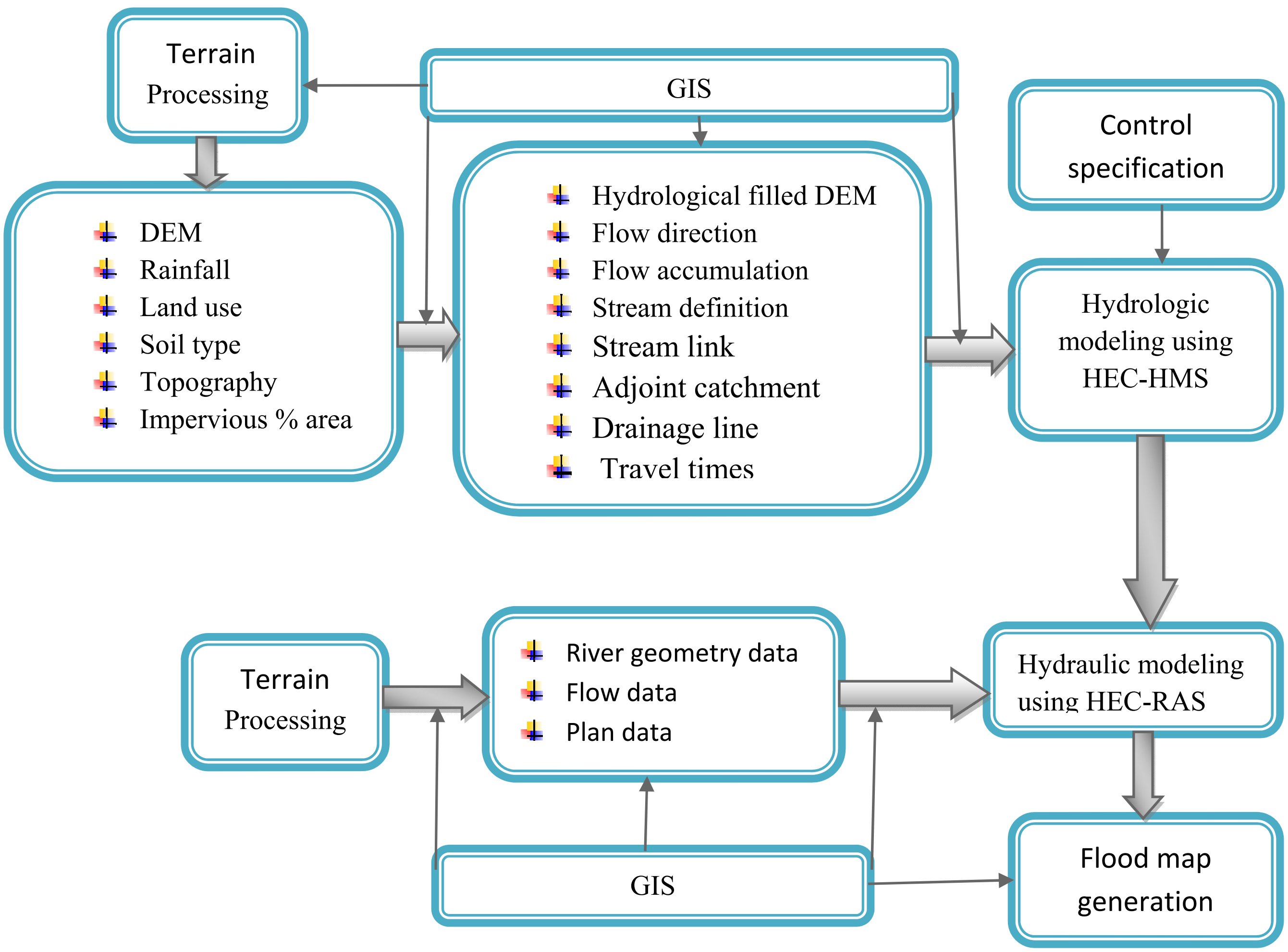


Figure 3.5: Runoff modeling system used

CHAPER 4: RESEARCH METHODOLOGY

4.1. General

This chapter is the core of the paper and the methods used for generating run off for Great Akaki River is described in detail on each sub-chapter. The major activities accomplished are digital elevation model data processing, and Curve Number (CN) grid input preparation(land use classification, hydrological soil group preparation, and merging of soil and land use shape files) using GIS and GIS extension tools; hydrological modeling using HEC-HMS; hydraulic modeling and flood mapping using HEC-RAS are done.

4.2. Digital Elevation Model Data Processing

Delineation of a basin area using traditional method like processing topographic maps consumes much time and its accuracy is very low. But, now a time this traditional method has been replaced by automatic extraction from a Digital Elevation Model (DEM) due to the release of different type of high resolution satellites to space at different time and the production of high quality data. This high quality data is freely available on different websites. DEM data is used to describe topographic characteristics such as contour, slope, elevation difference, aspect, hill shade and others. For this research, DEM is the main dataset used for development of the basin model components and geometrical data in the HEC-HMS and HEC -RAS models respectively as well as for flood hazard map generation.

The Digital Elevation Model data used in this study is downloaded from the official website of United States Geological Survey (USGS) and it is accessible by using the following link http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=3accg. The data is available in the form of GCS_WGS_1984 raster form with 90X90m resolution and it is already conditioned. To make it available for hydrologic modeling purpose the following tasks are done.

1. The DEM in the form of GCS_WGS_1984 raster format is changed in to the Universal Transverse Mercator (UTM) projection raster form by considering zone of the study area which WGS-1984, UTM Zone 37N by using Arc GIS 10.1 software package.
2. The projected DEM clipped by using shape file of the study area as shown from picture 1
3. Fill sinks: If cells are available with higher elevation surrounding a cell, the water is trapped in that cell and cannot flow. Therefore this functions used for this study to modify the elevation value to eliminate these problems by creating a depression less or hydrologically corrected DEM based on the input row DEM.

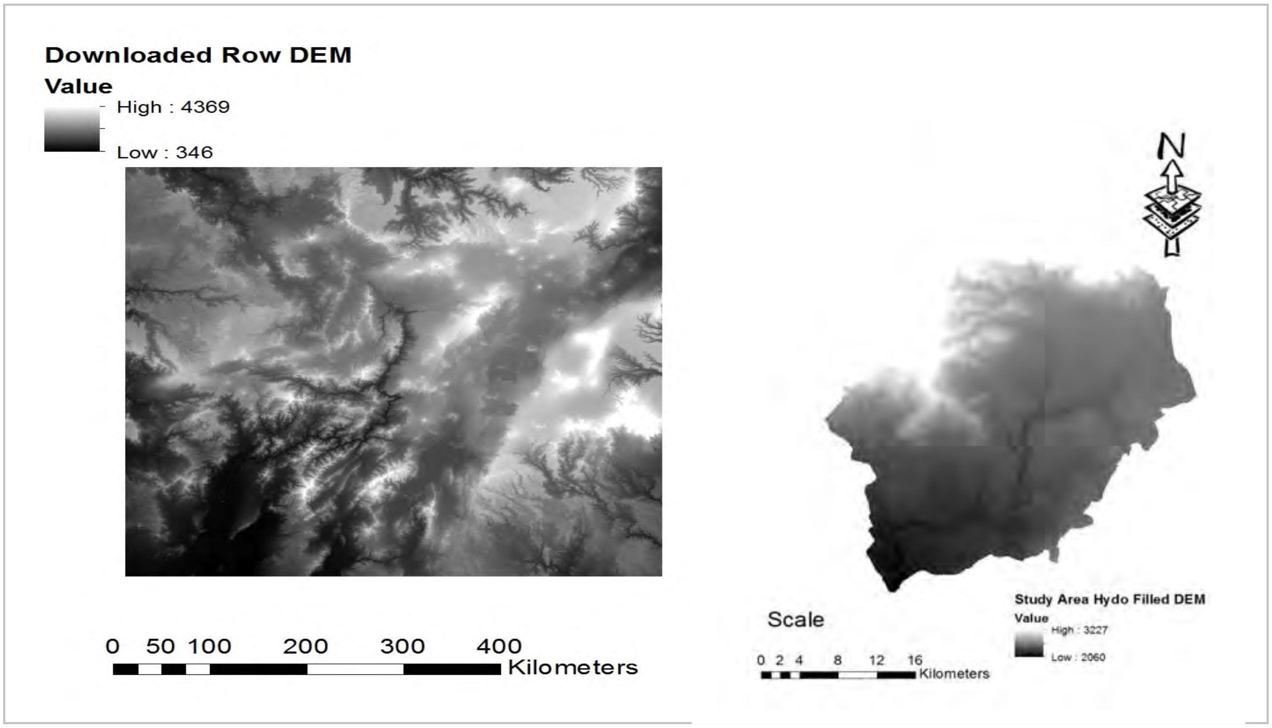


Figure 4.1: downloaded row DEM (left) and clipped hydro filled DEM (left)

4. Flow direction: It is generated from the fill sinks grid and indicates the direction of the steepest descent to a neighbor cell and defined for each grid cell. As shown from figure 4.2 the number in the legend represents directions; 1 = east, 2 = southeast, 4 = south, 8 =south west, 16 = west, 32 = northwest, 64 = north, 128 = northeast.

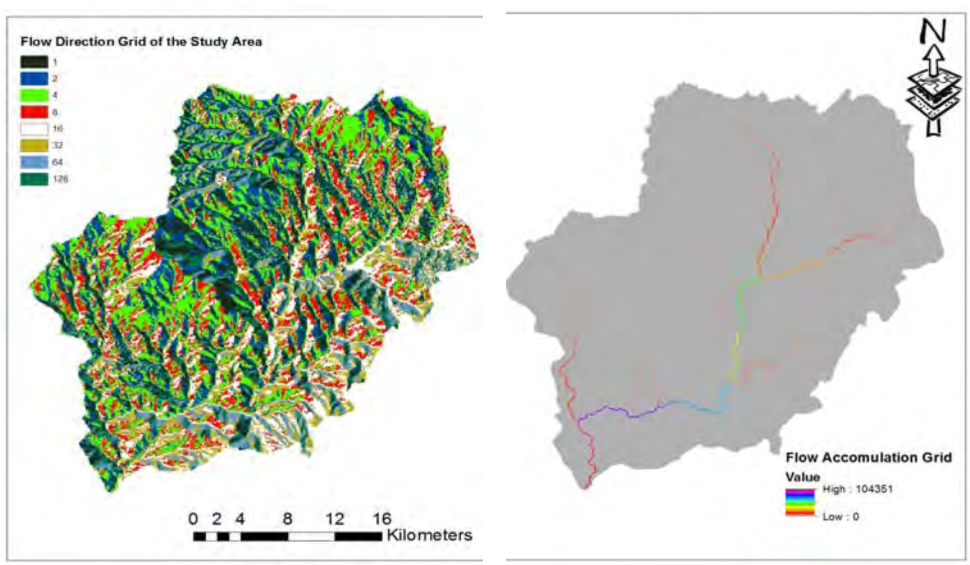


Figure 4.2: generated flow direction (left) and flow accumulation (right)

5. Flow accumulation**:** generated from the flow direction grid and defines the number of upstream cells draining into any given cell in the grid.
6. Stream definition: the cells that form the stream network are defined based on a threshold number of cells that drain into a given cell.
7. Stream segmentation: created by splitting the streams as defined in the stream definition grid at any junction.

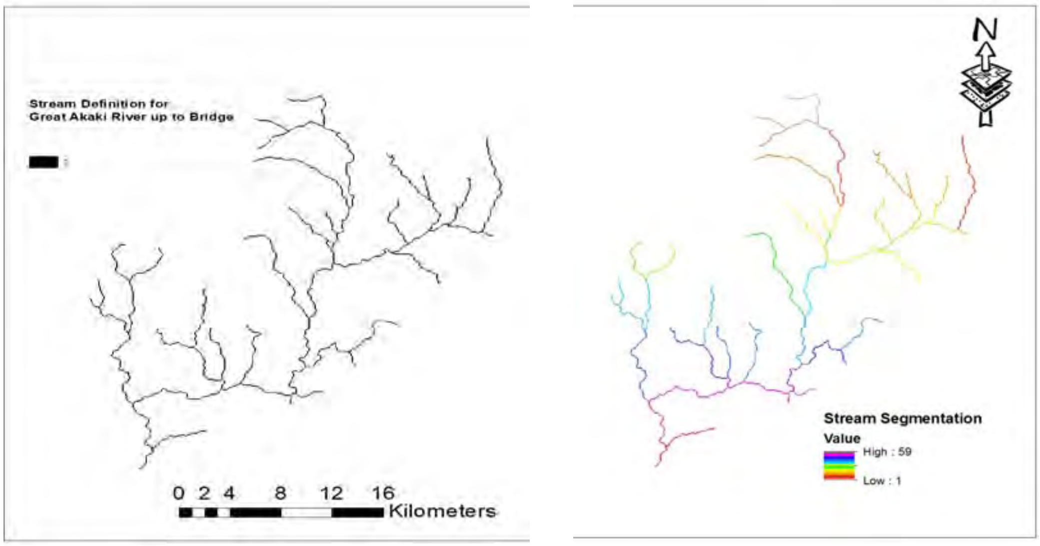


Figure 4.3: stream definition (left) and stream segmentation (right)

8. Catchment grid delineation: For every stream segment defined by the stream segmentation grid, the corresponding watershed is delineated and stored in a grid file. As shown from picture.
9. Catchment polygon processing: This polygon generated from the catchment grid to delineate the boundaries of each sub basin.

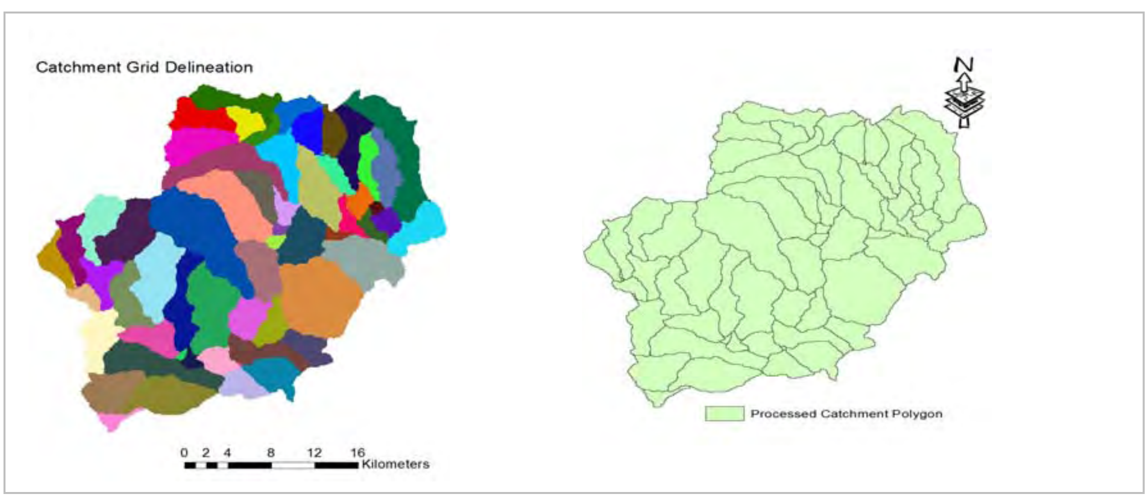


Figure 4.4: catchment grid (left) and polygon (right)

10. Drainage line processing: generated from stream segmentation grid are transformed into a vector stream layer by this function.
11. Adjoint catchment processing: the upstream sub basins are aggregated at any stream confluence

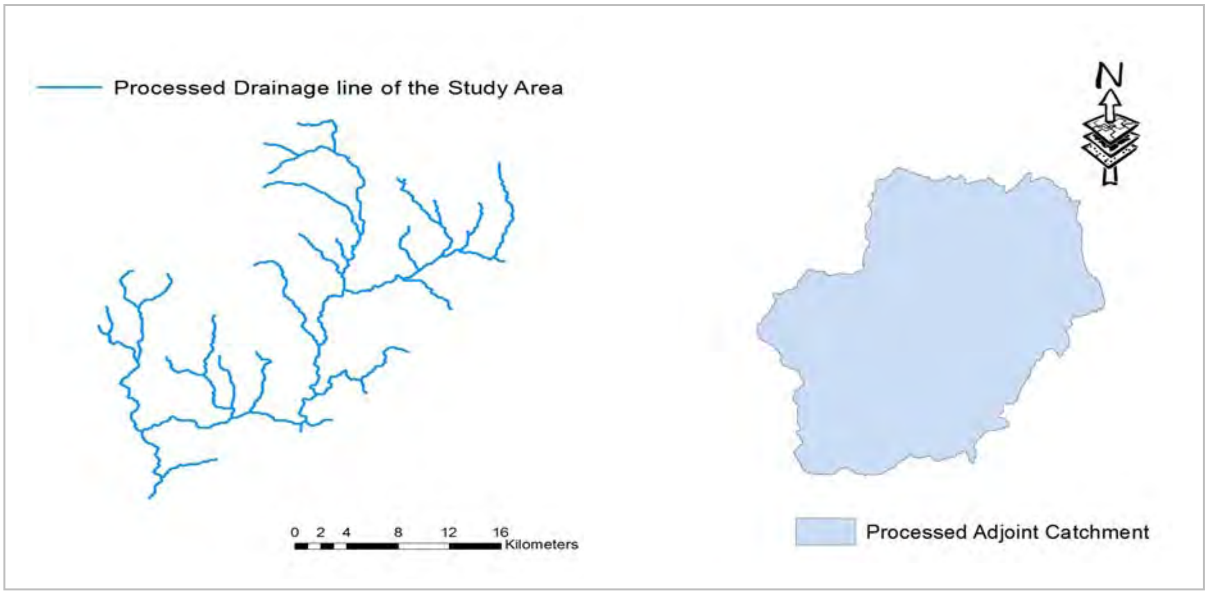


Figure 4.5: processed drainage line (left) and adjoint catchment (right)

12. Watershed slope

According to FAO (2006) slope classification, the study area is characterized on a range of flat (below 0.2 % slope) to very step which is > 60% around Intoto as shown from table 4.1 and figure 4.6.

Table 4.1: Slope gradient classes (FAO, 2006)

Class	Description	Slope %
01	Flat	0-0.2
02	level	0.2-0.5
03	Nearly level	0.5-1.0
04	Very gently slope	1.0-2.0
05	Gently slope	2-5
06	Sloping	5-10
07	Strongly sloping	10-15
08	Moderately steep	15-30
09	Steep	30-60
10	Very step	>60

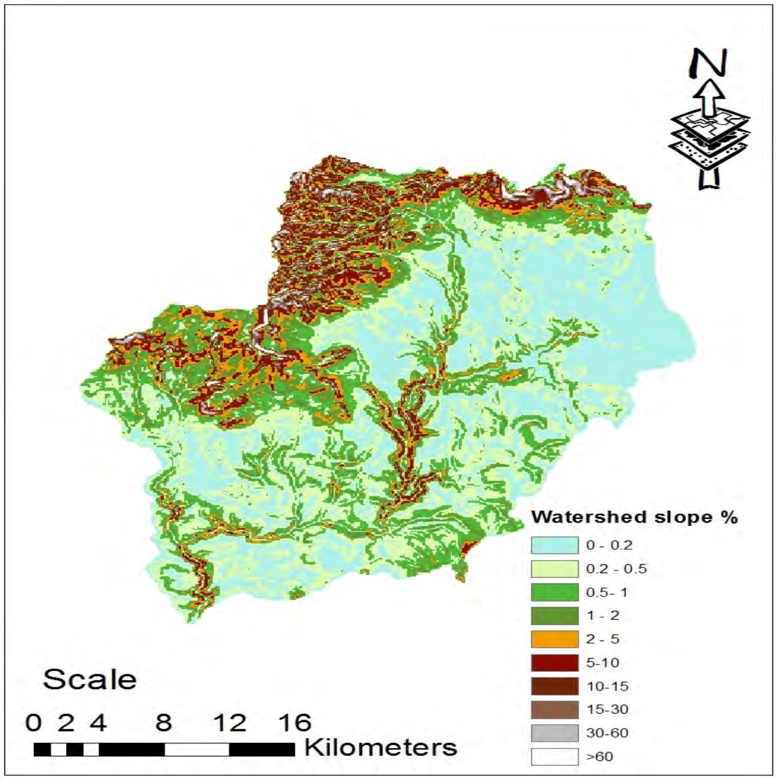


Figure 4.6: slope of the watershed extracted from DEM

Before continue to the next step of hydrological modeling, as discussed from the above the following datasets in the map document should be prepared and ready by the necessary data formats. Those datasets are inputs for HEC- GeoHMS for HEC-HMS basin model generation.

Raster forms

- Projected DEM (considered as raw DEM)
- Fil (sink filled DEM)
- Fdr (flow direction grid)
- Fac (flow accumulation grid)
- Str (stream network grid)
- StrLnk (stream link grid)
- Cat (catchment grid)
- WshSlopePct (slope grid in %)

Vector forms

- Catchment
- DrainageLine
- AdjointCatchment

4.3. Curve Number (CN) Grid Input Preparation

4.3.1. General

The U.S. Natural Resource Conservation Service (NRCS) (formerly the Soil Conservation Service (SCS)) Curve Number method used in this study estimates the effective rainfall as a function of the cumulative rainfall, the land use, the soil type and the antecedent moisture condition of the soil

The runoff curve number is an empirical parameter uses for estimating direct runoff or infiltration from rainfall excess. The runoff curve number is generated from the study area's land use and hydrologic soil groups.

Watershed land cover has a great importance in estimating the basin's curve number with the identification of soil textures and its permeability. Thus, according to the classification of Soil Conservation Service (SCS) method soil types of the catchment are grouped for each of the Great Akaki River sub-basins already created on previous. This method has been widely applied to estimate storm runoff depth for every patch within a watershed based on runoff curve numbers (CN) **(**Qihao Weng, 2001). The first step for curve number generation is landsat data processing and analysis by using Arc GIS 10.1 software package.

4.3.2. Landsat Data Processing

As previously described, determination of Runoff Curve Number (CN) requires land use classification and the potential of deriving land use maps from satellite images is one of the main aims of this study. Land use from large areas can be detected easily in a short time with low cost compared to the traditional methods.

The landsat data used is downloaded from the official website of United States Geological Survey (USGS) and it is freely accessible by using the following link: http://earthexplorer.usgs.gov/. For this study the landsat data of the catchment for 1989, 2000 and 2010 with a resolution of 30mX30m is selected and used. The selection is based on the available hourly rainfall, quality of image and resolution available for the above years.

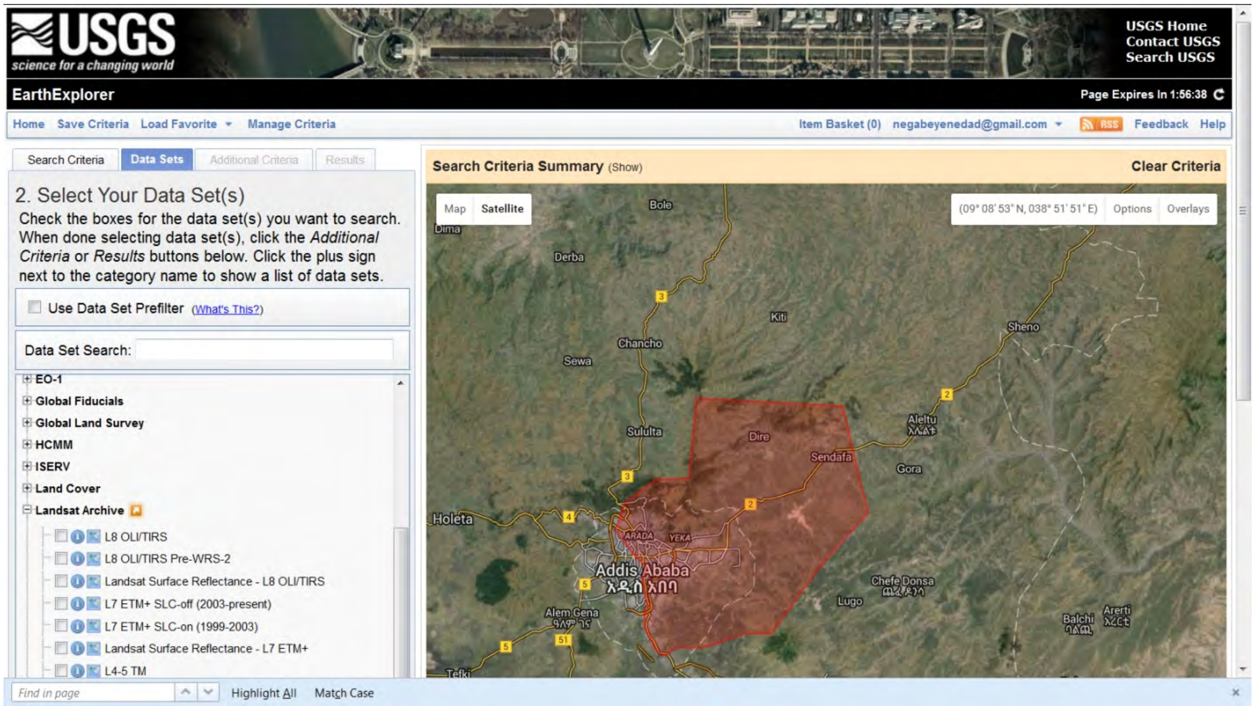


Figure 4.7: Landsat5 data downloaded from official website of US Geological Survey (USGS)

As shown from picture 6, to downloading the landsat data first KML file with a maximum of 30 points of the watershed is prepared and uploaded to the above site. The landsat data downloaded from the landsat archive in the form of Geotiff with different bands. Before utilizing the data the following activities are done using Arc GIS 10.1 software package.

1. All the available bands of satellite image are combined by using composite bands function
2. The combined landsat data in the form of GCS_WGS_1984 raster format is changed in to the Universal Transverse Mercator (UTM) projection raster form by considering zone of the study area which WGS-1984, UTM Zone 37N by using Arc GIS 10.1 software package.
3. The projected landsat data is clipped by using the shape file of the study area which is previously prepared.
4. Individual bands composited in a Red, Green and Blue (RGB) combination in order to visualize the data in color. There are many different combinations that can be made but in this case 3, 2, 1 RGB combination is selected**.** This color composite is as close to true color. As shown from the picture the numbers 3, 2, 1 are representing Red, Green and Blue respectively. At this stage the landsat data is ready for land use classification.

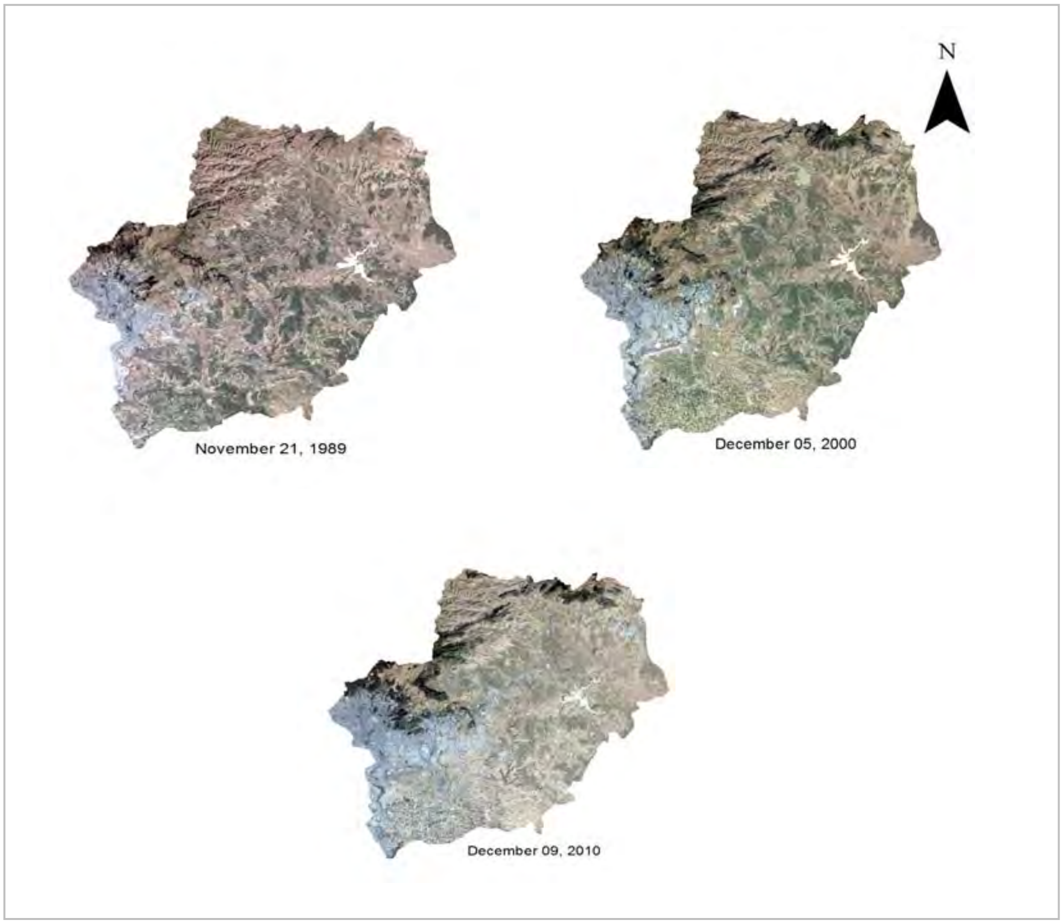


Figure 4.8: Landsat5 data used for land use classification

5. Land use classification: the land use classification was performing using a supervised classification method using create signature and maximum likelihood classification functions of ArcGIS. Land use/cover class is carried out by assigning a grid code for each class. Accordingly, six types of land use were identified in the study area, namely water body, residential, commercial/industry/transport, open spaces, mixed forest and agriculture land. Finally, the land use classification cross checked by using the land use map classification of Addis Ababa city for the respective years from Addis Ababa land City Land Development and Management Bureau The classified land use raster maps of each selected year were vectorized and converted to land use shape file maps using raster to polygon function. At this stage the land use data can merge with soil data for curve number generation and extraction of area coverage for each class is possible.

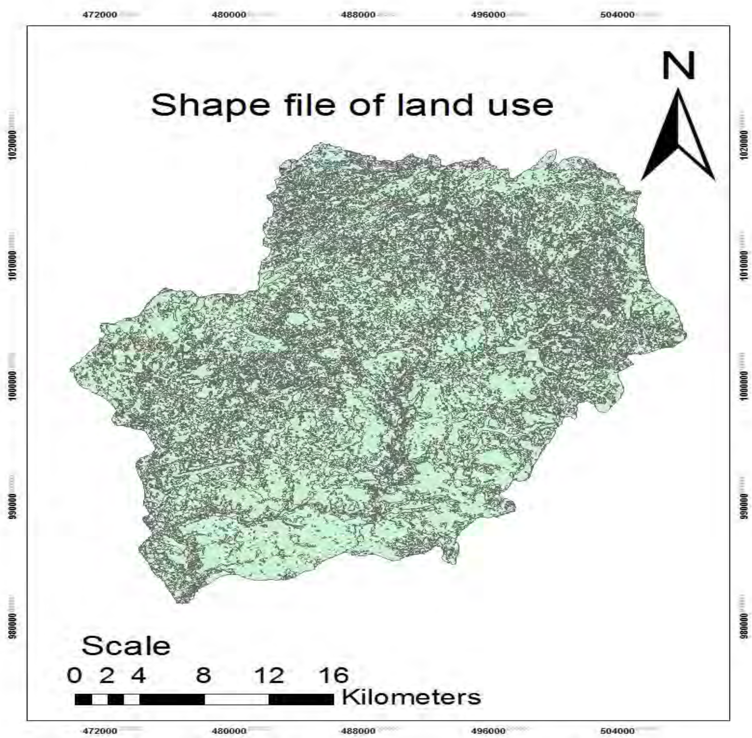


Figure 4.9: Processed land uses as shape file

Table 4.2: Land use area coverage of the study area (%)

No	Land use type	Percentage of land use		
		1989	2000	2010
1	Water body	0.52	0.66	0.63
3	Residential	8.77	12.88	17.96
4	Commercial/Industrial	2.13	2.61	3.97
5	Open spaces	31.58	28.56	26.61
6	Mixed forest	19.74	20.41	18.99
9	Agriculture	37.26	34.88	31.84
Total		**100**	**100**	**100**

4.3.3. Preparing Soil Data for CN Grid

According to the classification of (USDA, 1986), soils classified into four hydrologic groups namely A, B, C and D. A soil types has high infiltration rate; B soils types has moderate infiltration rates; C soil types has slow infiltration rate and D soil types has very slow infiltration rate. Accordingly the soil map of the study area found from Ministry of agriculture as shape file and all of these soil types found in the area categorized on three Hydrological Soil Groups (HSG), namely B, C and D. The proportional percentage area coverage of each HSG is 30.72%, 1.37% and 67.90% for B, C and D respectively and clearly indicated on table 4.3 and figure 4.10.

Table 4.3: Hydrological Soil Group (HSG) coverage of the study area

Hydrological Soil Groups (HSG)	Surface Area Coverage	
	Km^2	%
B	271.78	30.72
C	12.16	1.37
D	600.70	67.90
Total	**884.63**	**100**

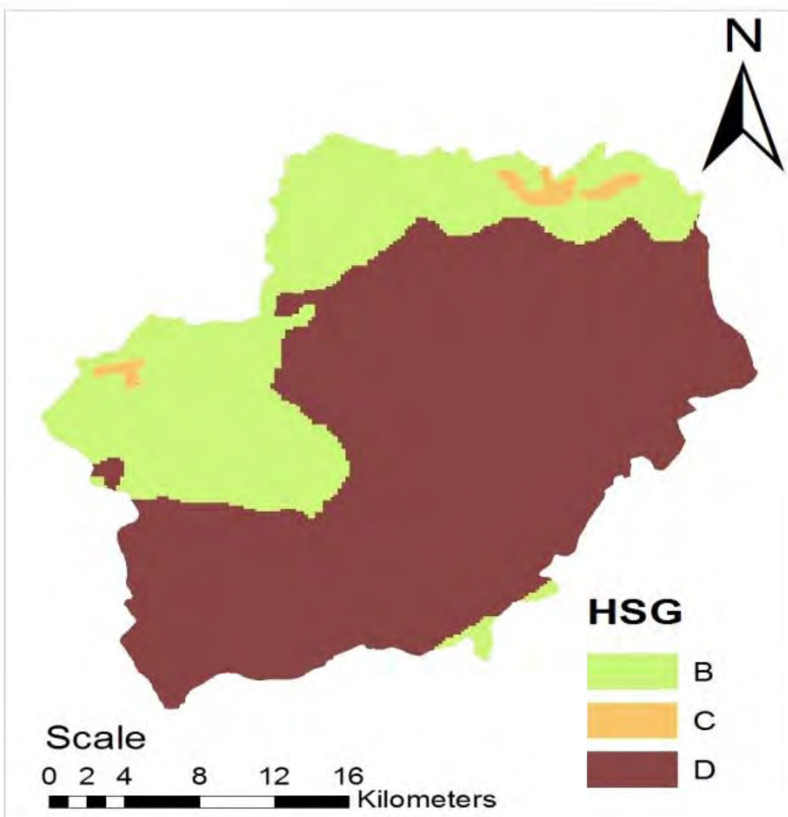


Figure 4.10: HSG coverage of the project area

4.3.4. Merging of Soil and Land Use Data

As previously discussed both the land use class and soil class of the project area are prepared in shape file format which are very important data's for curve number /CN generation. But, to utilize this data for CN generation the two shape files are merged by using union function of Arc GIS 10.1 software package. The union function uses the both land use and soil feature classes as input. The output of merged features contains attributes values from both inputs.

4.3.5. Creating CN Look-up Table

Curve number look up table is the most fundamental input table for CN grid generation and created by using create table function of Arc GIS 10.1 and assigned Hydrological Soil Group (HSG) for each land use type as shown from table 4.4.

Table 4.4: Created CN look up table

Description of land use type	**Hydrologic Soil Group (HSG)**			
	A	**B**	**C**	**D**
Water body	100	100	100	100
Residential	61	75	83	87
Commercial/industrial	89	92	94	95
Open spaces	68	79	86	89
Mixed forest	36	60	73	79
Agricultural Land	68	78	86	89

The columns represented by A, B, C and D stores curve numbers for each of corresponding soil groups for each land use category and the values are determined by using SCS TR55 (1986). The CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates. Accordingly the minimum and maximum CN values of the study area are 60 and 100 respectively.

Now all the necessary inputs for hydrological modeling are prepared and ready based on the required standard.

4.4. Hydrologic Model Development and Run off Generation

4.4.1. General

In this section, the methods, models and procedures that was applied to generate the runoff for Great Akaki River is described in detail. The hydrological modeling/simulation is completed by using the following HEC-HMS methods: for infiltration loss simulation SCS CN method; converting excess rainfall to runoff model SCS unit hydrograph (UH), and channel flow routing accomplished by using Muskingum routing method.

The main input data for the rainfall-runoff modeling was a topographic data's extracted from digital elevation model of 90m resolution two type of formats which are inputs for HEC-GeoHMS modeling.

Raster formats: projected DEM, sink filled DEM, flow direction grid, flow accumulation grid, stream definition grid, stream link grid, catchment grid and slope grid.

Vector formats: Catchment, drainage line and adjoint catchment.

In addition to this hourly rainfall, CN lookup table, impervious percentage area and land use/soil union shape file of the great Akaki River watershed are required and all are already prepared using ArcGIS software package.

4.4.2. Preparing HEC-HMS Model Inputs from HEC- GeoHMS

HEC-GeoHMS extension is developed by the US Arms Corps of Engineers Hydrology Engineering Center and freely available by using the link: http://www.hec.usace.army.mil/software/hec-geohms/downloads.aspx. It is an Arc GIS soft ware extension used to link and export the out puts of Arc GIS to HEC-HMS software. In this study HEC-GeoHMS 10.1 extension is used which is compatible for both ArcGIS 10.1 and HEC-HMS 4.0 software packages. The project setup menu of HEC-GeoHMS has tools for delineating the basin, and defining the outlet of the basin which are very important inputs for HEC-HMS project generation.

4.4.2.1. Creating Impervious Grid of Project Area

Now a day knowing percentage of impervious cover is very important in land use planning and management. It is a key factor for hydrological modeling especially in urban watersheds. Percentage of impervious grid needed to map as a continuous variable and its value ranges from 0 to 100 percent. 0 indicates the entire area is pervious almost all of the rain fall in the area infiltrates in to subsurface of the area and 100 means all the available rainfall gives runoff and infiltration is almost 0.

Based on the land use classification of this study; there are 6 classifications namely, water body, residential, commercial/industrial/transportation, open spaces, mixed forest, agriculture lands. Accordingly, percentage of impervious value for we assigned for each category and tabled. The assigned values are based on SCS TR55 (1986) and user's guide for the California impervious surface coefficients. Land uses may vary from watershed to watershed, but can be defined on a given range.

The first step in impervious grid generation using HEC-GeoHMS is converting land use map (grid) into a polygon feature class and add percentage of impervious as on the attribute table of land use polygon feature class. Percent land use impervious is prepared in excel format and opened in Arc GIS. By using join function of Arc GIS the land use polygon feature class and the excel table are joined. Previously created impervious field on the land use polygon feature class is calculated based on the assigned impervious percent values of excel by using field calculator function.

The second step is generating impervious grid using HEC-GeoHMS feature to raster function use (Input features: land use polygon, field: land use impervious percentage area). This generated percentage of impervious grid is basic input for HEC-HMS project generation.

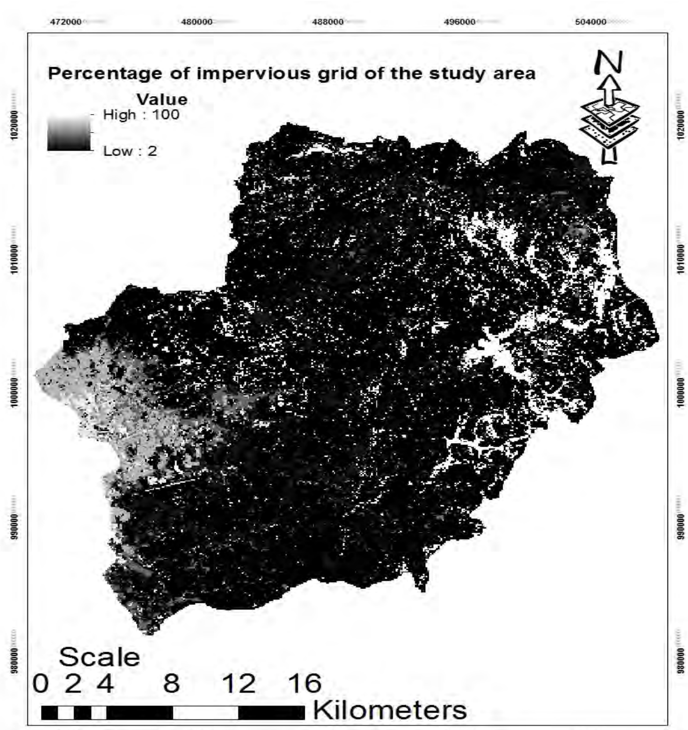


Figure 4.11: Generated impervious grid

4.4.2.2. Curve Number Grid Generation

To create the curve number grid HEC-GeoHMS needs the following files; merged land use and soil data, sink filled DEM and CN lookup table. All of those data are created on the previous steps in the appropriate format and using these three inputs the CN grid is generated by using generated grid function of HEC- GeoHMS model.

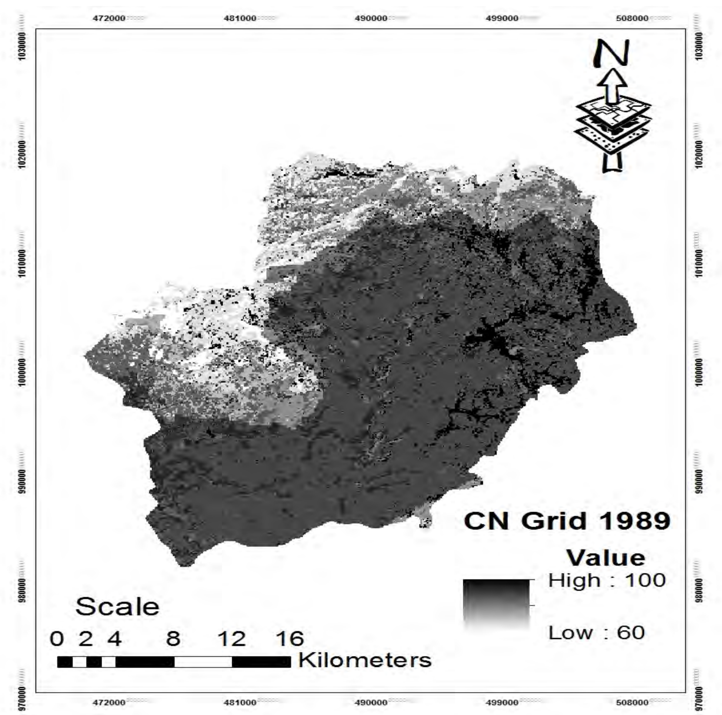


Figure 4.12: Generated Curve Number (CN).

4.4.2.3. HEC-HMS Project Generation

To create an HMS project different tools of HEC- GeoHMS are used which are found on four main views namely; HMS project set up, basin characteristics, HMS input parameters and HMS menus.

HMS project setup

- **Data management window**: The necessary data sets used for HMS project generation are added these are: row DEM, Sink filled DEM, flow direction grid, flow accumulation grid, stream network grid, stream link grid, catchment, adjoint catchment and drainage line. Theses data's are checked on the data management window of HEC- GeoHMS and assigned based on the corresponding map layers used to generate the project.
- **Creating new HMS project**: start new project; assign **GreatAkakiWatershed** on project area and **BridgePoint** on the project point. Then project point and project area feature classes are created.
- **Main outlet of the watershed assigned:** the main outlet of the watershed is at the Bridge of Addis Ababa to Bishoftu road and assigned for each year: 1989, 2000 and 2010 by using add project point tool of HEC- GeoHMS.
- **Generate HMS project**: before generating a project the data management window of HEC GeoHMS is checked and HMS project is generated by creating a mesh (by delineating watershed for previously created main outlet of the Great Akaki watershed)

Extracting watershed characteristics

Extracting physical characteristics of sub-basins and streams into attribute tables is accomplished by using the basin characteristics menu of HEC- GeoHMS these are:

- **River length:** the length of each river segments is computed and stored by using the Great Akaki River name as input.
- **River slope:** this tool computes the slope of the river segments and stores by using raw DEM and created river.
- **Basin slope:** average slope of each the 59 sub-basins is computed using the slope grid and sub-basin polygons.
- **Longest flow path:** the longest flow path for each sub-basins of Great Akaki River is created by using raw DEM, flow direction grid and sub basins as in put.
- **Basin centroid:** a point feature class is created and stored for the centroid of each sub-basin.
- **Basin centroid elevation:** the elevation for each centroid point is created by using raw DEM and basin centroid as inputs.

- **Centroidal longest flow path:** a polyline feature class is created by using this tool. The creation of this polyline shows the flowpath for each centroid point along longest flow path each sub basin.

HMS Inputs/Parameters

The hydrologic parameters menu of HEC - GeoHMS has tools to estimate and assign watershed and stream parameters. With this menu HMS processes selected, river auto name, basin auto name, sub-basin parameters and CN lag method are computed.

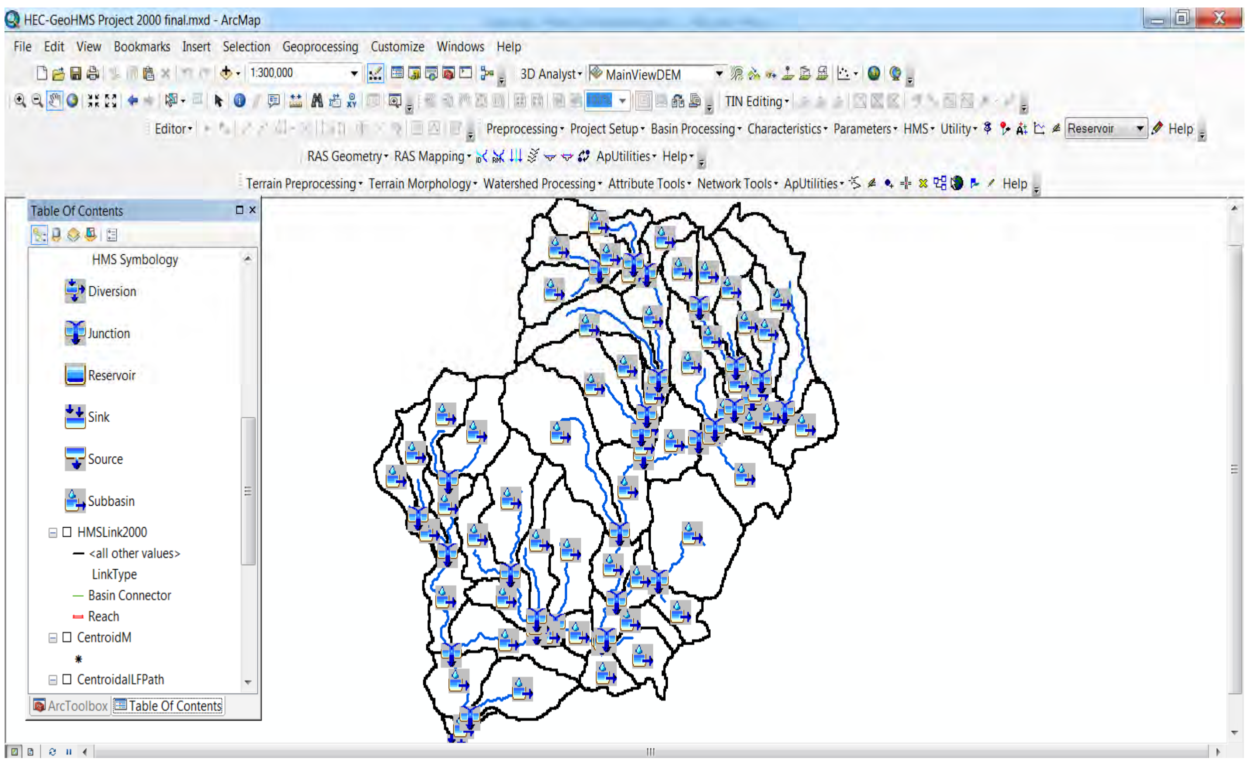


Figure 4.13: Generated HEC-HMS project using HEC- GeoHMS

HMS project creation

By using tools found in the HMS menu input files for HEC-HMS are created. Activities accomplished using those HEC- GeoHMS menu are: HMS units assigned, data checking, HMS schematic, HMS toggling and legend, add coordinates, prepare data for model export, background shape file, basin model, meteorological model created and finally HMS project is created know the project is ready for HMS Process as shown on the picture.

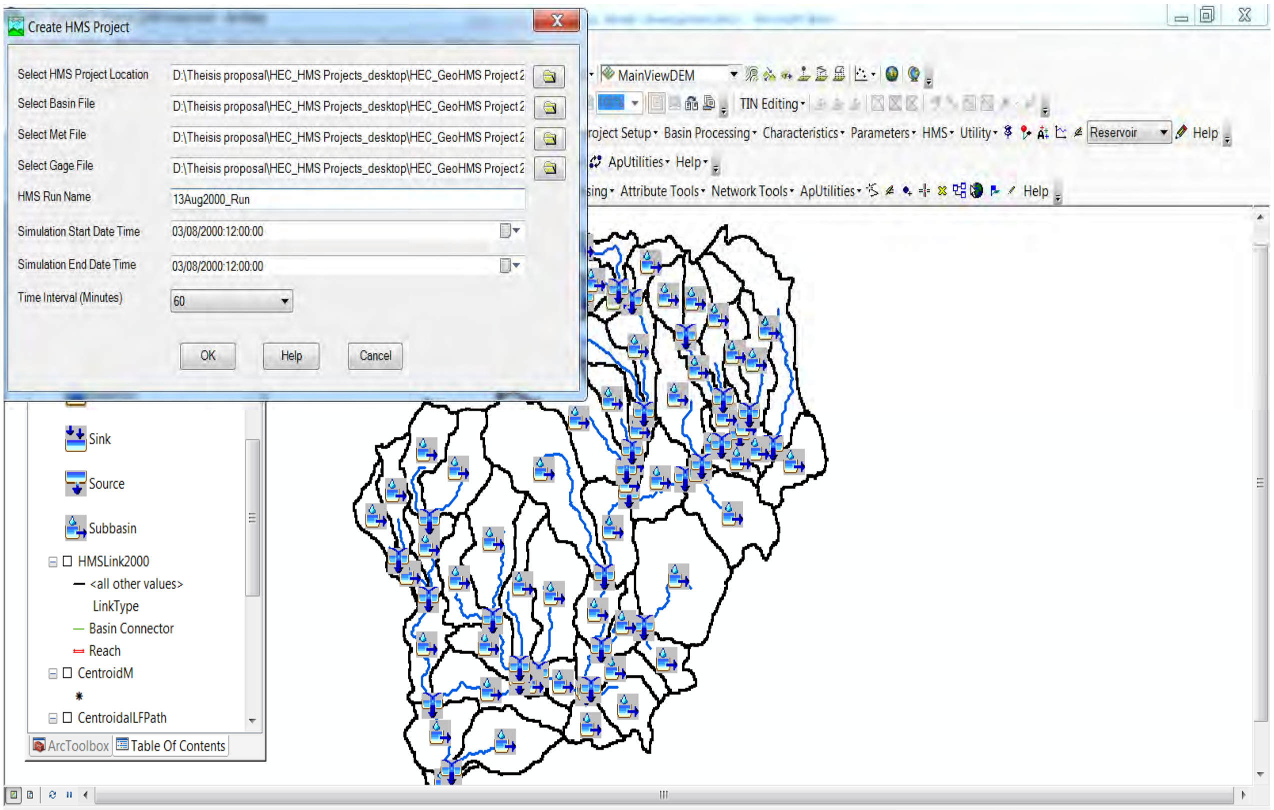


Figure 4.14: created HEC-HMS project

4.4.3. HEC-HMS Model Analysis

4.4.3.1. General

First HEC-HMS 4.0 is downloaded from the official website of US Army Corps of Engineers freely by using this down load link: http://www.hec.usace.army.mil/software/hec-hms/downloads.aspx. For simulating precipitation-runoff processes the HEC-HMS model has the following major components these are: basin model, meteorologic model and control specification. Totally the watershed has 59 sub basins, 29 reaches and 29 junctions with upstream to downstream sequence. The control specification contains time related information (year, starting date and time, end date and time) for the simulation. The HEC-HMS model analysis categorized in to two:

- Flood modeling using hourly rainfall for urbanization effect analysis
- Flood modeling by frequency storm method for hydraulic analysis

4.4.3.2. Flood Modeling Using Hourly Rainfall

Creating a meteorological model

A time series of rainfall data is defined for each of the available meteorological stations and these gauges are associated based on the nearest sub-basins as shown on figure 4.15.

The source of meteorological data for the study area is Ethiopia National Meteorological Agency (NMA). Generally ten rain fall gauging stations are found in the project area namely; Sendafa, Dire dam, Akaki, Kotebe, Kality, Megabit_28, Intoto, Addis Ababa Bole NMA head office, Addis Ababa Bole Airport and Addis Ababa Observatory station, but only Addis Ababa Bole Airport and Observatory stations are first class rainfall stations and the only stations which have automatic recorders.

Table 4.5: Meteorological stations used

Station	Year of establishment	Geographical location	
		Latitudes	Longitudes
Addis Ababa Bole	1954	9^0 2’ 00”	38^0 45’ 00’’
Addis Ababa Observatory	1944	9^0 1’ 08’’	38^0 44’ 51’’

Source: National Meteorological Agency.

For this study hourly rainfall intensity of the two first class stations used for 18 July 2010 is taken and applied for 1989, 2000 and 2010. To avoid rainfall variation and distribution equal amount of rainfall is taken for all years and these years are selected based on available hourly rainfall for both stations and cloud free land sat data.

Table 4.6: Hourly rainfall intensity used for the study,

Day/Month/ Year			18/07/ 2010		
Hours	Stations		Hours	Stations	
	Addis Ababa Bole	Addis Ababa Observatory		Addis Ababa Bole	Addis Ababa Observatory
23:00	0	0	13:00	0	0
0:00	8	0	14::00	0	0
1:00	5.2	0	15:00	0	0
2:00	1.4	8.5	16:00	0	0
3:00	1.2	9	17:00	0	0
4:00	0	3.6	18:00	0	0
5:00	0.3	1.1	19:00	0	0
6:00	0	0.9	20:00	0	0
7:00	0	0.1	21:00	0	0
8:00	0	0	22:00	0	0
9:00	0	0	23:00	0	0
10:00	0	0	0:00	0	0
11:00	0	0	**Total Depth (mm)**	**16.1**	**23.2**
12:00	0	0			

Source: National Meteorological Agency

Division of Great Akaki basin into various sub-basins

A catchment was already delineated in to 59 sub basins, 29 river reaches and 29 junctions on the HEC-HMS input preparation using HEC-GeoHMS. As shown from figure 24 each sub basins of the study area are given unique and clear name, and saved.

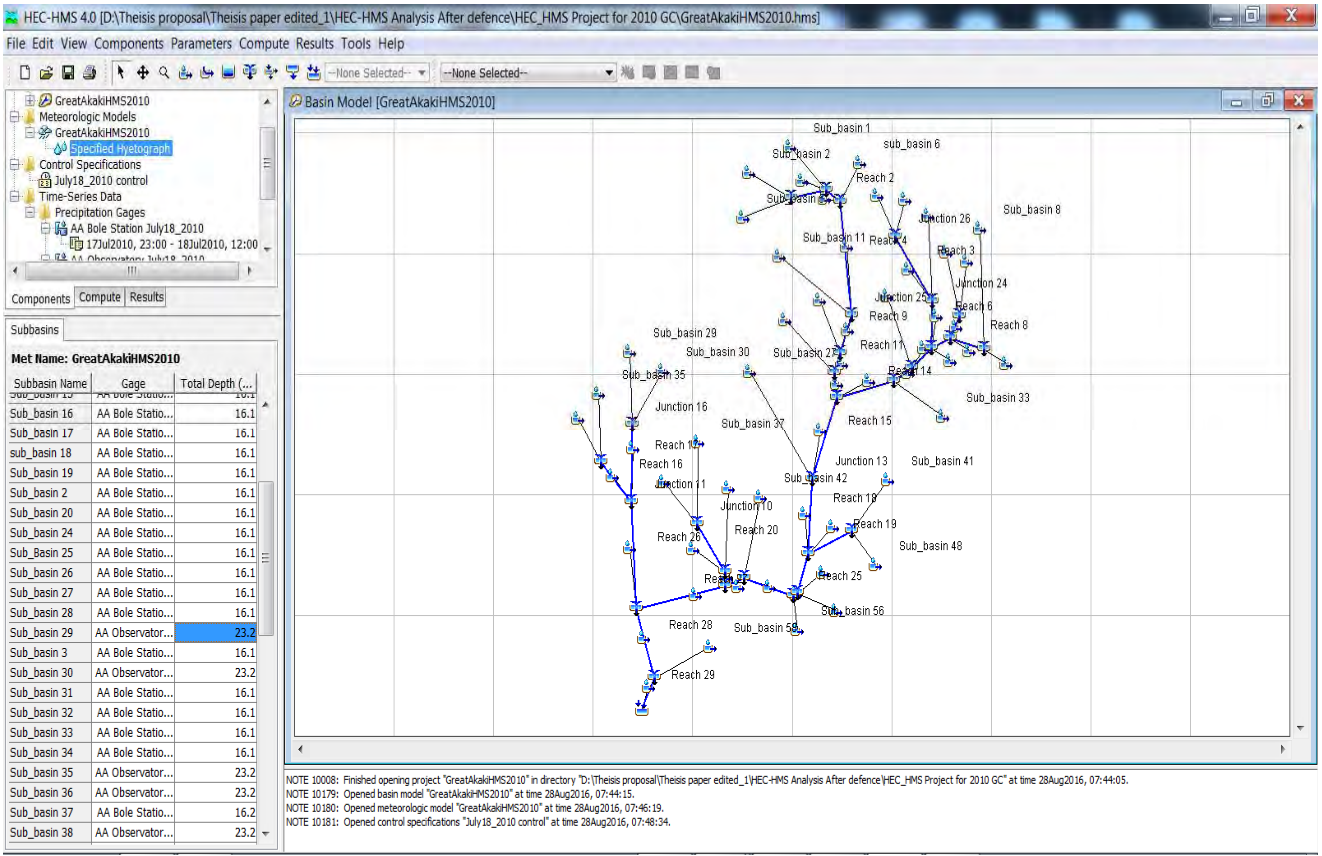


Figure 4.15: Created sub-basins of the study area

Checking HMS parameters

Some of the parameters are already processed and assigned previously on the HMS project generation using HEC-GeoHMS and it is important checking them. These are values of SCS curve number, % impervious and SCS Unit Hydrograph.

Routing method

The other important HMS parameter is routing method determination of reaches which is a key factor in hydrologic modeling. In this study Muskingum routing method is selected due to the following reason; Muskingum routing method a simple conservation of mass approach to route flow through the stream reach (HEC-HMS 4.0 user's Manual). Muskingum routing method has two basic parameters called Muskingum K and Muskingum X. Muskingum K is the travel time of the water through the reach and its unit is hour. It can be estimated from knowledge of the cross section properties and flow properties (HEC-HMS 4.0 user's Manual). Muskingum X is the weighting between inflow and out flow influence and it ranges from 0 .0 – 0.5 and a value of 0.0

gives results of maximum attenuation and 0.5 gives a result of no attenuation (HEC-HMS 4.0 user's Manual).

The travel time K of the flood wave was estimated using the following equation

$$K = \frac{L}{V} \quad \text{[eq. 4.1]}$$

Where, L = length of the river reaches (m) extracted from DEM

V = Velocity of flood (m/s)

$$V = \frac{Q}{A} \quad \text{[eq. 4.2]}$$

Where, Q = flood discharge (m^3/s)

A = cross section area at (m^2)

Based on this research the study area has a total of 29 reaches and by considering the above points, the correct values for Muskingum K and Muskingum X is assigned.

Executing the model and viewing the result

After all HMS parameters were entered and checked the HMS model is executed for each of the selected years. With regard to the viewing the HMS result HMS allows to view results both graphical and tabular forms.

4.4.3.3. Model Calibration and Validation

The main aim of model calibration is to adjust the model parameters values and to fit the model results with the observed or measured values. Model validation involves running a model using input parameters measured or determined during the calibration process (Moriasi, Arnold, Van Liew, Bingner, Harmel and Veith, 2007).

Objective functions

To compare a computed hydrograph to an observed hydrograph, the HEC-HMS program computes an index of the goodness-of-fit. Algorithms included in the program for the model parameters that yield the best value of an index, also known as objective functions (USACE, 2000). Totally eight objective functions are available in HEC-HMS 4.0 optimization manager (figure 4.16) and some of them are explained below:

- **Sum of absolute errors.** This objective function compares each ordinate of the computed hydrograph with the observed, weighing each equally. The index of comparison, in this case, is the difference in the ordinates. However, as differences may be positive or negative, a simple sum would allow positive and negative differences to offset each other. In hydrologic modeling, both positive and negative differences are undesirable, as overestimates and underestimates as equally undesirable. To reflect this, the function sums the absolute differences. Thus this function implicitly is a measure of fit of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs. If the value of this function equals zero, the fit is perfect: all computed hydrograph ordinates equal exactly the observed values (USACE, 2000).
- **Sum of squared residuals.** This is a commonly-used objective function model calibration. It too compares all ordinates, but uses the squared differences as the measure of fit. This function too is implicitly a measure of the comparison of magnitudes of peaks, volumes, and times of peak of the two hydrographs (USACE, 2000).
- **Percent error in peak.** This measures only the goodness-of-fit of the computed-hydrograph peak to the observed peak. It quantifies the fit as the absolute value of difference, expressed as a percentage. It does not reflect errors in volume or peak timing. This function is a logical choice if the information needed for designing or planning is limited to peak flow or peak stages. This might be the case for a floodplain management study that seeks to limit development in areas subject to inundation, with flow and stage uniquely related (USACE, 2000).
- **Peak-weighted root mean square error.** It compares all ordinates squaring differences, and it weights the squared differences. The weight assigned to each ordinate is proportional to the magnitude of the ordinate. Ordinates greater than the mean of the

observed hydrographs are assigned a weight greater than 1.00, those smaller, a weight less than 1.00. The peak observed ordinate is assigned the maximum weight.

The peak observed ordinate is assigned the maximum weight. The sum of ordinates; the weighted, squared differences is divided by the number of computed hydrograph thus, yielding the squared error. Taking the square root yields the root mean squared error. This function is an implicit measure of comparison of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs (USACE, 2000).

Objective functions for calibration.

Criterion	Equation	
Sum of absolute errors	$Z = \sum_{i=1}^{NQ} \lvert q_O(i) - q_S(i) \rvert$	[eq. 4.3]
Sum of squared residuals	$Z = \sum_{i=1}^{NQ} \left[q_O(i) - q_S(i) \right]^2$	[eq. 4.4]
Percent error in peak	$Z = 100 \left\lvert \frac{q_S(peak) - q_O(peak)}{q_O(peak)} \right\rvert$	[eq. 4.5]
Peak-weighted root mean square error objective function	$Z = \left\{ \frac{1}{NQ} \left[\sum_{i=1}^{NQ} \left(q_O(i) - q_S(i) \right)^2 \left(\frac{q_O(i) + q_O(mean)}{2 q_O(mean)} \right) \right] \right\}^{1/2}$	[eq. 4.6]

Where, Z = objective function; NQ = number of computed hydrographs ordinates; $q_O(t)$ = observed flows; $q_S(t)$ = calculated flows, computed with a selected sets of model parameters; $q_O(peak)$ = observed peak; $q_O(mean)$ = mean of observed flows; and $q_S(peak)$ = calculated peak (USACE, 2000)

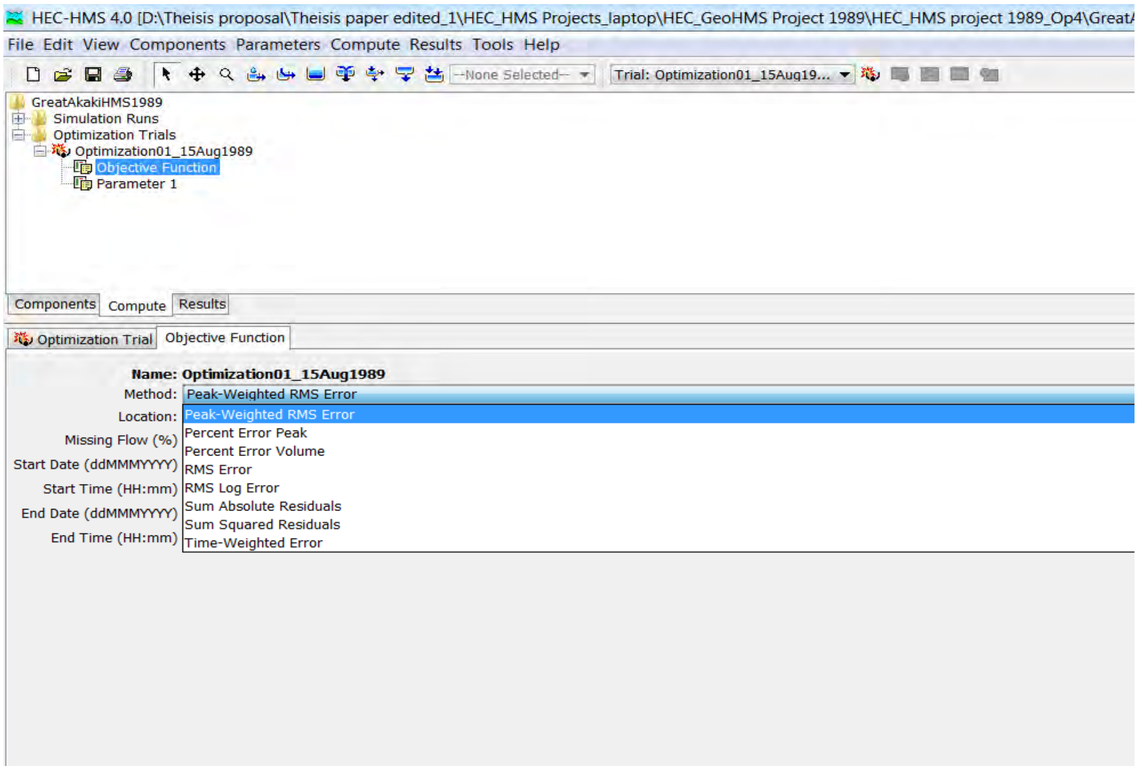


Figure 4.16: Objective function selection

Model efficiency criteria

To evaluate the efficiency of the model two efficiency criteria's are considered in this study. These are Nash Sutcliffe Efficiency (NSE and coefficient of determination (R^2) which are widely applicable in hydrologic modeling. The Nash-Sutcliffe Efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Moriasi, Arnold, Van Liew, Bingner, Harmel and Veith, 2007).

$$NSE = 1 - \frac{\sum (Q_{obs(t)} - Q_{sim(t)})^2}{\sum (Q_{obs(t)} - \overline{Q_{obs}})^2} \qquad \text{[eq. 4.7]}$$

Where,

NSE = Nash and Sutcliffe Efficiency, Q_{obs} = observed value at the i^{th} time interval, Q_{sim} = simulated value at the i^{th} time interval and $\overline{Q_{obs}}$ = mean of the observed discharges.

Coefficients of determination (R^2) describe the degree of collinearity between simulated and measured data (Moriasi, Arnold, Van Liew, Bingner, Harmel and Veith, 2007).

$$R^2 = \frac{\left(\sum (Q_{obs(t)} - \overline{Q}_{obs}) \sum (Q_{sim(t)} - \overline{Q}_{sim(t)})\right)^2}{\sum (Q_{obs(t)} - \overline{Q_{obs}})^2 \sum (Q_{sim(t)} - \overline{Q}_{sim(t)})^2} \qquad \text{[eq. 4.8]}$$

Where,

R^2 = coefficient of determination, Q_{obs} = observed value at the i^{th} time interval, Q_{sim}= simulated value at the i^{th} time interval, $\overline{Q_{obs}}$ = mean of observed discharges and $\overline{Q_{sim}}$= mean of simulated discharges.

For this study the model calibration is carried out for 15 consecutive days ‘from 01 August 1989 to 15 August 1989. The HEC-HMS model calibration executed by entering daily rainfalls and observed flow discharges on precipitation gage and discharge gage models of HEC-HMS 4.0 respectively (figure 4.17). The overall calibration procedure used in this study is clearly shown on figure 4.18.

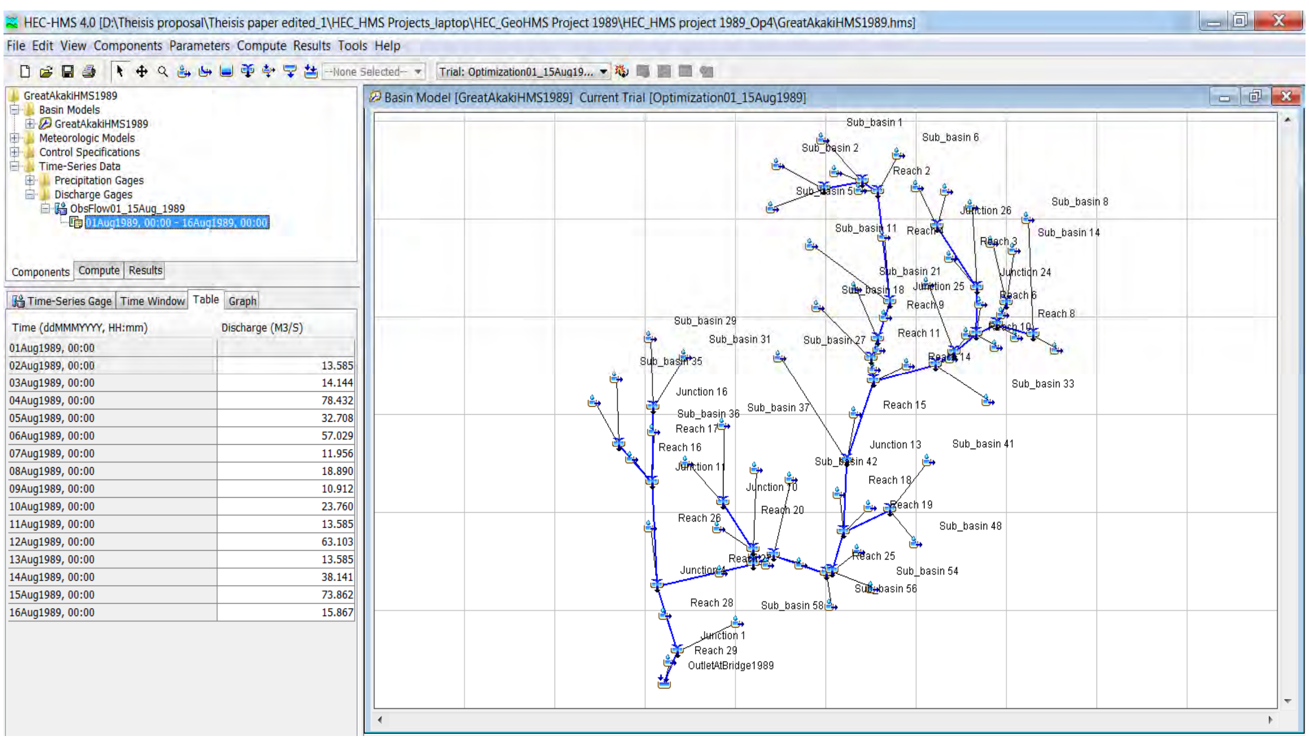


Figure 4.17 daily rainfalls and daily peak observed discharges entered for calibration

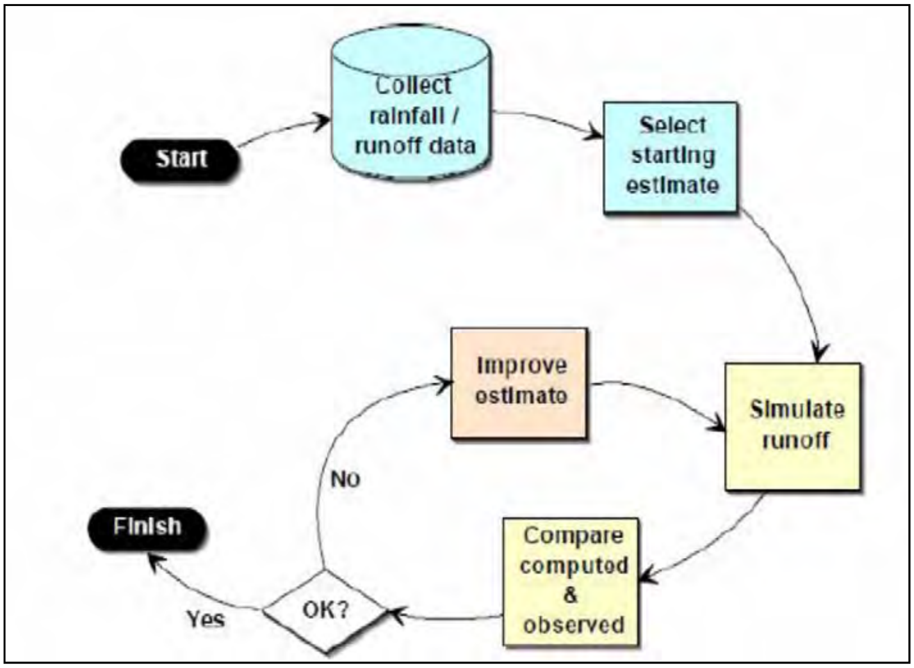


Figure 4.18 HEC-HMS calibration procedures (USACE, 2000)

4.4.3.4. Flood Modeling by Frequency Storm Method

The rain fall intensity used for this study is found from ERA rainfall intensity-duration curves figure 4.19. Based on the Ethiopian Road Authority (ERA) 2002 drainage manual the country has divided into different meteorological regions as shown on table 4.7.

Table 4.7: Meteorological regions and stations used for ERA drainage manual development

Meteorological Region	Station	Years of Record	Meteorological Region	Station	Years of Record
A1	Axum	18	B	Bedele	19
	Mekele	35		Gore	45
	Maychew	24		Nekempte	27
A2	Gondar	40		Jima	45
	Debre Tabor	22		Arba Minch	11
	Bahir Dar	35		Sodo	28
	Debre Markos	44		Awasa	26
	Fitche	25	C	Kombolcha	46
	Addis Ababa	33		Woldiya	23
A3	Nazareth	40		Sirinka	17
	Kulumsa	31	D1	Gode	29*
	Robe/Bale	19		Kebri Dihar	38
A4	Metehara	28	D2	Kibre Mengist	24
	Dire Dawa	46		Negele	45
	Mieso	35		Moyale	18
* max 24 hour rainfall not given				Yabelo	34

Based on the above ERA classification the study area found in meteorological region of A2 and rainfall depth for 10, 50, and 100 return periods is obtained from rainfall intensity-duration curves. The 24 hour rainfall depth for rain fall region A2 is given and for 1, 2, 3, 6, 12 hour duration is found by using SCS rain fall distribution type II which recommended by ERA for Ethiopia.

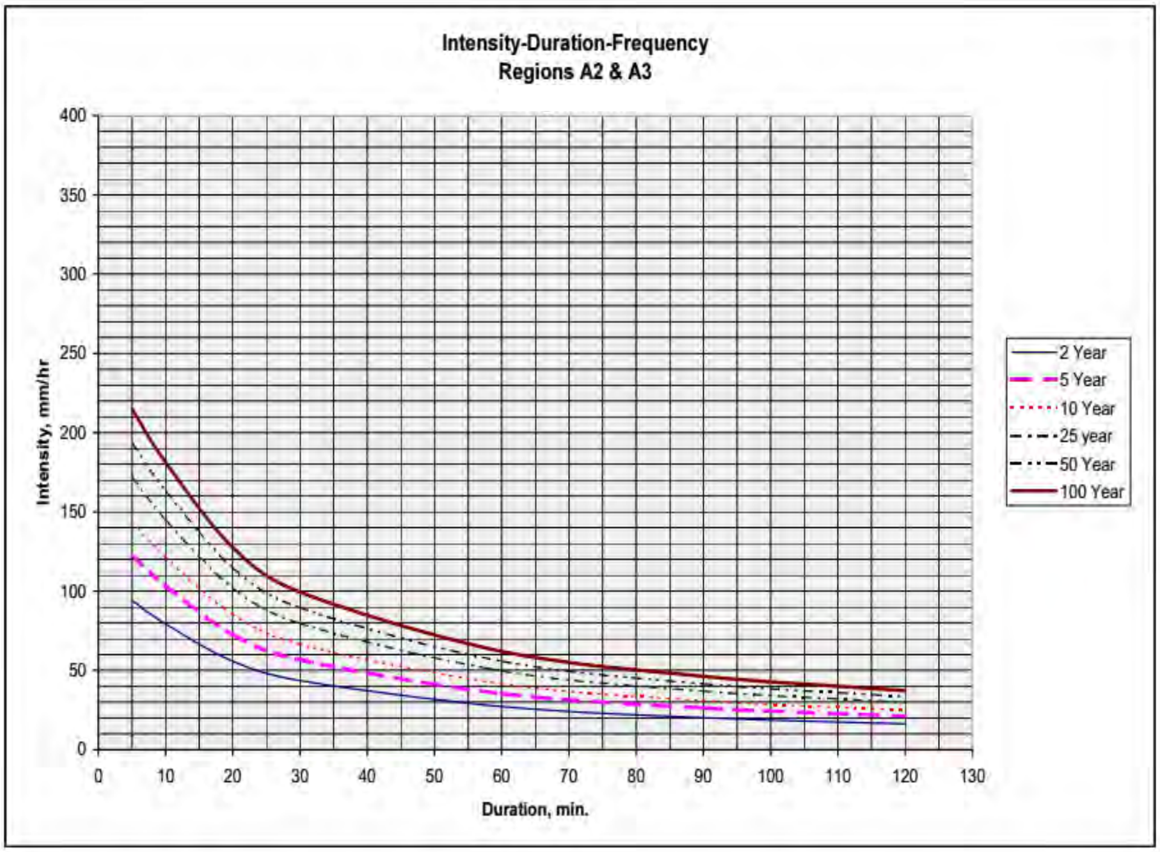


Figure 4.19: ERA drainage manual rainfall Intensity-Duration Curves for region A2 and A3

Table 4.8: rainfall depth from IDF of A2 for study area (ERA Drainage Design Manual, 2002)

Duration in (hr)	SCS Ratio to 24hr rainfall distribution type II	Rain fall depth with return period		
		10	50	100
1	0.454	35.87	48.58	53.58
2	0.538	42.50	57.57	63.49
3	0.595	47.00	63.67	70.21
6	0.707	55.85	75.65	83.43
12	0.841	66.44	89.99	99.24
24	1.000	79.00	107.00	118.00

The necessary steps used for HEC-HMS model development is described on the previously sections and the difference in this case is the meteorological model uses frequency storm method for peak discharge generation. HEC-HMS model simulation is carried out for each return period by using the rainfall intensity of the above mentioned return period as shown on figure 4.21.

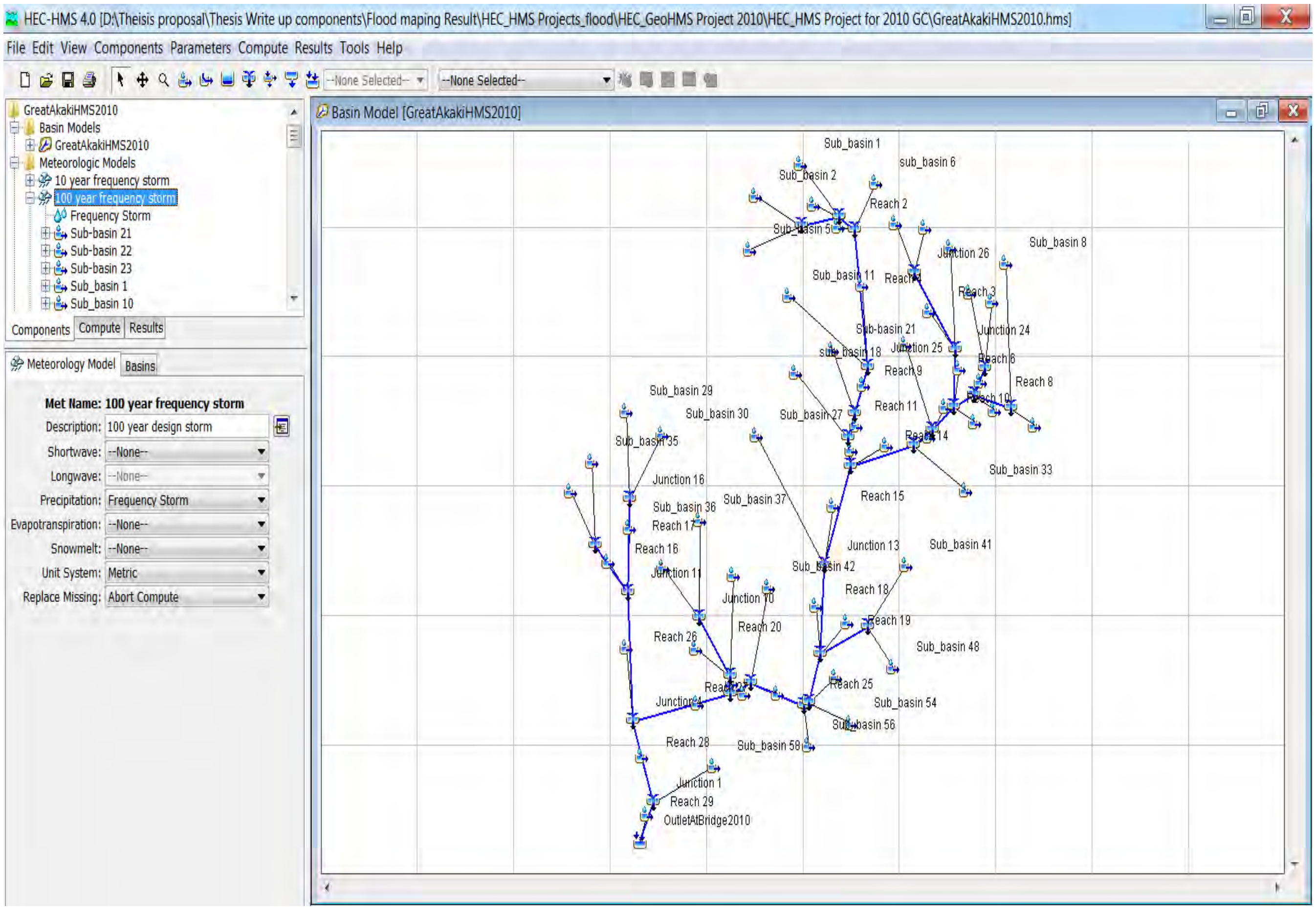


Figure 4.20: Peak discharge generation using HEC-HMS frequency storm method

4.5. Hydraulic Model Development

4.5.1. General

In this section, the methodology applied to obtain the hydraulic modeling analysis results is described in detail. Its main aim is to estimate the amount of peak flood generated from Great Akaki River related return periods of 10, 50 and 100 years up to the Bridge of Addis Ababa Bishoftu Road/Akaki. For this purpose, ArcGIS 10.1 software package is used by integrating with HEC-GeoRAS 10.1 extension and HEC-RAS 4.1.0 for preparation of spatial data, hydraulic analyses and flood plain delineation. The activities are classified in to three major categories:

- Triangulated Irregular Network (TIN) and Geometric data preparation for HEC-RAS input using ArcGIS.
- Hydraulic/flow analysis using HEC-RAS and,
- Floodplain delineation using HEC-GeoRAS

4.5.2. Pre-processing of Geometric Data.

This is the first stage for hydraulic model development and accomplished by integrating ArcGIS with HEC-GeoRAS extension. TIN development, RAS layer creation, HEC-RAS attributes addition, layer set up and exporting RAS data are the major activities accomplished.

TIN formation:

The HEC-RAS analysis is started with the development of a Digital Elevation Model (DEM) in to Triangulated Irregular Network (TIN) format using 3DAnalysis of Raster to TIN function of ArcMap 10.1 which is the basic input file for river analysis.

In the TIN model, each point has defined x, y, and z coordinates. The coordinate z represents the height. These points are connected by their edges to form a network of overlapping triangles (finite surfaces) that represent the terrain surface (Dragan and Slobodan, 2009).

Hydraulic model development requires high resolution DEM, but the available best resolution DEM for the project are in general for Ethiopia is 30m and above. For this study, different resolutions of DEM are collected from Ministry of Water Resources and Electric, and from different websites. The TIN developed from each DEM is compared as shown from figure 4.22. Accordingly, conditioned SRTM 90m resolution is the best DEM for the project area TIN development which is downloaded from official website of United States Geological Survey (USGS) and by using the following link http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=3accg. As shown from the figure 4.22 left one, the TIN developed from ASTER 30m resolution is poor.

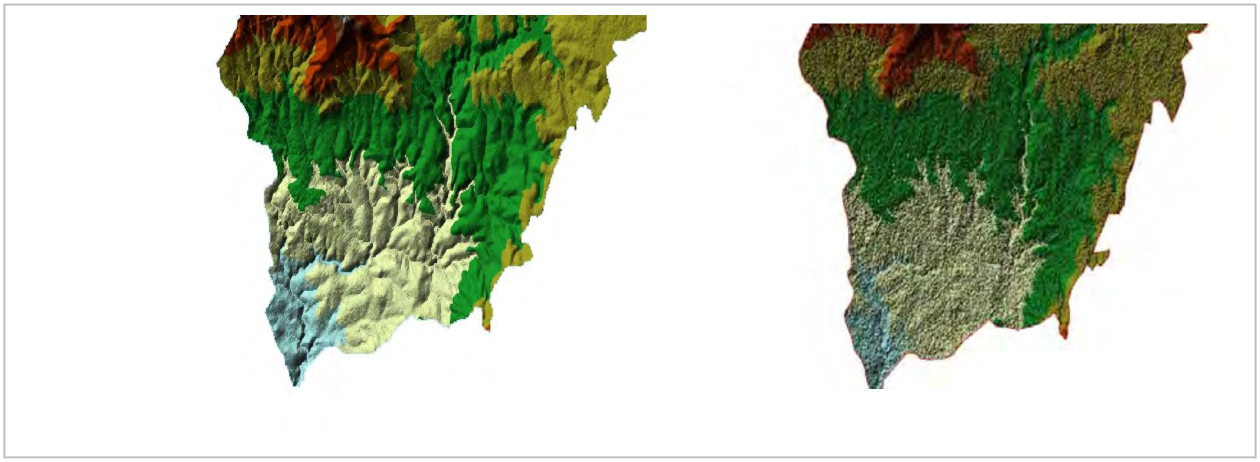


Figure 4.21: Developed TIN from SRTM 90m resolution DEM left and ASTER 30m resolution (very poor TIN) right

Even if the TIN developed from SRTM 90m resolution is better than ASTER 30m resolution DEM still needs editing using field data.

The editing work was tedious and takes much time but it was a must for a better flood modeling.

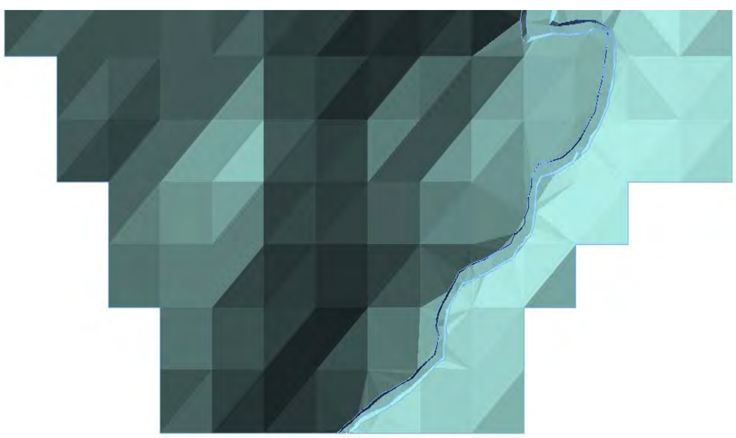


Figure 4.22: closely view of the edited TIN using geometric field data

Creating RAS layers: by using this HEC- GeoRAS geometry menu creating RAS layers function river center line, bank lines, flow paths and cross sections layers are created.

Adding HEC-RAS attributes: attributes values assigned for stream lines which include topology, river length, stations and elevation. For river cross-sections river names, reach names, stationing, bank stations, downstream lengths and elevations assigned.

HEC- RAS layer set up and exporting RAS data: These functions of HEC- GeoRAS are used for checking the prepared GIS layer data and for exporting it to HEC-RAS usable format respectively.

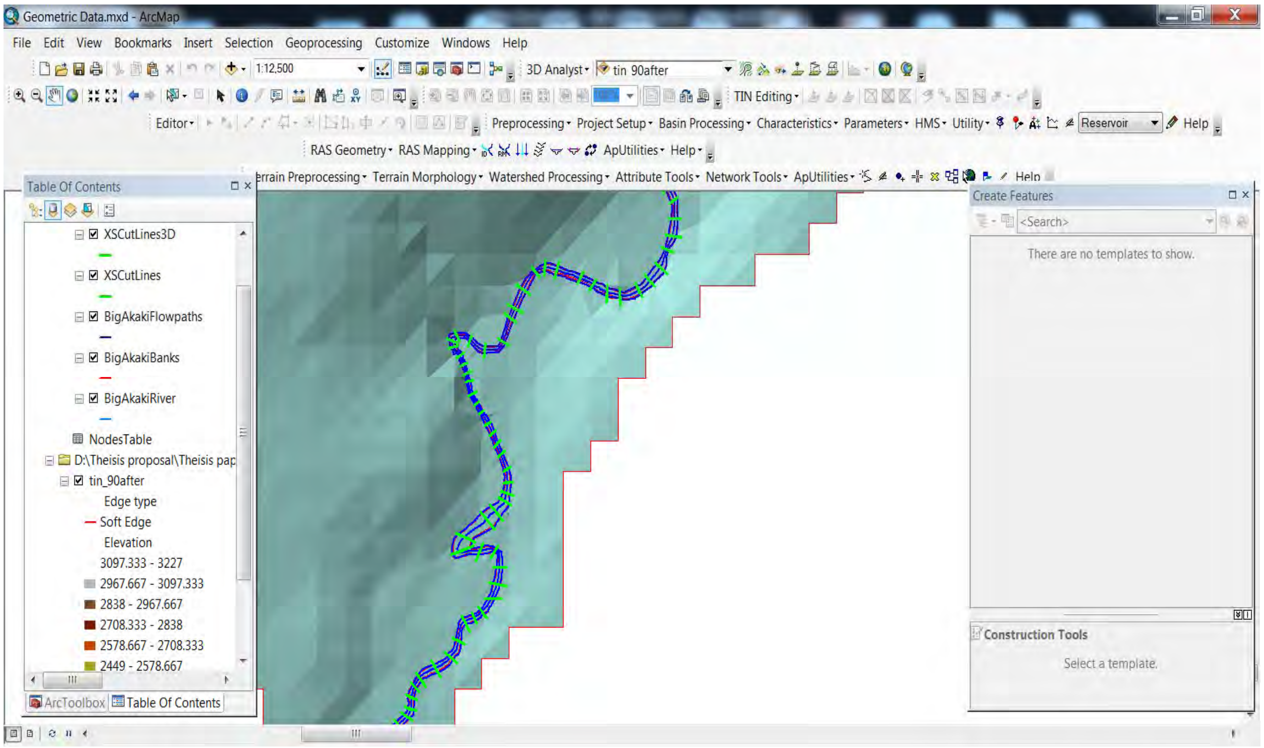


Figure 4.23: Generated geometric data using HEC-GeoRAS extension

4.5.3. Hydraulic Analysis

HEC-RAS 10.1 software package downloaded from the official website of US Army Corps of Engineers and freely available on this link: http://www.hec.usace.army.mil/software/hec-ras/downloads.aspx. The hydraulic model package River Analysis System (RAS) has the three basic components to accomplished the hydraulic modeling these are geometry data which describes the size, shape and connectivity of stream cross sections; the flow data that provides discharge rates; and the plan data, which contains information to run specifications of the model, for example description of the flow regime.

To compute water surface profiles steady flow analysis is used. Flow in an open channel is steady if the depth, discharge, and mean velocity of flow at a particular location does not change with time, or if it can be assumed constant during the time period under consideration (Dragan and Slobodan, 2009). Steady flow analysis described by the following energy equation

$$H = Z + \frac{P}{\rho g} + \frac{V^2}{2g}$$ [eq. 4.9]

Where, H = Total energy head (m)

Z = Potential head (m)

P/ρg = Pressure head (m)

P = pressure (N/m2)

ρg = Unit weight (N/m3)

$V^2/2g$ = Kinetic (velocity) head (m)

V = Velocity of flow (m/s)

g = Acceleration due to gravity (m/s^2)

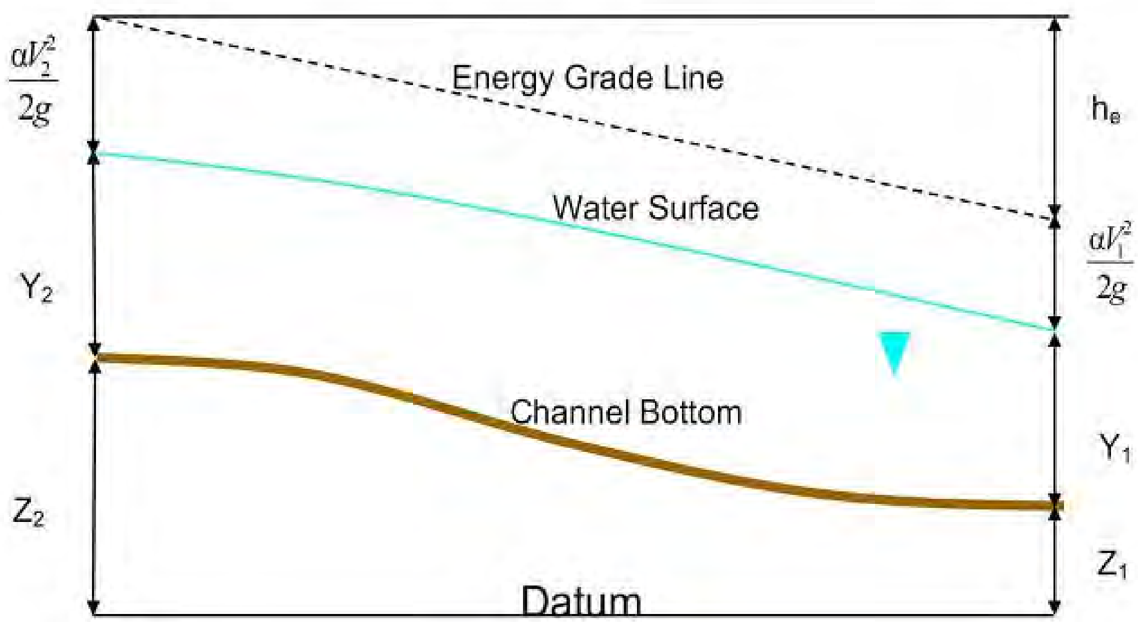


Figure 4.24: Representation of terms in the energy equation (Dragan and Slobodan, 2009)

Importing GIS data created from HEC-GeoHMS

HEC-RAS analysis was started by creating HEC-RAS project. Then geometry data which is previously created using HEC- GeoRAS was imported by preserving the project unit which is SI unit.

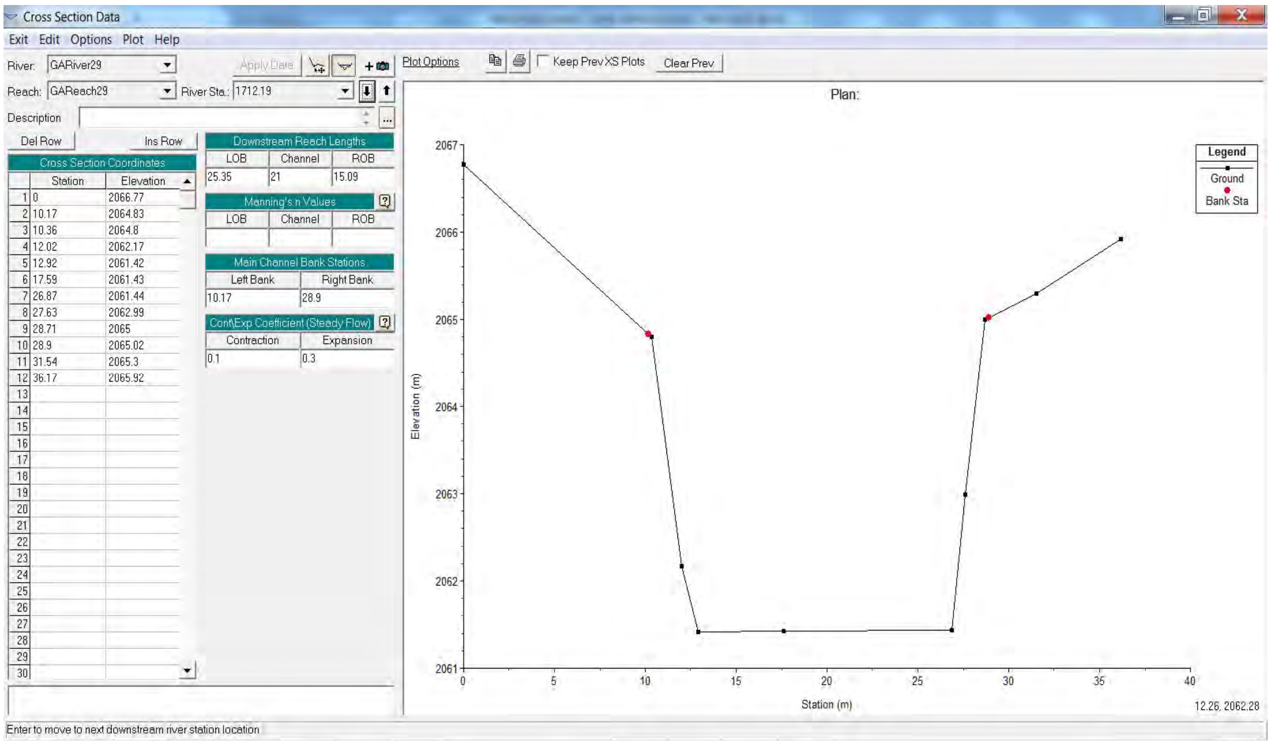


Figure 4.25: River geometry at river station 1712.19

Entering flow data and boundary conditions

Contraction or expansion of flow due to changes in the cross section is a common cause of energy losses within a reach and multiplied by the absolute difference heads between the current cross section and the next cross section downstream, which gives the energy loss caused by the transition. when the change in river cross section is mall, the flow is subcritical, coefficient of contraction and expansion are typically on the order of 0.1 and 0.3 (HEC-RAS hydraulic reference manual, 2010).

Selecting the appropriate Manning's n value is very important for accurate computation of water surface profiles. The value of Manning's n is highly variable and depends upon a number of factors including: surface roughness, channel irregularities, channel alignment, size and shape of channel, scour and deposition, vegetation, obstructions, stage and discharge, seasonal change, temperature, suspended materials and bed load . The n value decreases with increases in stage and discharge. When the water depth is shallow, irregularities of the channel bottom are exposed and their effect may become pronounced. However, the n value may be large at high stages if the banks are rough and grassy ((Dragan and Slobodan, 2009)). For this study Manning's n values of 0.035 for main stream channels and 0.04 for stream banks is used (Source: HEC-RAS hydraulic reference manual, 2010). On the other hand assigning appropriate flow boundary condition for each return period is mandatory as shown on figure 4.27.

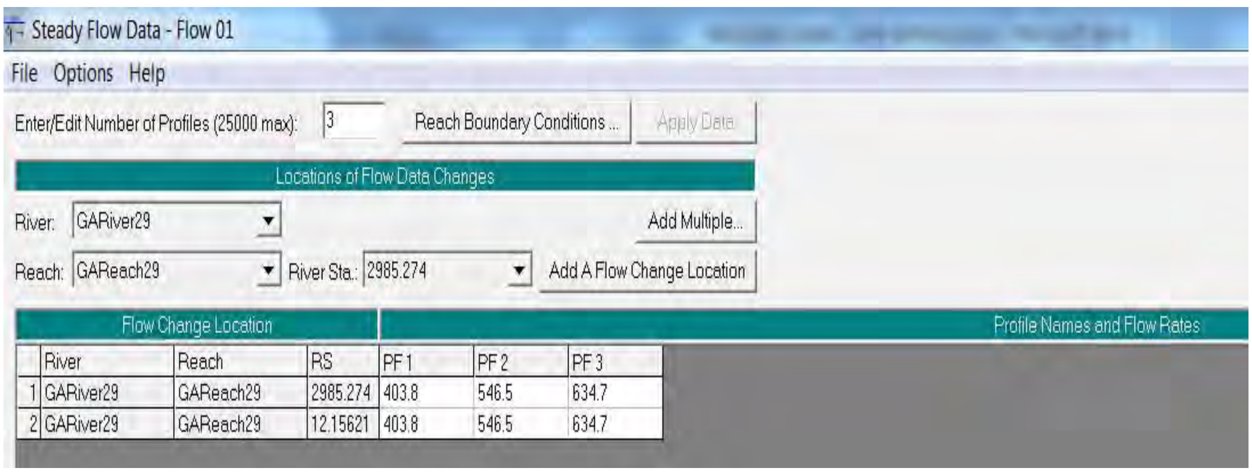


Figure 4.26: Boundary condition entered for steady flow analysis

Run steady flow analysis and exporting to GIS

The model was run for subcritical flow regime conditions and the peak discharge values at the main outlet of the basin (at Addis Ababa Bishoftu Road Bridge) for return periods of 10, 50 and 100 are entered on the steady flow analysis window manually as shown from the above table. The values generated from HEC-HMS previously are 403.80m^3/s, 546.50m^3/s and 634.70m^3/s for 10, 50 and 100 return periods respectively. The final step of HEC-RAS process was exporting the HEC-RAS result computation results to GIS in the form of "RASexport.sdf".

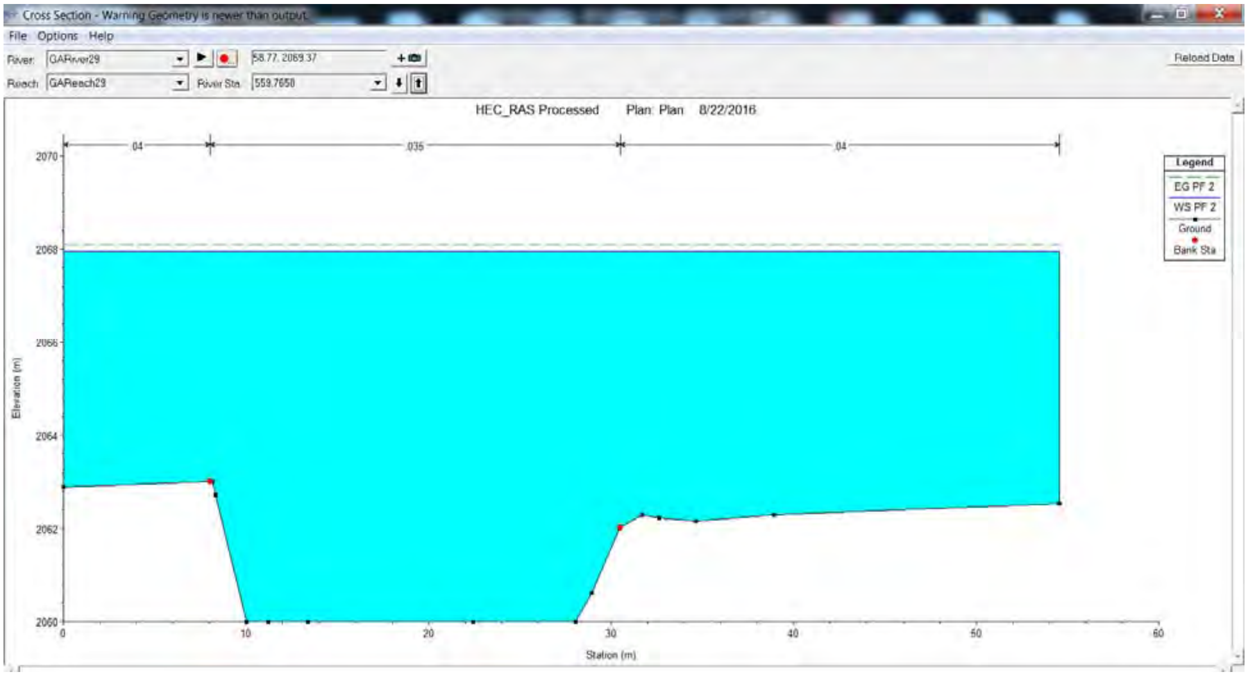


Figure 4.27: Water surface profile at river station 559.7658 for 50 year return period.

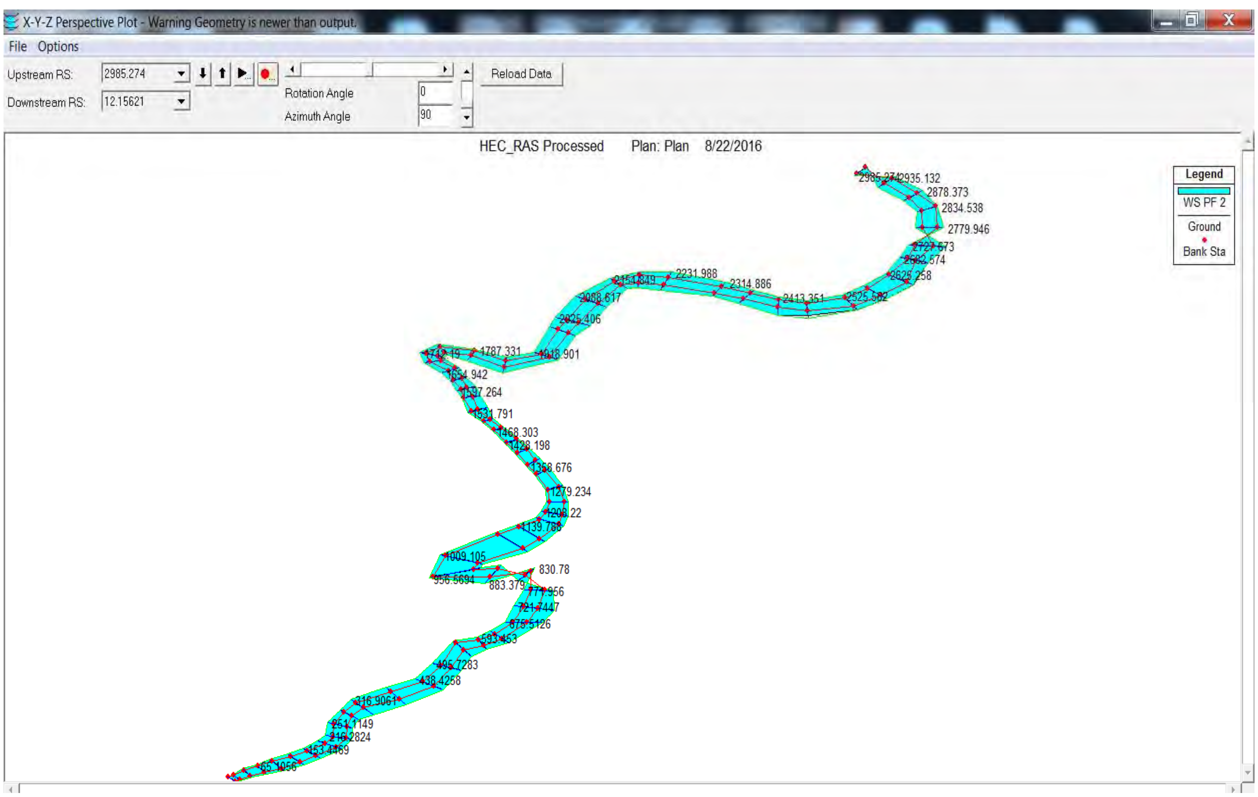


Figure 4.28: x, y, z perspective view of river flow

4.5.4. Post-processing of Hydraulic Results and Floodplain Mapping

In this section, the delineation of floodplains was accomplished by integrating the RAS GIS output file (RASexport.sdf) and the TIN layer on GIS. The next step was overlaying the terrain TIN with water surface TIN. From this, inundation depths and floodplain boundaries are extracted. The details are described as follows:

RAS GIS output conversion: HEC- GeoRAS cannot support the direct output of RAS GIS file format and must change in to HEC-GeoRAS usable format. By using "Import RAS SDF File" toolbar of HEC-GeoRAS the RASexport.sdf file is converted in to XML file format. This format is very important input for further flood map delineation.

Layer setup: by using the layer setup window of HEC- GeoRAS the type of analysis(in this case steady flow analysis), input(RAS GIS file, terrain TIN) and output data directory were identified.

Reading RAS GIS export file: the "Read RAS GIS Export File" toolbar of HEC-GeoRAS was used to extract the river2D; cross section cut lines, and flood bounding polygon maps. The result is displayed on figure 4.30.

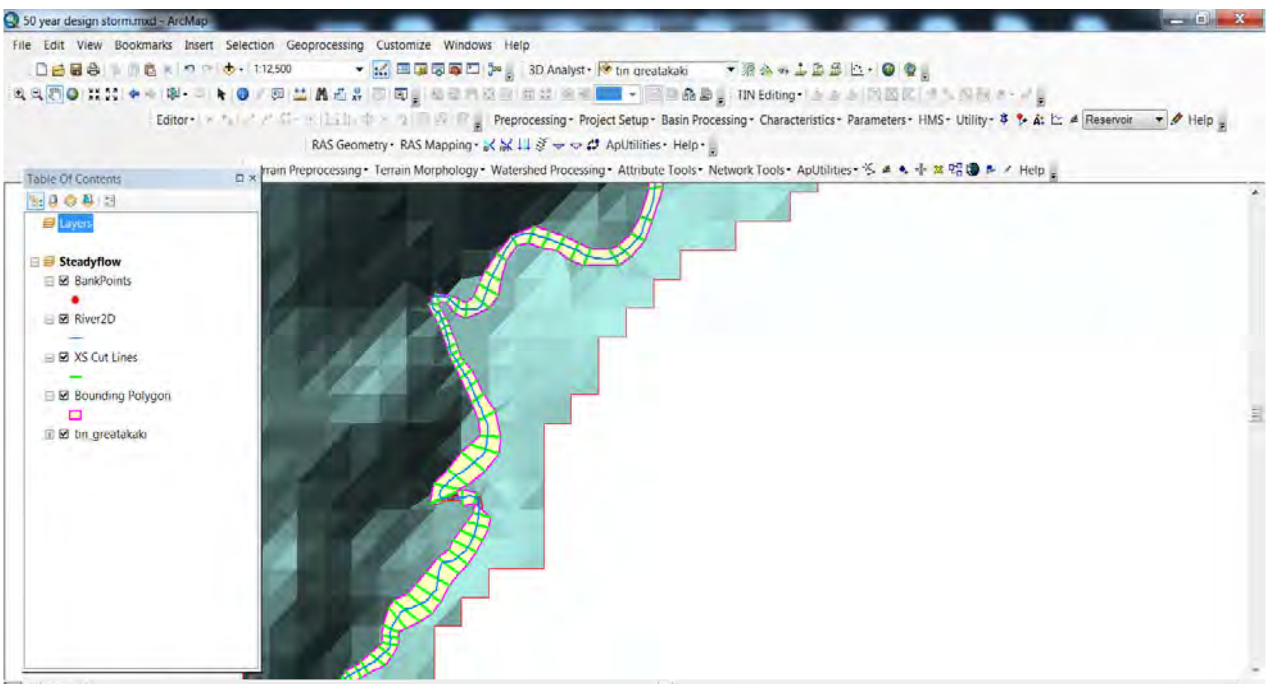


Figure 4.29: Result of the above three processes (RAS GIS output, layer setup and reading RAS file)

Floodplain mapping: flood mapping process performed in two steps using water surface elevations along the cross section cut lines. The first step was development of water surface TIN for all peak discharges return periods by using water surface generation toolbar of HEC-GeoRAS as shown on figure 4.31.

Figure 4.30: Generated water surface TIN

The second step in flood mapping is floodplain delineation this process is completed by using flood plain delineation using raster's tool of HEC-GeoRAS 10.1. Accordingly, flood inundation depth grid and flood boundary feature class (flood width) are created for each return period years.

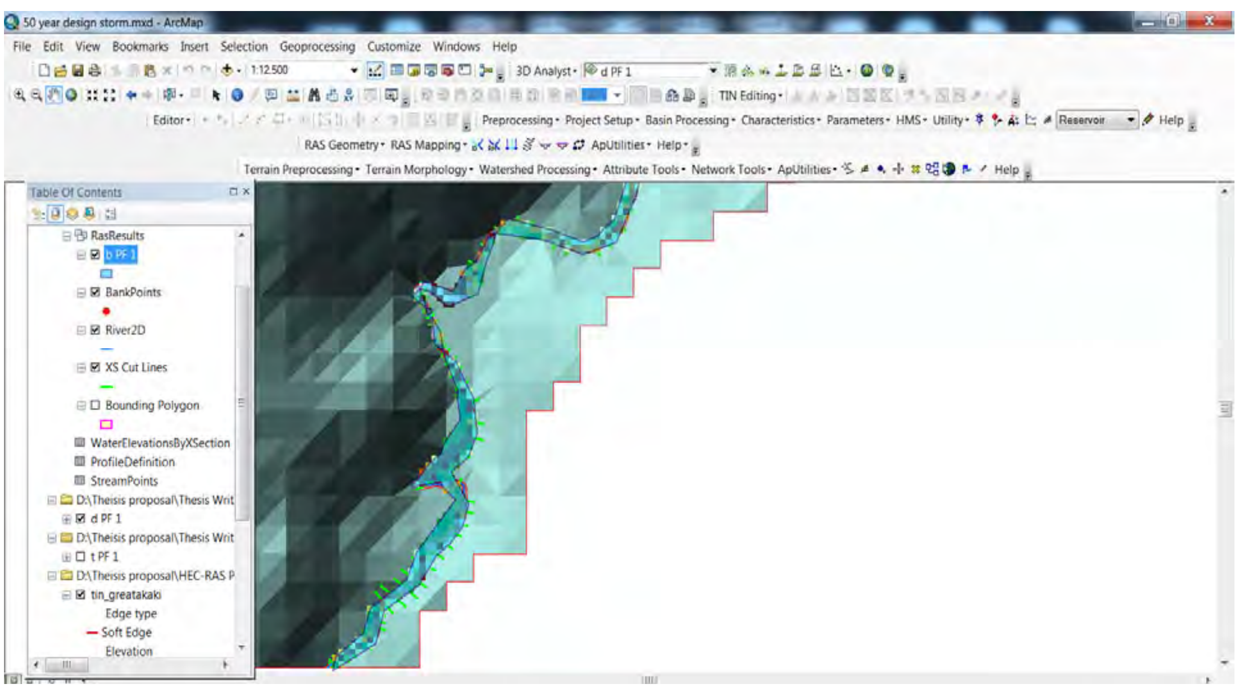


Figure 4.31: Generated flood depth grid and flood width extent

5. RESULTS AND DISCUSSION

5.1. General

In this chapter, the result of the paper is described in detail. Accordingly the result discussion is categorized in to thee. The first category describes the HEC-HMS calibration result in detail; the second category focuses on the effect of major hydrological characteristics of Great Akaki watershed on generated surface runoff for 1989, 2000 and 2010. The third and final section focuses on the result of the hydraulic analysis on different return periods on catchment.

5.2. HEC-HMS Calibration and Validation Result

HEC-HMS calibration was performed for 15 consecutive days from August 01 - 15/1989 for Great Akaki Watershed up to Addis Ababa Bishoftu Bridge using rainfall and flow discharge at outlet on daily basis. The simulated flow or HEC-HMS flow result was calibrated using the observed flow and optimization of the model parameters values were carried out within the recommended ranges.

Based on the calibration result using the peak weighted root mean square error objective function there was a good agreement between the HEC-HMS flow results and measured or observed flow at the outlet of the study area

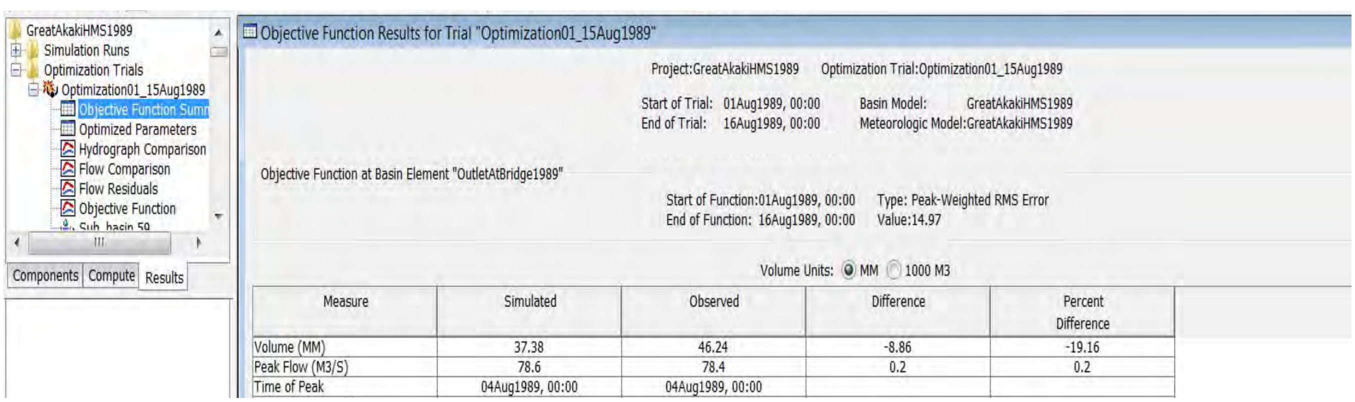


Figure 5.1: Objective function result

As discussed on the methodology section the efficiency of the model was evaluated using Nash-Sutcliffe efficiency and coefficient of determination. Nash-Sutcliffe Efficiency (E_{NS}) value ranges between -∞ and 1.0 (1 inclusive), with NSE =1 being the optimal value. Values between

0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi, Arnold, Van Liew, Bingner, Harmel and Veith, 2007). On the other hand coefficient of determination (R^2) estimates the dispersion of the measured flow predicted by the model. The value of R^2 ranges between 0 and 1; value of zero means no correlation at all and one means best or perfect. For Great Akaki River up to the Bridge HEC-HMS Modeling; Nash-Sutcliffe efficiency, coefficient of determination and validation result has a value of 0.628, 0.613 and 0.639 respectively. All results are on acceptable range and resemble each other.

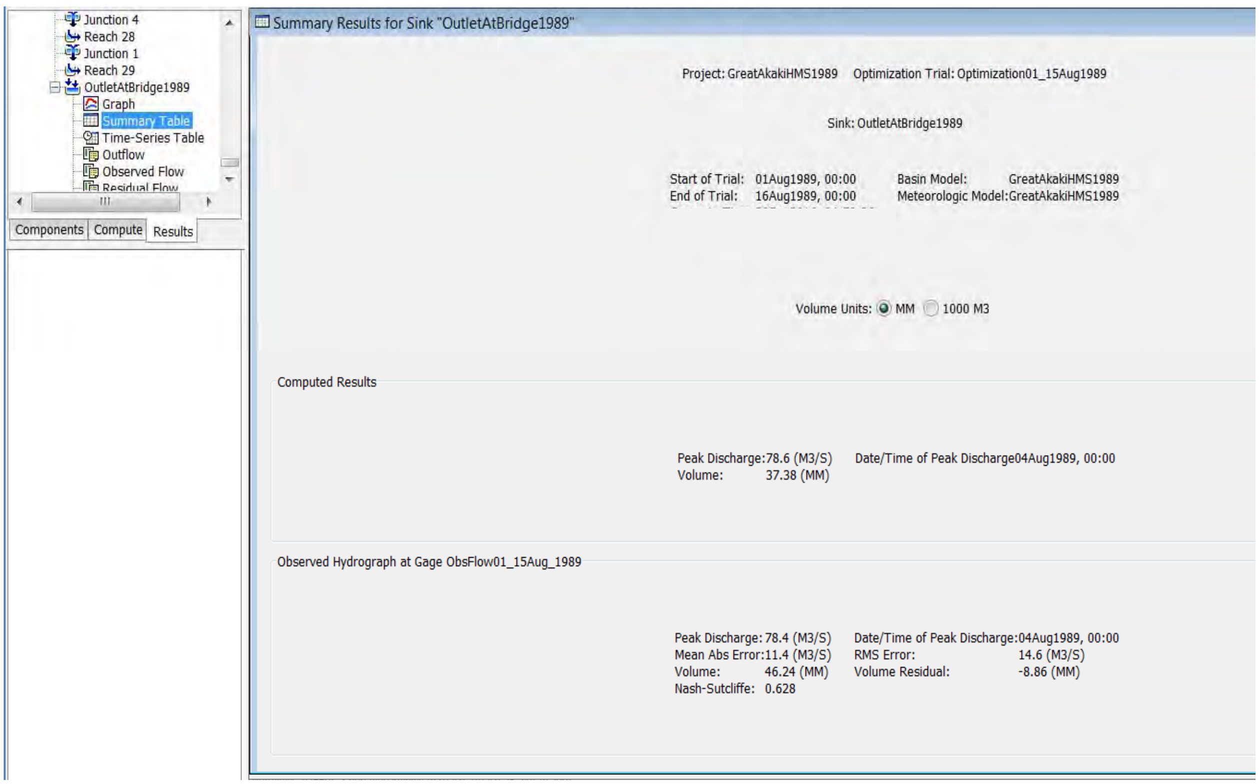


Figure 5.2: Model efficiency result

5.3. Land Use Change Effect and Hydrological Modeling Result

Based on this study, the land use of the study area is changing from time to time. Since Addis Ababa is found at the center of the catchment large portion of the agriculture land was converted in to residential. Especially in recent years the change is dynamic. As shown from table 5.1 the percentage of residential area increases from 8.77% in 1989 to 17.96% in 2010 where as, agricultural land decreases from 37.26% to 31.84% within these years.

Table 5.1: Percentage of land use for 1989, 2000 and 2010

No	Land use type	Percentage of land use		
		1989	2000	2010
1	Water body	0.52	0.66	0.63
3	Residential	8.77	12.88	17.96
4	Commercial/Industrial	2.13	2.61	3.97
5	Open spaces	31.58	28.56	26.61
6	Mixed forest	19.74	20.41	18.99
9	Agriculture	37.26	34.88	31.84
Total		**100**	**100**	**100**

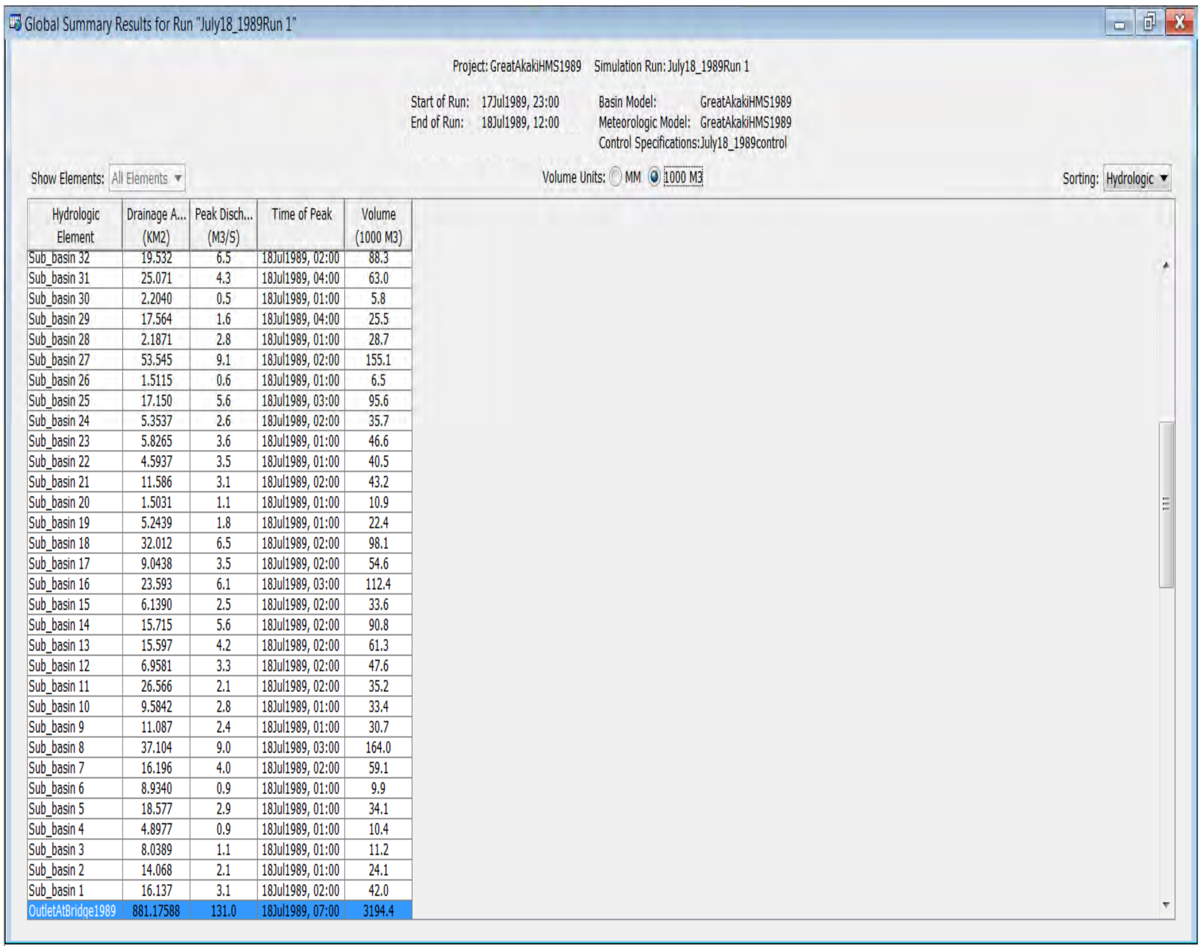
To evaluate the effect of the land use on surface runoff as discussed from previous sections, equal amount of daily rainfall is selected. This helps to avoid the effect of rainfall variation on the generated peak discharge for all selected years. Accordingly, the generated peak discharge difference was found due to the land use change on the catchment.

On the other hand, the Soil Conservation Service Curve Number (SCS CN) method used in this study is found very simple method to estimating runoff. The CN value is the cumulative effect of different soil types and land use/cover of the project area. The Curve Number value of the project area is increased from 1989 to 2010 as shown on table 5.2. This result shows hydrological characteristics of the catchment are the major factors which alter the peak discharge of the study area using equal rain fall distribution. When the Curve Number (CN) increase the amount of peak discharge generated from Great Akaki River increases table 5.3.

Table 5.2: CN and impervious area for 1989, 2000 and 2010

Year	Composite Curve Number (CN) of the study area	Composite % of impervious area
1989	80.29	17.23
2000	83.15	21.36
2010	87.59	27.15

The peak discharges found from HEC-HMS model at the main outlet of the study area for 1989, 2000 and 2010 are shown on figure 5.3 and table 5.3.



Hydrologic Element	Drainage A... (KM2)	Peak Disch... (M3/S)	Time of Peak	Volume (1000 M3)
Sub_basin 32	19.532	6.5	18Jul1989, 02:00	88.3
Sub_basin 31	25.071	4.3	18Jul1989, 04:00	63.0
Sub_basin 30	2.2040	0.5	18Jul1989, 01:00	5.8
Sub_basin 29	17.564	1.6	18Jul1989, 04:00	25.5
Sub_basin 28	2.1871	2.8	18Jul1989, 01:00	28.7
Sub_basin 27	53.545	9.1	18Jul1989, 02:00	155.1
Sub_basin 26	1.5115	0.6	18Jul1989, 01:00	6.5
Sub_basin 25	17.150	5.6	18Jul1989, 03:00	95.6
Sub_basin 24	5.3537	2.6	18Jul1989, 02:00	35.7
Sub_basin 23	5.8265	3.6	18Jul1989, 01:00	46.6
Sub_basin 22	4.5937	3.5	18Jul1989, 01:00	40.5
Sub_basin 21	11.586	3.1	18Jul1989, 02:00	43.2
Sub_basin 20	1.5031	1.1	18Jul1989, 01:00	10.9
Sub_basin 19	5.2439	1.8	18Jul1989, 01:00	22.4
Sub_basin 18	32.012	6.5	18Jul1989, 02:00	98.1
Sub_basin 17	9.0438	3.5	18Jul1989, 02:00	54.6
Sub_basin 16	23.593	6.1	18Jul1989, 03:00	112.4
Sub_basin 15	6.1390	2.5	18Jul1989, 02:00	33.6
Sub_basin 14	15.715	5.6	18Jul1989, 02:00	90.8
Sub_basin 13	15.597	4.2	18Jul1989, 02:00	61.3
Sub_basin 12	6.9581	3.3	18Jul1989, 02:00	47.6
Sub_basin 11	26.566	2.1	18Jul1989, 02:00	35.2
Sub_basin 10	9.5842	2.8	18Jul1989, 01:00	33.4
Sub_basin 9	11.087	2.4	18Jul1989, 01:00	30.7
Sub_basin 8	37.104	9.0	18Jul1989, 03:00	164.0
Sub_basin 7	16.196	4.0	18Jul1989, 02:00	59.1
Sub_basin 6	8.9340	0.9	18Jul1989, 01:00	9.9
Sub_basin 5	18.577	2.9	18Jul1989, 01:00	34.1
Sub_basin 4	4.8977	0.9	18Jul1989, 01:00	10.4
Sub_basin 3	8.0389	1.1	18Jul1989, 01:00	11.2
Sub_basin 2	14.068	2.1	18Jul1989, 01:00	24.1
Sub_basin 1	16.137	3.1	18Jul1989, 02:00	42.0
OutletAtBridge1989	881.17588	131.0	18Jul1989, 07:00	3194.4

Figure 5.3: Great Akaki River HEC- HMS model simulation result for 1989

Table 5.3: Great Akaki River HEC- HMS model simulation result

Year	HEC-HMS simulation flow result (m^3/S)
1989	131
2000	153.4
2010	188.1

5.4. Frequency Storm Method Analysis Result

Based on frequency storm method analysis peak discharge of each return period is obtained. As shown from the table 5.4 the minimum and maximum peak flood discharges are 403.80, 546.50 and 634.70m^3/s for 10, 50 and 100 frequency storms respectively.

Table 5.4: Peak discharge found from HEC-HMS frequency storm method

No	Return period (years)	Peak discharge (m^3/s)
1	10	403.80
2	50	546.50
3	100	634.70

The HEC-HMS result found is compared with different techniques of frequency analysis like Gumbel, log normal and log Pearson. These frequency analysis techniques are worldwide accepted methods and simple to use. For this purpose annual peak discharge record of Great Akaki River at the Bridge along Addis Ababa Bishoftu from 1981-2004 is taken and the result is shown on table 5.5.

Table 5.5: Frequency analysis and HEC-HMS result comparison

Return period	HEC-HMS	Log Pearson	Gumbel	Log normal
10	403.80	496.75	494.44	531.03
50	546.50	685.83	711.55	885.11
100	634.70	755.50	803.49	1060.38

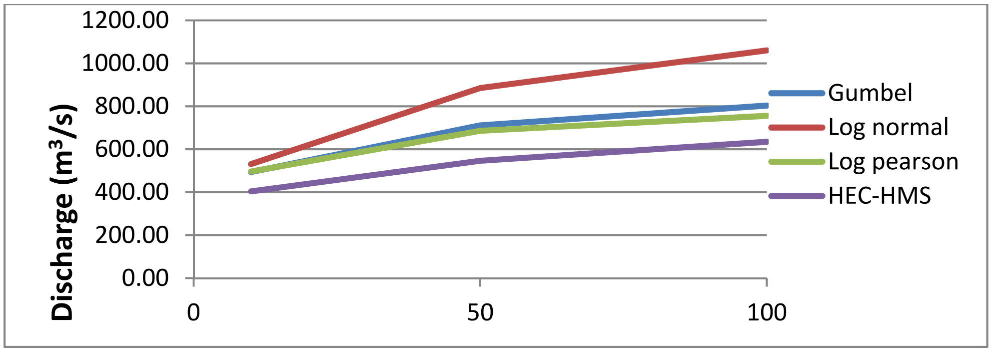


Figure 5.4: Frequency analysis and HEC-HMS result comparison

As shown on both table 5.5 and figure 5.4 the log Pearson and Gumbel frequency analysis type values have a closer value than log normal. Based on physical observation and different studies the Addis Ababa city poor sewerage system creates high accumulation of plastics and other materials on the river channel. This has high effect on the result found from the automatic recorder and creates less reliability on the historical river discharge data. Due to this, the result found from HEC-HMS assumed as a good representative.

5.5. Hydraulic Modeling Result

The two most important issues with regard to flood mapping are flood depth and width (extent) which are found from the HEC-GeoRAS post processing. The flooded prone areas are identified for the 10, 50 and 100 year flood frequency storm. Based on this study, the most flood prone area is located around the final river reach (reach 29). The maximum flood depth along this reach is 7.86, 9.07 and 9.82m for 10, 50, and 100 year return periods respectively. The maximum flood extent (width) is 82.34 for 10 year return period and 100.15m for both 50 and 100 year return periods at river station 956.5694 which is found around the middle of reach 29. The hydraulic parameters of the most highly affected river station of the reach29 are tabulated on table 5.6.

Table 5.6: Hydraulic parameters of the most highly affected river station

Reach	River station	Return Period (profile)	Total peak discharge (m^3/s)	Velocity of flow (m/s)	Flow area (m^2)	Flood width(m)	Maximum flood depth (m)
Reach 29	956.5694	10	403.80	0.91	479.16	82.34	7.86
Reach 29	956.5694	50	546.50	1.02	582.55	100.15	9.07
Reach 29	956.5694	100	634.70	1.07	643.63	100.15	9.82

In addition to the above most important points other hydraulic parameters are extracted from HEC-RAS outputs. These parameters are flows (left, channel and right flows) from the main center line of the river, channel velocity, flow area, different elevation (water surface, minimum channel, critical water surface, and energy grade level elevations), and velocity head and channel froude number. The outputs are available in the form of both graphical and tabular. For example we can see the some of the parameters in tabular form on table 5.7 and X-Y-Z perspective plots of flow as shown on figure 5.5.

Profile Output Table - Standard Table 2

File Options Std. Tables Locations Help

HEC-RAS Plan: plan River: GARiver29 Reach: GAReach29

Reach	River Sta	Profile	E.G. Elev (m)	W.S. Elev (m)	Vel Head (m)	Frctn Loss (m)	C & E Loss (m)	Q Left (m3/s)	Q Channel (m3/s)	Q Right (m3/s)	Top Width (m)
GAReach29	1993.861	PF 1	2069.35	2069.24	0.12	0.03	0.00	89.92	241.32	72.55	48.29
GAReach29	1918.901	PF 1	2069.32	2069.18	0.14	0.03	0.00	88.74	197.49	117.57	42.93
GAReach29	1846.959	PF 1	2069.29	2069.13	0.16	0.04	0.02	52.56	281.29	69.95	43.71
GAReach29	1787.331	PF 1	2069.22	2068.82	0.41	0.05	0.04	35.80	279.04	88.96	33.96
GAReach29	1738.741	PF 1	2069.14	2068.86	0.28	0.02	0.00	44.18	326.29	33.33	34.46
GAReach29	1712.19	PF 1	2069.11	2068.82	0.29	0.02	0.01	39.38	333.63	30.78	36.17
GAReach29	1691.067	PF 1	2069.08	2068.70	0.39	0.05	0.01	23.82	349.14	30.84	33.38
GAReach29	1654.942	PF 1	2069.02	2068.50	0.51	0.06	0.01	82.58	273.95	47.27	29.56
GAReach29	1625.763	PF 1	2068.94	2068.30	0.64	0.08	0.02	20.18	340.25	43.38	26.14
GAReach29	1597.264	PF 1	2068.85	2068.04	0.81	0.05	0.12	22.83	266.02	114.96	31.22
GAReach29	1571.733	PF 1	2068.68	2068.26	0.42	0.06	0.00	13.26	297.13	93.41	29.07
GAReach29	1531.791	PF 1	2068.62	2068.20	0.42	0.09	0.09	35.69	233.61	134.50	33.19
GAReach29	1498.389	PF 1	2068.45	2067.18	1.27	0.20	0.06	24.58	340.57	38.65	19.41
GAReach29	1468.303	PF 1	2068.19	2066.33	1.87	0.13	0.39	16.51	353.08	34.22	19.78
GAReach29	1428.198	PF 1	2067.67	2067.11	0.56	0.05	0.01	12.48	375.27	16.05	24.34
GAReach29	1395.382	PF 1	2067.61	2067.08	0.53	0.05	0.03	13.99	353.76	36.05	26.59
GAReach29	1358.676	PF 1	2067.52	2067.10	0.42	0.05	0.01	10.39	318.38	75.03	29.70
GAReach29	1327.337	PF 1	2067.47	2066.95	0.52	0.08	0.01	15.11	314.73	73.96	28.84
GAReach29	1279.234	PF 1	2067.38	2066.91	0.47	0.05	0.04	14.80	344.96	44.04	28.88
GAReach29	1239.976	PF 1	2067.29	2066.96	0.33	0.02	0.04	22.46	352.33	29.01	33.09
GAReach29	1208.22	PF 1	2067.23	2067.03	0.20	0.01	0.02	30.06	328.34	45.40	42.96
GAReach29	1182.935	PF 1	2067.20	2067.06	0.14	0.01	0.02	26.38	349.82	27.61	48.06
GAReach29	1139.788	PF 1	2067.17	2067.09	0.08	0.01	0.01	25.10	352.75	25.96	64.79
GAReach29	1101.692	PF 1	2067.16	2067.10	0.06	0.01	0.00	10.43	373.27	20.10	72.22
GAReach29	1009.105	PF 1	2067.14	2067.08	0.06	0.01	0.01	18.84	370.21	14.75	70.18
GAReach29	956.5694	PF 1	2067.13	2067.09	0.04	0.01	0.01	17.42	372.16	14.21	82.34
GAReach29	883.379	PF 1	2067.11	2066.99	0.12	0.03	0.02	97.19	276.13	30.48	57.51
GAReach29	830.78	PF 1	2067.07	2066.80	0.27	0.05	0.02	56.72	219.99	127.08	43.44
GAReach29	771.956	PF 1	2067.00	2066.80	0.19	0.02	0.02	50.47	295.15	58.17	44.46
GAReach29	721.7447	PF 1	2066.95	2066.83	0.12	0.02	0.00	60.71	252.74	90.35	61.54
GAReach29	675.5126	PF 1	2066.93	2066.81	0.13	0.02	0.00	58.57	257.58	87.65	57.15
GAReach29	625.2098	PF 1	2066.91	2066.74	0.17	0.02	0.01	72.69	229.54	101.56	44.65
GAReach29	593.453	PF 1	2066.88	2066.65	0.23	0.02	0.03	40.45	297.38	65.97	37.18
GAReach29	559.7658	PF 1	2066.83	2066.71	0.12	0.03	0.01	26.96	256.73	120.11	54.55
GAReach29	495.7283	PF 1	2066.79	2066.57	0.22	0.04	0.02	95.40	247.26	61.15	46.69
GAReach29	438.4258	PF 1	2066.74	2066.58	0.16	0.03	0.01	81.15	261.02	61.62	52.18

Table 5.7: Values of hydraulic parameters from HEC-RAS for 10 year frequency storm

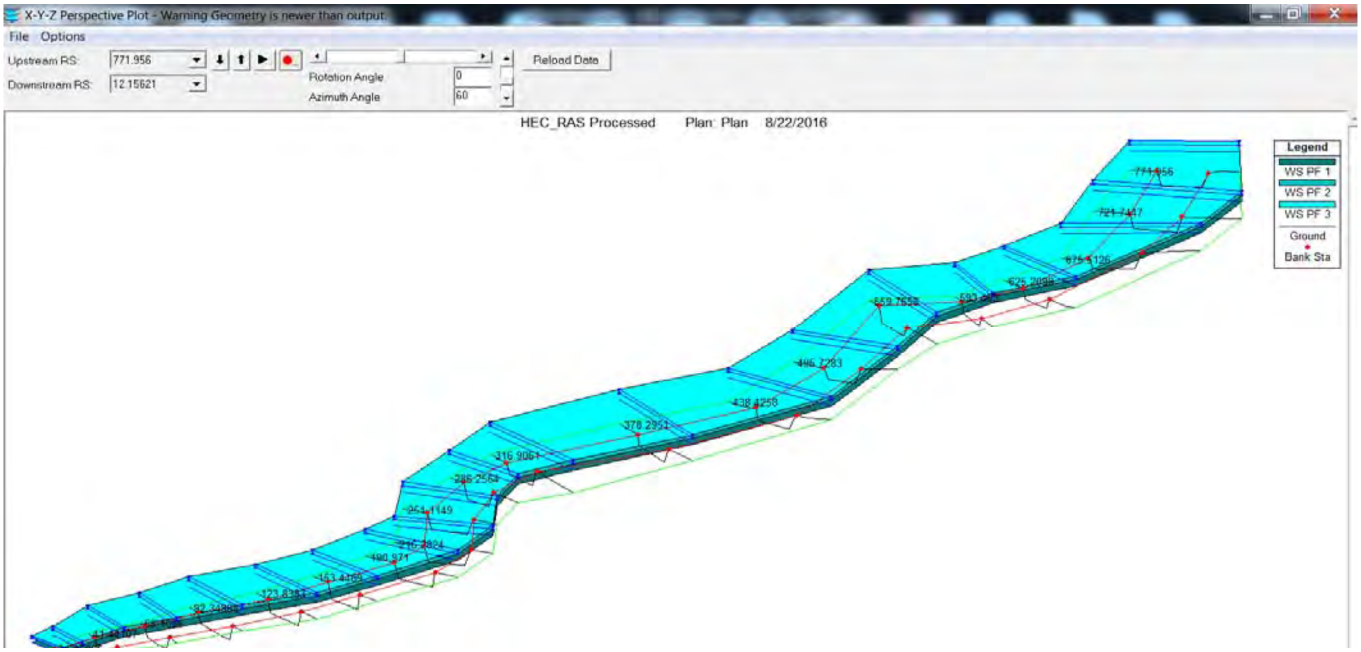


Figure 5.5: x, y, z perspective view of flow around bridge for 10, 50,100 year frequency storm

Finally the flood map for the 10 and 100 year return periods is prepared shown on figure 5.6 and figure 5.7.

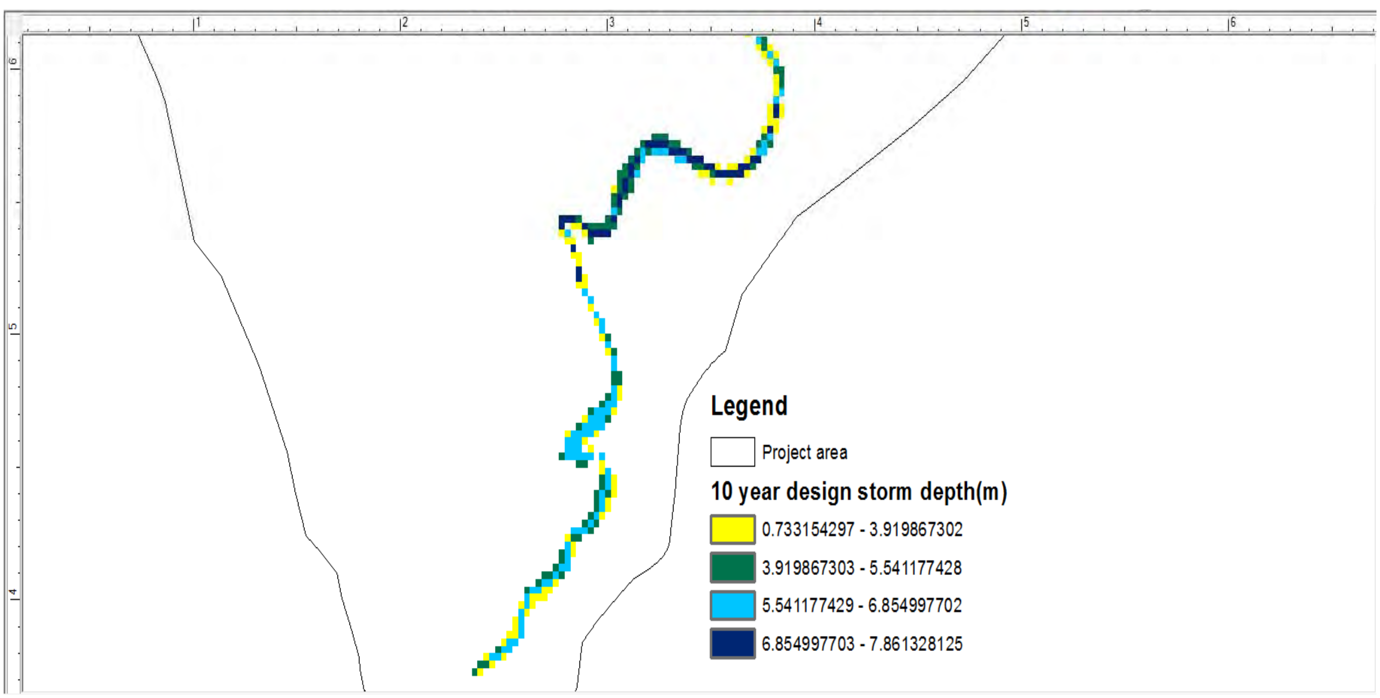


Figure 5.6: Flood hazard map for a 10 year frequency storm

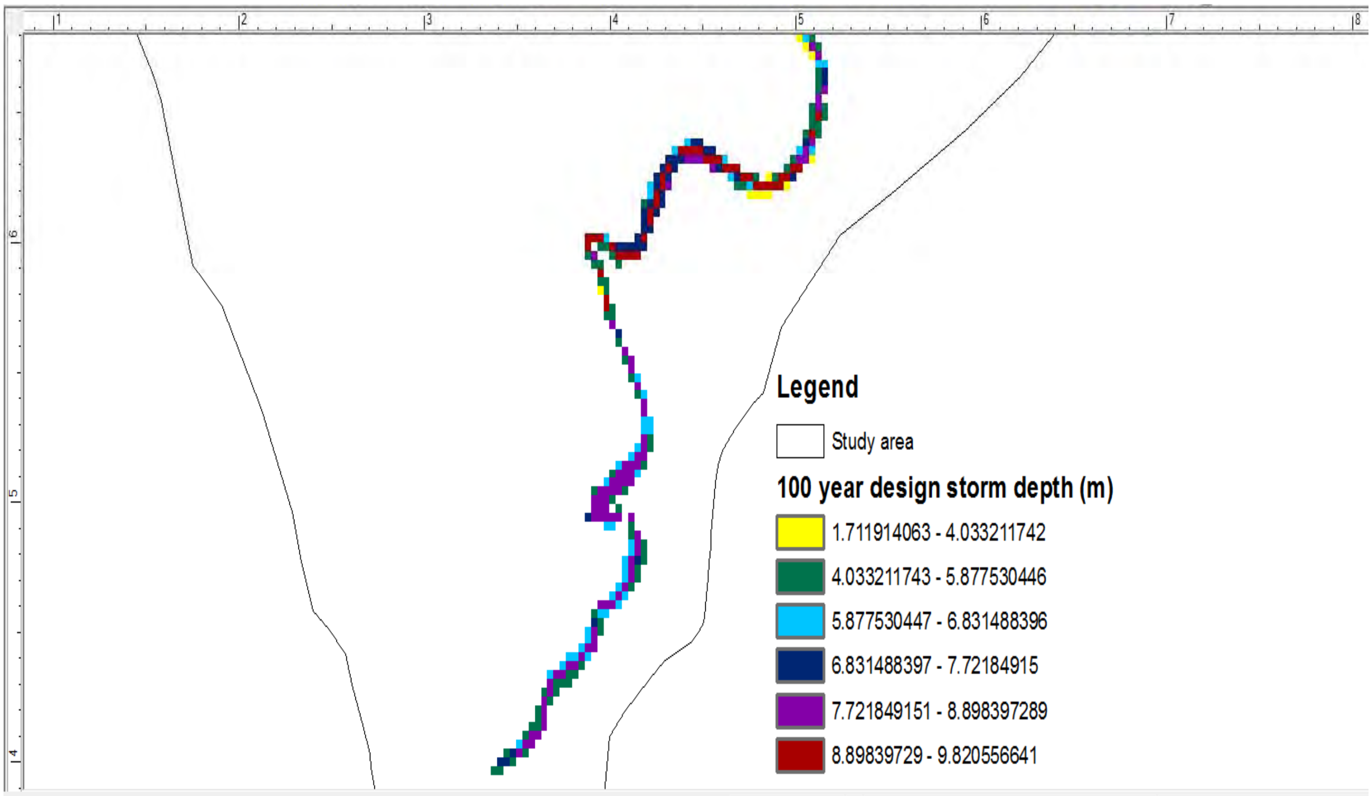


Figure 5.7: Flood hazard map for a 100 year frequency storm

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

The main aim of this research is to show the effect of high rate of growth of the Addis Ababa City in general the project area on the amount of runoff generated at Great Akaki River for 1989, 2000 and 2010. These years are selected based on the available cloud free satellite image; map from Addis Ababa City Administration Land Development and Management Bureau; and nearly similar amount of hourly rainfall for selected days of each respective years. After research data collected from field survey, different originations and from well known websites hydrological and hydraulic analysis area completed and good result is founded from the analysis.

6.1.1. Hydrological Modeling

To develop hydrological modeling first development of basin model using ArcGIS and GIS extension tools was completed. The main input data's used for pre-hydrological modeling are extracted basin characteristics of the study area from DEM; merged land use/soil data; impervious percentage area and excel format CN look up table. After the pre-hydrological modeling finished HEC-HMS project was created and opened on HEC-HMS computer software version 4.0.

The rainfall – runoff analysis was successfully performed using basin model, meteorological model and by defining the control specifications in two ways: the first simulation tried to show the effect of high urbanization growth on the basin and hourly rainfall intensity used. The peak discharge for 1989, 2000 and 2010 is 131, 153.4 and 188.1m^3/s respectively. This result shows the generated peak run off difference was due to the land use change on the catchment within these years.

The second simulation result used for flood mapping. To complete this hydrological modeling frequency storm method of HEC-HMS used for 1, 2, 3, 6, 12 and 24 hour intensity duration rainfall depths. The rainfall depth for the above intensity durations found from ERA rainfall intensity-duration curve of the study area for 10, 50 and 100 return periods. After the rainfall data entered and the method of hydrological modeling determined the simulation run executed. Accordingly, peak discharge of 403.80, 546.50 and 634.70 m^3/s for 10, 50 and 100 return period is obtained. This result found from HEC-HMS frequency storm method used for hydraulic analysis and flood map generation.

6.1.2. Hydraulic Modeling

By using the result from HEC-HMS frequency storm method, the hydraulic model development accomplished using HEC-RAS. River Analysis System (RAS) has the three basic components these are geometry data which describes the size, shape and connectivity of stream cross sections; the flow data that provides discharge rates; and the plan data, which contains information to run specifications of the model. After the above hydraulic parameters analyzed the result exported to GIS for flood mapping.

Finally flood inundation maps produced using ArcGIS and HEC-GeoRAS extension to visualize flood depth and extent for each return period. The maximum channel flood depths found around the middle reach29 is 7.86, 9.07 and 9.82m for 10, 50 and 100 year design frequency storms respectively with flood extent of 82.34m for 10 year turn period, and 100.15m for both 50 and 100 year return periods.

6.2. Recommendations

Based on the population projection of Addis Ababa city by Central Statics Agency of Ethiopia 2013 report, the population of the city will increase from 3,195,000 to 3,433,999 from 2014 – 2017. This shows how the population of the city increases dynamically from year to year. As the population of the city continues like this the demand of housing and conversion of agriculture, forest land and open spaces will increase also the result of this paper proofs this. Especially on the eastern part of the city which is also the main central location of the study area such as Bole, Hayat, Tafo, Legedadi and Sendafa there is high urbanization development and one of the most active parts of the city and the study area in terms of development. This is a good indication of how the city is growing fastly. As the hydrological analysis result of this research showed there are problems associated with high urbanization of the city. For example the peak run off discharge generated on river tributaries found on the city and study area increasing from time to time. Some flood hazards area shown on the houses found on border of the rivers. This is associated with an overall increasing of impervious percentage area of the study area. However, this effect can be protected if effective flood modeling and management strategies are developed and the recommendation of this paper focuses on issues related to the above.

Even if this research was conducted by using available limited data and with different constraints the following recommendations are made for further studies;

- As discussed on chapter seven the most affected part of the study area is the lower reach of the river with inundation depth of 9.82m up to 100.15m flood width. During construction of structures like bridge across this reach should consider this effect. The area up to the above mentioned flood extent/width should be free from any activity unless otherwise other mitigation measurements taken which is out of this aim of this study.
- As discussed on chapter six and seven the amount of runoff generated from the catchment increases from time to time and has also advantage if it manages appropriately. If the water collected and treated well with other tributaries of Akaki River it can be used for different purposes (hydro power, irrigation, fishery and recreation).

- As shown on historic images of the catchment we can see it also easily on Google earth by using "show historic imagery" icon, the river morphology of Great Akai River is changing through time. Therefore, for a better hydrological and hydraulic modeling up to date digital elevation model/DEM with high resolution should be adapted. Especially Triangulated Irregular Network (TIN) development should be supported by LIDAR (Light Detection and Ranging) for a better representation of digital terrain.

- Freely available DEM data's for Ethiopia specifically for the study area are STRM 90m and ASTER GDEM Version 1 and 2 both 30m resolution. But, we found STRM 90m resolution is the best for model development of the study area. Moreover, STRM 30 resolution is releasing globally since 2014 and since September 2015 also released for Northeast Africa. As shown on figure 6.1 STRM 30m resolution is released for only Ethiopia-Somalia region not for the whole Ethiopia, but the release is ongoing. Accordingly, before using the above DEM's researchers should check the release of STRM 30m resolution for their study area.

- All the hourly rainfall data used for this study was from stations found only inside Addis Ababa (Bole and Observatory stations), but well organized hourly rainfall should be delivered from all meteorological stations found on the study area like Sendafa, Dire dam, Intoto, Cotebe and Akaki stations for a better hydrological and hydraulic analysis.

- The automatic river flow data recorder at the outlet of the study area was not functional since 2005. Therefore this automatic flow recorder should be maintain or change.

Finally, this hydrological and hydraulic modeling's were specifically developed for Great Akaki watershed up to the Bridge along Addis Ababa to Bishoftu Road and cannot be applied for any other watersheds. This is due to that the data sets used for the study area are only belongs to the study area. But, the methods, procedures and software's used in this model development can be used if the right type datasets found specific to that target watershed.

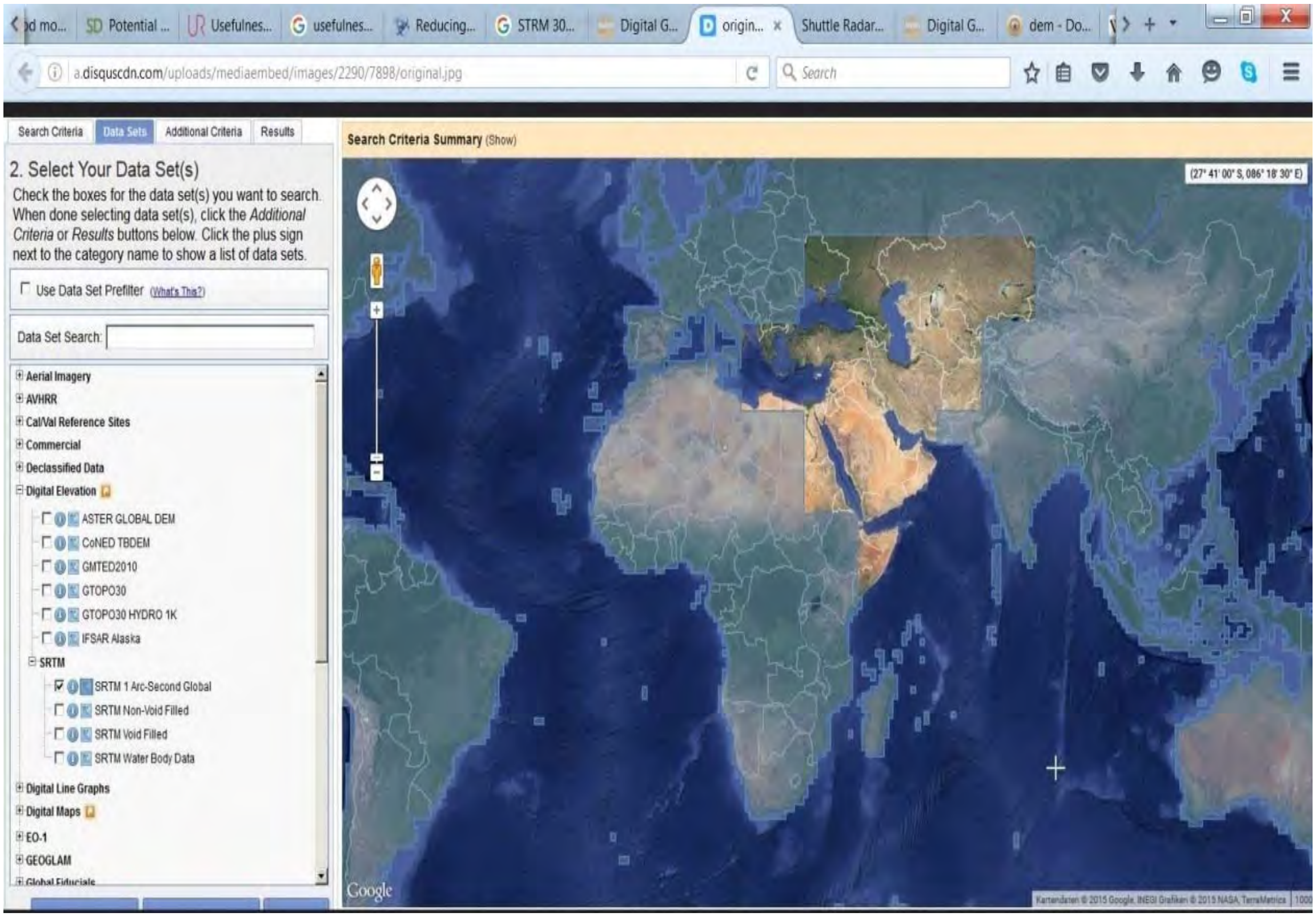


Figure 6.1: SRTM 30m released since September 2015 for Northeast Africa (source: by Digital Geography.com from USGS)

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ANNEXES

Appendix A: Hydrological Analysis Results

Table A1: Great Akaki River HEC- HMS model simulation result for 1989

Global Summary Results for Run "July18_1989Run 1"

Project: GreatAkakiHMS1989 Simulation Run: July18_1989Run 1

Start of Run: 17Jul1989, 23:00 Basin Model: GreatAkakiHMS1989
End of Run: 18Jul1989, 12:00 Meteorologic Model: GreatAkakiHMS1989
Control Specifications: July18_1989control

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

Hydrologic Element	Drainage A... (KM2)	Peak Disch... (M3/S)	Time of Peak	Volume (1000 M3)
Sub_basin 32	19.532	6.5	18Jul1989, 02:00	88.3
Sub_basin 31	25.071	4.3	18Jul1989, 04:00	63.0
Sub_basin 30	2.2040	0.5	18Jul1989, 01:00	5.8
Sub_basin 29	17.564	1.6	18Jul1989, 04:00	25.5
Sub_basin 28	2.1871	2.8	18Jul1989, 01:00	28.7
Sub_basin 27	53.545	9.1	18Jul1989, 02:00	155.1
Sub_basin 26	1.5115	0.6	18Jul1989, 01:00	6.5
Sub_basin 25	17.150	5.6	18Jul1989, 03:00	95.6
Sub_basin 24	5.3537	2.6	18Jul1989, 02:00	35.7
Sub_basin 23	5.8265	3.6	18Jul1989, 01:00	46.6
Sub_basin 22	4.5937	3.5	18Jul1989, 01:00	40.5
Sub_basin 21	11.586	3.1	18Jul1989, 02:00	43.2
Sub_basin 20	1.5031	1.1	18Jul1989, 01:00	10.9
Sub_basin 19	5.2439	1.8	18Jul1989, 01:00	22.4
Sub_basin 18	32.012	6.5	18Jul1989, 02:00	98.1
Sub_basin 17	9.0438	3.5	18Jul1989, 02:00	54.6
Sub_basin 16	23.593	6.1	18Jul1989, 03:00	112.4
Sub_basin 15	6.1390	2.5	18Jul1989, 02:00	33.6
Sub_basin 14	15.715	5.6	18Jul1989, 02:00	90.8
Sub_basin 13	15.597	4.2	18Jul1989, 02:00	61.3
Sub_basin 12	6.9581	3.3	18Jul1989, 02:00	47.6
Sub_basin 11	26.566	2.1	18Jul1989, 02:00	35.2
Sub_basin 10	9.5842	2.8	18Jul1989, 01:00	33.4
Sub_basin 9	11.087	2.4	18Jul1989, 01:00	30.7
Sub_basin 8	37.104	9.0	18Jul1989, 03:00	164.0
Sub_basin 7	16.196	4.0	18Jul1989, 02:00	59.1
Sub_basin 6	8.9340	0.9	18Jul1989, 01:00	9.9
Sub_basin 5	18.577	2.9	18Jul1989, 01:00	34.1
Sub_basin 4	4.8977	0.9	18Jul1989, 01:00	10.4
Sub_basin 3	8.0389	1.1	18Jul1989, 01:00	11.2
Sub_basin 2	14.068	2.1	18Jul1989, 01:00	24.1
Sub_basin 1	16.137	3.1	18Jul1989, 02:00	42.0
OutletAtBridge1989	881.17588	131.0	18Jul1989, 07:00	3194.4

Table A2: Great Akaki River HEC- HMS model simulation result for 2000

Global Summary Results for Run "July18_2000Run 1"

Project: GreatAkakiHMS2000 Simulation Run: July18_2000Run 1

Start of Run: 17Jul2000, 23:00
End of Run: 18Jul2000, 12:00

Basin Model: GreatAkakiHMS2000
Meteorologic Model: GreatAkakiHMS2000
Control Specifications:18July_2000control

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

Hydrologic Element	Drainage A... (KM2)	Peak Disch... (M3/S)	Time of Peak	Volume (1000 M3)
Sub_basin 32	19.532	7.8	18Jul2000, 02:00	105.2
Sub_basin 31	2.2040	1.5	18Jul2000, 01:00	14.6
Sub_basin 30	25.071	5.0	18Jul2000, 04:00	72.0
Sub_basin 29	17.564	2.6	18Jul2000, 04:00	41.3
Sub_basin 28	2.1871	2.8	18Jul2000, 01:00	28.8
Sub_basin 27	53.545	12.1	18Jul2000, 02:00	197.9
Sub_basin 26	1.5115	0.8	18Jul2000, 01:00	7.5
Sub_basin 25	17.150	5.2	18Jul2000, 03:00	88.4
Sub_basin 24	5.3537	3.3	18Jul2000, 01:00	43.3
Sub_basin 23	5.8265	2.1	18Jul2000, 02:00	28.2
Sub_basin 22	4.5937	2.7	18Jul2000, 01:00	32.4
Sub_basin 21	11.586	4.0	18Jul2000, 02:00	55.2
Sub_basin 20	1.5031	0.8	18Jul2000, 01:00	7.8
Sub_basin 19	5.2439	2.4	18Jul2000, 01:00	28.1
Sub_basin 18	32.012	7.7	18Jul2000, 02:00	114.6
Sub_basin 17	9.0438	2.5	18Jul2000, 02:00	41.5
Sub_basin 16	23.593	8.5	18Jul2000, 03:00	149.4
Sub_basin 15	6.1390	2.9	18Jul2000, 01:00	40.3
Sub_basin 14	15.715	4.7	18Jul2000, 02:00	78.2
Sub_basin 13	15.597	2.1	18Jul2000, 02:00	31.3
Sub_basin 12	6.9581	2.7	18Jul2000, 02:00	39.9
Sub_basin 11	26.566	2.4	18Jul2000, 02:00	39.1
Sub_basin 10	9.5842	2.4	18Jul2000, 01:00	28.1
Sub_basin 9	11.087	2.1	18Jul2000, 01:00	27.0
Sub_basin 8	37.104	5.7	18Jul2000, 03:00	110.4
Sub_basin 7	16.196	6.1	18Jul2000, 02:00	86.8
Sub_basin 6	8.9340	0.6	18Jul2000, 01:00	7.5
Sub_basin 5	18.577	1.8	18Jul2000, 01:00	22.7
Sub_basin 4	4.8977	0.7	18Jul2000, 01:00	7.9
Sub_basin 3	8.0389	0.7	18Jul2000, 01:00	8.2
Sub_basin 2	14.068	2.0	18Jul2000, 01:00	22.6
Sub_basin 1	16.137	3.2	18Jul2000, 02:00	43.4
OutletAtBridge2000	881.17588	153.4	18Jul2000, 07:00	3580.3

Table A3: Great Akaki River HEC- HMS model simulation result for 2010

Global Summary Results for Run "18July2010Run 1"

Project: GreatAkakiHMS2010 Simulation Run: 18July2010Run 1

Start of Run: 17Jul2010, 23:00 Basin Model: GreatAkakiHMS2010
End of Run: 18Jul2010, 12:00 Meteorologic Model: GreatAkakiHMS2010
Control Specifications: July18_2010 control

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

Hydrologic Element	Drainage A... (KM2)	Peak Disch... (M3/S)	Time of Peak	Volume (1000 M3)
Sub_basin 32	19.352	8.0	18Jul2010, 02:00	108.8
Sub_basin 31	2.2040	1.3	18Jul2010, 01:00	12.9
Sub_basin 30	25.071	6.8	18Jul2010, 04:00	110.2
Sub_basin 29	17.564	5.0	18Jul2010, 04:00	82.2
Sub_basin 28	2.1871	2.7	18Jul2010, 01:00	27.6
Sub_basin 27	53.545	11.0	18Jul2010, 02:00	181.8
Sub_basin 26	1.5115	0.7	18Jul2010, 01:00	7.1
Sub_Basin 25	17.150	5.6	18Jul2010, 03:00	95.0
Sub_basin 24	5.3537	2.7	18Jul2010, 01:00	37.3
Sub-basin 23	5.8265	2.4	18Jul2010, 02:00	33.3
Sub-basin 22	4.5937	2.9	18Jul2010, 01:00	34.6
Sub-basin 21	11.586	4.2	18Jul2010, 02:00	57.3
Sub_basin 20	1.5031	1.0	18Jul2010, 01:00	10.5
Sub_basin 19	5.2439	2.7	18Jul2010, 01:00	31.0
sub_basin 18	32.012	8.1	18Jul2010, 02:00	120.3
Sub_basin 17	9.0438	2.7	18Jul2010, 02:00	44.6
Sub_basin 16	23.593	9.8	18Jul2010, 03:00	171.3
Sub_basin 15	6.1390	3.2	18Jul2010, 01:00	42.9
Sub_basin 14	15.715	6.6	18Jul2010, 02:00	103.8
Sub_basin 13	15.597	2.7	18Jul2010, 02:00	40.1
Sub_basin 12	6.9581	4.4	18Jul2010, 02:00	61.3
Sub_basin 11	26.566	2.3	18Jul2010, 02:00	37.6
Sub_basin 10	9.5842	2.0	18Jul2010, 01:00	23.5
Sub_basin 9	11.087	2.2	18Jul2010, 01:00	27.9
Sub_basin 8	37.104	6.1	18Jul2010, 03:00	115.7
Sub_basin 7	16.196	6.5	18Jul2010, 02:00	91.8
sub_basin 6	8.9340	0.6	18Jul2010, 01:00	7.1
Sub_basin 5	18.577	2.6	18Jul2010, 01:00	30.6
Sub_basin 4	4.8977	0.6	18Jul2010, 01:00	7.0
Sub_basin 3	8.0389	1.0	18Jul2010, 01:00	10.5
Sub_basin 2	14.068	2.3	18Jul2010, 01:00	25.5
Sub_basin 1	16.137	3.5	18Jul2010, 02:00	47.8
OutletAtBridge2010	881.17588	188.1	18Jul2010, 07:00	4372.3

Appendix B: Tables and Graphs Used for Frequency Storm Analysis

Table B1: ERA 24 hour rainfall depth vs. return period

Region	24 HOUR DEPTH (mm) vs. FREQUENCY (yrs) TABLE					
	2	5	10	25	50	100
A1, A4	60	79	93	113	127	142
A2, A3	52	67	79	95	107	118
B and C	65	84	98	118	132	147
D	67	89	105	127	144	161
Bahir Dar	74	106	131	163	187	211

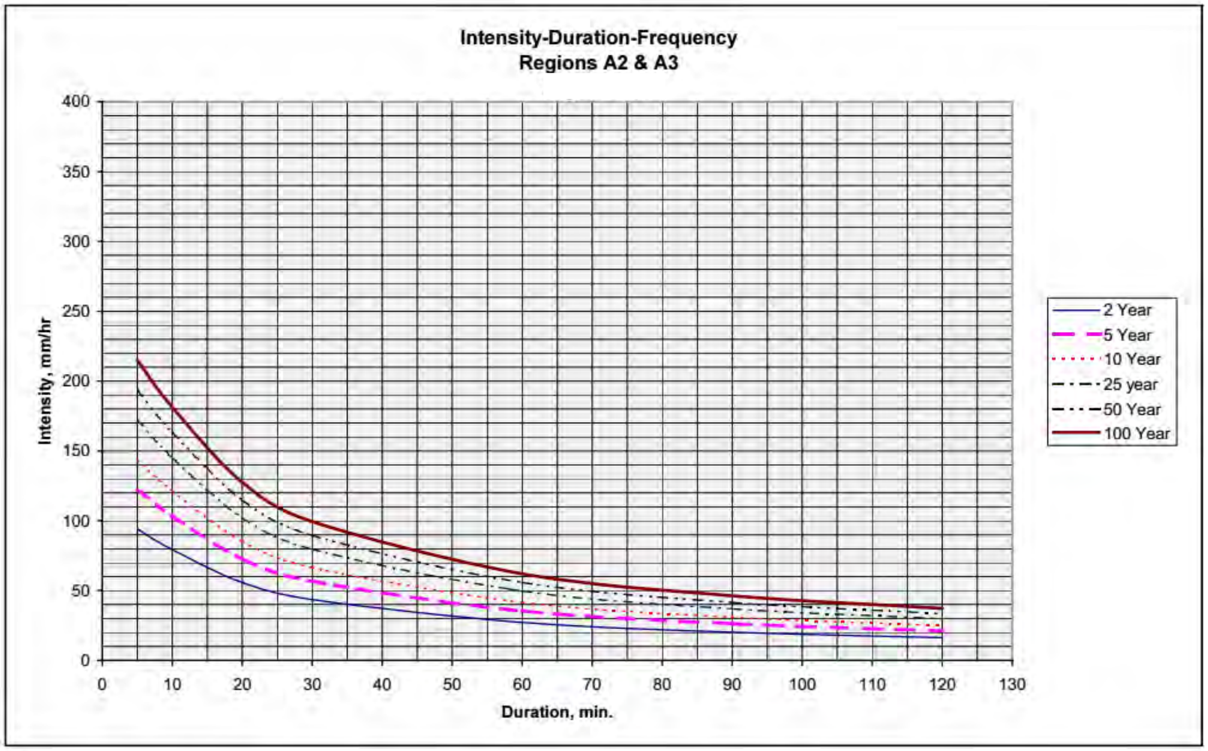
Table B2: SCS maximum ration to 24 hour rainfall values (NEH, 2015)

Duration	Ratio to 24-hour rainfall
5-minutes	0.114
10-minute	0.201
15-minutes	0.270
30-minutes	0.380
1-hour	0.454
2-hours	0.538
3-hours	0.595
6-hours	0.707
12-hours	0.841
24-hours	1.00

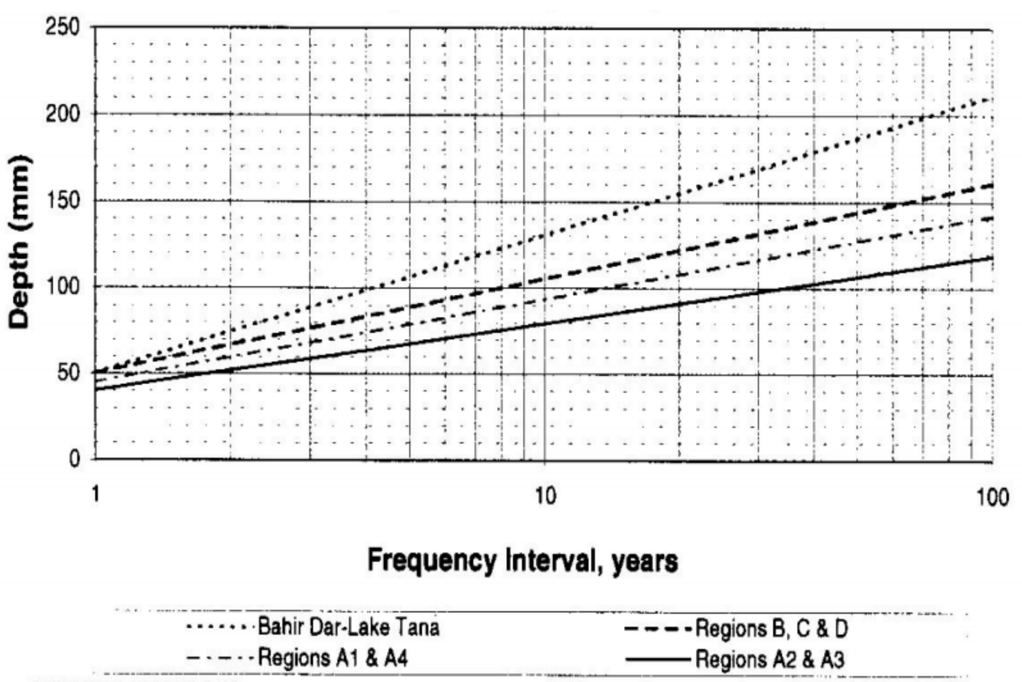
Table B3: 1981-2004 recorded monthly peak discharge at Bridge used for frequency analysis found from Ministry of Water Resources and Electric.

Year	**Peak discharge (m^3/s)**	**$(xi-x)^2$**	**Y = LogX**	**$(Yi-Y)^2$**	**$(yi-y)^3$**
1981	201.312	5326.901457	2.303	0.002878412	-0.00015442920
1982	172.772	10307.45253	2.237	0.014316322	-0.00171295985
1983	138.717	18382.10588	2.142	0.046074980	-0.00989003291
1984	189.383	7210.493539	2.277	0.006344255	-0.00050532522
1985	165.65	11804.30642	2.219	0.018947752	-0.00260817384
1986	68.777	42238.7273	1.837	0.270036989	-0.14032494615
1987	36.554	56522.03123	1.56293	0.629992761	-0.50003837947
1988	148.353	15862.04857	2.171	0.034466232	-0.00639868468
1989	233.769	1642.569444	2.368	0.000128804	0.00000146181
1990	277.219	8.534431891	2.442	0.007284480	0.00062172432
1991	215.224	3489.693171	2.33289	0.000564577	-0.00001341482
1992	153.074	14695.16726	2.1849	0.029498349	-0.00506636598
1993	573.569	89563.35589	2.7585	0.161482753	0.06489170962
1994	162.58	12480.82774	2.211	0.021214165	-0.00308986085
1995	257.976	266.3954426	2.411	0.002953832	0.00016053830
1996	615.761	116597.2365	2.789	0.186925802	0.08081721469
1997	276.323	4.102143891	2.4414	0.007182421	0.00060870422
1998	421.518	21673.83882	2.624	0.071475577	0.01910893593
1999	693.102	175397.1045	2.84	0.233626417	0.11292313393
2000	255.776	343.0505926	2.407	0.002535039	0.00012763708
2001	435.338	25934.002	2.638	0.079157354	0.02227085547
2002	219.869	2962.475219	2.342	0.000214647	-0.00000314476
2003	420.059	21246.37844	2.623	0.070941879	0.01889531024
2004	250.468	567.8510276	2.398	0.001709754	0.00007069689
Sum	**6583.143**	**654526.6499**	**56.5596**	**1.899953551**	**-0.34930779522**
Mean	**274.297625**		**2.35665**		

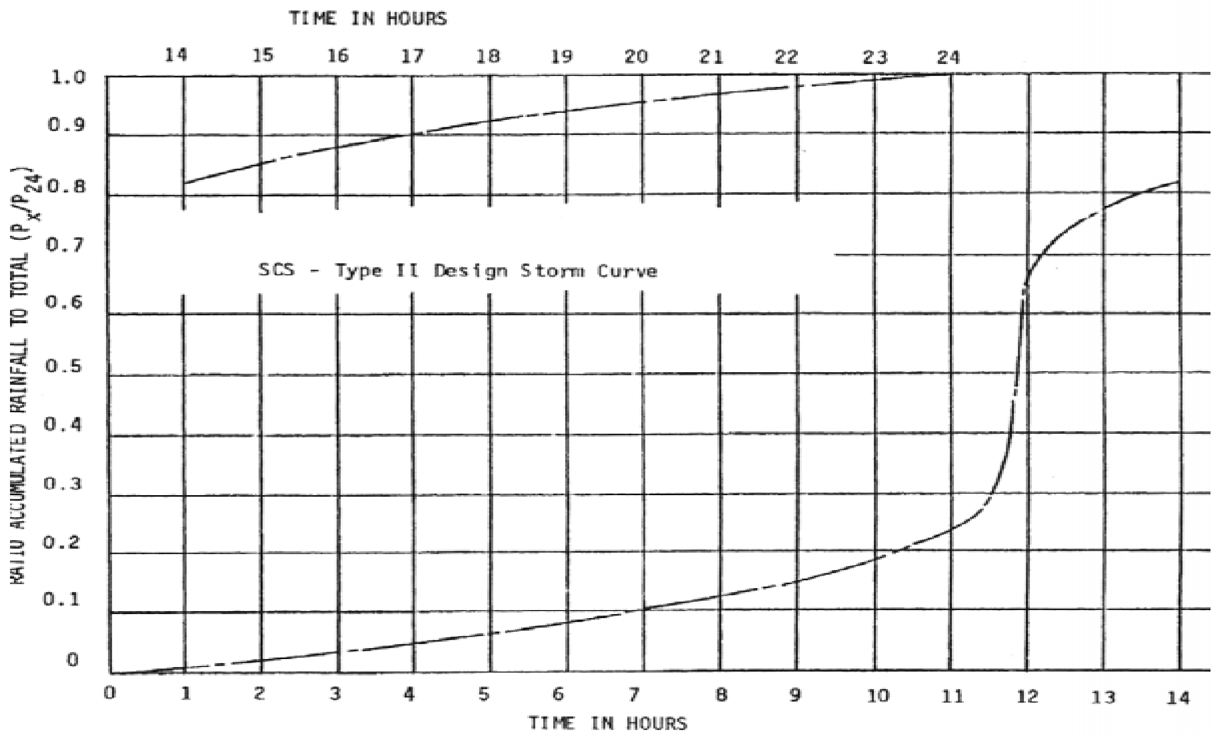
Graph B1: ERA Intensity Duration Curve Frequency (IDF) of the study area



Graph B2: ERA 24 hour rainfall depth frequency curve



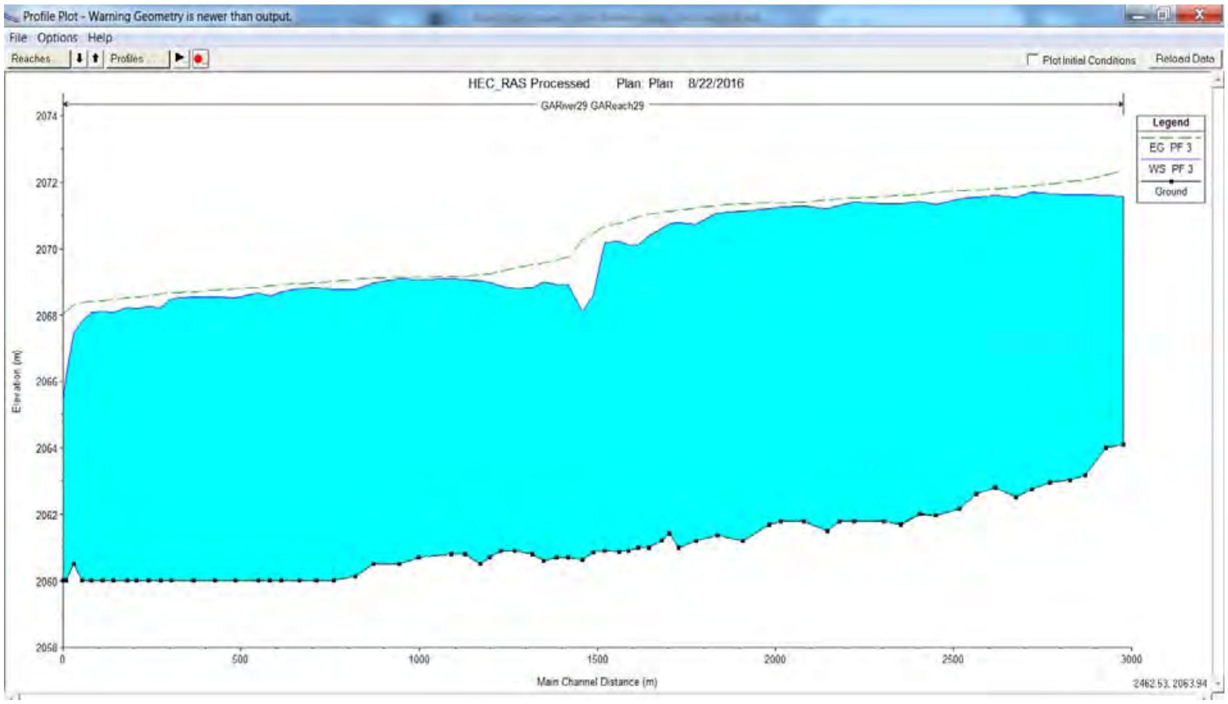
Graph B3: SCS rain fall type II distribution recommended by ERA



Source: SCS-TP-149

Appendix C: Hydraulic Analysis and Flood Mapping Results

Graph C1: Water Surface Profile (100 Frequency Storm) of Reach 29 (Up Stream to Down Stream)



Graph C2: Hydraulic Depth of 10, 50 and 100 Year Water Surfaces

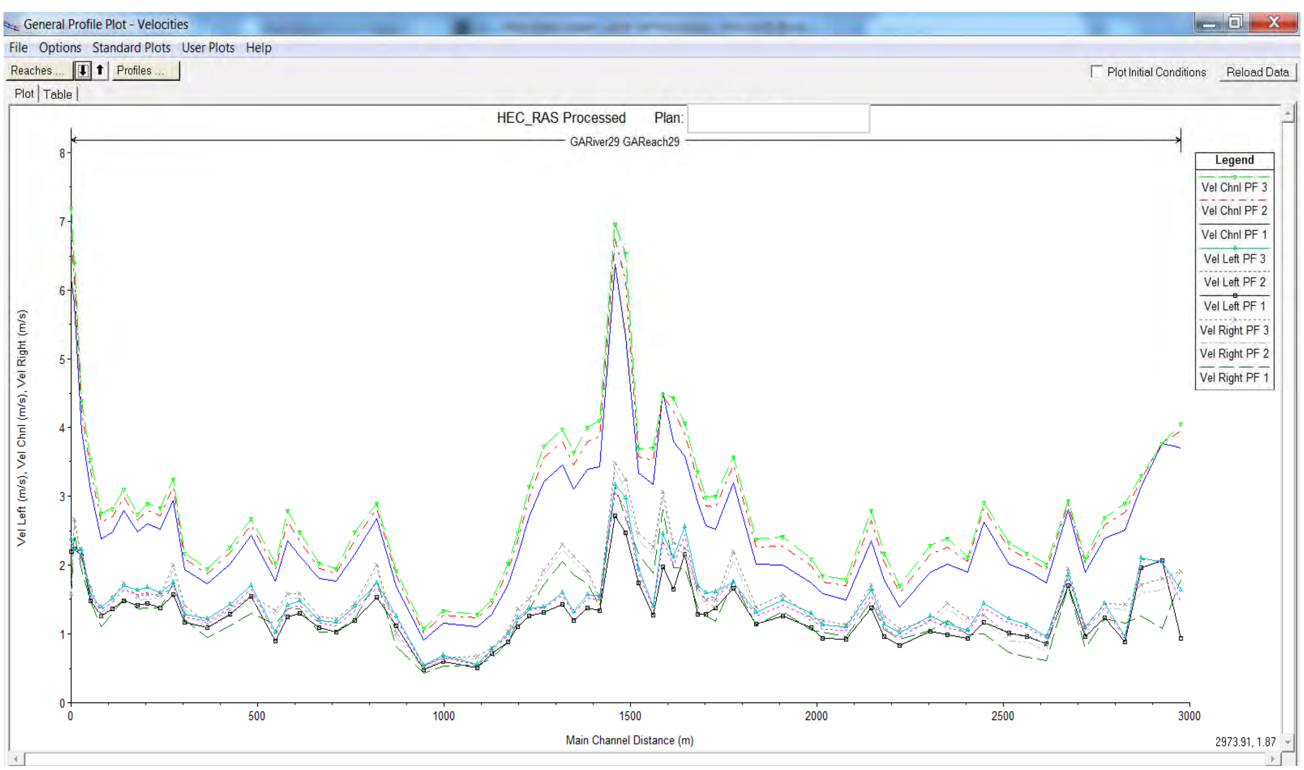


Figure C1: 10 Year Frequency Storm Flood Map

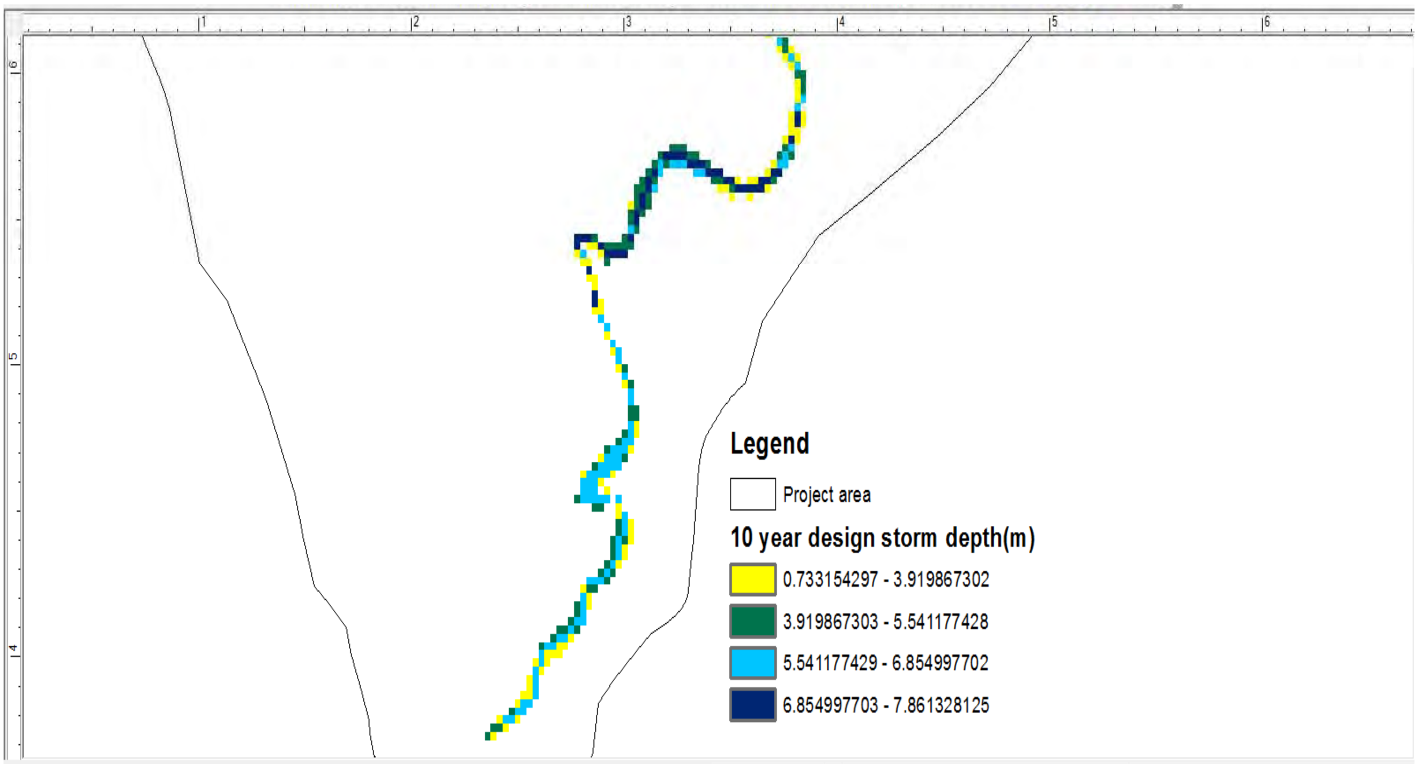


Figure C2: 50 Year Frequency Storm Flood Map

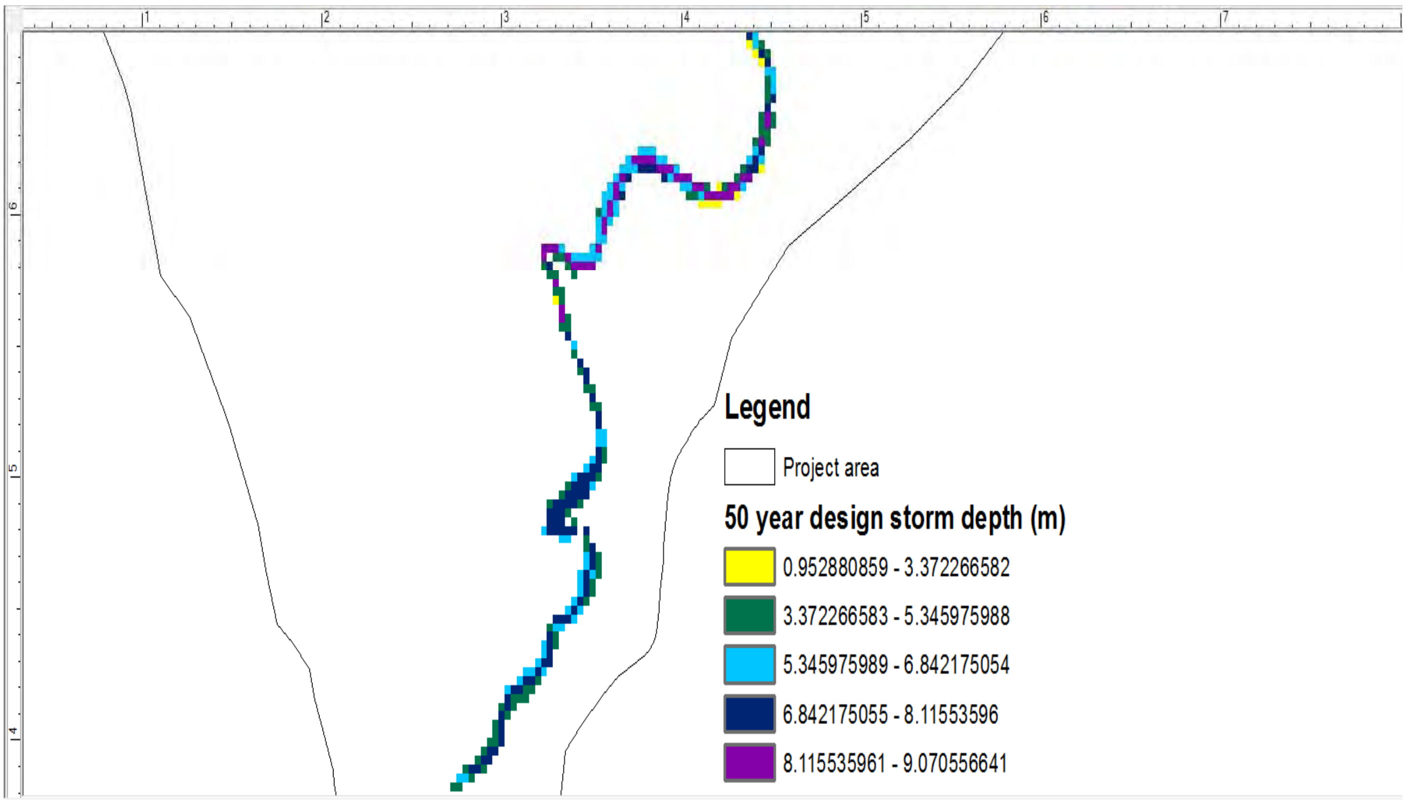


Figure C3: 100 Year Frequency Storm Flood Map