# FLOOD MODELING & RISK FORECASTING FOR AL-BATIN WATERSHED, SAUDI ARABIA

**Ahmed Mohammed Al-Areeq**

**CIVIL ENGINEERING**

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# FLOOD MODELING & RISK FORECASTING FOR AL-BATIN WATERSHED, SAUDI ARABIA

BY

**Ahmed Mohammed Al-Areeq**

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**Dedicated**

**To**

**My mother**

**My wife, my children, and to the soul of my father**

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| | | |
|---|---|---|
| *A* | : | cross section area ($m^2$) / catchment area (ha) |
| *C* | : | runoff coefficient |
| CN | : | curve number |
| CNs | : | curve numbers |
| DEM | : | digital elevation model(s) / map |
| *g* | : | gravitational acceleration ($m/s^2$) |
| GIS | : | Geographic Information System |
| GP | : | Generalized Pareto |
| *h* | : | flow depth (m) |
| HEC-HMS | : | Hydrologic Engineering Center-Hydrologic Modeling System |
| HEC-RAS | : | Hydrologic Engineering Center-River Analysis System |
| *i* | : | rainfall intensity (mm/h) |
| *I* | : | inflow ($m^3/s$) |
| IDF | : | intensity-duration-frequency |
| LIDAR | : | light detection and ranging |
| *m* | : | exponent of the kinematic wave |

| | | |
|---|---|---|
| MTM | : | Modified Talbot Method |
| $n$ | : | channel roughness |
| NRCS | : | Natural Resources Conservation Service |
| $O$ | : | outflow ($m^3/s$) |
| $P$ | : | rainfall (mm) |
| PRM | : | Probabilistic Rational Method |
| $q$ | : | lateral inflow per unit area ($m^3/s\ m^2$) |
| $Q$ | : | discharge / flow rate ($m^3/s$) |
| $Q_p$ | : | rate of peak runoff ($m^3/s$) |
| $Q_r$ | : | direct runoff (mm) |
| $R$ | : | hydraulic radius (m) |
| RFFA | : | Regional Flood Frequency Analysis |
| RMSE | : | Root Mean Square Error |
| $S$ | : | water storage volume ($m^3$) |
| SCS | : | Soil Conservation Service |
| SCS-CN | : | Soil Conservation Service-curve number |
| $S_f$ | : | friction slope (energy gradient) (m/m) |

| | | |
|---|---|---|
| $S_o$ | : | bed slope / channel slope (m/m) |
| $S_r$ | : | potential difference between direct runoff and rainfall (mm) |
| SWBM | : | Spatial Water Budget Model |
| $t$ | : | time (s) |
| TINs | : | triangulated irregular networks |
| $u$ | : | velocity of longitudinal flow (m/s) |
| USGS | : | United States Geological Survey |
| WMS | : | Watershed Modeling System |
| $x$ | : | longitudinal distance (m) |
| $\alpha$ | : | kinematic wave parameter |

# ABSTRACT

Full Name : Ahmed Mohammed Ahmed Al-Areeq

Thesis Title : Flood Modeling & Risk Forecasting for Al-Batin Watershed, Saudi Arabia

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The study of flood in arid and semi-arid regions is a challenging task for water resources engineers. In this research, the occurrence of flood in Hafar Al-Batin city will be investigated to identify the areas within the city with high risk of flooding. As a result of the limited data about the catchment of Hafar Al-Batin, Geographic Information System (GIS) has been used to obtain and prepare the input data prior to constructing and executing the hydrologic, hydraulic, and floodplain models. Moreover, Hafar Al-Batin intensity-duration-frequency (IDF) curves have been used in this study and two scenarios were applied to estimate the design storms. The first scenario was by using the Soil Conservation Service (SCS) hypothetical storm method while the second scenario was by using the frequency storm method. The catchment was divided into three main parts, and each part was divided into many sub-basins to run the hydrologic model in a semi-distributed mode. The effect of urbanization was investigated by simulating different urbanization scenarios to find its effect on peak discharge resulting from the design storms.

Flood modeling and simulation can help decision-makers to take the necessary actions to control or minimize the consequences of floods. To achieve the objectives of this research, Watershed Modeling System (WMS), Hydrological Modeling System (HEC-HMS), and River Analysis System (HEC-RAS) were used to construct the hydrologic, hydraulic, and

floodplain models, which were used to estimate the expected flow due to flood and identify the areas with high risk of flooding. Urbanization and rainfall characteristics were investigated and the results show their significant effects on the peak discharge and runoff volume. On the other side, it presents the estimated volume of water that can be collected during the design storm in the whole catchment area of 1,669.014 $km^2$, which can cause inundation of a wide portion of Hafar Al-Batin city. Accordingly, three proposed actions (retention pond at the entrance of the city, two trapezoidal channels at the south and north sides of the city) were suggested to reduce the risk of flood on the city of Hafr Al-Batin.

# ملخص الرسالة

**الاسم الكامل :أحمد محمد أحمد العريق**

**عنوان الرسالة :نمذجة الفيضانات والتنبؤ بالمخاطر لحوض حفر الباطن،المملكه العربيه السعودية**

**التخصص:هندسة مدنية**

**تاريخ الدرجة العلمية: إبريل 2016**

تعتبر دراسة الفيضانات في المناطق الجافة وشبة الجافة تحديا كبيرا في هندسة مصادر المياة .في هذا البحث تم دراسة حدوث الفيضانات في مدينة حفر الباطن، الواقعه في المنطقه الشرقيه من المملكة العربية السعودية، لتحديد المناطق ذات الخطورة العالية داخل المدينة .نتيجة لشحة البيانات في منطقة الدراسه فقد تم استخدام نظام المعلومات الجغرافية (GIS)للحصول على واعداد البيانات المدخله قبل انشاء وتنفيذ النموذج الهيدرولوجي،الهيدرولوكي، والسهول الفيضيه .علاوة على ذلك، في هذه الدراسة تم استخدام منجنيات الشدة، الاستدامة و التكرار (IDF) لمحطة حفر الباطن وتم تطبيق سيناريوهين لتقدير العواصف التصميمية .تم استخدام طريقة مصلحة حماية التربة لعاصفة افتراضية SCS في السيناريو الاول بينما تم استخدام طريقة عاصفة التكرار في السيناريو الثاني .تم تقسيم المسقط المائي الى ثلاثة اجزاء رئيسية وكل جزء تم تقسيمة الى عدة اجزاء وذلك لتنفيذ النموذج الهيدرولوجي في نمط نصف موزع .تمت دراسة التمدد الحضري من خلال نمذجة سيناريوهات مختلفة للتمدد الحضري لايجاد الجريان الاقصى الناتج من العواصف التصميمية.

نمذجة ومحاكاة الفيضانات يمكن ان تساعد صناع القرار على اتخاذ الاجراءات اللازمة للسيطرة أو التقليل من اثار الفيضانات .لتحقيق اهداف هذه الدراسة، فقد تم استخدام برامج ( WMS Watershed Modeling System, Hydrologic Modeling System HEC-HMS, and River Analysis System HEC-RAS ) لبناء النموذج الهيدرولوجي، الهيدرولوكي و السهول الفيضية التي تستخدم لتقدير الجريان المتوقع الناتج عن الفيضانات وتحديد المناطق ذات المخاطر العالية. أظهرت الدراسة بان التوسع العمراني وخصائص المطر لها تاثير واضح على التصريف الاقصى وحجم الفيضان. من ناحية اخرى، وبناء على نتائج الدراسة فقد تم تقدير حجم الفيضان الناتج عن سقوط الامطار ل 24ساعه وتكرار 100عام بحوالي 13,016,600م$^3$ مما يسبب باغراق جزء كبير من مدينة حفر

الباطن. ووفقا لذلك تم اقتراح بعض الاجراءات التي تساهم في تخفيف حدة السيول على مدينة حفر الباطن والتي من شأنها تقليل الخسائر والاضرار المتوقعه في حالة حدوث سيول على المدينة.

# CHAPTER 1

# INTRODUCTION

Floods are one of the dangerous natural catastrophes which hit many countries around the world every year, causing massive losses in human lives, property, and structures and affect millions of people. Moreover, huge amount of money is spent every year to avoid and protect the people and infrastructure from the effects of the floods.

Jonkman [1] mentioned that about 100,000 persons were killed and over 1.4 billion people were affected by floods during the last decade of the 20th century. Table 1.1 shows a comparison between the effects of flood events worldwide and other natural disasters. It can be noticed from the table that the floods are the most frequently occurring events, followed by the windstorm.

There are many types of floods which can be classified as [1]:

**Flash floods:** generally, this type of flood occurs in a mountainous region due to the rapid rise of water levels resulting from the high rainfall intensity.

**River floods:** caused by high precipitation levels either inside or outside the flooded region or due to melting snow, causing the river to overflow outside its normal boundaries.

Table 1.1 Effects of flood events worldwide and other natural disasters[1]

| **Disaster type** | **No. of events** | | **Total killed** | | **Total affected** | |
|---|---|---|---|---|---|---|
| | ***No.*** | ***%*** | ***No.*** | ***%*** | ***No.*** | ***%*** |
| Earthquake | 548 | 9 | 483,552 | 24 | 79,316,329 | 2 |
| Drought | 495 | 8 | 560,381 | 28 | 1,381,353,218 | 33 |
| Famine | 62 | 1 | 282,299 | 14 | 62,913,301 | 2 |
| Epidemic | 656 | 10 | 143,276 | 7 | 17,712,233 | 0 |
| Windstorm | 1741 | 28 | 279,894 | 14 | 462,772,019 | 11 |
| Freshwater floods | 1816 | 29 | 175,056 | 9 | 2,198,579,362 | 52 |
| Others | 969 | 15 | 65,892 | 3 | 19,484,370 | 1 |
| TOTAL | 6287 | | 1,990,350 | | 4,222,130,832 | |

**Coastal floods:** these occur along the big lakes and coasts of seas due to windstorms and low atmospheric pressure.

**Drainage problems:** these cannot be controlled by the normal drainage systems due to the high precipitation levels. However, the risk to life due to this type of flood is limited because of the limited water levels while it causes main economic damage.

**Tsunamis (or seismic sea waves):** caused by a submarine landslide, earthquake, or volcanic eruption resulting in generation of large waves, causing a destructive surge on reaching land.

## 1.1 Problem Definition

Flash floods are large events that happen in a relatively short duration due to excessive rainfall and form one of the most important challenges in the water science field. Floods in arid and semi-arid regions have specific characteristics, which makes them more hazardous than ordinary floods which occur in wet regions. Arid regions' floods occur fast and suddenly, so it is called flash floods. There are two main differences between ordinary flood and flash flood, which are the speed of occurrence and the time between the observed events and its flood occurrence. The hydrograph of flash flood distinguishes a single peak flood with a very short period in the time between the beginning of the flood event and its peak. Many researchers related to flood analysis, consider the usual duration of flash floods to be less than six hours, which is considered as an ideal value to distinguish between ordinary and flash floods [2].

In Saudi Arabia, floods may be the major catastrophic natural hazard as shown in Table 1.2. The table indicates that floods are the most frequently occurring disasters followed by epidemic. According to Momani and Fadil [4], more than 121 fatalities, around 20,000 sheltered families and billions of dollars in losses were due to the natural disasters in Saudi Arabia in 2009 in addition to the effects on human health as a result of flooding. Moreover, the amount of three billion riyals was the monetary loss. Maghrabi [5] stated that several fatalities and massive destruction in structures, properties, and highways occurred as a result of massive floods due to heavy rains, which affected Jeddah in 2009.

Hafar Al-Batin city, which is located in the eastern part of the Kingdom of Saudi Arabia, is also suffering from the occurrence of floods. In the past few years, flash floods hit the city many times and caused losses in economic and human life. The current study will focus on the effect of flash flood on Hafar Al-Batin by constructing a flood hazard map which will help the decision makers to adopt the appropriate plan to control and reduce the effect of floods.

## 1.2 Objectives of the Study

The aim of this study is to construct hydrologic, hydraulic and floodplain models that are capable of predicting the flood in the city of Hafar Al-Batin. The research objectives are as follows:

- Construct a flood model for Hafar Al-Batin watershed.
- Estimate the flood peak for the watershed using different methods.

Table 1.2 The top ten natural catastrophic events in Saudi Arabia[3]

| **Disaster** | **Date** | **No. of fatalities** |
|---|---|---|
| Flood | 24 Nov. 2009 | 163 |
| Epidemic | 11 Sep. 2000 | 76 |
| Epidemic | Mar. 2000 | 57 |
| Epidemic | 9 Feb. 2001 | 35 |
| Flood | 28 Apr. 2005 | 34 |
| Flood | 24 Dec. 1985 | 32 |
| Flood | 22 Jan. 2005 | 29 |
| Flood | 4 Apr. 1964 | 20 |
| Epidemic | 8 Apr. 2002 | 19 |
| Epidemic | 11 Nov. 2003 | 12 |

- Run the constructed model for different scenarios to predict the risk of flood.
- Perform sensitivity analysis to study the influence of urbanization and storm durations.
- Propose appropriate actions to minimize the risk of flood.

# CHAPTER 2

# LITERATURE REVIEW

In general, flood hazard maps can help to provide geographical information on flood inundation such as predicted inundation depth and inundation area, as well as on evacuation (location of evacuation routes, dangerous spots on evacuation routes, evacuation refuges, etc.) in an easy format to understand. Flood hazard maps are the effective way to reduce the impact of floods on people and property. In many countries, particularly the developed countries, the authorities develop flood hazard maps of known return periods which are used as a guide for the flood protection and land development plans to specify areas prone to flooding. On the other hand, in ungauged basins, several approaches range from indirect peak discharge and simple empirical methods to sophisticated rainfall-runoff modeling developed by using hydrologic and hydraulic models that can be applied to produce such maps.

Generally, three steps are required to develop the floodplain mapping [6]:

- Estimating 100-year peak discharge based on hydrological models or flow data.
- Computing the elevation profiles associated with the 100-year flood using hydraulic modeling.
- Delineating the inundated area.

Flood hazard maps are developed based on rainfall-runoff modeling. The main objective of rainfall-runoff models is to understand the rainfall-runoff process and extend streamflow

time series in both time and space [7]. These models are not only used for hydrologic investigation, but are also used for many purposes in engineering and environmental sciences, which include calculations of design floods, catchment response to climatic events, estimation of the impact of land use change, management of water resources, streamflow prediction, and flood forecasting.

## 2.1 Rainfall-Runoff Processes

When precipitation exceeds losses such as infiltration, surface storage, interception, and evaporation, runoff is generated to become concentrated flow in valleys and stream channel. Two mechanisms are included in runoff generation, which are Hortonian overland flow and saturation overland flow [9]. A severe storm will lead to runoff generation when the soil is saturated, while Hortonain overland flow depends on the relationship between infiltration capacity versus rainfall intensity. This means that runoff is generated when rainfall intensity exceeds infiltration capacity.

The hydrologic cycle can be obviously represented by watershed hydrologic models in various and appropriate ways. The hydrologic system embodies all of the physical processes that are involved in the conversion of precipitation to runoff as well as physical characteristics of the watershed and atmosphere that influence runoff generation. There are many factors affecting rainfall-runoff processes, such as physical processes, storm characteristics, and watershed characteristics [10].

The hydrologic cycle comprises all of the physical processes that affect the movement of water in its various forms, from its occurrence as precipitation near the earth's surface to its discharge to the ocean. Such processes include interception, water storage in depressions

in lakes and reservoirs, snow accumulation and melt, if there is any, infiltration through the earth's surface, percolation to various depths in the subsurface, storage of water in the subsurface, the later movement of water in both unsaturated and saturated portions of the subsurface, evaporation from water bodies and moist soil, transpiration from vegetation, overland flow, and streamflow. These processes are very complex and some of them are more significant than others for particular types of analyses.

Precipitation is viewed as an input to a hydrologic system. The precipitation might be associated with a historical storm, a design storm, or may result from a stochastic generation procedure. Generally, precipitation is averaged spatially over a sub-basin, which affects the shape of the outlet hydrograph. Likewise, precipitation intensity is averaged over a time interval which is significant on a small watershed. Thus, precipitation input to the hydrologic system is commonly represented by hyetographs of spatially and temporally averaged precipitation.

Topography has an effect on collecting and conveying water for any catchment system. Area, width, length, shape, slope, drainage patterns, and linear measures are some of the important catchment characteristics. Watersheds are heterogeneous with respect to topography, geology, soils, land use, vegetation, drainage density, and river characteristics.

## 2.2 Hydrologic Models

Hydrologic model is a mathematical representation of hydrologic processes which divide precipitation into two main parts, namely losses and runoff. The hydrologic system includes physical processes (interception, depressions, infiltration, evaporation, and transpiration) that are involved in the conversion to streamflow. In addition, the physical

characteristics of the watershed and atmosphere influence the runoff generation. The use of computer models to simulate the hydrologic system is of a major significance in the performance of such flood-runoff analysis. The aim of hydrologic models is often to establish rainfall-runoff relationships [11].

Nowadays, various hydrologic and hydraulic models have been used to predict floods and the required actions to reduce their effects. Many of these models are site specific containing assumptions and simplifications, which exclude their universal use. So, it is very important to understand the candidate model clearly in order to use it appropriately. Some of the models use physically based governing equations having computationally intensive numerical solutions, while others are based on simple empirical relations having strong algorithms. Sometimes, the simple models are insufficient in giving appropriately detailed results, and the detailed models are inefficient and prohibitive for the large catchment. Therefore, it is quite a challenging task to find an appropriate model for a certain watershed.

Harsh climatic conditions and lack of high-quality observations in arid regions make the flood simulation, especially flash flood forecasting, more difficult and of a great challenge. Due to the wide range of variety in hydrologic models which have been developed over the years, the classification of these models according to their structures and approaches has become necessary. Rainfall-runoff models were divided into three categories by model developers, which are the most commonly used classifications. The classifications are as follows [12, 13, 14]:

- Metric or empirical models which are derived from data observations to characterize the response of the catchment system [13]. Observed data, including rainfall and runoff records, are used to derive the model parameters and structure. Metric models derived as spatially lumped are not suitable for ungauged catchments because they treat the catchment as a single unit [7]. Generally, these models are simple, widely used, and easy to understand. However, several important factors may not be accounted for, such as antecedent moisture conditions. The Unit Hydrograph and Artificial Neural Networks are two of the most popular models of this type.
- Conceptual or parametric models describe all of the component hydrological processes. These models have a structure that is defined a priori using mostly fluxes of water between various reservoirs [7]. Conceptual models treat the catchment as a single unit, so these types of models are considered as a lumped approach.
- Physically based or mechanistic models are mathematical models based on the energy, momentum, and conservation of mass [7]. The aim of developing these types of models is to obtain models that can be run without calibration step, which would be applicable to ungauged catchment or applicable to catchment where the available data is not enough to calibrate conceptually.

Distributed and lumped models are another classification where the lumped models are appropriate to simulate the catchment as a single unit. Many lumped models were developed, such as AWBM [15], IHACRES model [16], and GR4J [17]. On the other hand, the predictions in the distributed models are done by dividing the catchment area into a large number of grid squares [18]. This type of model includes HEC-HMS [19],

TOPMODEL [20], and USDA SWAT [21]. Hydrological processes can be described in details in the distributed models where parameter values must be determined for each element. On the other hand, the parameter average values can be used in lumped models, which makes them suitable for the catchments of limited data. The following considerations must be taken when selecting a hydrologic model:

- The quality and availability of hydrological data.
- Model's ability in regionalization and model structure, and
- Characteristics of the catchment area and homogeneity of flow.

In this study, HEC-HMS rainfall-runoff model will be used for the following reasons:

- Model structure and availability.
- Applicability of the model in arid catchments, and
- Data availability.

The HEC-HMS input requirements are the basin model, meteorological model, and control specifications. Then, several techniques can be used to model the rainfall-runoff process. The basin model can be used to store and define the physical parameters which describe the catchment area. Meteorological data, such as precipitation and evapotranspiration, can be defined in the meteorological model, while the control specifications control the time span of a simulation.

## 2.3 Hydraulic Models

The hydraulic models are used to compute and predict the floodplain water level after executing the hydrologic model. The final calculated flood depth must be calibrated to actual flood depths observed from previous flood events within 0.5 feet [22]. The hydraulics models developed based on the following equations:

1. Conservation of mass or continuity
2. Momentum
3. Energy

The flow depth and rate of discharge, or the flow depth and velocity, are sufficient to define the flow conditions at a channel cross section. Therefore, the combined application of two governing equations may be used to analyze a typical flow situation. The continuity equation and the energy or momentum equation are used for this purpose.

**Steady flow**

Water surface profile for steady gradually varied flow is computed for two adjacent cross-sections based on an iterative solution of the energy equation. Figures 2.1 shows open channel energy concepts and equation (2.1) is the energy equation [63]:

$$Z_2 + Y_2 + \frac{\alpha V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha V_1^2}{2g} + h_e \qquad (2.1)$$

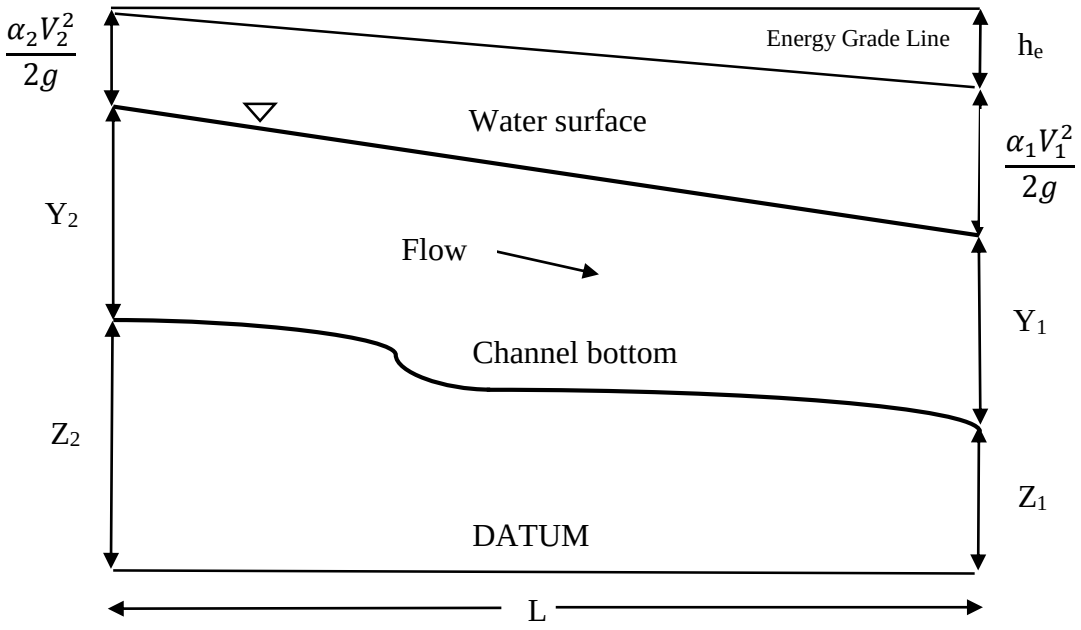



Figure 2.1 Energy in open channel flow

where $Z_1$,$Z_2$ = the main channel inverts elevation(m),$Y_1$,$Y_2$ = water depth at cross sections(m), $V_1$,$V_2$ = velocity of longitudinal flow (m/s), $\alpha_1$,$\alpha_2$ = velocity weighting coefficients, $g$ = gravitational acceleration (m/s$^2$). The total head loss, *he*, is calculated as follows:

$$h_e = h_f + h_o \tag{2.2}$$

where $h_f$ is the head loss due to friction and $h_o$ is the minor losses due to the expansion or contraction of the channel. The head loss due to friction, $h_{f,,}$ is estimated by

$$h_f = \left(\frac{Q}{K}\right)^2 \tag{2.3}$$

where $Q$ is the discharge and the loss coefficient $K$ is calculated based on Manning's equation as follows:

$$K = \frac{1.486}{n} AR^{\frac{2}{3}} \tag{2.4}$$

where $A_1$, $A_2$ = upstream and downstream wetted area respectively of the cross-sections(m$^2$), $R_1$,$R_2$ = downstream and upstream hydraulic radius(m), $n$ = manning's roughness coefficient.

The minor losses due to contraction or expansion is estimated by the following equation:

$$h_o = C_L\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \tag{2.5}$$

where $C_L$ = loss coefficient for contraction and expansion.

For steady rapidly varied flow, the momentum equation (2.6) is used to compute the water surface profile. Momentum equation is applicable to rapidly varying flow situation transition from supercritical to subcritical or subcritical to supercritical such as bridge construction, significant change in channel slope, drop structure and weirs [63].

$$\frac{Q_2^2\beta_2}{gA_2} + A_2\acute{Y}_2 + \left(\frac{A_1+A_2}{2}\right) L\, S_o - \left(\frac{A_1+A_2}{2}\right) L\, S_f = \frac{Q_1^2\beta_1}{gA_1} + A_1\acute{Y}_1 \quad (2.6)$$

where $Q_1$, $Q_2$ = upstream and downstream discharge ($m^3/s$), $\beta$ = momentum coefficient for a varying velocity distribution in irregular channels, $\acute{Y}_1$, $\acute{Y}_2$ = depths measured from the water surface to the centroid of the cross-sectional area (m), $L$ = distance between sections along the channel(m), $S_o$ = bed slope (m/m), and $S_f$ = friction slope (energy gradient) (m/m).

**Unsteady flow**

The continuity and momentum equations are the physical laws which govern water flow in a stream. Broad assumptions are required to develop the governing equations of the hydraulic models when numerical methods are used to describe the natural physical phenomena.

**Continuity equation**

Consider an element of the fluid volume as shown in Figures 2.2. The rate of inflow to the control volume may be written as [63]:

$$Q + q\,\Delta x \quad (2.7)$$

The rate of outflow

$$Q + \frac{\partial Q}{\partial x}\Delta X \quad (2.8)$$

The rate of change in control volume

$$\frac{\partial A}{\partial t}\Delta X \tag{2.9}$$

According to the continuity equation:

Inflow – outflow = rate of change in volume

The change in mass in the control volume is equal to:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2.10}$$

Where $q$ = the lateral inflow rate per unit length of channel ($m^3/s\ m^2$), $x$ = longitudinal distance (m), $t$ = time (s).

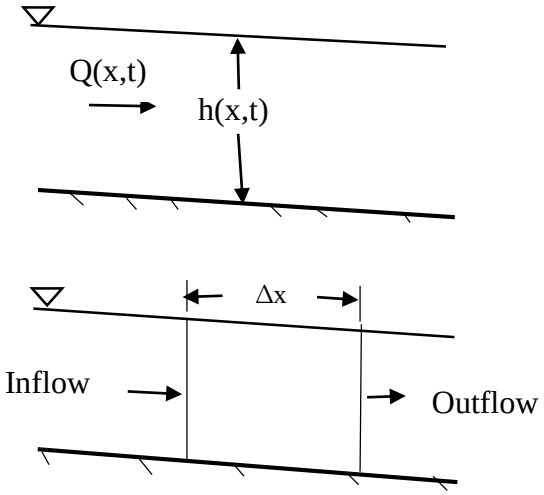



Figure 2.2 Elementary control volume

**Momentum equation**

The conservation of momentum states that the rate of change in momentum equal to the external forces (pressure, gravity, and friction force) acting on the system.

Pressure force:

$$F_{pn} = -\rho g A \frac{\partial h}{\partial x}\Delta x \quad (2.11)$$

where $F_{pn}$ = the net pressure force, x = distance between two sections, A= cross section area, $h$ = flow depth, $\rho$ = water density.

Gravity force:

$$F_g = \rho\, g\, A \frac{\partial z}{\partial x}\Delta x \quad (2.12)$$

where $F_g$ = gravity force, $z$ = invert elevation.

Friction force:

$$F_f = \rho\, g\, A\, S_f \Delta x \quad (2.13)$$

where $S_f$ = friction slope.

Momentum flux:

The net rate of momentum (momentum flux) entering the control volume can be written as:

$$-\rho \frac{\partial QV}{\partial x}\Delta x \quad (2.14)$$

The rate of accumulation of momentum may be written as:

$$\frac{\partial}{\partial t}(\rho\, Q\, \Delta x) = \rho\, \frac{\partial Q}{\partial t}\Delta x \tag{2.15}$$

From the principle of momentum conservation, the momentum flux plus the external forces = the rate of accumulation of momentum.

Therefore:

$$\frac{\partial z}{\partial x} = \frac{\partial h}{\partial x} = \frac{\partial z}{\partial x} \tag{2.16}$$

Where $\frac{\partial z}{\partial x}$ =water surface slope

Substituting (2.15) in (2.16) and dividing through by $\rho \Delta x$, the final form of momentum equation [63]:

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + g\, A\, (\frac{\partial z}{\partial x} + S_f) = 0 \tag{2.17}$$

The full Saint-Venant equations are the most widely used approach to model river hydraulics [23]. In differential form, Saint-Venant equations (the dynamic wave equations) consist of the equations of continuity and momentum for gradually varied unsteady flow are described in (2.10) and (2.17) [24]. Approximate numerical solutions have been used to solve these equations in stream flood routing models. Due to the computationally intensive numerical solutions of the dynamic wave equations (Saint-Venant equations), there used is limited in watershed models. Some models use approximation of these equations by ignores certain terms in the momentum equation (2.17).

The continuity and simplified momentum equations constitute the diffusive wave equations [24]:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2.18}$$

$$\frac{\partial h}{\partial x} = S_o - S_f \tag{2.19}$$

Similar to the Saint-Venant equations, the above equations can be solved numerically because there is no analytical solution of the diffusive wave equations [23].

The simplest form of the dynamic wave equations is the kinematic wave equations which can be expressed as:

$$S_o = S_f \tag{2.20}$$

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2.21}$$

Equation (2.5), the momentum equation, assumes bed slope equals energy gradient and can be expressed as a parametric function of the stream hydraulic parameters by using any suitable law of flow resistance. A commonly used expression is:

$$Q = \alpha\, h^m \tag{2.22}$$

where $\alpha$ = kinematic wave parameter, and $m$ = exponent of the kinematic wave. These two parameters ($\alpha$ and $m$) are related to geometry and plane (or channel) roughness and their values can be determined by using Manning's formula [25]. Therefore, kinematic wave equations consist of Equations (2.6) and (2.7). Some watershed models, such as KINEROS, DWSM, and PRMS, were developed based on the kinematic wave equations. Accordingly,

the continuity equation and flow equation constitute the non-linear reservoir equations. Manning's equation as an example, is expressed below:

$$\frac{\partial s}{\partial t} = I - O \tag{2.23}$$

$$Q = \frac{1}{n} A R^{2/3} S_0^{1/2} \tag{2.24}$$

where $S$ = water storage volume ($m^3$), $I$ = inflow ($m^3/s$), $O$ = outflow ($m^3/s$), $Q$ = flow rate ($m^3/s$), $n$ = channel roughness, $S_o$ = channel slope, $R$ = hydraulic radius (m), and $A$ = cross section area ($m^2$). Equations (2.23) and (2.24) do not represent any waveforms and assume a leveled water surface throughout the overland plane or channel reach. Equation (2.23) is useful in reservoirs and lakes.

## 2.4 Modeling Flash Floods in Arid Zones

Several models have been applied to watershed analysis with different conditions (sizes, different climatic, hydrologic, and geologic conditions) to evaluate their suitability and performances. However, a limited number of hydrologic models have been developed in arid regions.

Lange et al. [26] concluded that the analysis of single events in arid regions is very important for better understanding of high magnitude floods. Abdulla et al. [27] used the water balance equation to develop their model for simulating the surface runoff hydrograph in the western part of Iraq, and they found that their model results show a good agreement between model output and observed data. Al-Abed et al. [28] studied the performance of HEC-HMS / HEC-GeoHMS extension model and the Spatial Water Budget Model

(SWBM) and found that the two models give satisfactory results. Al-Qurashi [29] applied distributed and lumped models for streamflow simulation in the Wadi Dhuliel arid catchment, north-east Jordan. They found that HEC-HMS results show a good agreement with the observed streamflow data, while IHACRES shows some weaknesses.

Al-Qurashi et al. [30] evaluated the distributed model (Kineros2) in application to an arid catchment in Oman where they conducted a series of three experiments with different calibration strategies. They found that the prediction performance was generally poor. They recommended that significant data collection and further research are required to realize the potential value of distributed physically-based models. McIntyre and Al-Qurashi [31] concluded that using parameters between 2 and 4 instead of a 9-parameter version of IHACRES (which was developed as an appropriate model for semi-arid and arid areas) produced simple models which gave the best performance for predicting flood peaks in Wadi Ahin, North-East of Oman. On the other hand, better results for predicting time to peak were achieved by using a 1-parameter model. However, uncertainty was very high in all predictions. Timpson [32] mentioned that there is no good method that can be used in Utah to estimate the peak flood discharge for rural watersheds with an area between 0.5 $mi^2$ and 30 $mi^2$. Accordingly, Timpson conducted the flood frequency analysis for small rural watersheds within the state of Utah to determine regression formulas in the style of the rational method for the desired area.

With reference to Zaman et al. [33], the partial duration series was found to be better than the annual maximum series in the arid regions of Australia, and based on this finding, data exponential and generalized Pareto were selected. They found that the generalized Pareto distribution is better than the exponential distribution to fit the partial duration series flood

data. Also, it was found that smaller runoff coefficient values and a higher loss were observed in semi-arid and arid catchments. Ghoneim and Foody [34] developed a hydrologic model for Wadi El-Alam, Egypt using HEC-HMS. They found that HEC-HMS is suitable for modeling the rainfall-runoff process in arid and semi-arid regions and it also gives satisfactory results in the absence of sufficient data for surface flow.

Mediero and Kjeldsen [35] used an extended generalized least squares model to investigate a semi-arid Ebro catchment in Spain. They found that their new model improved the existing ordinary least squares models. In addition, a suitable description of flood processes was obtained and more reliable flood predictions in ungauged catchments were achieved.

Table 2.1 summarizes some of the popular hydrologic and hydraulic models used worldwide.

## 2.5 Floods in Saudi Arabia

In recent years, there has been a considerable amount of attention to flooding in Saudi Arabia. Despite the proposed actions to avoid the effects of flooding, there is a lack of proper solutions in the flooded areas. Studies have been conducted in different regions of Saudi Arabia using different techniques. Following presents some studies which have been conducted in some regions of Saudi Arabia:

Table 2.1 Summary of flood models

| Software | Study area | Country | Aim of study | Used tools / Method | Reference(s) |
|---|---|---|---|---|---|
| Excel and Matlab | Wadis Hali and Yibah | Saudi Arabia | flood inundation map | 1/50,000 scale topographic map | [36] |
| Global mapper, Excel | Al-Kharj | Saudi Arabia | flood hazards | Soil Conservation Service (SCS) and Muskingum | [37] |
| WMS | Jeddah | Saudi Arabia | simulate the floods | HEC-HMS | [38] |
| WMS | Wadi Marwani basin | Saudi Arabia | The most accurate model for peak discharge estimation. | A regional flood frequency analysis (RFFA), the modified Talbot method (MTM), the probabilistic rational method (PRM), and the HEC-HMS program | [39] |
| WMS | Dez River basin | Iran | flood modeling | HEC-1, HEC-RAS | [40] |
| WMS | Midas Creek | Jordan | predict the area of flooding in the specified area, flood control | HEC-RAS | [41] |
| WMS | Koycegiz Lake-Dalyan Lagoon watershed | Turkey | delineation of boundaries | Rational method | [42] |
| WMS | Ciderewak River, west Java | Indonesia | flood risk reduction | HEC-1, HEC-HMS, HEC-RAS | [43] |
| HEC-RAS | Peace River, Alberta | Canada | flood routing and flood level forecasting | | [44] |
| HEC-RAS and ArcView GIS | Waller Creek, Austin, Texas | USA | floodplain mapping | | [45] |
| WMS | Mangla watershed | Pakistan | modeling flood conditions | Hydrological Simulation Program – FORTRAN (HSPF), HEC-RAS | [46] |

Nouh [47] used three methods (region curves, common peak flow models, and duration reduction curves) to estimate the maximum flood in the southwest region of Saudi Arabia. Statistical measures were used to compare the accuracy of the three methods. The study concluded that the region curve method gives the best statistics. Al-Turbak [48] constructed a geomorphoclimatic model in three arid catchments in Saudi Arabia and found that the developed model is capable of predicting surface runoff hydrographs accurately when detailed and accurate data are available.

Subyani [49] studied flood probability and the hydrological characteristics in western Saudi Arabia of some main wadis, including Fatimah and Usfan, and found that Gumbel's extreme value distribution is the best fitting model for identifying and predicting future rainfall occurrence. Al-Shareef et al. [39] conducted a study on Wadi Marwani basin in Jeddah, Saudi Arabia and tried to find the best method that can be used to estimate the peak discharge. Four methods were tested, namely the Modified Talbot Method (MTM), the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), the Regional Flood Frequency Analysis (RFFA) regression equations, and the Probabilistic Rational Method (PRM). The Root Mean Square Error (RMSE) was used to measure the accuracy of the four methods. The results indicate that the PRM is a more accurate model to compute the peak discharge compared to the others.

Dawod et al. [50] concluded that the most accurate national hydrological model for the Makkah area is the model developed based on actual precise field measurements in the southwest part of Saudi Arabia. However, they mentioned that the curve number method should be considered as the optimum flood modeling approach when the topography, land use, meteorological and geological datasets are available. Sharif et al. [51] produced a flood

hazard map for the rapidly urbanizing catchment of Al-Aysen in Riyadh, Saudi Arabia, using hydrologic/hydraulic model simulation. They also studied the impact of urbanization on the peak discharge and runoff volume resulting from different storms with various urbanization scenarios.

Hafar Al-Batin city, like many other cities in Saudi Arabia, has never had a comprehensive set of flood inundation maps. This study will investigate the risk of flood to the city of Hafar Al-Batin by constructing hydrologic, hydraulic and floodplain delineation models for the investigated region. Then, based on the constructed models, flood hazard maps will be generated to identify the areas within the city at high risk.

# CHAPTER 3

# STUDY AREA AND DATA ACQUISITION

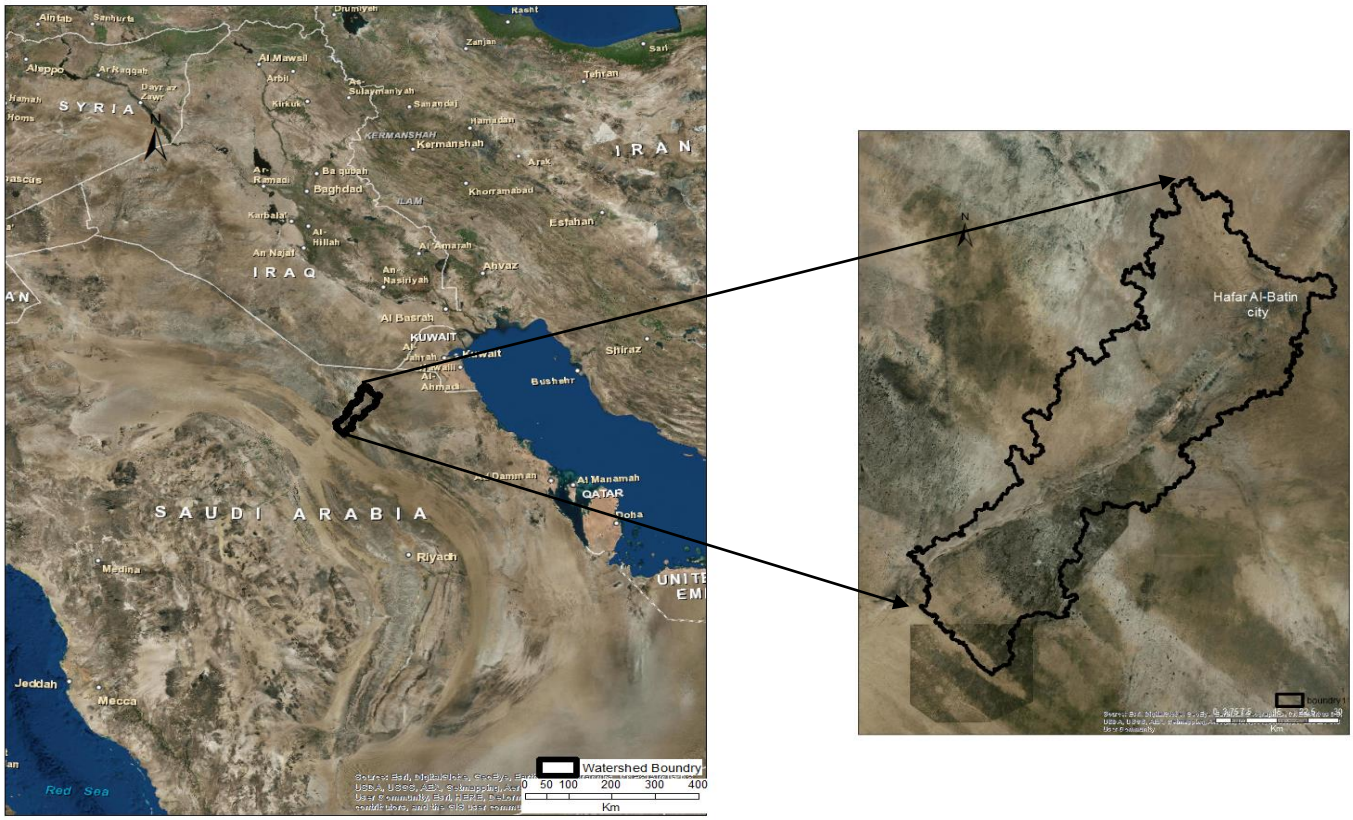
## 3.1 The Study Area

Hafar Al-Batin is one of many cities in Saudi Arabia, which were affected by flash floods. It is located in the northeast of Saudi Arabia, 430 km to the north of Riyadh, 74.3 km from the Iraq border, and 94.2 km from the Kuwait border. The city lies in the dry valley of Wadi Al-Batin, which is the main source of the flash flood. In 2003, the population of Hafar Al-Batin was estimated to be around 190,000 and reached 600,000 in 2010 [52]. Figure 3.1 shows the location of Hafar Al-Batin city and boundary of Hafar Al-Batin watershed.

The partially urbanized Wadi Al-Batin catchment was selected for this study with a drainage area of 1669.014 $km^2$ as shown in Figure 3.1b. The catchment drains in the dry valley of Wadi Al-Batin, which is part of the larger valley of the long, now-dry river Wadi Al-Rummah. The city of Hafar Al-Batin occupies approximately 3.6% of the catchment area.

## 3.2 The Basin Topography

Figure 3.2 shows Hafar Al-Batin contour map, which was developed from the 30-m resolution digital elevation models (DEM) by using global mapper and surfer programs.




(a)

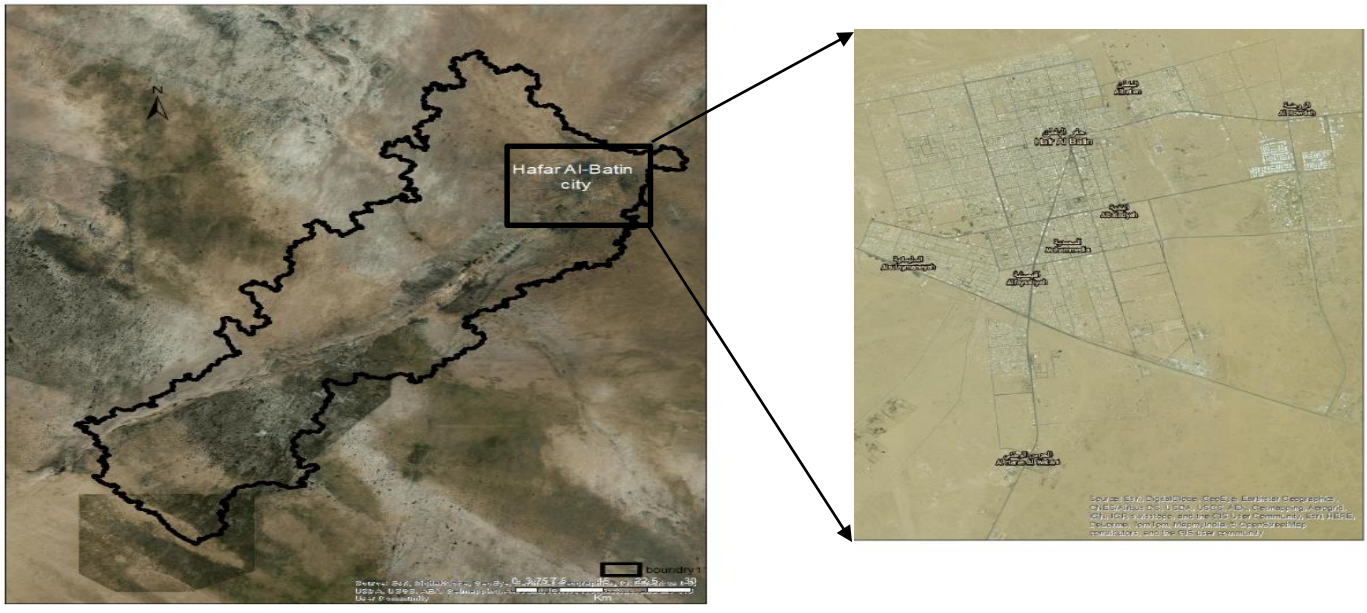
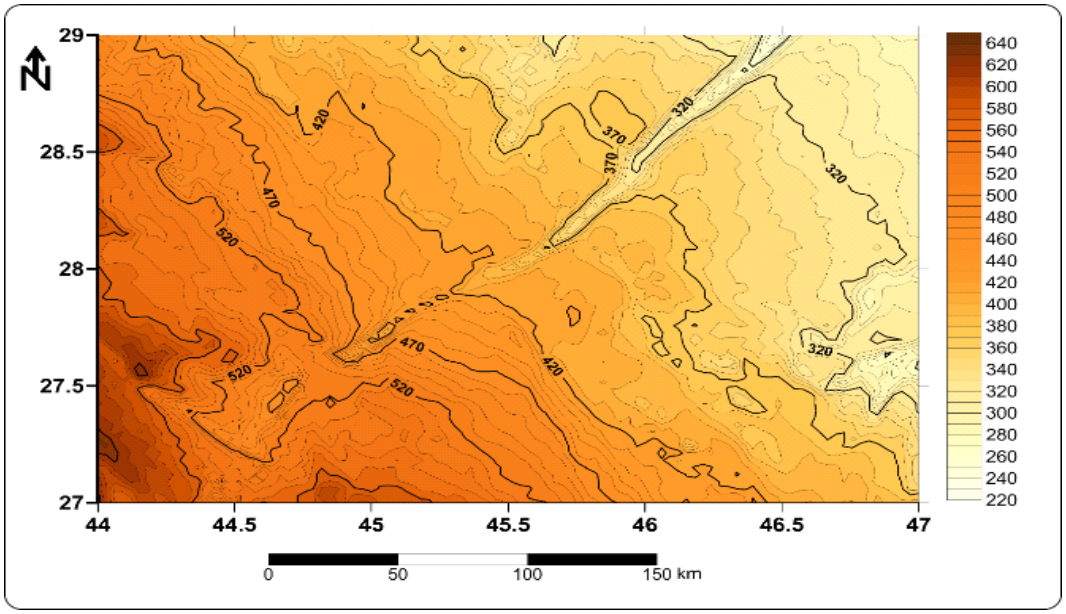
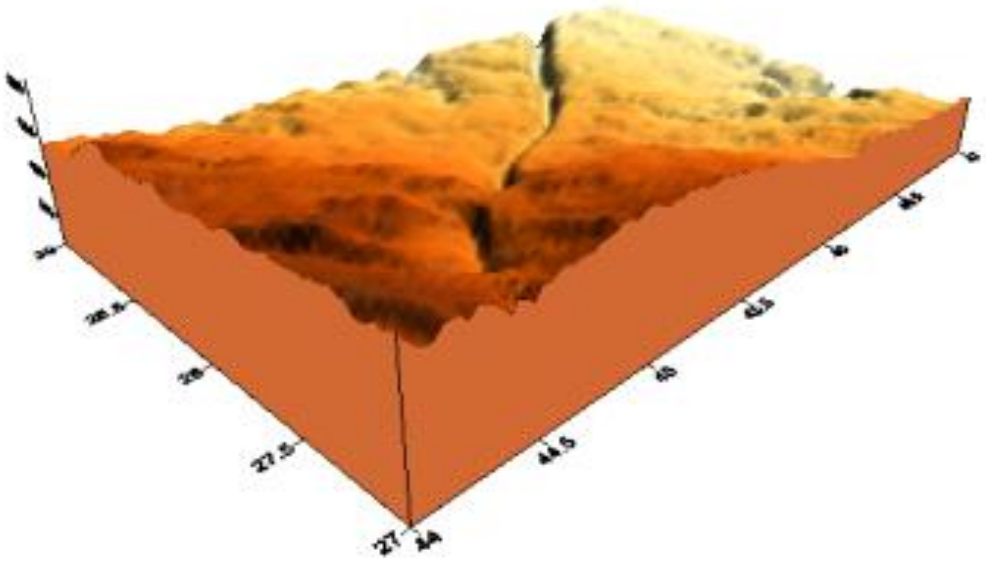



Figure 3.1 Hafar Al-Batin catchment area: (a) Hafar Al-Batin boundary of the watershed and (b) Hafar Al-Batin city




(a)



(b)

Figure 3.2 Hafar Al-Batin topography: (a) Hafar Al-Batin contour map and (b) 3D contour map of Hafar Al-Batin watershed

The lowest point above sea level, located at the northeast of the district, is approximately 200 m, while the highest point above sea level in the district reaches 640 m. The topography of Hafar Al-Batin can be divided into two parts: Al-Batin valley and the northeast slopes.

The 30-m resolution DEM, which was produced by the General Directorate of Military Survey (GDMS), was used to obtain topographic data for the study area (Figure 3.3). Four main streams are distinguished in Hafar Al-Batin district. The first stream runs from southeast to northwest and is called Al-Batin valley, which is the largest one. The second stream is north Fleaj stream which runs from north to south, the third stream is south Fleaj stream which runs from south to north, and the fourth stream is northwest Fleaj which run from northwest to the southeast. These four streams are considered as the main sources of runoff for Al-Batin valley as shown in Figure 3.4.

## 3.3 Rainfall Data

Precipitation is considered as one of the major input parameters required for hydrologic studies. In Saudi Arabia rainfall is the only form of precipitation. Precipitation data are essential and play an important role in the hydrologic model.

There are seven methods to define the meteorological model in HEC-HMS. One of these methods is the SCS hypothetical storm method which was used in this study for floodplain delineation, while the frequency storm method was used in the sensitivity analysis.

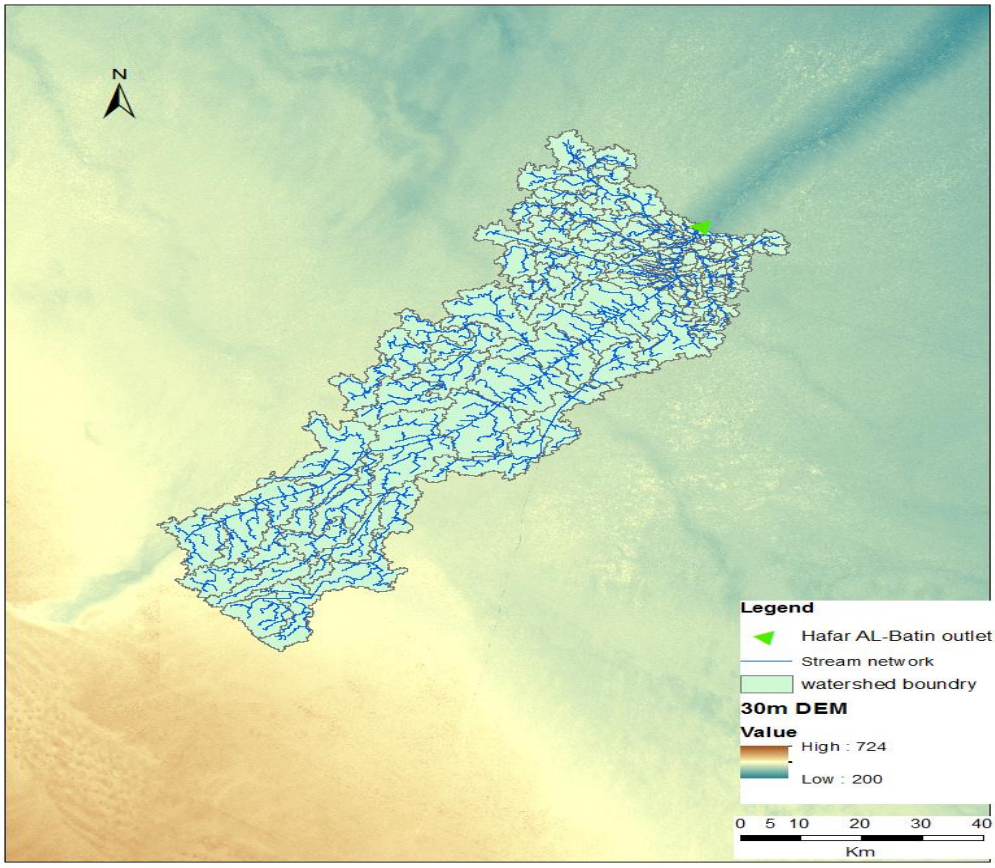



Figure 3.3 Hafar Al-Batin digital elevation model (DEM)

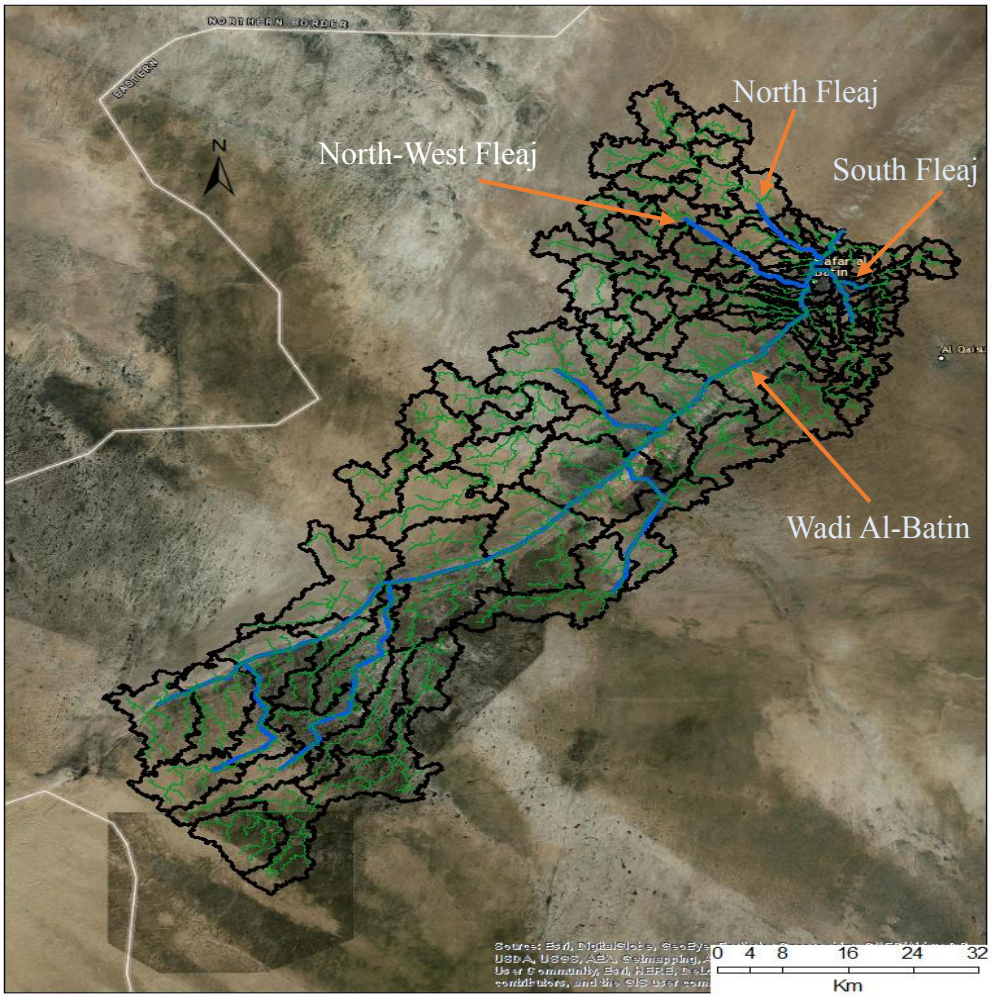



Figure 3.4 Hafar Al-Batin watershed

Usually, floods occur due to the extreme rainfall events, which are difficult to collect. Moreover, it is difficult to collect enough data to find the extreme values of rainfall events using the standard techniques of statistics, which makes the use of extreme distributions as the best choice.

The design return period for storm sewers can vary from 2 to 25 years, while for detention basin, it is 50 years, which is also the design value for major highway bridges. For floodplain delineation, a return period of 100 years is used [22].

Figure 3.5 shows the annual rainfall distribution in Saudi Arabia. The average rainfall ranges between 180 and 260 mm in various parts of Wadi Al-Batin and could reach over 240 mm in the study area [54]. In urban hydrology, two types of rainfall are usually required: actual hyetographs and processed data, which are usually frequency information. The 100, 50, 25, 10, 5, and 2-year events are the frequencies analyzed in this study. The 24 hours of the 100-year rainfall depth and a cumulative precipitation time series corresponding to the Soil Conservation Service (SCS) Type II dimensionless unit hydrograph were used in the model to estimate the rainfall events. Table 3.1 shows the design rainfall depths adopted in this study. These depths were estimated based on the IDF curves developed by Elsebaie [55]. Since an actual gauge rainfall was not available to work with, an artificial one was created to find the effectiveness of different storm durations on the peak discharge as will be described in Chapter 5.

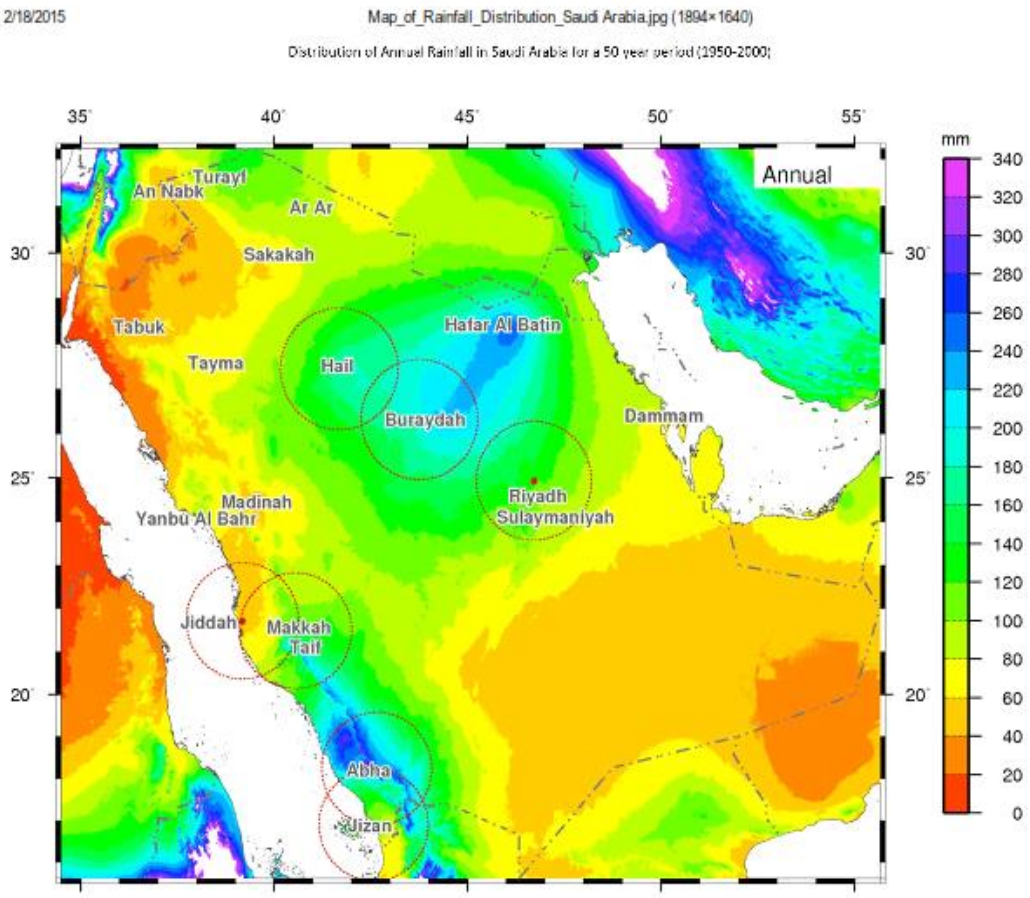



Figure 3.5 Annual rainfall distribution depth for Saudi Arabia [56]

Table 3.1 Design storm for Hafar Al-Batin [55]

| **Frequency (Years)** | **Depth (mm)** |
|---|---|
| 2 | 28.754 |
| 5 | 42.297 |
| 10 | 51.263 |
| 25 | 62.593 |
| 50 | 70.997 |
| 100 | 79.34 |

## 3.4 Methodology

In this study, Watershed Modeling System (WMS), Geographic Information System (GIS), AutoCAD, global mapper, Surfer-12, FlowMaster, HEC-HMS, and Hydrologic Engineering Center-River Analysis System (HEC-RAS) were used to construct the hydrologic, hydraulic and floodplain models.

The following steps summarize the methodology that was followed in this study:

1. Use the IDF curves for Hafar Al-Batin to determine the maximum rainfall intensity for specific return periods.
2. Generate Digital Elevation Map (DEM) for the study area.
3. Delineate the watershed, which depends on the generated flow directions and accumulation map.
4. Use an appropriate Hydrologic Modeling System (HEC-HMS) to establish a hydrologic model for Hafar Al-Batin.
5. Develop a hydraulic model for Hafar Al-Batin watershed using HEC-RAS.
6. Propose appropriate actions that can be taken to reduce the risk of flood.

# CHAPTER 4

# HYDROLOGIC AND HYDRAULIC MODELING USING WMS – RESULTS AND ANALYSIS

Floodplain delineation is a difficult task because it involves an interaction of models and variables to determine a floodplain boundary for a specific return period. To delineate the floodplain, hydrologic, hydraulic and water surface interpolation models should be integrated. Figure 4.1 shows a summary of the steps involved in floodplain delineation. The delineated watershed of Hafar Al-Batin and the streams contributing to Hafar Al-Batin catchment are shown in Figures 4.2 and 4.3, respectively [57]. These streams will help as a guide to determine the boundary of the watershed. In this study, a hydrologic model using HEC-HMS, a hydraulic model using HEC-RAS, and a floodplain delineation model using WMS have been used to develop a flood hazard map for Hafar Al-Batin catchment area.

## 4.1 Hydrologic Model (HEC-HMS)

The HEC-HMS program was developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers to simulate precipitation-runoff processes with many choices of infiltration losses [58]. The USDA Soil Conservation Service runoff curve number method (SCS-CN) is used to compute peak flows based on the soil type, land use and

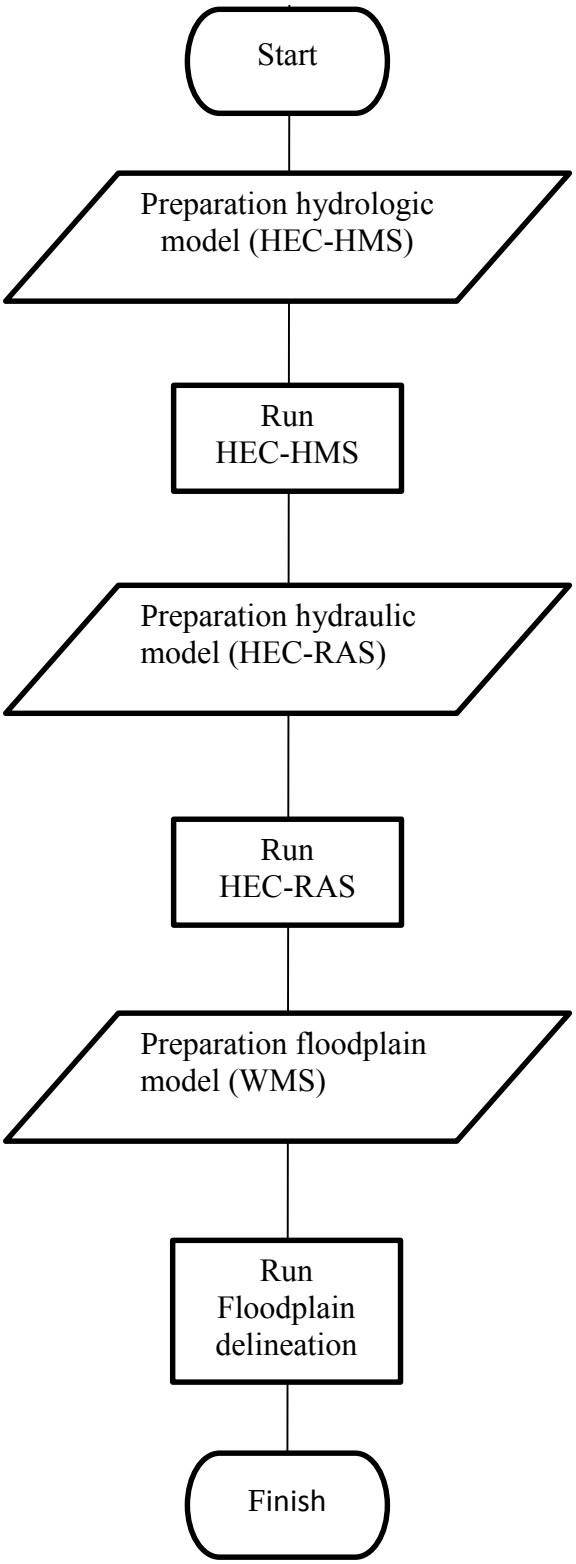



Figure 4.1 Flow chart of the steps involved in floodplain analysis

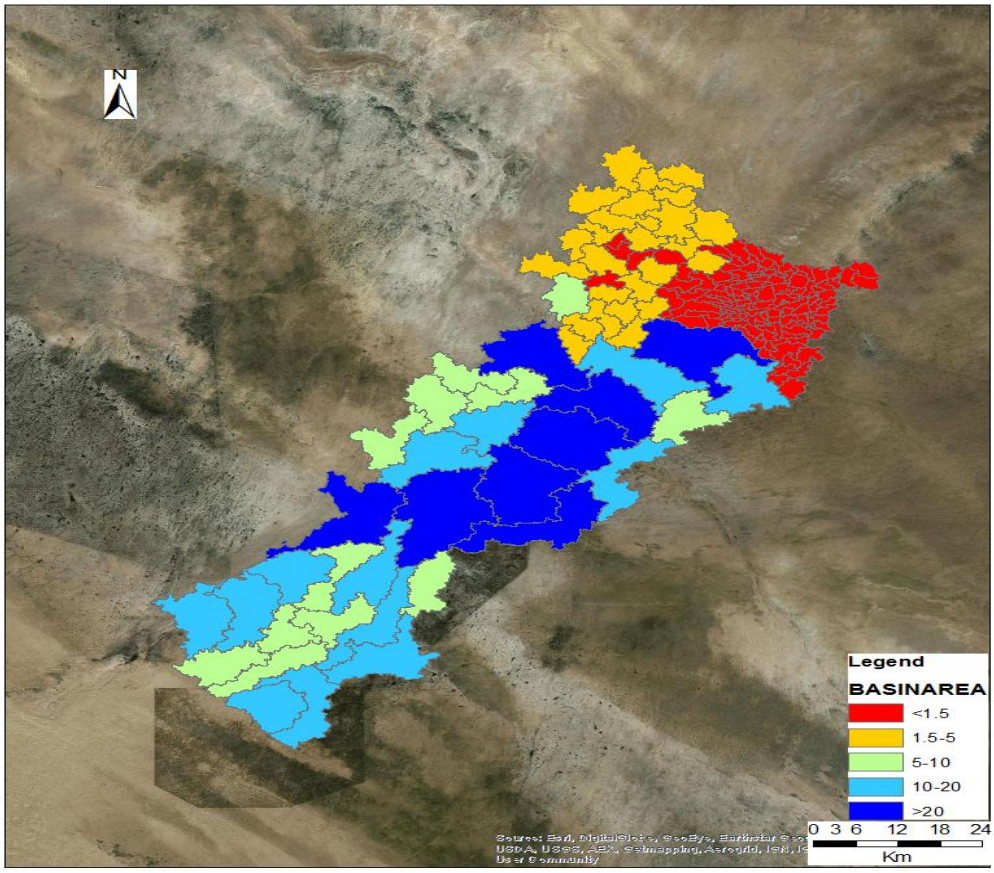



Figure 4.2 Delineated Hafar Al-Batin watershed classified by the basin area

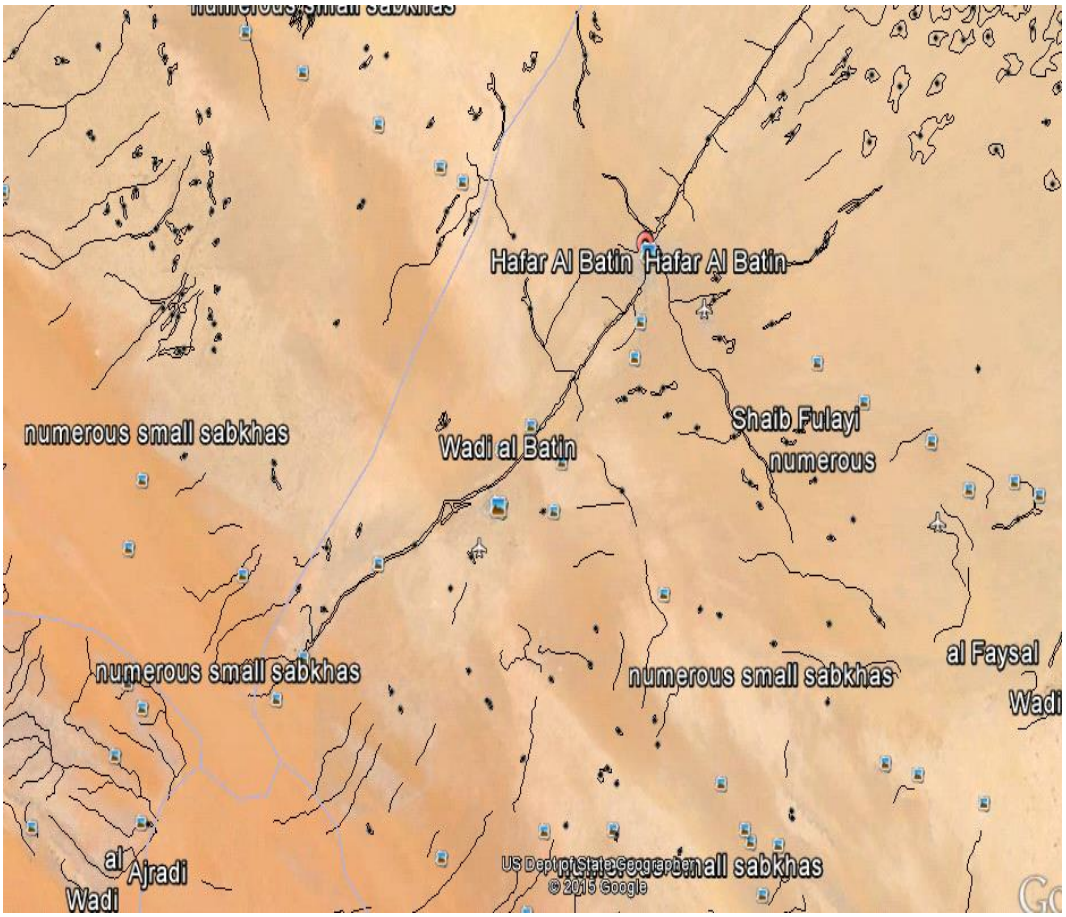



Figure 4.3 Hafar Al-Batin approximate streams [57]

hydrologic soil group [59]. The SCS-CN is widely used in arid regions and semi-arid regions. It has high accuracy in catchments where flood observations are not available, and it is also the most popular method to find the volumes of the runoff [60, 61].

The USDA Soil Conservation Service runoff curve number method is used by many models to find the volumes of the runoff peak flows [59], which can be expressed as:

$$Q_r = \frac{(P-0.2Sr)^2}{P+0.8\,Sr} \tag{4.1}$$

$$S_r = \frac{25400}{CN} - 254 \tag{4.2}$$

$$Q_p = 2.08\,\frac{A}{Tp} \tag{4.3}$$

$$T_p = \frac{\Delta t}{2} + t_{lag} \tag{4.4}$$

where $Q_r$ = direct runoff (mm), $P$ = rainfall (mm), $S_r$ = potential difference between direct runoff and rainfall (mm), $CN$ = curve number, $Q_p$ = the peak discharge for one unit of rainfall excess ($m^3/s$), $A$= the drainage area ($km^2$), $T_p$ = the time of rise of the flood hydrograph (hours), $\Delta t$ = the excess precipitation duration (hours), and $t_{lag}$ =lag time (hours).

Obtaining the elevation data is the first step to develop the hydrologic model, which is very important in delineating the watershed and computing the basin parameters such as watershed area, concentration time, lag time, centroid, and slope. The 30-m resolution DEM was previously downloaded from the United States Geological Survey (USGS), which was then prepared by the Geographic Information System (GIS).

Due to the large size of the study area, about 1669.014 $km^2$, the catchment area was divided into three main parts, and each part was divided into sub-basins with different sizes. These three parts are upstream with large size sub-basins, middle with medium size sub-basins, and downstream, which includes Hafar Al-Batin city, with small size sub-basins to get more and accurate details due to the importance of this part.

The DEM was imported to the WMS after converting it to UTM coordinates to delineate the watershed and the sub-basin boundaries. TOPAZ software was run to compute flow directions and flow accumulations. After that, the stream network was computed. Next, the WMS delineated the watershed boundary after defining an outlet point at the required location of the stream network. To delineate the sub-basin boundaries, more outlet points, about 182, were defined, which takes into account the changes in the land use, soil type, and the catchment topography. This large number of sub-basin can help to estimate flooding over the whole catchment and not only at the catchment outlet. The WMS delineated the sub-basin boundaries from these outlet points and computed the geometric parameters (Appendix I), which were used as an input for the HEC-HMS model. Figure 4.4 shows Hafar Al-Batin watershed after delineation. The next step is to estimate the surface runoff due to a specified rainfall storm using the SCS method. Land use and soil data for the study area were extracted from the watershed modeling system (WMS), which were then prepared by the GIS program. Soil and land use data were imported to WMS, which combined them with a table relating land use and soil types to compute the curve numbers (CNs) for each sub-basin in the watershed. These CNs will be used as input in the SCS method to estimate the runoff.

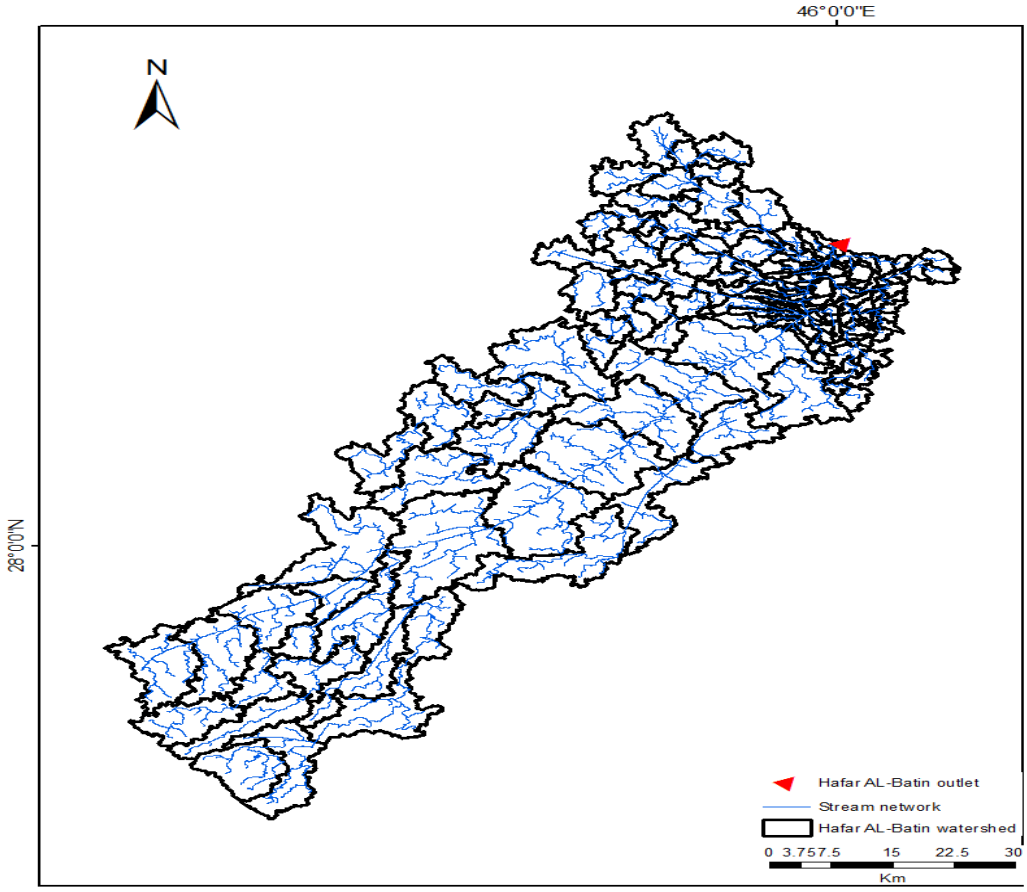



Figure 4.4 Delineation of Hafar Al-Batin watershed

Depending on the geometric parameters and the land use and soil type data, WMS and HEC-GeoHMS were integrated to compute the composite CNs, as shown in Table 4.1 and Figure 4.5, for HEC-HMS.

Appendix II summarizes the CN values for various combinations of hydrologic soil group and land use. Also, the table shows the area for each sub-basin, which was used by WMS to compute the lag time and the time of concentration for each sub-basin. The basin lag time for each sub-basin was calculated using SCS according to the following relation [62]:

$$L = \frac{2.587 l^{0.8} \left(\frac{1000}{CN} - 9\right)^{0.7}}{1900 y^{0.5}} \qquad (4.5)$$

where $L$ = lag time (hour), $l$ = hydraulic length of catchment (m), $CN$ = runoff curve number, and $y$ = average watershed land slope (%).

The SCS hypothetical storm method implements four synthetic rainfall distributions developed by the Natural Resources Conservation Service (NRCS) based on the observed precipitation events. Each distribution contains rainfall intensities arranged to maximize the peak runoff for a given total storm depth. The four distributions correspond to different geographic regions [59]. The estimated discharges for Wadi Al-Batin were calculated for the following return periods: 100, 50, 25, 10, 5, and 2 years. Figure 4.6a shows the hourly distribution of 24 hours corresponding to a return period of 100 years for Hafar Al-Batin catchment area based on the Type II rainfall distribution of the Natural Resources Conservation Service (NRCS), which is suitable for arid and semi-arid regions. Figure 4.6b shows the 1-hour hyetograph of the 100, 50, 25, 10, 5, and 2-year return periods.

Table 4.1 Runoff curve numbers for hydrologic soil group [62]

| Land use | Curve number for hydrologic soil group | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Residential | 75 | 80 | 85 | 90 |
| Desert shrubs | 55 | 68 | 80 | 86 |

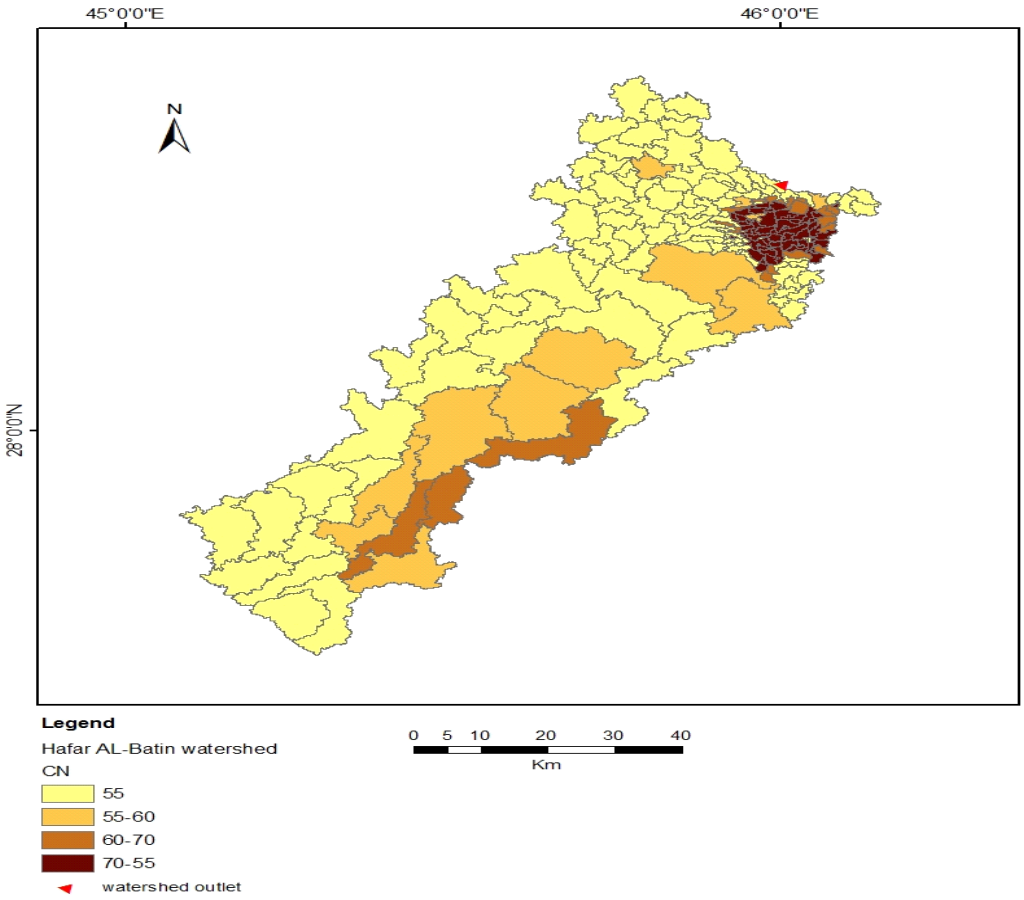
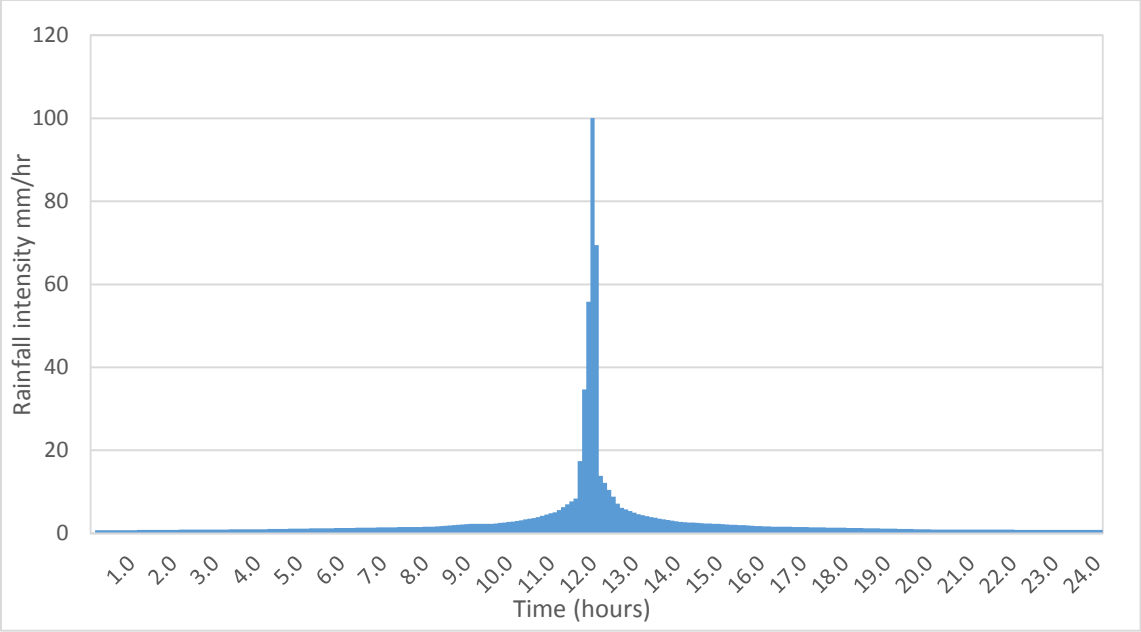
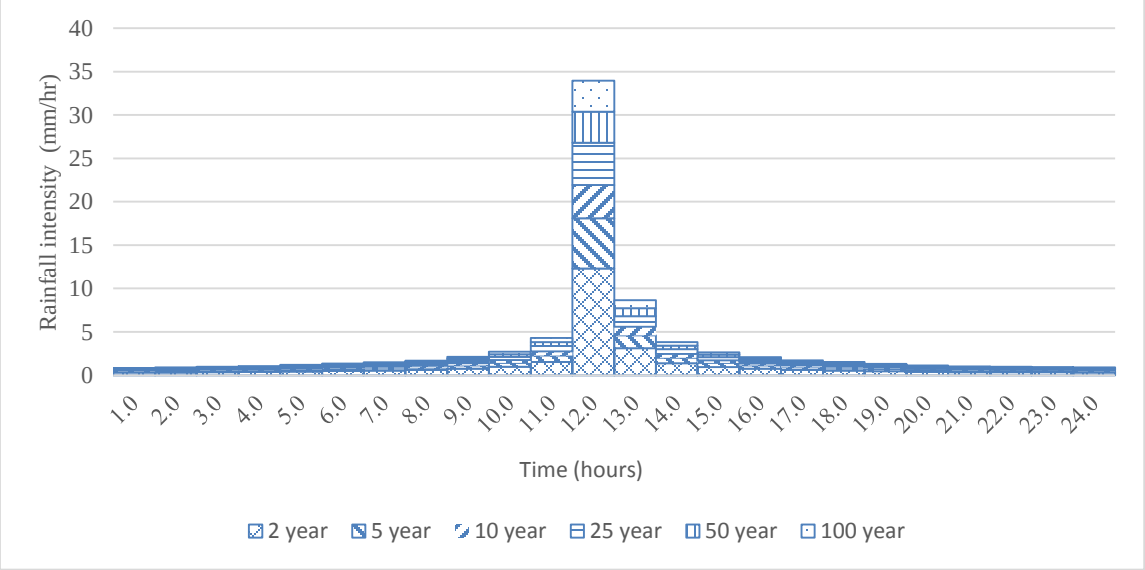



Figure 4.5 Hafar Al-Batin watershed classified by curve number




(a)




(b)

Figure 4.6 Rainfall hyetograph: (a) the 6-minute hyetograph of the 100-year storm (storm total is 79.34 mm) and (b) the 1-hour hyetograph of the 2, 5, 10, 25, 50, and 100-year storms

The 6-minute resolution of time intervals was used as rainfall input in HEC-HMS, which can give the highest possible level of accuracy.

All required data needed to run HEC-HMS were saved in a specific file. These data were imported by HEC-HMS as shown in Figure 4.7, and the model was run successfully. Appendix III shows the peak discharges for each sub-basin. Figure 4.8 shows the hydrograph at the outlet of Hafar Al-Batin watershed for 100, 50, 25, 10, 5, and 2-year return periods. From the figure, it can be noticed that the second peak is higher than the first peak in the 100-year return period, but in the remaining return periods, the first peak discharge is higher than the second peak. This is due to the amount of the rainfall for the 100-year return period, which is large enough to allow the whole catchment area to contribute to the outflow hydrograph. In other words, the infiltration in the upstream sub-basins, which are far from the watershed outlet, is higher than the rainfall for all the return periods except for 100 years. Table 4.2 shows the values of peak discharge and runoff volume for different return periods at Hafar Al-Batin watershed outlet.

## 4.2 Hydraulic Model (HEC-RAS)

HEC-RAS, which is considered as a powerful program, has been used widely in hydraulic simulation and floodplain studies [63]. It is also used to model one-dimensional steady and unsteady river flow and is capable of simulating many types of hydraulic structures. Three main equations (continuity, energy, and Manning equations) are used in HEC-RAS to determine water depths and water surface elevations, based on which flood mapping and floodplain delineation can be performed.

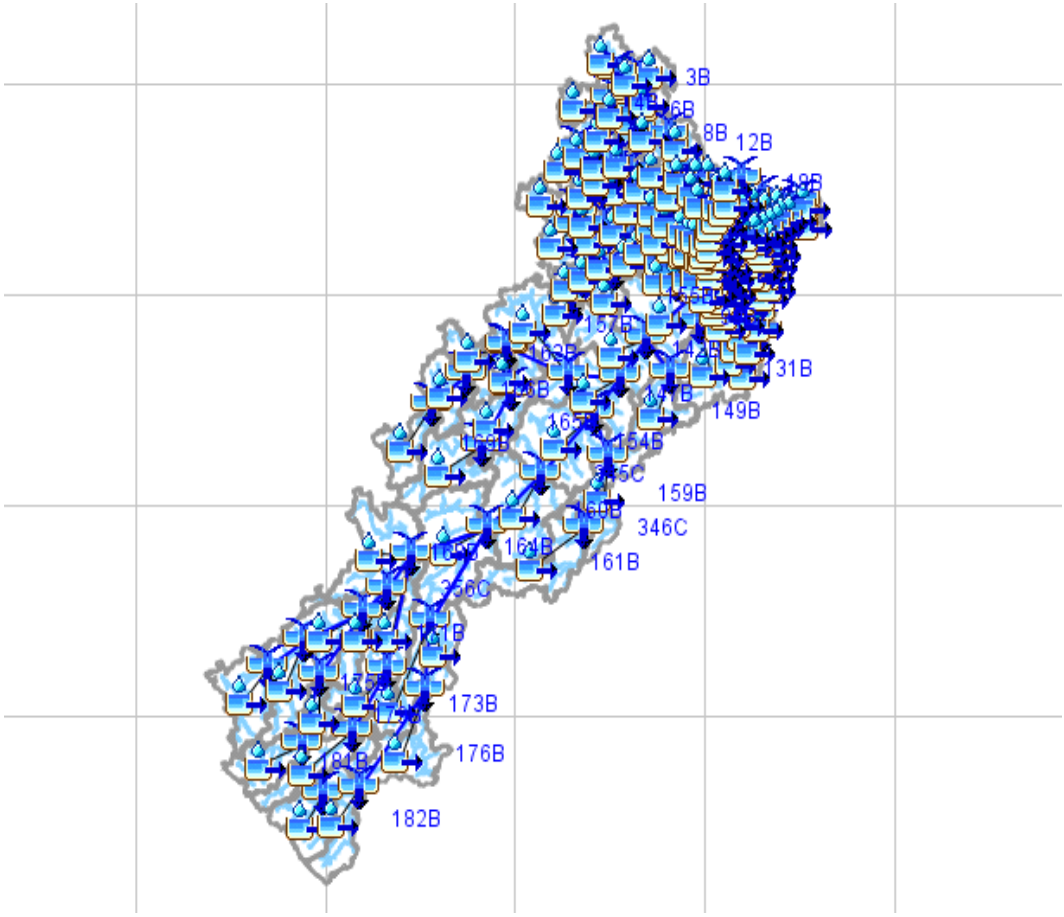
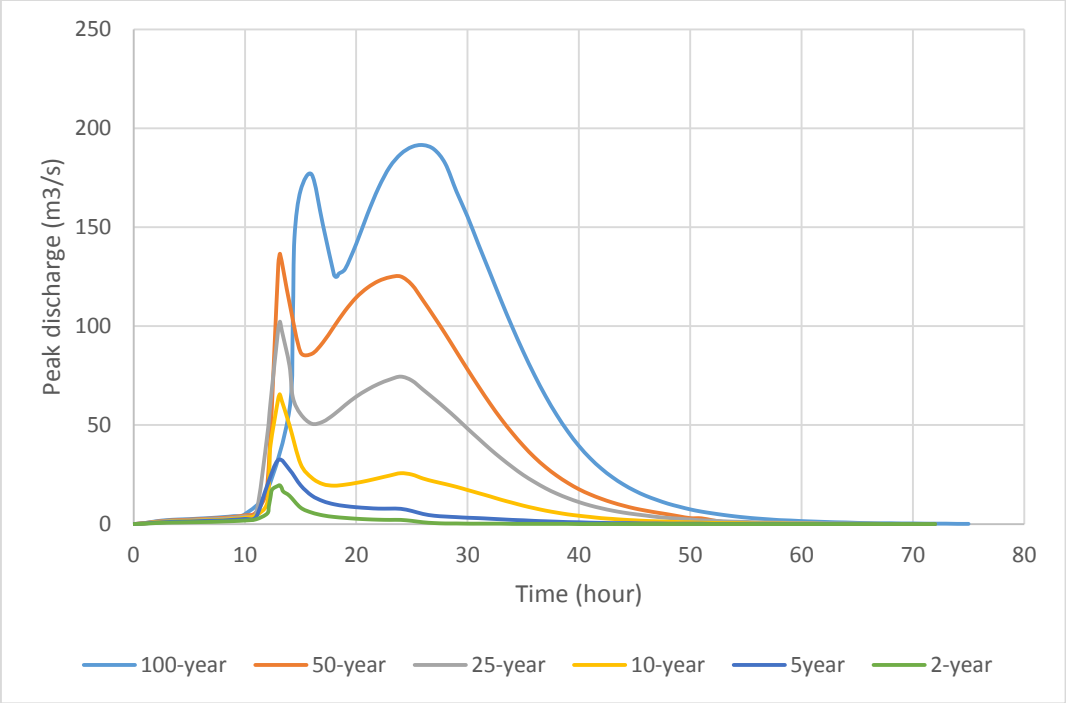
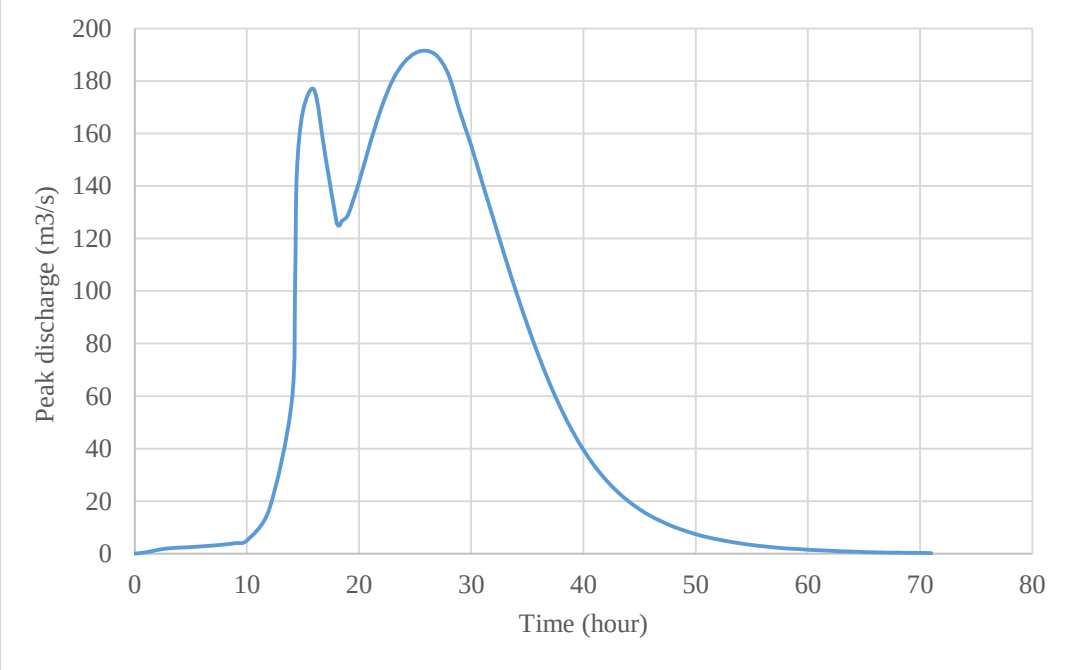



Figure 4.7 HEC-HMS basin model of Hafar Al-Batin watershed




(a)




(b)

Figure 4.8 Hafar Al-Batin outlet hydrograph: (a) for different return periods and (b) for 100-year storm runoff

Table 4.2 Peak discharge, runoff volume, and runoff coefficient of Hafar Al-Batin outlet

| **Item** | **Return period (year)** | | | | | |
|---|---|---|---|---|---|---|
| | **2** | **5** | **10** | **25** | **50** | **100** |
| **Peak discharge ($m^3/s$)** | 19.6 | 42.7 | 65.6 | 102.3 | 136.7 | 191.5 |
| **Runoff volume ($m^3$)** | 329700 | 904900 | 2206900 | 5456400 | 8876700 | 13016600 |

Generally, water surface elevation at a location in a floodplain is a more direct interest for flood analysis than the magnitude of discharge. Water elevation is determined by a hydraulic analysis, which is often performed subsequent to a hydrologic analysis.

Hydraulic model (HEC-RAS) requires identification of watershed boundary and surface roughness values. For this purpose, HEC-RAS data were prepared using WMS and HEC-GeoRAS software. The first step in the hydraulic simulation is to get the watershed elevation data, which can be obtained from the digital elevation map (DEM). However, the resolution of the DEM used in this study is 30 m, which does not include bathymetry and may give an inaccurate hydraulic model. To overcome any expected missing data when using DEM, a new method called light detection and ranging (LIDAR)-survey triangulated irregular networks (TINs), developed by the researchers to provide data at a very high resolution, was used [64]. However, this method gives more points, more than what is required, which makes data filtering technique necessary. Omer et al. [65] used data filtering technique with a filter angle of 4 degrees, where they found that this value can be used without affecting the hydraulic or floodplain model results. In this study, a filter angle of 5 degrees was used, which does not affect the results of the floodplain model. The method generates too many triangles, approximately more than 1.5 million, which makes the contour lines impossible to be displayed and does not give a clear picture about the inundated area. This problem can be solved by using different values of filter angle until reaching a suitable value that makes the filled contours possible to be displayed and at the same time does not affect the output of the floodplain model. Figure 4.9 shows the final TIN network of the investigated catchment, which was used to extract the cross sections for the purpose of hydraulic simulation using HEC-RAS model.

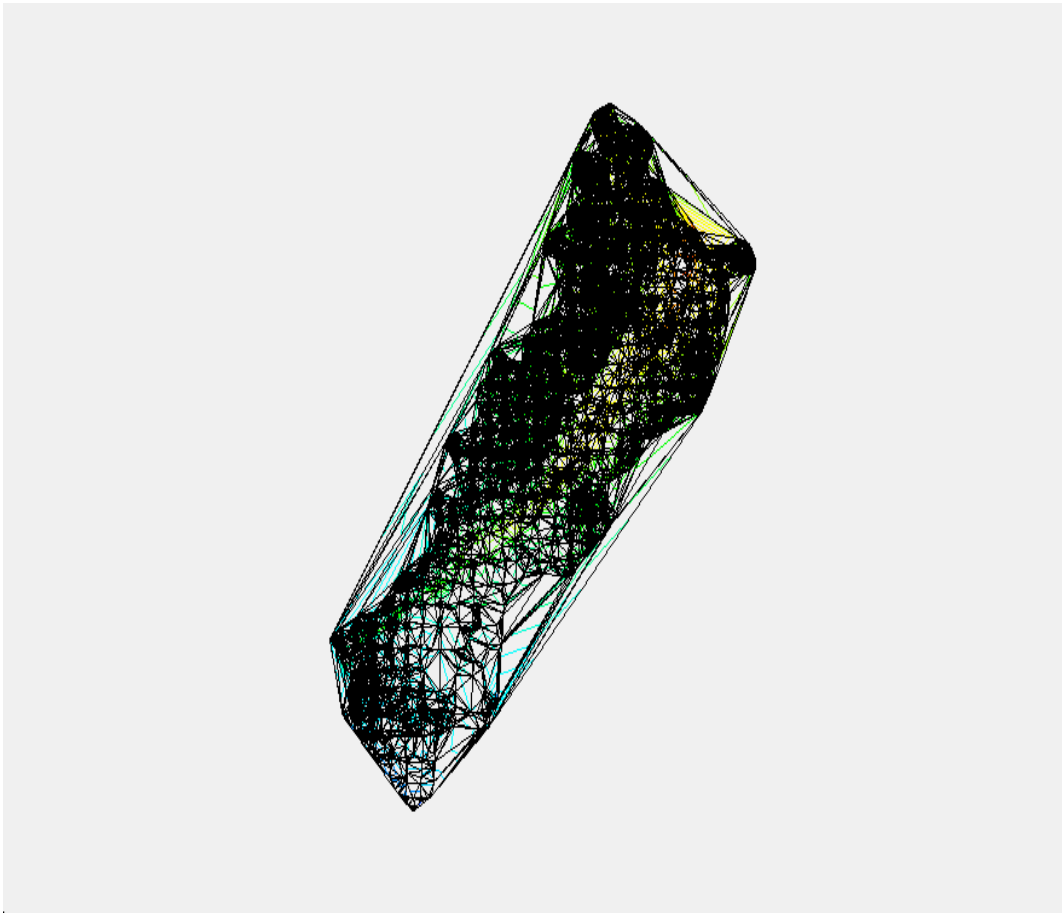


Figure 4.9 TIN map for Hafar Al-Batin watershed

Roughness values are one of the input requirements of HEC-RAS, so surface type was designated to different areas in the constructed model depending on the channel type and land use, and then each surface was assigned with the proper roughness value. The most important part of the map in HEC-RAS is the cross sections where most of the model input data are associated with. Moreover, at the cross sections, solutions or outputs are generated. At least two cross sections on each reach were considered. These cross sections should be perpendicular with the expected flow path and extend across the entire floodplain [63]. In this study, the AutoCAD program was used as the best choice to construct the cross sections at a specific distance, which can be considered much better than using WMS to develop the cross section manually and at an arbitrary distance. Figure 4.10 shows the geometry of the hydraulic model with the wadi reaches and cross sections.

Next, any required boundary condition should be entered to establish the starting water surface at the ends of the wadi channel. This starting water surface is used by HEC-RAS to start the calculation. In this study, the normal depth was assumed to be the boundary condition at the downstream of Hafar Al-Batin wadi. Then, the generated peak discharges using HEC-HMS (Appendix IV) were entered manually into HEC-RAS. The outputs of HEC-RAS simulations were extracted by WMS and used to determine the floodplain boundary. Figure 4.11 shows the water levels for return periods of 2, 5, 10, 25, 50, and 100 years, while Figure 4.12 represents water surface levels at different cross sections along the main channel. Water level analysis shows that the most affected reaches are those located inside the city.

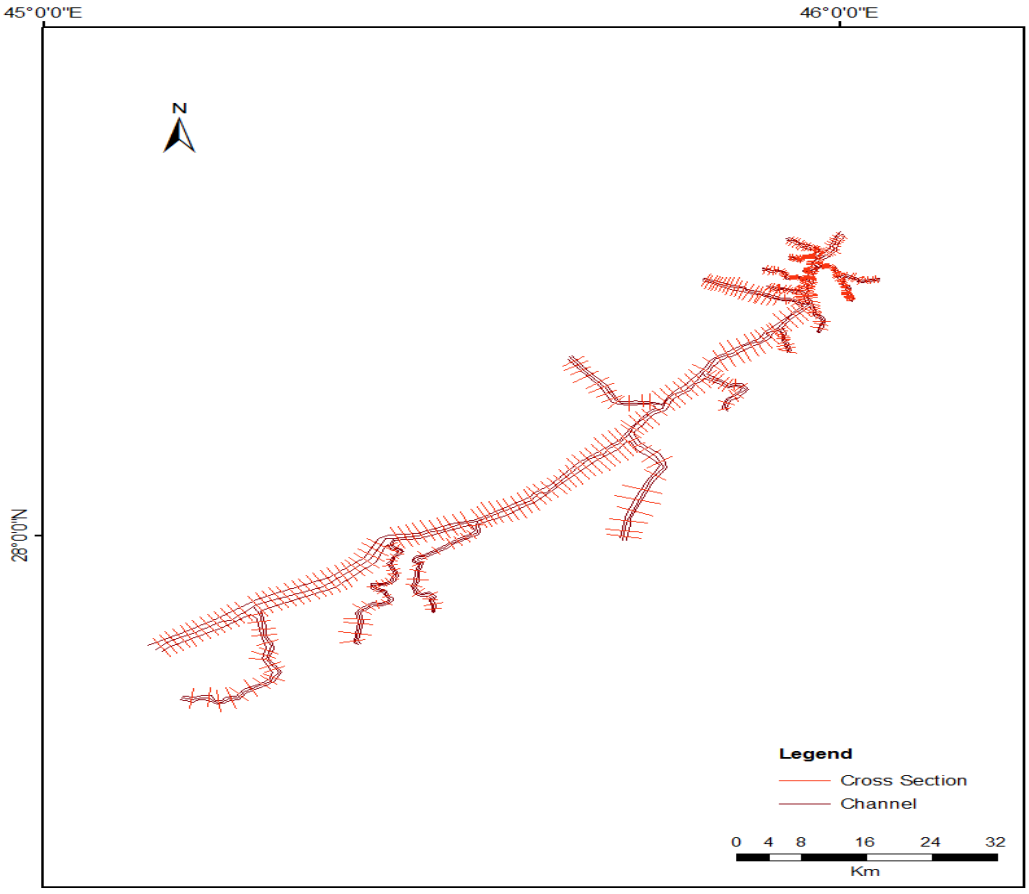
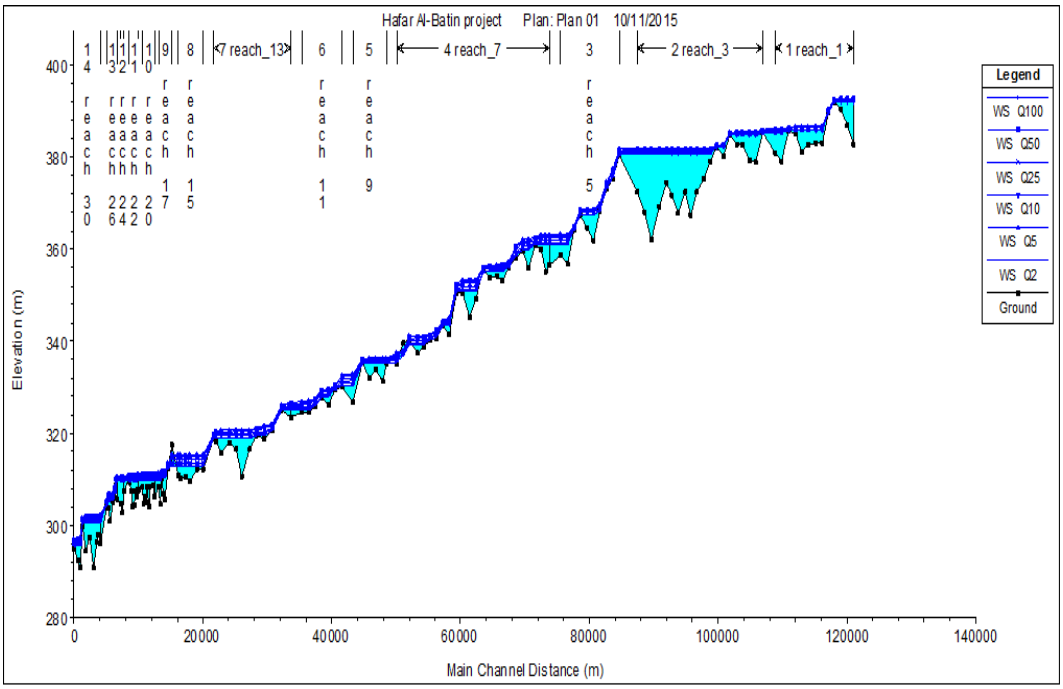
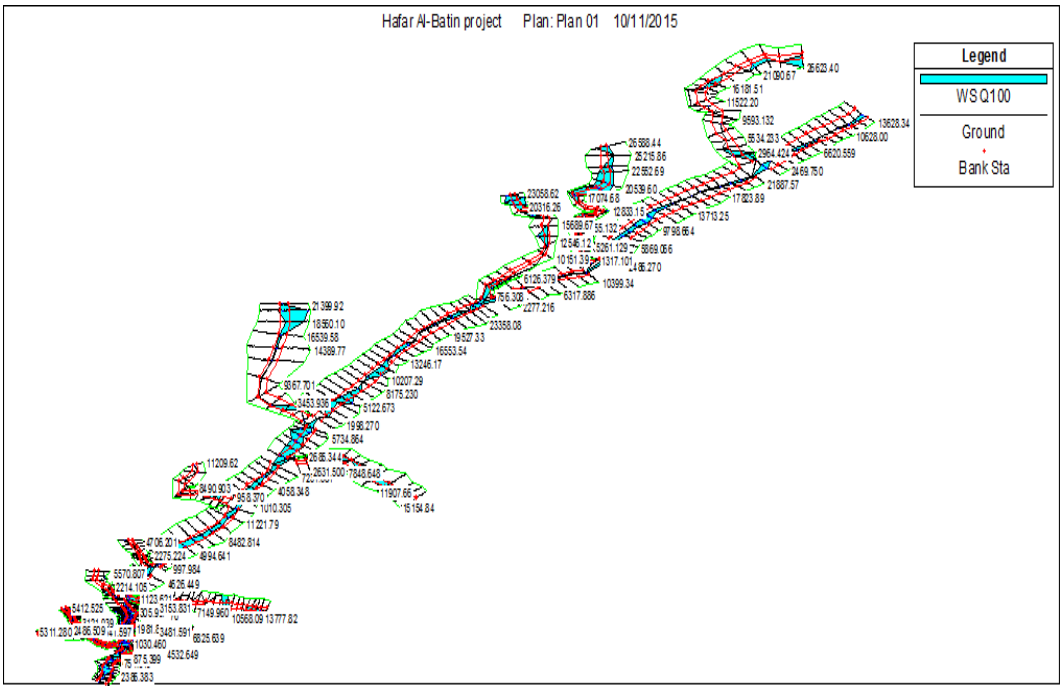



Figure 4.10 Main reaches and sections along the main reach of Hafar Al-Batin watershed

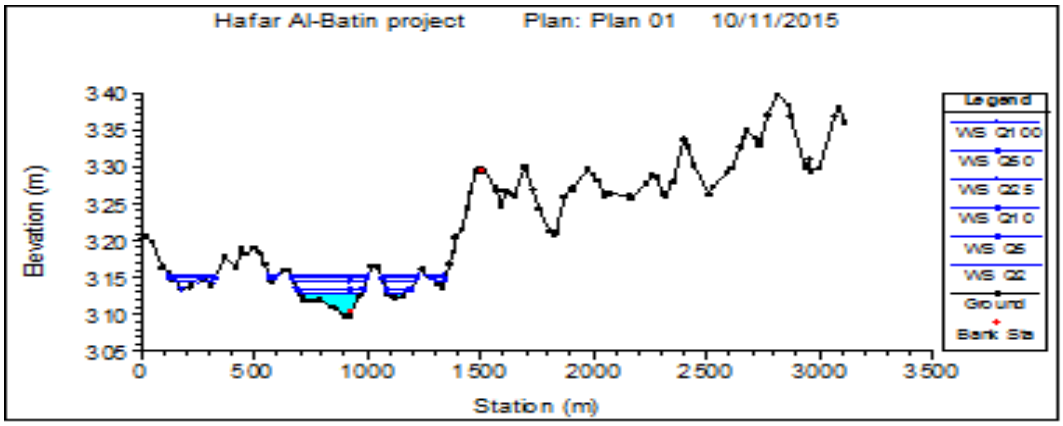



(a)

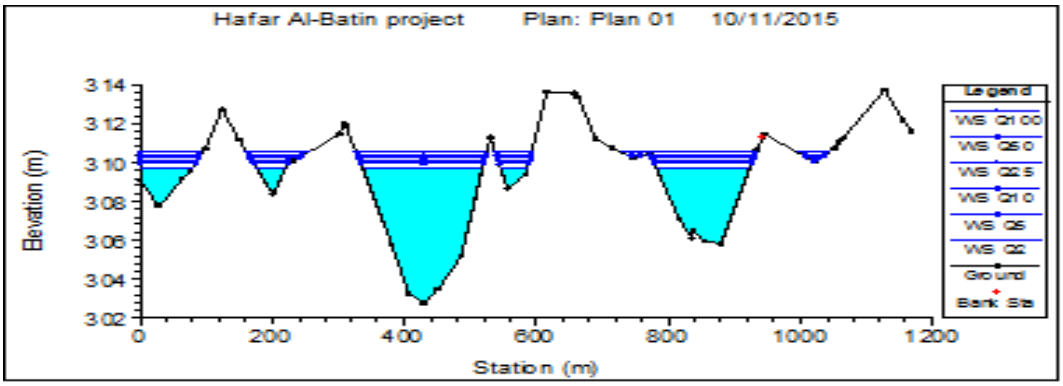



(b)

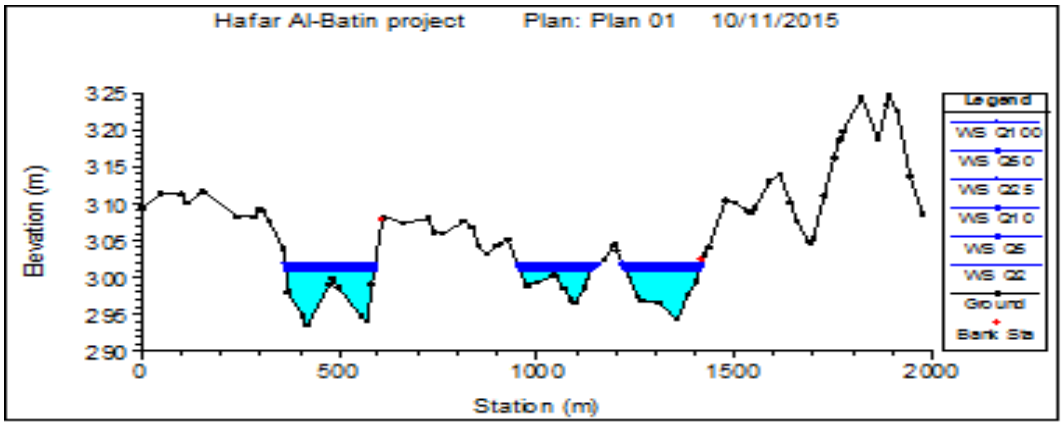
Figure 4.11 Water surface level across the main channel (a) longitudinal profile for different return periods and (b) perspective plot for 100 years




(a)




(b)




(c)

Figure 4.12 Water surface elevation at different cross sections along the main reach for different return periods: (a) city entrance, (b) middle of the city, and (c) end of the city (outlet)

Starting from the city entrance point to the outlet downstream, flood exceeds the bank levels of the existing channel for most of the return periods as shown in Figure 4.13.

## 4.3 Floodplain Delineation Model

Watershed Modeling System (WMS) is an integral program for developing watershed computer models that support 2D hydrologic modeling, regression, and lumped parameter of watersheds. It supports river hydraulic and storm drain models such as HEC-1, HEC-HMS, HEC-RAS, TR-55, TR-20, NFF, HSPF, Rational MODRAT, GSSHA, CE-QUAL-W2, EPA SWMM, SMPDBK, and other models [42, 66, 67, 68].

Floodplain delineation using WMS requires identification of the water depths at each section along the channel. For this purpose, a file containing the water depths resulting from HEC-RAS, needs to be imported to WMS. The scatter points which contain the water surface elevations were interpolated at a 60-m spacing along the wadi centerline and cross sections to achieve more accurate floodplain delineation. Then, the interpolated data was used as input data to the floodplain delineation models by switching to the terrain data module which has the floodplain process and delineation. For this purpose, 1000 m max search radius (the maximum search radius defines the limiting distance that will be used when collecting the nearest stage scatter points) and 4 numbers of stages (which were used for interpolation) were selected for the project, which have been used after many trials with different values.

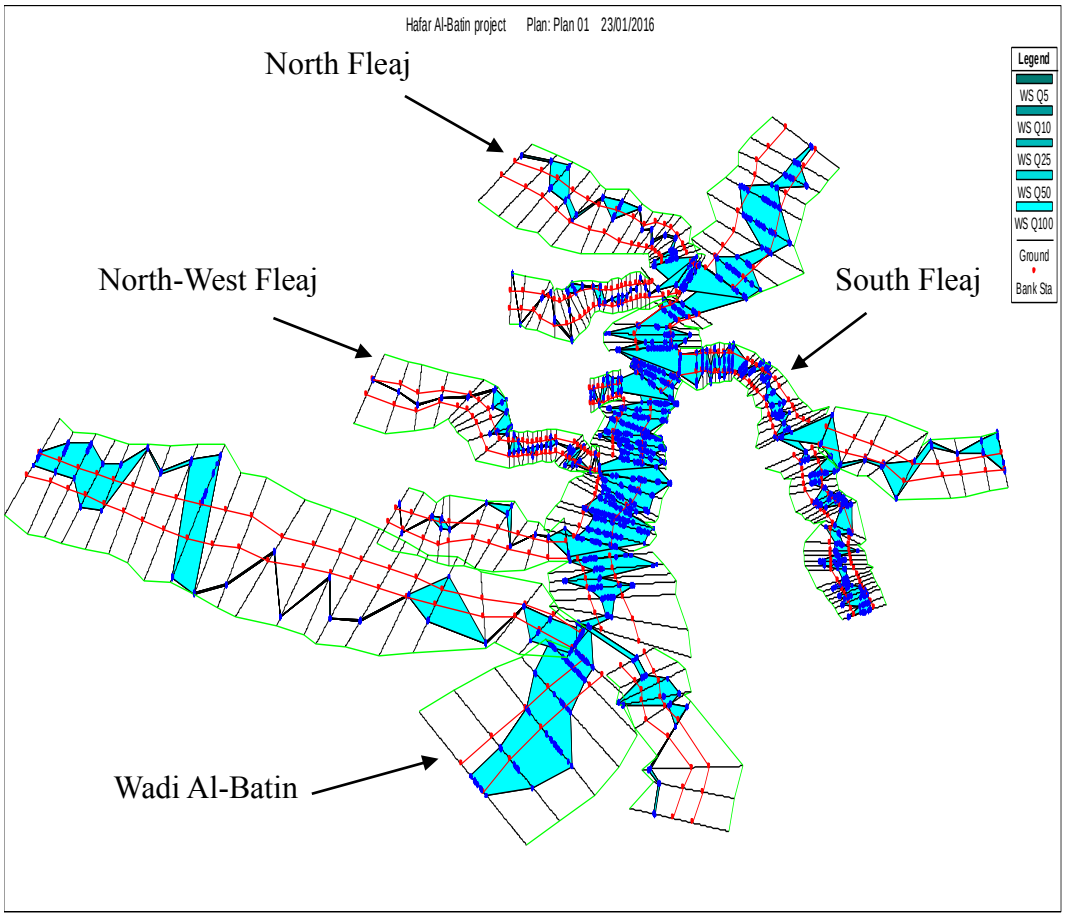
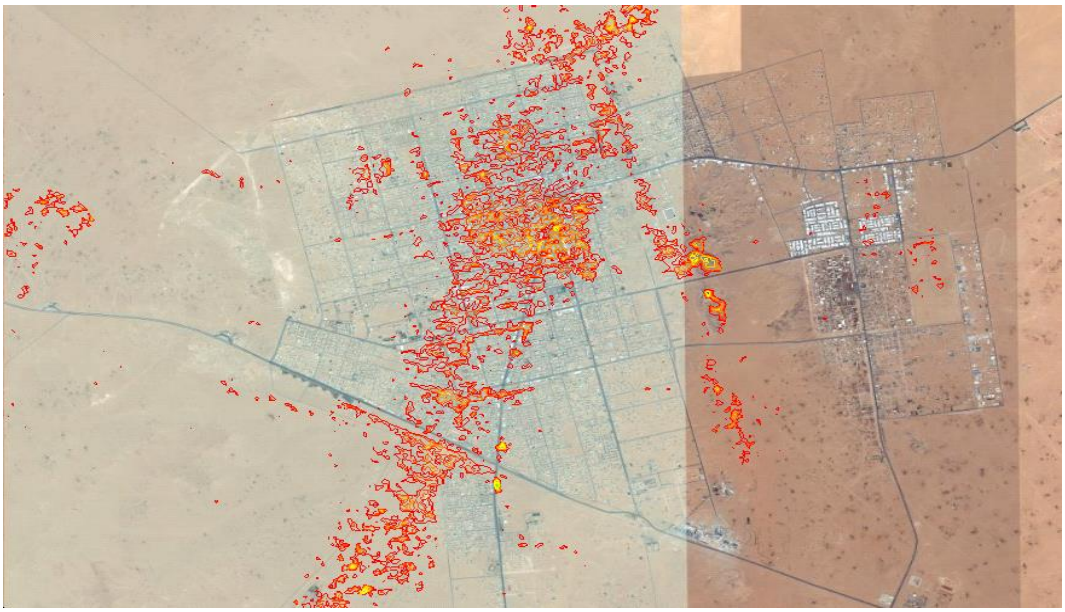



Figure 4.13 Perspective plot of Hafar Al-Batin city

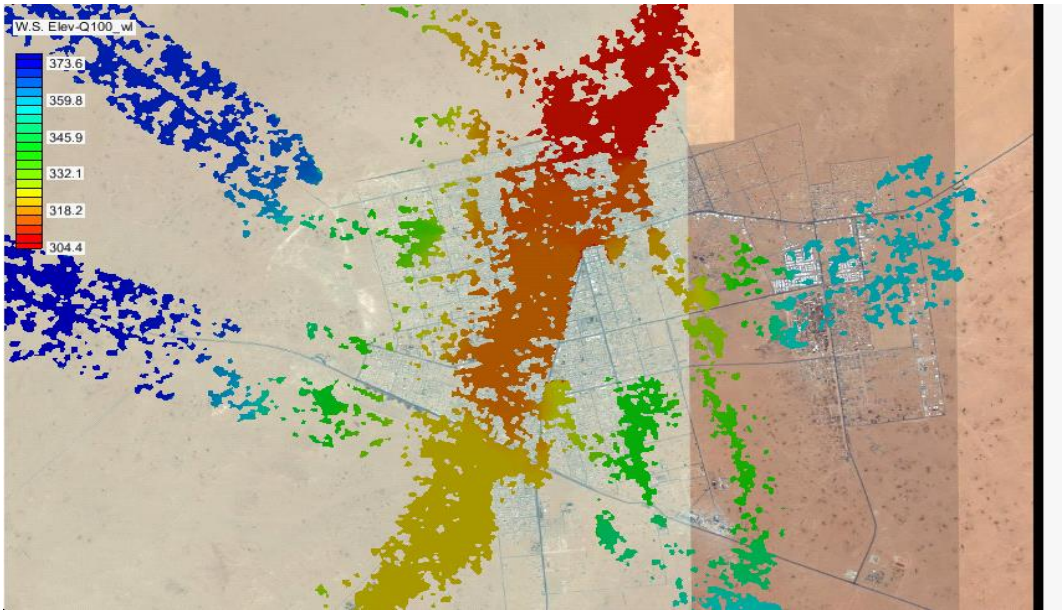
In this step, two new datasets which are water surface elevations and floodplain depths (flood depth and river bed elevation) were computed. These datasets are named W.S. Elev-PF 1 (fd) which represents the flood depth and W.S. Elev-PF 1 (wl) which represents the water surface elevation. Finally, the inundated areas were presented as flood polygons in a developed flood hazard map as shown in Figure 4.14, which represent the flood depth values and the water elevation values, respectively, for a return period of 100 years.

Figure 4.15 shows the flood depth values and the water elevation values, respectively, for a return period of 2 years. From Figures 4.14 and 4.15, the inundated areas in the case of 100-year storm are larger than those of 2 years because the amount of the 2-year storm is much less than that for 100 years.

The inundation area resulting from this study was compared with a study conducted by Hafar Al-Batin municipality as shown in Figure 4.16. The figure reveals that the model output based on WMS resulting from this study (Figure 4.16a) and the risk map constructed by Hafar Al-Batin municipality (Figure 4.16b) are matching. This proves the capability of WMS to model flood events and their expected risks to the city of Hafar Al-Batin.

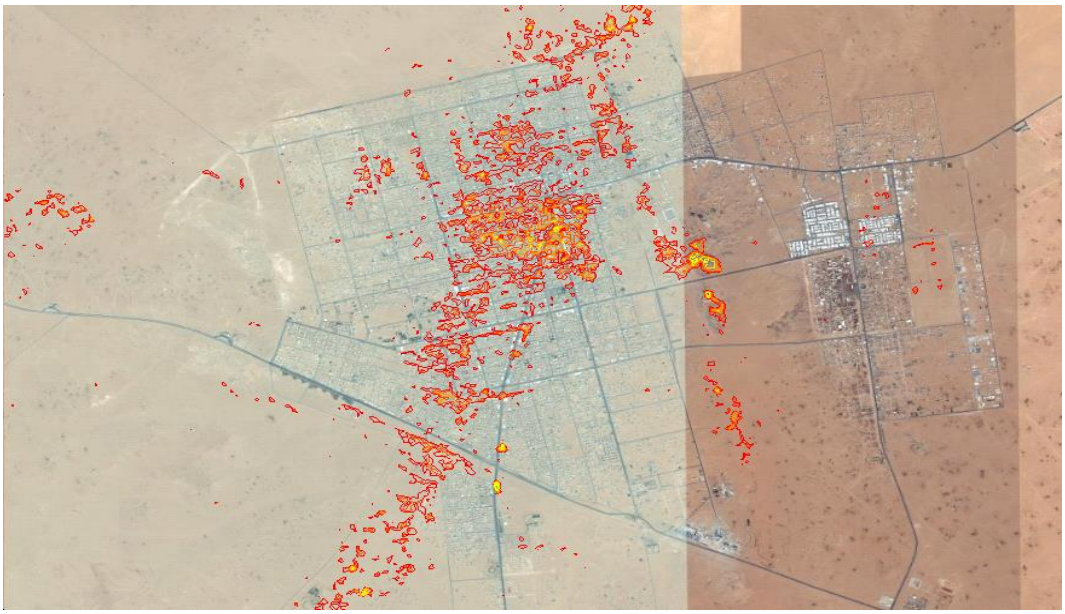


(a)

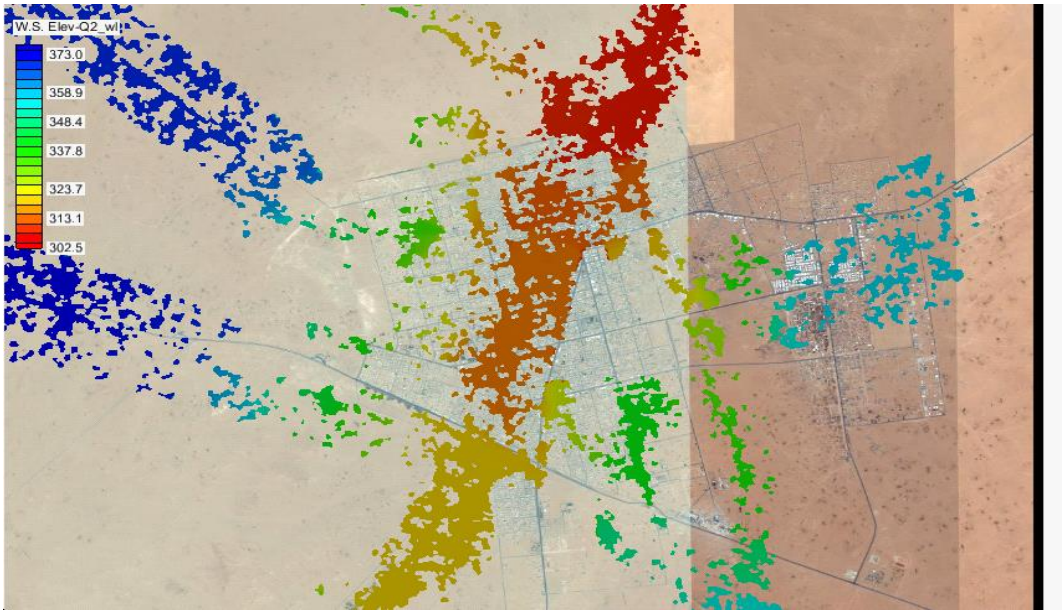



(b)

Figure 4.14 The 100-year floodplain map from WMS: (a) floodplain depths and (b) water surface elevations

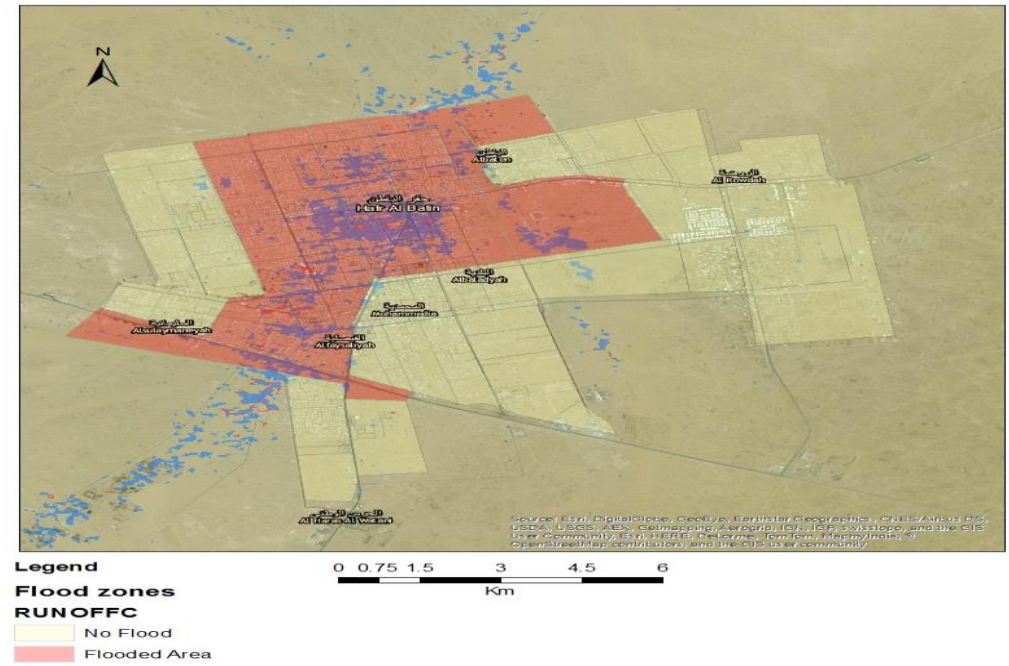


(a)

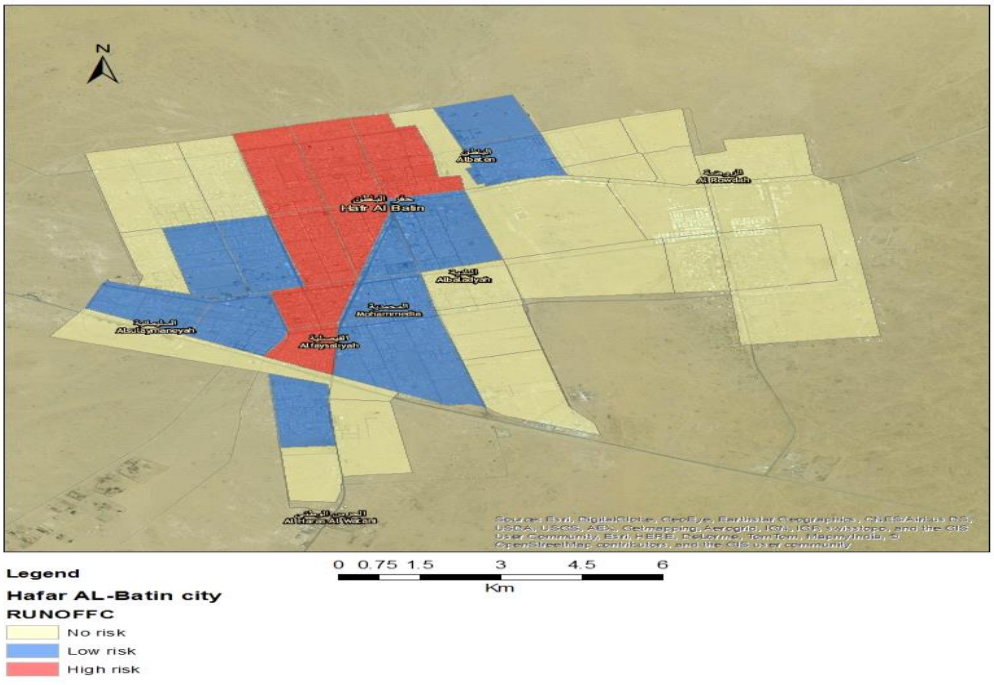



(b)

Figure 4.15 The 2-year floodplain map from WMS: (a) floodplain depths and (b) water surface elevations




(a)




(b)

Figure 4.16 Flood risk map: (a) 100-year flooded area and (b) flooded area developed by Hafar Al-Batin municipality

Geographic information system (GIS) is an effective tool in hazard assessment. In this study, four important factors, which are runoff depth, watershed slope, soil type, and land use, were taken into account to estimate the flood hazard map. Each parameter was valued and weighed according to its contribution in causing a flood. After that, the total sum of the three developed maps was determined to estimate the probability of flood occurrence in the studied area as shown in Figure 4.17. It is clear from the figure that the city of Hafar Al-Batin is located in the high risk regions, which reflects the bad location of the city. Obviously, the CN values, sub-basins slopes, and runoff depth have high values in the city, which makes it within the high risk region.

## 4.4 Proposed Actions to Control Floods

Recently, flood has become a very serious problem for Hafar Al-Batin city due to its effect on the property and infrastructure of the city in addition to the risk to human lives. Unfortunately, the existing measures to control and resolve the problems associated with flood occurrences adopted by Hafar Al-Batin municipality are not sufficient. This study proposes some actions, based on the output of the constructed models, to control and reduce the effects of floods on the city of Hafar Al-Batin.

According to this study, four main streams contribute to the runoff in the city of Hafar Al-Batin, which are north Fleaj, northwest Fleaj, south Fleaj, and Wadi Al-Batin as shown in Figure 4.18. The contribution of the north Fleaj stream is approximately 18.96 $m^3/s$, but as indicated in Figure 4.18, the streamflow does not have any influence on the city of Hafar Al-Batin since most of the runoff is collected outside the city. On the other

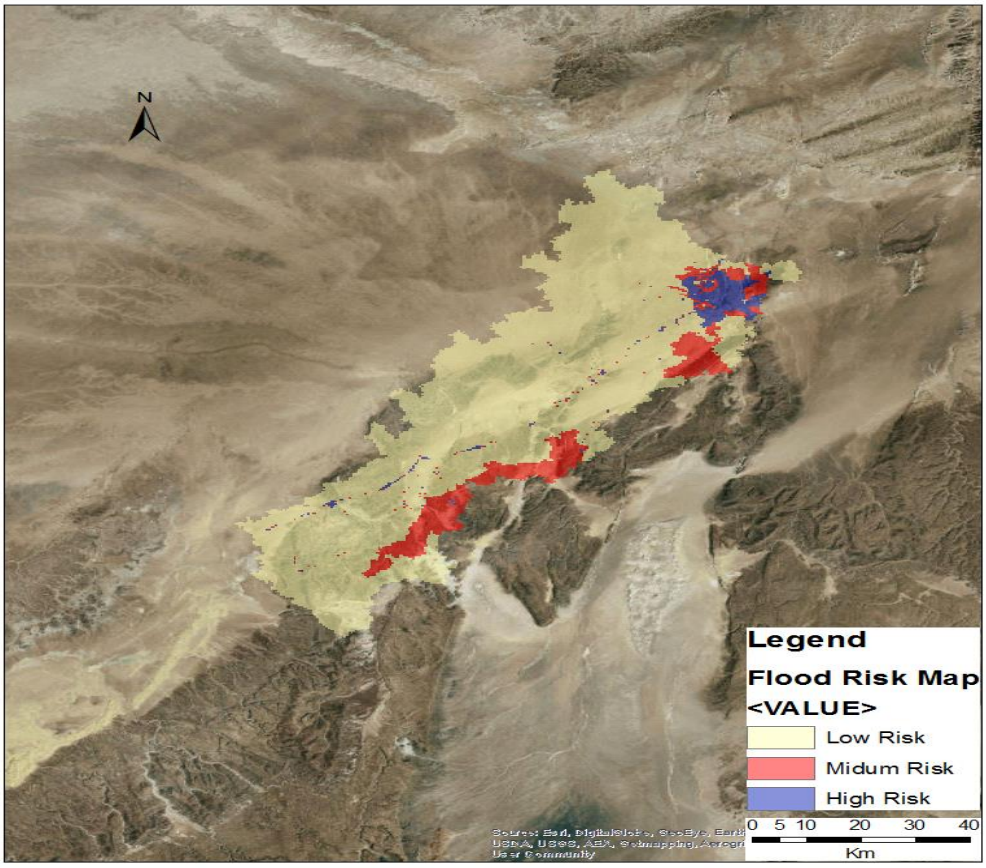



Figure 4.17 Hafar Al-Batin flood risk map

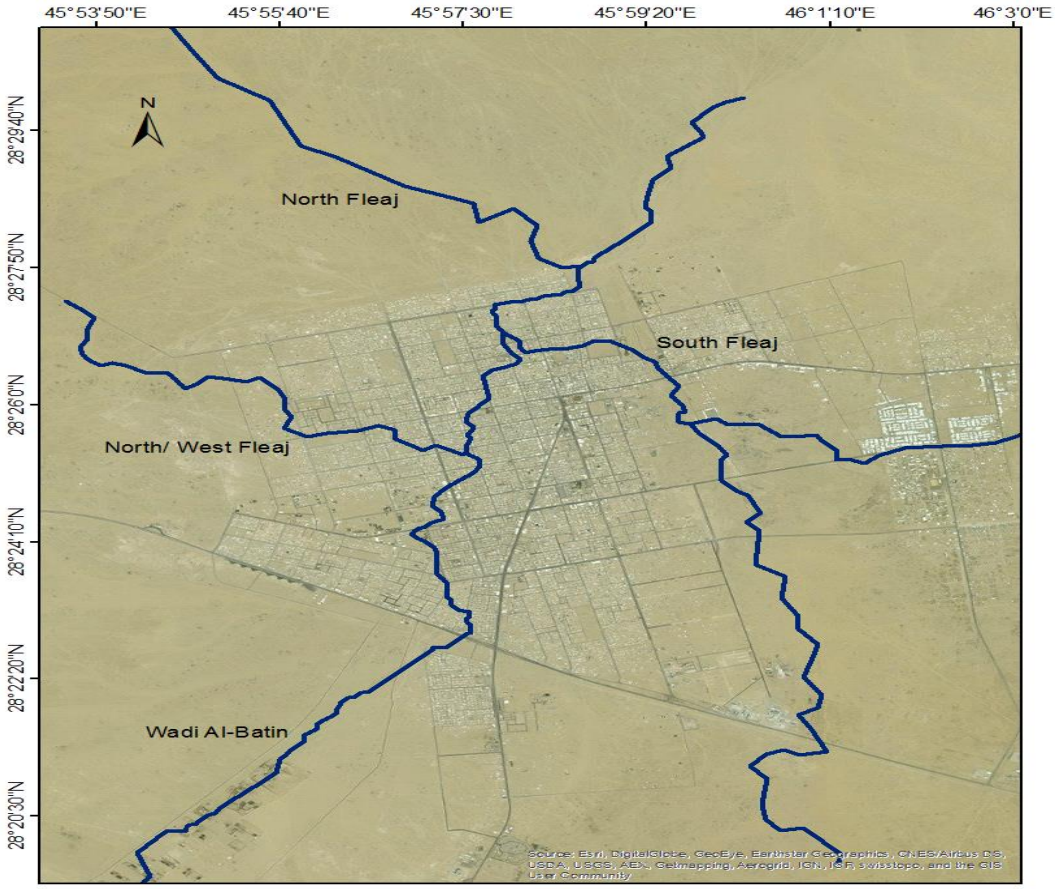



Figure 4.18 Hafar Al-Batin main streams

hand, the flows generated by the other streams will run through the city. The contributions of northwest Fleaj, south Fleaj, and Wadi Al-Batin are 12.16 $m^3/s$, 67.12 $m^3/s$, and 144 $m^3/s$, respectively. These three streams are the main sources of Hafar Al-Batin flood. Based on this summary, the study suggests constructing two trapezoidal channels and a retention pond. The first channel is called the south channel and is located at the south of the city. The second one is called the north channel and is divided into two parts. The first part is at the north of the city and the second is at the east of the city. The locations of the proposed actions are shown in Figure 4.19. The dimensions and characteristics of these channels are presented below.

### 4.4.1 The south channel

The south channel is a trapezoidal section with a length of 1600 m. FlowMaster software was used to design the channel to carry the discharge of south Fleaj, which is 67.12 $m^3/s$. Figure 4.20 shows the details of the proposed cross section.

### 4.4.2 The north channel

This channel is divided into two parts, the first part with a length of 1200 m and the second part with a length of 6500 m. Accordingly, two trapezoidal channels were designed in the north and east of the city to carry the discharge of north Fleaj, which is 12.16 $m^3/s$. Figure 4.21 shows the details of these sections.

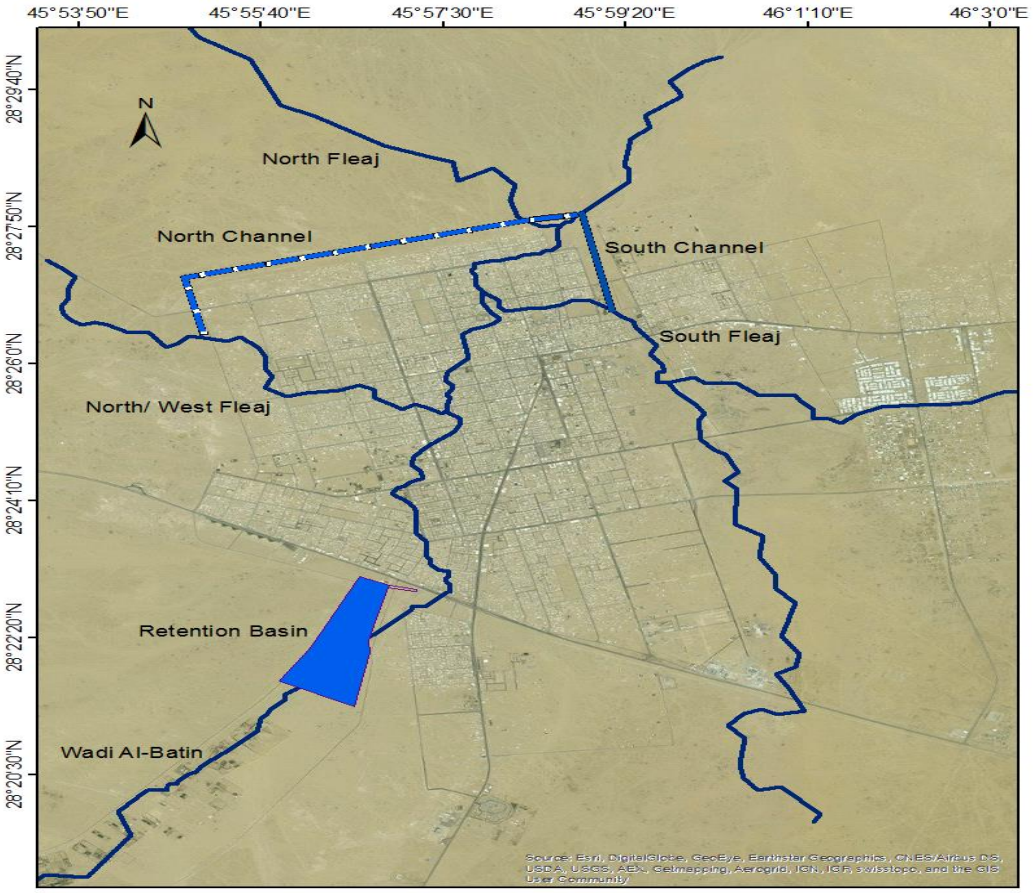



Figure 4.19 Proposed actions

| | |
|---|---|
| Roughness Coefficient | 0.015 |
| Channel Slope | 0.00534 m/m |
| Normal Depth | 1.50 m |
| Left Side Slope | 1.00 m/m (H:V) |
| Right Side Slope | 1.00 m/m (H:V) |
| Bottom Width | 6.96 m |
| Discharge | 67.21 $m^3/s$ |

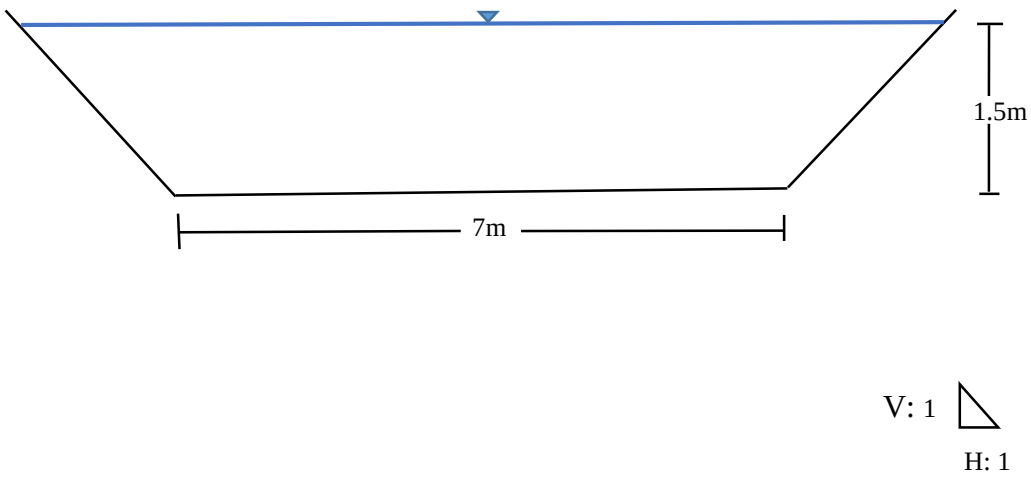
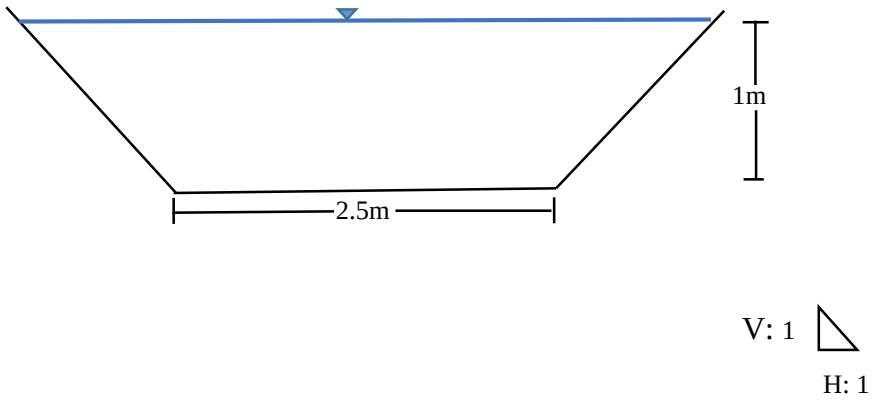


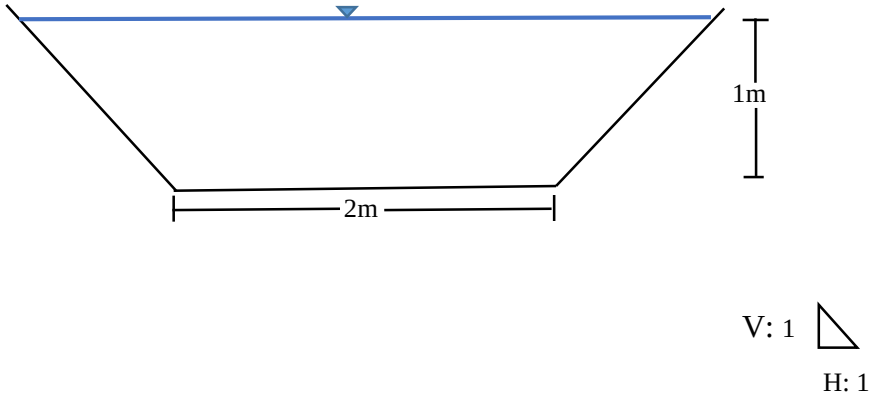

Figure 4.20 The south channel

| | |
|---|---|
| Roughness Coefficient | 0.015 |
| Channel Slope | 0.00500 m/m |
| Normal Depth | 1.00 m |
| Left Side Slope | 1.00 m/m (H:V) |
| Right Side Slope | 1.00 m/m (H:V) |
| Bottom Width | 2.43 m |
| Discharge | 12.16 m³/s |




(a)

| | |
|---|---|
| Roughness Coefficient | 0.015 |
| Channel Slope | 0.00739 m/m |
| Normal Depth | 1.00 m |
| Left Side Slope | 1.00 m/m (H:V) |
| Right Side Slope | 1.00 m/m (H:V) |
| Bottom Width | 1.93 m |
| Discharge | 12.16 m³/s |




(b)

Figure 4.21 Details of the trapezoidal sections: (a) north channel and (b) east channel

Table 4.3 summarizes the final dimensions of the proposed channels of Hafar Al-Batin watershed.

### 4.4.3 Hafar Al-Batin retention pond

Wadi Al-Batin is the main stream of Hafar Al-Batin watershed. It has a major contribution to the flood of Hafar Al-Batin city with a peak discharge of 144 $m^3/s$ and runoff volume of 8,456,700 $m^3$. This study suggests a retention pond at the entrance of the city as shown in Figure 4.19. Retention pond is a natural measure that can be implemented in urban areas to reduce runoff and flood risks. Retention pond is a downstream control measure that can be implemented in urban areas to reduce the potentially dangerous impacts of high runoff volumes and high peak flow rates. Additionally, it provides a permeable area which allows more runoff to infiltrate into the ground. This study suggests implementing a retention pond to retain about 3,750,000 $m^3$ of water. A retention pond was designed based on the 100-year rainfall storm and the area-elevation function for the retention pond as shown in Table 4.4. The design parameters for the retention pond are summarized in Table 4.5. Figure 4.22 shows the HEC-HMS output graph and summary table. As can be revealed from the summary table and Figure 4.22, the peak flow was reduced to 31.1 $m^3/s$, which emphasizes the efficiency of the proposed retention pond.

Table 4.3 The designed channels of Hafar Al-Batin watershed

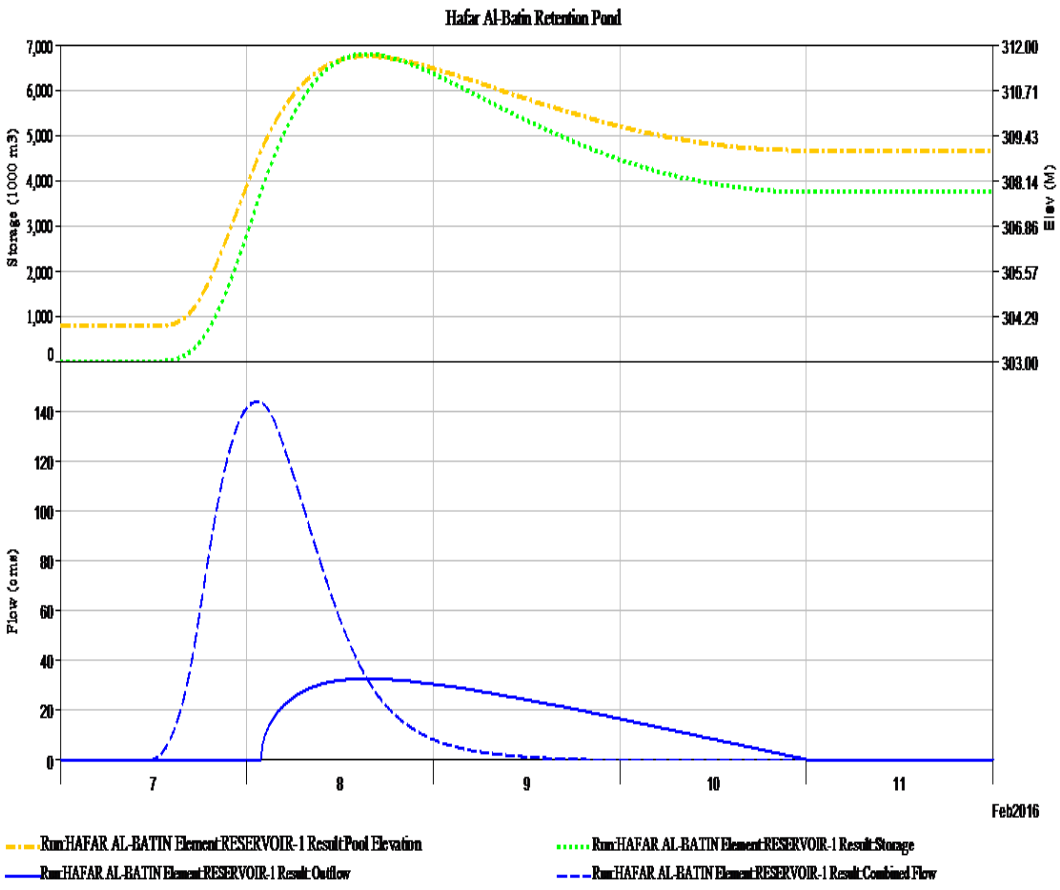
| Channel name | Left side slope m/m (H:V) | Right side slope m/m (H:V) | Bottom width (m) | Normal water depth (m) | Total depth (m) |
|---|---|---|---|---|---|
| South channel | 1 | 1 | 7 | 1.5 | 1.7 |
| North channel | 1 | 1 | 2.5 | 1 | 1.2 |

Table 4.4 Elevation-area function for Hafar Al-Batin retention basin design analysis

| **Elevation (m)** | **Area ($km^2$)** | **Volume (1000 $m^3$)** |
|---|---|---|
| 304 | 0.5 | 0.00 |
| 305 | 0.6 | 550000 |
| 306 | 0.7 | 1200000 |
| 307 | 0.8 | 1950000 |
| 308 | 0.9 | 2800000 |
| 309 | 1 | 3750000 |
| 310 | 1.1 | 4800000 |
| 311 | 1.2 | 5900000 |
| 312 | 1.3 | 7150000 |

Table 4.5 Design parameters for each detention basin design capacity

| Outlet (Orifice) (m) | Outlet Area ($m^2$) | Total Runoff ($m^3$) | Basin Depth (m) | Basin Volume ($m^3$) | Volume Fraction % | Outlet Capacity ($m^3/s$) |
|---|---|---|---|---|---|---|
| 3 | 7.07 | 8456700 | 7.7 | 6866500 | 0.81 | 31.1 |




(a)

Project: Hafar Al-Batin retention po

Simulation Run: Hafar Al-Batin  Reservoir: Reservoir-1

| | | | |
|---|---|---|---|
| Start of Run: | 07Feb2016, 00:00 | Basin Model: | Basin 1 |
| End of Run: | 12Feb2016, 00:00 | Meteorologic Model: | Met 1 |
| Compute Time: | 07Feb2016, 23:02:19 | Control Specifications: | Control 1 |

Volume Units: ○ MM ◉ 1000 M3

Computed Results

| | | | |
|---|---|---|---|
| Peak Inflow : | 144.0 (M3/S) | Date/Time of Peak Inflow : | 08Feb2016, 01:15 |
| Peak Outflow : | 31.1 (M3/S) | Date/Time of Peak Outflow : | 08Feb2016, 15:45 |
| Total Inflow : | 8817.5 (1000 M3) | Peak Storage : | 6866.5 (1000 M3) |
| Total Outflow : | 5070.0 (1000 M3) | Peak Elevation : | 311.7 (M) |

(b)

Figure 4.22 Effect of constructing retention pond: (a) HEC-HMS output graph and (b) summary table

# CHAPTER 5

# SENSITIVITY ANALYSIS

The models results should be compared with the real data and then the models calibration should be done to adjust the model parameters. The best values of the parameters which give the best agreement between the measured and modeled data will be considered as an input value of the models. However, this process needs detailed data which are available for the hydrologic and hydraulic models, while not available for floodplain model for this study. Sensitivity analysis will be the other choice in this study due to the lack of the detailed calibration data.

In this study, sensitivity analysis is performed to investigate the effects of the following factors:

- Urbanization
- Rainfall storm
- Rainfall duration

Sensitivity analysis is performed by changing one factor while keeping other parameters unchanged and assessing the change in the model output.

## 5.1 Effect of Urbanization

Urbanization (a population shift from rural to urban areas) has a greater effect on surface runoff in watersheds with soils having high infiltration rates (sands and gravels) than in watersheds predominantly composed of silts and clays, which generally have low infiltration rates. A watershed's response to precipitation is changed by urbanization, which significantly increases the runoff and peak discharges due to the decrease in travel time and reduction in infiltration. Another impact of urbanization is a reduction in lag time as water moves faster through the basin.

Hafar Al-Batin city like many cities in Saudi Arabia, faces a rapid rate of urbanization. This rapid change in urbanization affects the occurrence of flooding as a major factor. In this study, the urbanization impact was examined using different urbanization scenarios which represent possible development conditions (the past and future) of the study area to simulate the runoff generated in Hafar Al-Batin and the peak discharge at its outlet.

The future urbanization scenarios were generated using HEC-HMS where fractions of built area (ranging from 0% to 30%) were considered to run HEC-HMS simulations. For each scenario, the hydrographs for the outlet of Hafar Al-Batin were generated with different storm scenarios.

The results indicate that urbanization has a direct effect on outflow hydrograph. As the percentage of urbanization increases, an increase in excess precipitation as well as an increase in surface runoff were observed as shown in Figure 5.1.

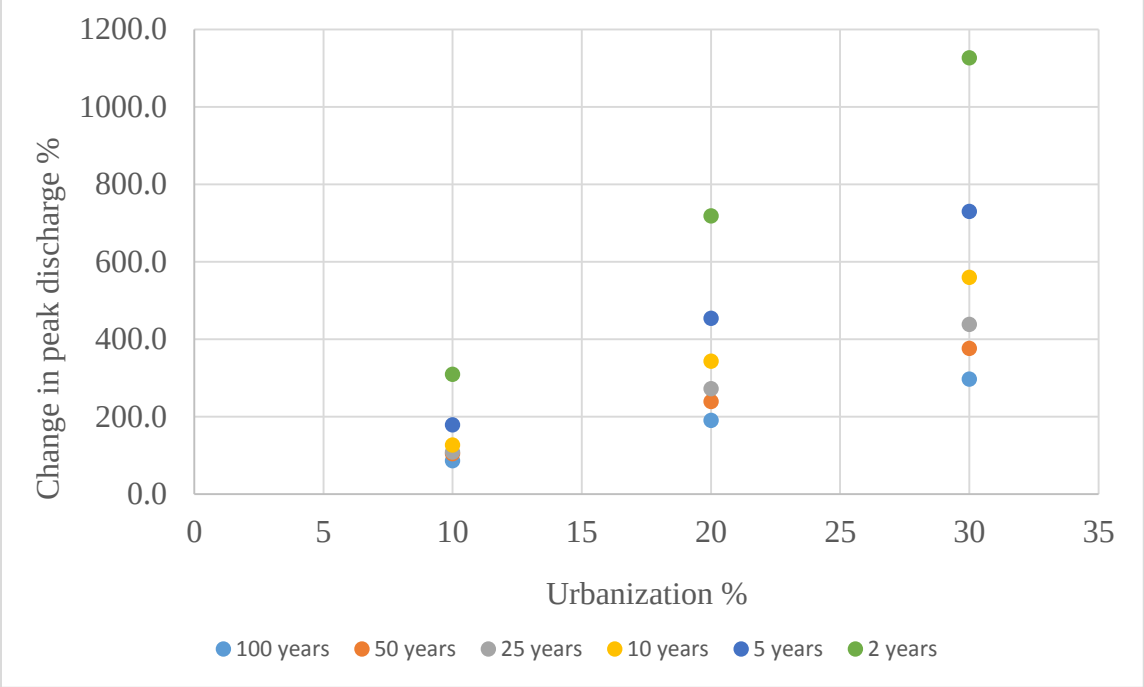



Figure 5.1 Effect of urbanization on the change in peak discharges for different return periods

Currently, the urban area (Hafar Al-Batin) represents approximately 3.6% of the total catchment area with urbanization ratio of 1.8%, which can be used as a reference for the urbanization level. In general, the results indicate that storms of short return period have more effect than larger events on the watershed response to the degree of urbanization as shown in Figure 5.1.

For instance, the peak discharge will be increased by 1126.5%, 729.5%, 559.3%, 437.7%, 375.9%, and 296.7% above the current value when the watershed becomes at 30% urbanization for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year storms, respectively. Similar effects were found with the runoff volume when the watershed becomes at 30% urbanization; the runoff volume increased above its current value by 4236.2%, 2235.6%, 1087.9%, 518.5%, 351.1%, and 259.6% for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year storms, respectively, as shown in Figure 5.2.

In general, urbanization tends to increase the peak discharge and runoff volume and, as a result, the flood inundation area is expected to increase within the catchment. Table 5.1 summarizes the effect of urbanization on the peak flow and runoff volume for different return periods. As shown in Table 5.1, the 100-year storm, at the current level of urbanization, would result in peak discharge and runoff volume lower than what will be caused by a 2-year storm at 30% urbanization. This change is due to the fact that a large fraction of the rainfall is infiltrated for the 2- year event, which makes it more sensitive to the urbanization level. Another impact of urbanization is a reduction in lag time as water moves faster through the basin. For the 100-year event, infiltration represents a much smaller fraction of the rainfall, which makes it less sensitive to the changes in the water losses.

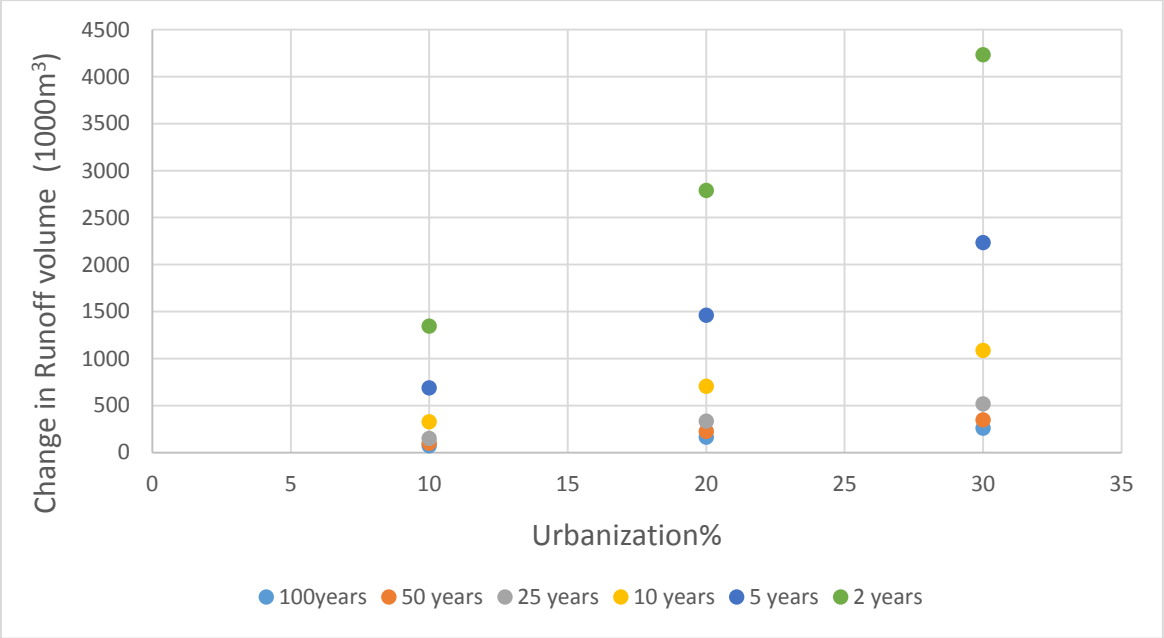



Figure 5.2 Effect of urbanization on the change in runoff volume for different return periods

Table 5.1 Summary of the effect of urbanization on peak flow, runoff volume for different return periods

| | **100YEAR (79.34mm)** | | **50 YEAR (70.997 mm)** | | **25YEAR (62.593 mm)** | | **10YEAR (51.263mm )** | | **5YEAR (42.297 mm)** | | **2YEAR (28.754 mm)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Urbanization (%)** | **Q ($m^3$/S)** | **Runoff volume (1000$m^3$)** | **Q ($m^3$/S)** | **Runoff volume (1000$m^3$)** | **Q ($m^3$/S)** | **Runoff volume (1000$m^3$)** | **Q ($M^3$/S)** | **Runoff volume (1000$m^3$)** | **Q ($m^3$/S)** | **Runoff volume (1000$m^3$)** | **Q ($m^3$/S)** | **Runoff volume (1000$m^3$)** |
| Current case | 191.5 | 13016 | 136.7 | 8877 | 102.3 | 5456 | 65.6 | 2207 | 42.7 | 905 | 19.6 | 330 |
| 10 | 355.6 | 22623 | 278.6 | 17869 | 213.3 | 13758 | 148.7 | 9437 | 118.7 | 7150 | 80.1 | 4769 |
| 20 | 555.6 | 34716 | 462.8 | 28954 | 380.6 | 23753 | 290.4 | 17826 | 236.4 | 14142 | 160.3 | 9533 |
| 30 | 759.7 | 46809 | 650.5 | 40039 | 550.1 | 33748 | 432.5 | 26215 | 354.2 | 21135 | 240.4 | 14296 |

According to the results of the study, it becomes very clear that urbanization (i.e. increase in impervious cover) tends to increase excess precipitation and surface runoff. In addition, the results show that urbanization has a direct impact on lag time. The increase in urbanization level will reduce lag time, causing the surface runoff to move faster over the catchment.

## 5.2 Effect of Rainfall Storm

This part describes a comparison of the calculated peak discharges with two kinds of rainfall data: design rainfall developed from the SCS hypothetical storm method and intensity-duration-frequency relationships. A simulation using HEC-HMS has been done to compare between these two approaches by finding the peak discharge for the study area. The design rainfalls have been used to simulate the peak discharge for a runoff area in Hafar Al-Batin, Saudi Arabia. The two methods used the 24-hour rainfall, which ensures that the distribution includes the maximum of any duration less than 24 hours.

The SCS storm distribution method identified as Type I, Type IA, Type II, and Type III, is used for different hydrologic studies (floodplain management studies, urban damage evaluations, flood insurance studies, flood routings, etc.) with a return period of 1 year up through the 500-year event. Selecting one of the four distributions depends on regions of the country. For example, Type II is appropriate for dried regions type thunderstorm. In Type II, 45 percent of the 24-hour rainfall are assumed to be distributed in the maximum 1 hour [69]. Mass curves are used to indicate what fraction of precipitation has fallen at any time of the total 24 hours (Figure 5.3). The same data for IDF curves were used to develop these mass curves.

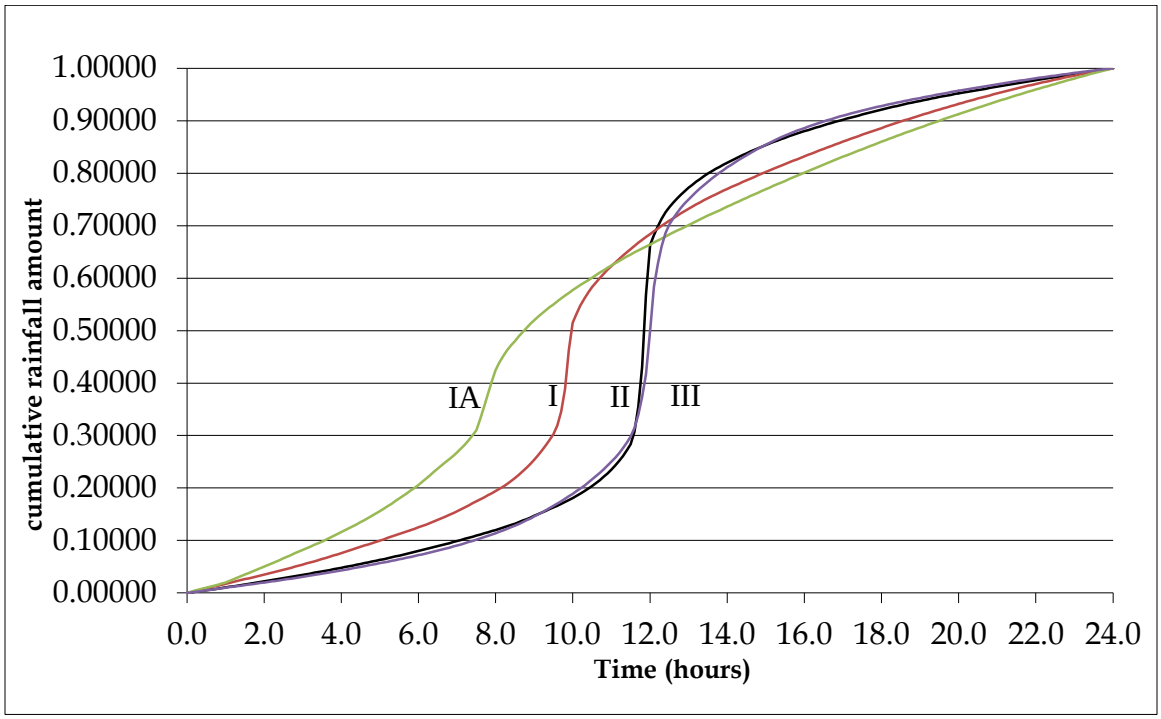



Figure 5.3 SCS rainfall distributions **[70]**

Type II distribution is arranged so that the gratest 30-minute depth occurs at the middle of the 24-hour storm, the second largest in the next 30-minutes, while the third largest depth in the preceding 30 minutes. The entire 24-hour distriburtion is developed by repeating this process up to 24 hours [70]. The SCS hyetograph distribution for Hafar Al-Batin watershed is shown in Figure 4.6. The frequency storm method can be used to create a balanced, synthetic storm with a known exceedance probability. Automatic adjustments for storm area and series type are based on the exceedance probability. Depth-duration data were obtained from Hafar Al-Batin IDF curves developed by Elsbaie [55] as shown in Appendix V. Figure 5.4 shows the maximum peak discharge at the watershed outlet. By comparing Figure 5.4 with Figure 4.8, it can be noticed that the calculated peak discharge based on SCS method is 27.7% higher than the one obtained when using the frequency storm method. By comparing Figure 5.5 with Figure 4.6, it can be found that the reason for this difference is related to the rainfall distribution estimated by each method. Appendix III shows the peak discharge for each sub-basin based on the two methods of rainfall, and according to these results, the SCS hypothetical storm method was used to produce Hafar Al-Batin hazard map, which gives the worst case.

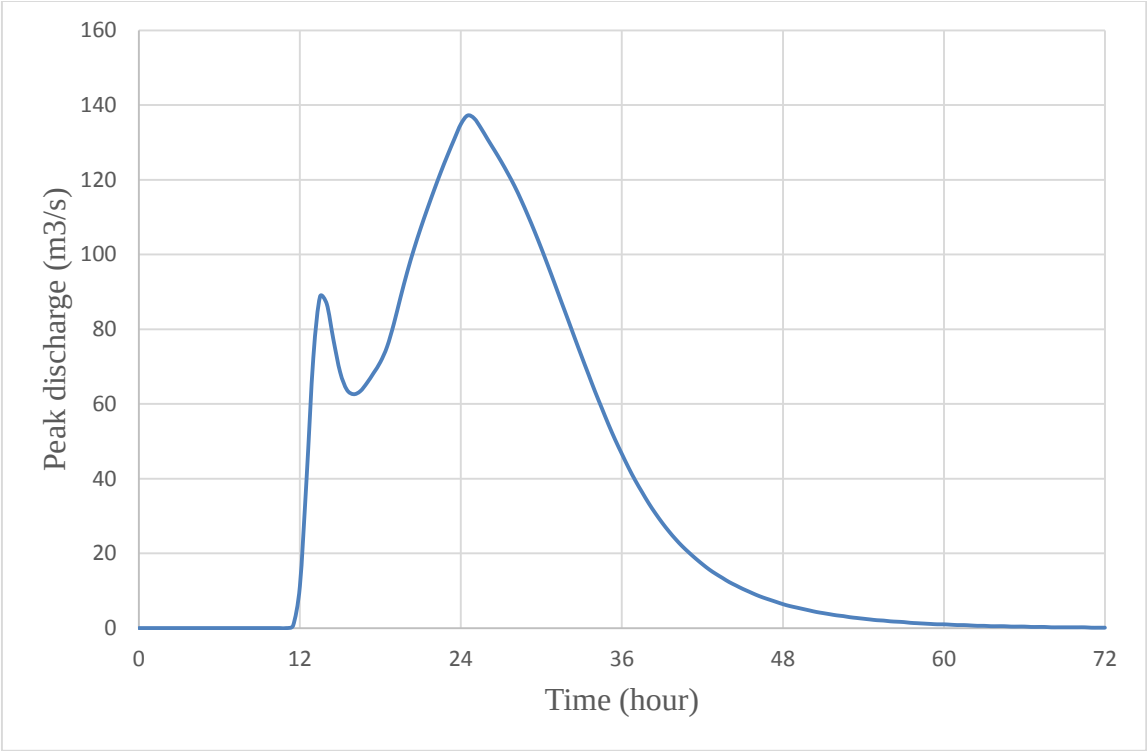



Figure 5.4 The 100-year storm runoff hydrograph of Hafar Al-Batin watershed (frequency storm method)

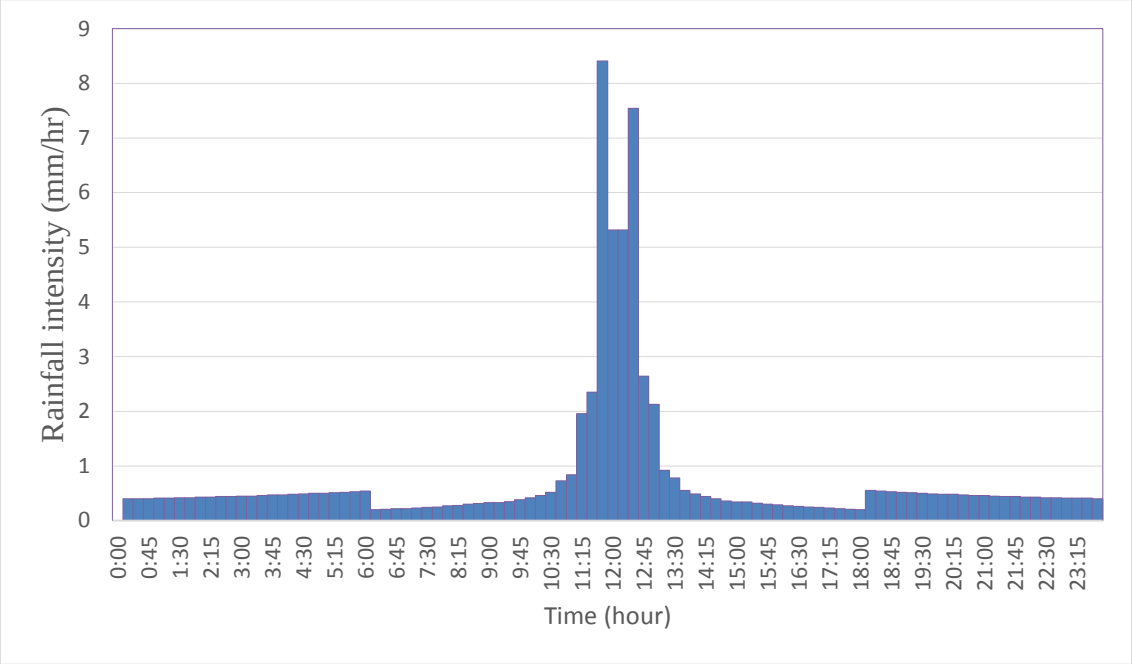



Figure 5.5 Frequency storm distribution hyetograph of the 100-year storm

## 5.3 Effect of Rainfall Duration

The duration of the design storm is usually selected based on the catchment response time, which is a function of the time of concentration. The time of concentration represents the time the flow will take to move from the most remote point of the watershed to the watershed outlet. In general, the design duration of a storm used in water control system design must be equal or exceed the time of concentration of the catchment area. The duration of the design storm is selected equal to the time of concentration for small urban catchment (< 1 $km^2$), which leads to the peak discharge for a given return period. However, the duration which causes the largest detention volume is the design rainfall duration for the design of the detention basins [71]. On the other side, the critical design-storm duration for the catchment with high infiltration losses may be less than the time of concentration [72]. Typically, for large watersheds with a long time of concentration, the storm duration should exceed the time of concentration to achieve the maximum hydrological response [69].

In this study, different rainfall durations (1, 2, 3, 6, 12, and 24 hours) have been used to find the design rainfall duration which causes the peak discharge. Table 5.2 shows the values of the peak discharge and runoff volume for each duration. The 2-hour duration gave a peak discharge higher than 1, 3, 6, and 12 hours but less than 24 hours. The peak discharge for 1 hour, 3 hours, 6 hours, and 12 hours represents 35.2%, 1.4%, 7.9%, and 7.8%, respectively, lower than that for 2-hour duration. However, the peak discharge for 2 hours is lower than that for the 24-hour duration by 158.8%. On the other hand, the change in the runoff volume increases for the storms of high return period as shown in Table 5.2.

Table 5.2 Watershed peak discharge and volume for different design storm durations for a return period of 100 years

| **Time (hour)** | 1 | 2 | 3 | 6 | 12 | 24 |
|---|---|---|---|---|---|---|
| **Peak discharge ($m^3/s$)** | 47.6 | 73.5 | 72.5 | 67.7 | 67.8 | 191.5 |
| **Runoff volume (1000 $m^3$)** | 500 | 1290.6 | 1583.1 | 2205.8 | 3342.2 | 13016.6 |

By close inspection of Figure 5.6, it can be observed that the double peak discharges were obtained for storm durations of 24, 12, and 6 hours, while the second peak is not clear for the remaining durations. The reason for this is that the whole watershed does not contribute to the outlet flow, especially that is far from the watershed outlet. In other words, the time of concentration for some sub-basins is much higher than the storm durations, which means that these basins do not contribute to the outlet flow. On the other side, the second peak for the 24-hour duration is higher than the first peak because the whole catchment contributes to the outlet flow. The runoff from the sub-basins with a high CN value flows faster than that having low values. On the other hand, the differences in the time of peak for each duration are related to the hyetograph distribution for these durations, which are concentrated in the middle half of each duration.

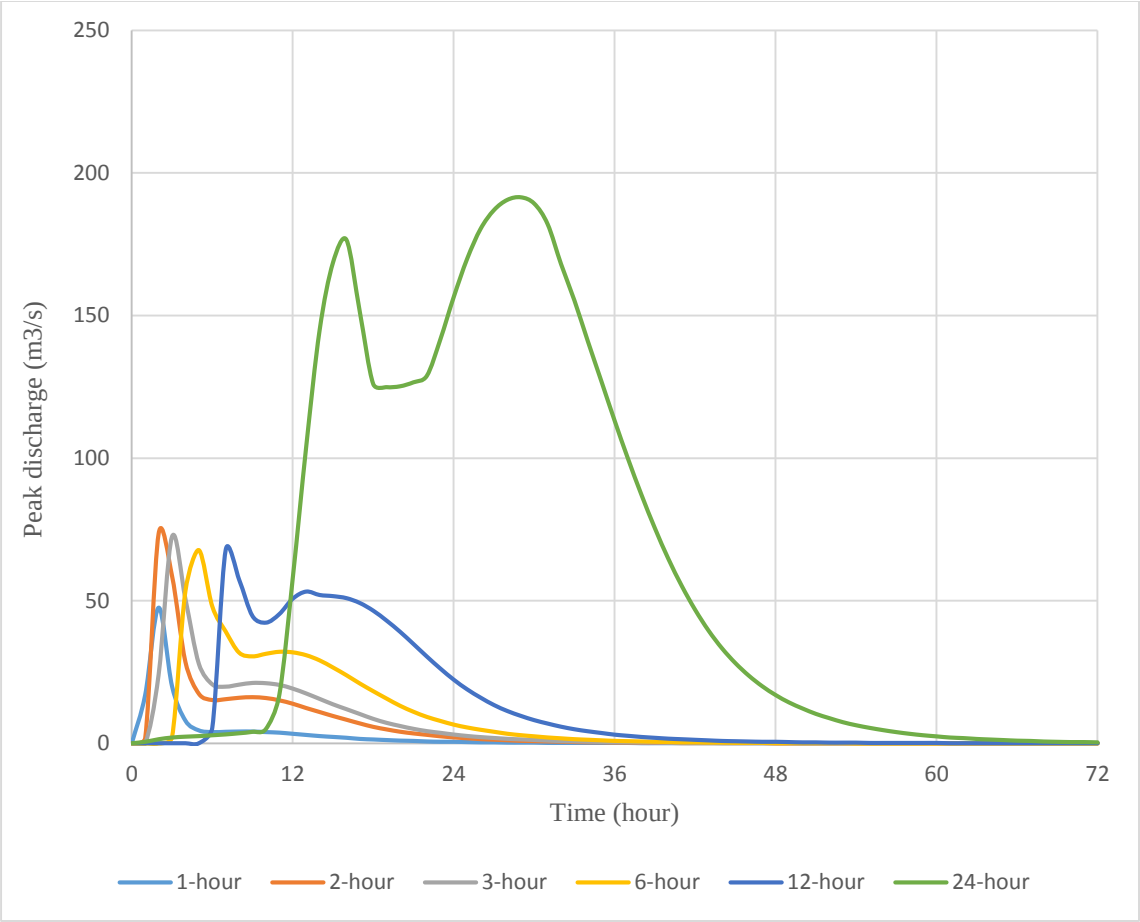



Figure 5.6 Watershed hydrographs for different storm durations for 100-year storm

# CHAPTER 6

# SUMMARY, CONCLUSION AND RECOMMENDATIONS

## 6.1 Summary and Conclusion

In this study, a flood model was constructed for Hafar Al-Batin watershed located in the eastern part of Saudi Arabia. The model integrates a hydrologic model (HEC-HMS), a hydraulic model (HEC-RAS), and a floodplain delineation model (WMS) and (GIS). First, HEC-HMS was applied to Wadi Al-Batin arid watershed to simulate the wadi flow by dividing the catchment area into many sub-basin areas. The peak discharge and the flow volume were estimated for different return periods. Next, the flow depths were calculated by HEC-RAS, then the flood depth maps were delineated using WMS and, finally, the flood risk maps were generated using GIS.

For various magnitudes of rainfall storms and different urbanization scenarios, the effect of urbanization on peak discharge and runoff volume was investigated. The results indicate that the flood depth and flood hazard area can significantly be increased as a result of the urbanization on the peak discharge and runoff volume resulting from a given storm. This is due to the decreased infiltration and obstruction of natural runoff. Therefore, the whole city, including properties, critical facilities, and people, will be significantly exposed to the

risk of flooding. Also, the results indicate that storms of short return period have more effect than larger events on the watershed response to the degree of urbanization. This is due to the high impermeability where most of the rainfall is infiltrated for 2 years. However, for 100 years, the amount of rainfall is much more than that for 2 years, which makes 100 years less sensitive to urbanization. But when the ratio of urbanization increases, the impermeability will decrease and the runoff will increase. Unfortunately, Hafar Al-Batin city is located in the downstream of the watershed, which makes it more affected by any changes within the watershed. In addition, the hydrograph at the outlet has two peaks, which means that the flood will hit the city two times during the same storm in contrast if the city is located in the upstream.

The response of the watershed was also examined for the effect of the storm distribution using two methods, frequency storm and SCS. The results show that the SCS is more appropriate with dried regions type thunderstorm due to its distribution, which assumes the rainfall to be distributed in the maximum 1 hour. In addition, the change of the outlet peak discharge and runoff volume due to the change in storm duration was examined. The result shows that the 24-hour duration is suitable for floodplain simulation. This is due to the big difference in the peak discharge values between 24 hours and the other durations. This big difference is attributed to the size of the catchment area and the big difference in the amount of rainfall.

A good understanding of the watershed response to storm events will lead to a good successful flood hazard management. In addition, floods impact the road networks, creating hazards for drivers, so decision makers must protect drivers by taking the necessary precautions. Reliable hydrologic, hydraulic, and floodplain models will be required in

addition to the effect of the future urbanization for creating successful planning studies. Data management and spatial analysis tool's capabilities in GIS make flood hazard studies easier. The city's vulnerability to flood impact could be reduced by using wisely managed development. The large catchment area, which included Hafar Al-Batin city, was used to perform this study. The outflow from Hafar Al-Batin watershed will be useful for flood analysis at the downstream watershed, while for flood analysis in HafarAl-Batin city, the peak discharge at the entrance of the city should be considered. The expected volume of water that can be collected during the design storm from the whole area of Hafar Al-Batin is 13,016,600 $m^3$ and the peak discharge reached 191.5 $m^3/s$ for 100 years, which caused inundation of the widest parts of Hafar Al-Batin city. For planning purposes, such as flood control structures and the design of drainage, design storms will be helpful. However, high temporal and spatial resolutions of actual storms should be involved in detailed flood risk assessment due to their significant influence on the watershed response.

## 6.2 Recommendations

Based on the findings of this study, the following recommendations are suggested:

- The results of this study can be used to understand and manage the flood in Hafar Al-Batin watershed.
- Flow measuring devices should be installed at the outlet of Hafar Al-Batin to get high-quality data and, thus, to examine the applicability of the developed models. Also, the availability of real storms can help in this evaluation.

- More metrological stations should be installed at different locations of the catchment to record hydrological parameters which can be used in any future studies.
- Filed data related to channel roughness coefficient need to be collected which can help to get better results of the hydraulic model.
- Evaluate the existing flood protection works in the study area to specify the efficiency of these structures.
- Early warning networks should be constructed in the city for the people to take the necessary precaution to avoid the damage resulting from the flood.
- Preventing any new residential structures in the areas with high risk of flood.
- Construct a stormwater drainage system that covers all parts of Hafar Al-Batin city to collect and transport stormwater outside the city.
- Explore the consequences of the occurrences of flood events on the economy of Hafr Al-Batin city
- Investigate input parameters uncertainties on hydrologic and hydraulic models outputs.

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# APPENDICES

# List of Appendices

# APPENDIX I

# The morphology characteristics of the basins of Hafar Al-Batin

| Basin ID | Basin Area ( Km2) | Basin Slope | Basin Length (m) | Perimeter (m) | Mean Elevation (m) |
|---|---|---|---|---|---|
| 178 | 37.82210 | 0.0768265500 | 14343.97611 | 115104.90685 | 436.28877 |
| 178 | 37.82210 | 0.0768265500 | 14343.97611 | 115104.90685 | 436.28877 |
| 181 | 27.46860 | 0.0677157400 | 13546.03625 | 86123.10939 | 461.20587 |
| 178 | 37.82210 | 0.0768265500 | 14343.97611 | 115104.90685 | 436.28877 |
| 181 | 27.46860 | 0.0677157400 | 13546.03625 | 86123.10939 | 461.20587 |
| 175 | 39.61700 | 0.0642785300 | 17079.21260 | 105580.32949 | 437.88644 |
| 180 | 26.64370 | 0.0575125000 | 20038.73592 | 91592.21419 | 458.03467 |
| 183 | 30.15520 | 0.0446432400 | 10462.02253 | 63316.80327 | 469.49844 |
| 174 | 31.82710 | 0.0571187000 | 13822.33184 | 75669.61442 | 423.03052 |
| 182 | 34.42720 | 0.0467252000 | 15414.77355 | 112841.79959 | 465.76300 |
| 179 | 18.95380 | 0.0510745300 | 11092.84766 | 74050.05049 | 447.14035 |
| 182 | 34.42720 | 0.0467252000 | 15414.77355 | 112841.79959 | 465.76300 |
| 168 | 55.77980 | 0.0617610400 | 20319.91457 | 136229.12045 | 415.50612 |
| 177 | 23.32980 | 0.0358592100 | 12220.50063 | 84246.27888 | 437.42235 |
| 171 | 25.66240 | 0.0473858000 | 17183.38665 | 93090.33179 | 419.97146 |
| 182 | 34.42720 | 0.0467252000 | 15414.77355 | 112841.79959 | 465.76300 |
| 173 | 33.84570 | 0.0395554700 | 26318.56781 | 125304.07105 | 434.90258 |
| 176 | 39.26190 | 0.0464234700 | 18796.98013 | 116775.48708 | 443.79752 |
| 167 | 35.18400 | 0.0389558900 | 22551.81727 | 111609.45735 | 419.28584 |
| 169 | 25.51970 | 0.0629347700 | 14414.42332 | 90061.48623 | 416.81097 |
| 170 | 40.12620 | 0.0627513800 | 16736.79445 | 106768.84369 | 414.08436 |
| 164 | 77.80970 | 0.0494605500 | 19359.90820 | 135066.90156 | 402.76702 |
| 172 | 24.30780 | 0.0335114800 | 11254.75650 | 76305.88636 | 419.39670 |
| 166 | 25.86280 | 0.0632528200 | 10829.63563 | 72442.82314 | 406.98810 |
| 162 | 21.16430 | 0.0738980400 | 11942.45789 | 76795.87762 | 401.09520 |
| 165 | 30.47920 | 0.0692627800 | 13066.56549 | 91045.51631 | 404.39760 |
| 165 | 30.47920 | 0.0692627800 | 13066.56549 | 91045.51631 | 404.39760 |
| 161 | 49.00230 | 0.0500585900 | 23618.67595 | 134123.45148 | 408.53017 |
| 163 | 21.36920 | 0.0718959100 | 10662.63400 | 84038.33107 | 398.46497 |
| 160 | 63.71790 | 0.0563518000 | 15759.08963 | 112256.71614 | 395.68214 |
| 157 | 49.36780 | 0.0750052500 | 17194.57225 | 114505.17152 | 390.83486 |
| 154 | 62.68030 | 0.0596608100 | 15405.44024 | 104159.60424 | 376.27449 |
| 150 | 14.00980 | 0.0830435000 | 10345.85846 | 60808.55564 | 382.89702 |
| 147 | 49.04820 | 0.0588382000 | 16003.48172 | 113948.91789 | 371.19054 |
| 151 | 17.31460 | 0.0712572400 | 8602.48043 | 56200.36021 | 384.13920 |
| 161 | 49.00230 | 0.0500585900 | 23618.67595 | 134123.45148 | 408.53017 |
| 9 | 8.37520 | 0.0812954400 | 6888.99066 | 39719.18612 | 382.51194 |

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|---|---|---|---|---|---|
| 158 | 8.61510 | 0.0829610600 | 6541.41045 | 42903.02025 | 390.39438 |
| 156 | 8.03410 | 0.0741098700 | 5315.21309 | 39502.69352 | 385.30065 |
| 0 | 0.00000 | 0.0000000000 | 0.00000 | 0.00000 | 0.00000 |
| 4 | 14.14830 | 0.0793526200 | 9472.84071 | 53934.37684 | 377.73683 |
| 142 | 43.19660 | 0.0673732100 | 13749.16488 | 119013.29809 | 370.18953 |
| 10 | 5.97870 | 0.0732697800 | 6270.44426 | 37542.14961 | 379.23655 |
| 159 | 33.04380 | 0.0671369000 | 16153.50825 | 114136.00584 | 397.38351 |
| 16 | 11.93340 | 0.0804375700 | 6186.38953 | 47054.72751 | 381.03372 |
| 153 | 9.11050 | 0.0769722000 | 8472.52356 | 46687.84178 | 384.39017 |
| 144 | 5.15850 | 0.0813162200 | 6070.56571 | 36156.21489 | 380.70070 |
| 160 | 63.71790 | 0.0563518000 | 15759.08963 | 112256.71614 | 395.68214 |
| 7 | 11.76290 | 0.0706533700 | 10630.30205 | 59106.95847 | 375.34451 |
| 145 | 7.10770 | 0.0850198100 | 5958.19278 | 35020.27228 | 382.32200 |
| 1 | 16.16980 | 0.0773739600 | 7533.54216 | 60285.96713 | 367.96559 |
| 153 | 9.11050 | 0.0769722000 | 8472.52356 | 46687.84178 | 384.39017 |
| 11 | 2.42550 | 0.0660209400 | 4341.23784 | 21754.63233 | 376.95826 |
| 152 | 7.02150 | 0.0779984900 | 6027.28359 | 35491.79641 | 385.19504 |
| 15 | 3.39990 | 0.0714280300 | 3751.59232 | 24382.75912 | 376.94462 |
| 155 | 8.79480 | 0.0855218100 | 7818.31830 | 41248.77264 | 388.78815 |
| 6 | 10.86530 | 0.0615943500 | 7672.74068 | 43106.33286 | 368.52218 |
| 141 | 8.49700 | 0.0702213800 | 6830.50285 | 43600.82368 | 378.88580 |
| 14 | 8.60580 | 0.0615238000 | 5799.17596 | 41734.65309 | 373.86596 |
| 17 | 3.61870 | 0.0792819700 | 5563.67344 | 23589.44391 | 377.18866 |
| 145 | 7.10770 | 0.0850198100 | 5958.19278 | 35020.27228 | 382.32200 |
| 152 | 7.02150 | 0.0779984900 | 6027.28359 | 35491.79641 | 385.19504 |
| 99 | 59.89970 | 0.0668015600 | 15780.54443 | 130767.04635 | 357.75100 |
| 3 | 7.57030 | 0.0720939000 | 5886.35823 | 44155.42276 | 369.70332 |
| 140 | 6.63740 | 0.0760668600 | 5613.49701 | 32808.74974 | 383.58129 |
| 129 | 9.14970 | 0.0736765400 | 6267.28952 | 34933.71443 | 375.98344 |
| 8 | 15.92220 | 0.0657772500 | 7909.31390 | 69818.14002 | 367.45428 |
| 127 | 5.09350 | 0.0723676500 | 6005.55220 | 28597.97869 | 373.54705 |
| 149 | 28.19900 | 0.0615936000 | 12994.85536 | 86062.40875 | 388.41006 |
| 5 | 7.15870 | 0.0761792700 | 6297.69970 | 36020.71247 | 372.95041 |
| 2 | 9.37680 | 0.0830394300 | 6641.09996 | 40725.44921 | 375.72968 |
| 136 | 4.66720 | 0.0681978000 | 4972.13488 | 33709.07464 | 379.28775 |
| 7 | 11.76290 | 0.0706533700 | 10630.30205 | 59106.95847 | 375.34451 |
| 13 | 6.73190 | 0.0784453700 | 8107.17368 | 42838.13916 | 372.39582 |
| 102 | 3.73580 | 0.0701731500 | 5914.83851 | 26729.30924 | 374.64764 |
| 109 | 5.50990 | 0.0631570700 | 8397.67568 | 35409.72844 | 370.33398 |

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| 93 | 3.04090 | 0.0586716300 | 5958.21294 | 27097.13943 | 374.44867 |
| 123 | 3.82180 | 0.0672529000 | 5321.31989 | 20882.17251 | 367.56217 |
| 116 | 2.66200 | 0.0784349900 | 3216.81976 | 20333.30340 | 373.95970 |
| 12 | 14.81990 | 0.0765600800 | 8502.29550 | 48200.00178 | 369.79608 |
| 108 | 2.22040 | 0.0655815500 | 5311.40001 | 20029.45059 | 359.67857 |
| 48 | 7.73550 | 0.0743500800 | 6645.98792 | 30564.12175 | 364.92567 |
| 80 | 3.68400 | 0.0700098100 | 4866.72224 | 31131.79886 | 369.08754 |
| 74 | 1.45450 | 0.0523152300 | 4279.94247 | 15634.76405 | 362.63961 |
| 47 | 2.67910 | 0.0839018400 | 5569.37760 | 22408.70550 | 355.18011 |
| 131 | 36.06010 | 0.0705079200 | 13808.49656 | 99131.04559 | 380.73449 |
| 110 | 1.92100 | 0.0628579900 | 3226.90497 | 16985.55498 | 346.28675 |
| 58 | 1.93060 | 0.0528252200 | 5225.28105 | 19581.76643 | 348.90552 |
| 66 | 0.98810 | 0.0515998000 | 4133.86854 | 16351.60111 | 343.95594 |
| 42 | 2.64770 | 0.0578990700 | 4561.00980 | 18875.10041 | 354.30573 |
| 65 | 1.37220 | 0.0510724900 | 4832.77725 | 21926.77218 | 341.12715 |
| 85 | 0.86350 | 0.0600113200 | 4589.39210 | 16007.21946 | 334.80568 |
| 71 | 0.81970 | 0.0521038300 | 2347.41477 | 10344.96072 | 351.84608 |
| 39 | 1.67000 | 0.0861260300 | 4678.39476 | 19835.51673 | 338.02103 |
| 35 | 1.17510 | 0.0538551000 | 4184.09233 | 14149.32957 | 341.03222 |
| 97 | 0.57780 | 0.0607699200 | 1962.14101 | 9605.83653 | 337.89097 |
| 98 | 0.55630 | 0.0537824100 | 2184.50824 | 9978.94544 | 334.32194 |
| 73 | 1.61120 | 0.0561602100 | 4289.30572 | 18730.77453 | 323.23997 |
| 104 | 0.23700 | 0.0574174900 | 937.43595 | 4907.49469 | 339.04255 |
| 28 | 3.04840 | 0.0651843500 | 5547.46088 | 24294.62429 | 331.09302 |
| 40 | 4.08390 | 0.0785064100 | 6225.92366 | 26638.72039 | 353.99446 |
| 61 | 0.53300 | 0.0548748900 | 1992.46893 | 7052.97154 | 338.42913 |
| 94 | 0.22220 | 0.0620706800 | 1176.37334 | 4729.30113 | 332.31829 |
| 31 | 1.93390 | 0.0569783200 | 3668.60550 | 19842.82374 | 330.89976 |
| 55 | 0.85550 | 0.0578700100 | 2283.61219 | 11110.61875 | 328.96189 |
| 84 | 0.57700 | 0.0519718700 | 1770.60794 | 7945.86112 | 325.45817 |
| 43 | 1.16190 | 0.0561404900 | 3007.94260 | 11634.78476 | 326.15413 |
| 83 | 0.31390 | 0.0474212200 | 1484.61885 | 6171.18810 | 322.97019 |
| 91 | 0.27430 | 0.0671237700 | 1575.28783 | 6444.27260 | 319.83674 |
| 50 | 0.57860 | 0.0552364100 | 2315.32799 | 8077.20977 | 323.96210 |
| 56 | 0.56280 | 0.0576095600 | 2173.95443 | 10012.46758 | 317.77611 |
| 86 | 1.36830 | 0.0633787500 | 4452.61353 | 16115.31276 | 341.22722 |
| 59 | 0.12980 | 0.0662678500 | 1129.91784 | 4203.25363 | 321.62131 |
| 51 | 1.09430 | 0.0517979500 | 2268.20694 | 13801.10467 | 316.26055 |
| 69 | 2.16160 | 0.0498087600 | 3129.45967 | 26284.69656 | 326.04382 |

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| 23 | 2.46330 | 0.0645037300 | 5901.09316 | 22510.53189 | 349.01078 |
| 63 | 1.20020 | 0.0620956500 | 2824.55116 | 14974.66643 | 323.09725 |
| 41 | 1.12120 | 0.0411272600 | 1900.20236 | 14184.51000 | 314.03281 |
| 39 | 1.67000 | 0.0861260300 | 4678.39476 | 19835.51673 | 338.02103 |
| 49 | 0.23670 | 0.0507955800 | 1158.25150 | 5319.79440 | 318.00511 |
| 89 | 1.75700 | 0.0668239700 | 3454.45986 | 13596.60171 | 340.67848 |
| 32 | 1.25200 | 0.0443912900 | 1771.44012 | 12933.12406 | 313.08332 |
| 46 | 0.96010 | 0.0459605200 | 2437.03345 | 14854.14018 | 313.39123 |
| 33 | 0.25360 | 0.0588566400 | 1081.88166 | 4807.74261 | 317.86976 |
| 26 | 0.39500 | 0.0501556300 | 2496.09819 | 8710.32274 | 312.58207 |
| 19 | 2.00210 | 0.0709455600 | 3918.43450 | 19662.92141 | 319.51371 |
| 21 | 1.61330 | 0.0471115200 | 3677.56448 | 25250.94765 | 310.81725 |
| 21 | 1.61330 | 0.0471115200 | 3677.56448 | 25250.94765 | 310.81725 |
| 25 | 0.88760 | 0.0464860400 | 2618.97003 | 11218.96706 | 311.33460 |
| 117 | 1.09580 | 0.0602977000 | 2221.75929 | 10168.38122 | 367.17275 |
| 57 | 1.45870 | 0.0646908300 | 3227.57584 | 14376.00415 | 326.41655 |
| 72 | 0.04580 | 0.1245788700 | 636.55367 | 2263.57796 | 318.93846 |
| 76 | 0.58710 | 0.0595550400 | 2419.17916 | 10156.32136 | 336.25929 |
| 67 | 0.16080 | 0.0625259700 | 1546.69911 | 4826.94810 | 327.83851 |
| 44 | 2.60420 | 0.0478501600 | 3254.27967 | 17269.30487 | 317.67752 |
| 87 | 1.07980 | 0.0654831900 | 2825.22403 | 11531.23554 | 348.19461 |
| 27 | 0.48670 | 0.0574635700 | 2206.70594 | 9890.49561 | 310.66946 |
| 130 | 1.47090 | 0.0693821600 | 2959.17639 | 13403.19979 | 373.05942 |
| 111 | 0.34210 | 0.0576765300 | 1253.14315 | 6018.65893 | 360.44691 |
| 18 | 2.58660 | 0.0709723100 | 4015.57057 | 22204.20372 | 318.99661 |
| 75 | 0.51620 | 0.0685025300 | 1664.24934 | 7187.55331 | 334.67016 |
| 101 | 1.34600 | 0.0605549000 | 2888.32277 | 13427.42409 | 360.28275 |
| 36 | 0.00280 | 0.0314111100 | 108.19180 | 443.87905 | 310.69565 |
| 37 | 0.37500 | 0.0533695000 | 1597.37958 | 6624.64028 | 312.98172 |
| 122 | 0.96970 | 0.0683505800 | 2546.51077 | 10751.27402 | 368.66091 |
| 24 | 1.49600 | 0.0597965800 | 2770.07360 | 13571.61398 | 320.52777 |
| 79 | 1.16210 | 0.0528541900 | 2201.72182 | 10577.74334 | 340.84041 |
| 146 | 2.27010 | 0.0792961100 | 3454.50255 | 22541.33551 | 378.37601 |
| 103 | 0.79230 | 0.0597526300 | 1392.03441 | 8811.97596 | 345.13839 |
| 64 | 2.57340 | 0.0605717900 | 3243.03083 | 27061.59680 | 345.44177 |
| 20 | 0.68060 | 0.0450877100 | 2704.82101 | 11237.94656 | 307.10774 |
| 132 | 4.96760 | 0.0816367100 | 5623.60562 | 36427.54806 | 367.36361 |
| 113 | 1.51310 | 0.0655576400 | 4052.78435 | 18207.25731 | 357.20852 |

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| 126 | 2.35040 | 0.0727009700 | 3188.28423 | 24192.27817 | 362.15191 |
| 143 | 1.95910 | 0.0765223000 | 3702.98142 | 17959.71457 | 376.42236 |
| 45 | 1.89090 | 0.0602870900 | 3747.99894 | 17361.51512 | 331.20963 |
| 53 | 2.12090 | 0.0571846700 | 3266.27068 | 18636.47757 | 335.29071 |
| 148 | 4.80490 | 0.0841802900 | 4667.48448 | 25898.52145 | 380.23289 |
| 22 | 1.68270 | 0.0774928800 | 2914.44598 | 16755.58864 | 322.34269 |
| 54 | 1.20360 | 0.0555306100 | 4035.67111 | 16366.35483 | 345.28683 |
| 60 | 0.21860 | 0.0513710900 | 1187.09018 | 6080.51698 | 330.47248 |
| 82 | 1.85570 | 0.0665512600 | 2741.13630 | 19151.69959 | 348.48842 |
| 70 | 0.90880 | 0.0716101700 | 2230.46074 | 10505.84343 | 341.29866 |
| 120 | 1.27480 | 0.0785410800 | 3477.09428 | 15699.28911 | 359.76381 |
| 112 | 2.25590 | 0.0745319800 | 3223.40203 | 17202.12383 | 357.32404 |
| 92 | 1.08340 | 0.0688533600 | 2823.97685 | 15314.74868 | 352.61159 |
| 138 | 1.87830 | 0.0774858000 | 3642.77969 | 18021.79749 | 371.93963 |
| 30 | 1.33280 | 0.0637630200 | 3036.83130 | 19544.92301 | 335.68703 |
| 139 | 2.66330 | 0.0852448900 | 4402.95688 | 23857.87398 | 375.12977 |
| 18 | 2.58660 | 0.0709723100 | 4015.57057 | 22204.20372 | 318.99661 |
| 34 | 2.64570 | 0.0599977500 | 3112.04605 | 15901.78803 | 346.93194 |
| 62 | 0.56690 | 0.0576377300 | 2147.07509 | 8486.65020 | 349.88042 |
| 81 | 1.62550 | 0.0594750500 | 3290.49951 | 13918.25207 | 351.50196 |
| 29 | 1.86560 | 0.0643250000 | 4267.38802 | 18911.33279 | 341.81523 |
| 95 | 0.87180 | 0.0623710800 | 2322.20263 | 10900.69158 | 355.71429 |
| 137 | 3.71710 | 0.0857263900 | 4012.55012 | 26537.96742 | 369.37248 |
| 68 | 1.50660 | 0.0536786200 | 4112.71661 | 17261.88201 | 360.06994 |
| 95 | 0.87180 | 0.0623710800 | 2322.20263 | 10900.69158 | 355.71429 |
| 106 | 0.29730 | 0.0580375500 | 1176.76167 | 7024.55725 | 359.39154 |
| 133 | 1.72750 | 0.0774878400 | 2401.34656 | 16293.02014 | 365.61552 |
| 115 | 0.72420 | 0.0697401200 | 3079.22846 | 11953.87247 | 362.75564 |
| 88 | 0.79050 | 0.0465029800 | 2240.72215 | 9425.91707 | 359.62784 |
| 38 | 2.48330 | 0.0726210900 | 4121.83408 | 20036.52440 | 357.43130 |
| 96 | 1.14890 | 0.0436738300 | 2876.31442 | 13287.52483 | 360.59173 |
| 78 | 0.39240 | 0.0524758800 | 1638.02661 | 7315.83047 | 360.00917 |
| 114 | 1.76460 | 0.0647501900 | 4099.54772 | 17879.45673 | 362.91897 |
| 128 | 0.31420 | 0.0876933900 | 1356.96564 | 6134.98625 | 363.17496 |
| 100 | 0.70860 | 0.0765893200 | 1972.45227 | 8616.18197 | 361.67167 |
| 119 | 1.25100 | 0.0708316900 | 2616.72285 | 12372.61297 | 363.44301 |
| 124 | 1.30410 | 0.0736494600 | 3782.74179 | 14320.10043 | 365.29810 |
| 90 | 1.90340 | 0.0703939600 | 3335.39602 | 14953.99062 | 361.94606 |
| 107 | 1.24220 | 0.0775915800 | 2942.42991 | 14224.85906 | 363.71836 |

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| 105 | 1.23590 | 0.0654081400 | 3304.11843 | 13737.62720 | 363.69349 |
| 118 | 1.07380 | 0.0673085100 | 2213.13784 | 12404.15411 | 365.06095 |
| 52 | 1.74490 | 0.0968907000 | 2618.97003 | 13486.29408 | 362.68838 |
| 121 | 0.29780 | 0.0746881200 | 1592.62260 | 6311.33980 | 365.16868 |
| 125 | 3.04090 | 0.0814972100 | 3192.69972 | 23664.15440 | 366.13571 |
| 134 | 3.66560 | 0.0844584500 | 4346.23009 | 22259.49413 | 364.14746 |
| 135 | 3.83500 | 0.0954325100 | 4713.96512 | 25985.70647 | 366.53429 |

# APPENDIX II

# The curve numbers for each sub-basin and SCS Lag Time

| **sub-Basin name** | **Area km2** | **SCS Curve number** | SCS Lag Time (hours) |
|---|---|---|---|
| 100B | 0.71 | 75.00 | 0.75 |
| 101B | 1.35 | 75.00 | 1.03 |
| 102B | 3.74 | 55.00 | 3.04 |
| 103B | 0.79 | 75.00 | 0.67 |
| 104B | 0.24 | 55.00 | 0.72 |
| 105B | 1.24 | 65.00 | 1.65 |
| 106B | 0.30 | 53.00 | 1.21 |
| 107B | 1.24 | 65.00 | 1.41 |
| 108B | 2.22 | 55.00 | 2.93 |
| 109B | 5.51 | 55.00 | 4.81 |
| 10B | 5.98 | 55.00 | 3.27 |
| 110B | 1.92 | 55.00 | 2.25 |
| 111B | 0.34 | 75.00 | 0.68 |
| 112B | 2.26 | 68.33 | 1.39 |
| 113B | 1.51 | 75.00 | 1.41 |
| 114B | 1.76 | 75.00 | 1.52 |
| 115B | 0.72 | 75.00 | 1.17 |
| 116B | 2.66 | 55.00 | 2.39 |
| 117B | 1.10 | 75.00 | 1.11 |
| 118B | 1.07 | 61.67 | 1.37 |
| 119B | 1.25 | 75.00 | 1.12 |
| 11B | 2.43 | 55.00 | 2.59 |
| 120B | 1.27 | 55.00 | 2.07 |
| 121B | 0.30 | 75.00 | 0.59 |
| 122B | 0.97 | 68.33 | 1.12 |
| 123B | 3.82 | 55.00 | 3.40 |
| 124B | 1.30 | 68.33 | 1.46 |
| 125B | 3.04 | 55.00 | 2.45 |
| 126B | 2.35 | 55.00 | 1.84 |
| 127B | 5.09 | 55.00 | 3.34 |
| 128B | 0.31 | 75.00 | 0.54 |
| 129B | 9.15 | 55.00 | 3.58 |
| 12B | 14.82 | 55.00 | 4.32 |
| 130B | 1.47 | 61.67 | 1.58 |
| 131B | 36.06 | 60.18 | 6.73 |
| 132B | 4.97 | 55.00 | 3.27 |
| 133B | 1.73 | 75.00 | 1.20 |
| 134B | 3.67 | 55.00 | 2.33 |
| 135B | 3.84 | 55.00 | 2.52 |
| 136B | 4.67 | 55.00 | 3.15 |
| 137B | 3.72 | 55.00 | 2.34 |

| | | | |
|---|---|---|---|
| 138B | 1.88 | 55.00 | 2.18 |
| 139B | 2.66 | 55.00 | 2.77 |
| 13B | 6.73 | 55.00 | 3.90 |
| 140B | 6.64 | 55.00 | 3.91 |
| 141B | 8.50 | 55.00 | 3.62 |
| 142B | 43.20 | 55.00 | 7.00 |
| 143B | 1.96 | 55.00 | 2.10 |
| 144B | 5.16 | 55.00 | 3.05 |
| 145B | 7.11 | 55.00 | 3.81 |
| 146B | 2.27 | 55.00 | 2.48 |
| 147B | 49.05 | 55.00 | 8.59 |
| 148B | 4.80 | 55.00 | 2.91 |
| 149B | 28.20 | 55.00 | 7.53 |
| 14B | 8.61 | 56.00 | 3.72 |
| 150B | 14.01 | 55.00 | 4.39 |
| 151B | 17.31 | 55.00 | 5.51 |
| 152B | 7.02 | 55.00 | 3.65 |
| 153B | 9.11 | 55.00 | 4.95 |
| 154B | 62.68 | 55.41 | 9.33 |
| 155B | 8.79 | 55.00 | 3.72 |
| 156B | 8.03 | 55.00 | 4.46 |
| 157B | 49.37 | 55.00 | 9.09 |
| 158B | 8.62 | 55.00 | 4.04 |
| 159B | 33.04 | 55.00 | 8.42 |
| 15B | 3.40 | 55.00 | 2.15 |
| 160B | 63.72 | 56.17 | 9.83 |
| 161B | 49.00 | 66.24 | 9.84 |
| 162B | 21.16 | 55.00 | 6.88 |
| 163B | 21.37 | 55.00 | 7.17 |
| 164B | 77.81 | 58.17 | 10.22 |
| 165B | 30.48 | 55.00 | 6.90 |
| 166B | 25.86 | 55.00 | 7.37 |
| 167B | 35.18 | 56.79 | 15.52 |
| 168B | 55.78 | 55.00 | 9.65 |
| 169B | 25.52 | 55.00 | 9.07 |
| 16B | 11.93 | 55.00 | 3.74 |
| 170B | 40.13 | 55.00 | 8.58 |
| 171B | 25.66 | 55.00 | 10.15 |
| 172B | 24.31 | 69.73 | 6.98 |
| 173B | 33.85 | 61.25 | 11.57 |
| 174B | 31.83 | 55.00 | 7.88 |
| 175B | 39.62 | 55.00 | 8.57 |
| 176B | 39.26 | 55.53 | 12.35 |

| | | | |
|---|---|---|---|
| 177B | 23.33 | 56.82 | 9.92 |
| 178B | 37.82 | 55.00 | 7.02 |
| 179B | 18.95 | 55.00 | 7.35 |
| 17B | 3.62 | 55.00 | 2.94 |
| 180B | 26.64 | 55.00 | 9.50 |
| 181B | 27.47 | 55.00 | 7.84 |
| 182B | 34.43 | 55.00 | 10.29 |
| 183B | 30.16 | 55.00 | 8.90 |
| 18B | 2.59 | 55.00 | 3.24 |
| 19B | 2.00 | 55.00 | 2.62 |
| 1B | 16.17 | 55.00 | 3.72 |
| 20B | 0.68 | 55.00 | 2.06 |
| 21B | 1.61 | 65.00 | 1.94 |
| 22B | 1.68 | 55.00 | 1.76 |
| 23B | 2.46 | 55.00 | 3.58 |
| 24B | 1.50 | 75.00 | 1.30 |
| 25B | 0.89 | 75.00 | 1.28 |
| 26B | 0.40 | 55.00 | 1.78 |
| 27B | 0.49 | 55.00 | 1.47 |
| 28B | 3.05 | 55.00 | 3.84 |
| 29B | 1.87 | 55.00 | 2.82 |
| 2B | 9.38 | 55.00 | 3.86 |
| 30B | 1.33 | 65.00 | 1.57 |
| 31B | 1.93 | 60.00 | 2.01 |
| 32B | 1.25 | 75.00 | 1.40 |
| 33B | 0.25 | 75.00 | 0.50 |
| 34B | 2.65 | 70.00 | 1.56 |
| 35B | 1.18 | 68.33 | 1.81 |
| 36B | 0.00 | 57.00 | 0.15 |
| 37B | 0.38 | 75.00 | 0.69 |
| 38B | 2.48 | 59.00 | 2.29 |
| 39B | 1.67 | 55.00 | 2.13 |
| 3B | 7.57 | 55.00 | 3.66 |
| 40B | 4.08 | 55.00 | 3.55 |
| 41B | 1.12 | 57.00 | 1.89 |
| 42B | 2.65 | 55.00 | 2.78 |
| 43B | 1.16 | 75.00 | 1.17 |
| 44B | 2.60 | 75.00 | 1.38 |
| 45B | 1.89 | 75.00 | 1.48 |
| 46B | 0.96 | 75.00 | 1.43 |
| 47B | 2.68 | 55.00 | 3.02 |
| 48B | 7.74 | 55.00 | 4.65 |
| 49B | 0.24 | 75.00 | 0.58 |

| | | | |
|---|---|---|---|
| 4B | 14.15 | 55.00 | 4.88 |
| 50B | 0.58 | 75.00 | 0.94 |
| 51B | 1.09 | 75.00 | 1.05 |
| 52B | 1.74 | 55.00 | 1.41 |
| 53B | 2.12 | 75.00 | 1.41 |
| 54B | 1.20 | 75.00 | 1.44 |
| 55B | 0.86 | 75.00 | 0.95 |
| 56B | 0.56 | 75.00 | 0.96 |
| 57B | 1.46 | 75.00 | 1.04 |
| 58B | 1.93 | 55.00 | 3.55 |
| 59B | 0.13 | 57.00 | 0.76 |
| 5B | 7.16 | 55.00 | 3.61 |
| 60B | 0.22 | 75.00 | 0.73 |
| 61B | 0.53 | 75.00 | 0.91 |
| 62B | 0.57 | 75.00 | 0.91 |
| 63B | 1.20 | 75.00 | 1.15 |
| 64B | 2.57 | 75.00 | 1.76 |
| 65B | 1.37 | 68.33 | 2.15 |
| 66B | 0.99 | 55.00 | 2.52 |
| 67B | 0.16 | 50.00 | 1.14 |
| 68B | 1.51 | 75.00 | 1.66 |
| 69B | 2.16 | 75.00 | 1.18 |
| 6B | 10.87 | 55.00 | 4.77 |
| 70B | 0.91 | 75.00 | 0.96 |
| 71B | 0.82 | 55.00 | 1.81 |
| 72B | 0.05 | 57.00 | 0.34 |
| 73B | 1.61 | 55.00 | 2.67 |
| 74B | 1.45 | 55.00 | 2.78 |
| 75B | 0.52 | 75.00 | 0.67 |
| 76B | 0.59 | 75.00 | 1.13 |
| 77B | 0.34 | 55.00 | 1.34 |
| 78B | 0.39 | 75.00 | 0.67 |
| 79B | 1.16 | 75.00 | 1.24 |
| 7B | 11.76 | 55.00 | 5.41 |
| 80B | 3.68 | 55.00 | 2.89 |
| 81B | 1.63 | 75.00 | 1.22 |
| 82B | 1.86 | 75.00 | 1.17 |
| 83B | 0.31 | 55.00 | 1.23 |
| 84B | 0.58 | 55.00 | 1.34 |
| 85B | 0.86 | 55.00 | 2.38 |
| 86B | 1.37 | 55.00 | 2.57 |
| 87B | 1.08 | 75.00 | 1.19 |
| 88B | 0.79 | 75.00 | 0.99 |

| | | | |
|---|---|---|---|
| 89B | 1.76 | 75.00 | 1.35 |
| 8B | 15.92 | 55.00 | 4.48 |
| 90B | 1.90 | 68.33 | 1.46 |
| 91B | 0.27 | 55.00 | 1.01 |
| 92B | 1.08 | 75.00 | 1.12 |
| 93B | 3.04 | 55.00 | 4.22 |
| 94B | 0.22 | 75.00 | 0.55 |
| 95B | 0.87 | 75.00 | 1.10 |
| 96B | 1.15 | 75.00 | 1.38 |
| 97B | 0.58 | 55.00 | 1.45 |
| 98B | 0.56 | 55.00 | 1.55 |
| 99B | 59.90 | 56.13 | 7.90 |
| 9B | 8.38 | 55.00 | 4.13 |

# APPENDIX III

# The peak discharge for each sub-basin for the two method of rainfal

| Hydrologic Element | Drainage Area ($Km^2$) | Peak Discharge (M3/S) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCS | | | | | | Frequency Storm | | | | | |
| | | 2 Year | 5 Year | 10 Year | 25 Year | 50 Year | 100 Year | 2 Year | 5 Year | 10 Year | 25 Year | 50 Year | 100 Year |
| 23B | 2.4633 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 19B | 2.0021 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 52B | 1.7449 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 38B | 2.4833 | 0 | 0.27 | 1.32 | 3.65 | 6.01 | 8.79 | 0 | 0.06 | 0.69 | 2.37 | 4.17 | 6.38 |
| 29B | 1.8656 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 34B | 2.6457 | 1.13 | 4.23 | 7.41 | 12.42 | 16.72 | 21.4 | 0.17 | 2.23 | 4.63 | 8.59 | 12.1 | 15.97 |
| 30B | 1.3328 | 0.59 | 2.29 | 4.51 | 8.33 | 11.77 | 15.62 | 0 | 0.84 | 2.39 | 5.27 | 7.98 | 11.07 |
| 22B | 1.6827 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 42B | 2.6477 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 31B | 1.9339 | 0.43 | 1.03 | 2.37 | 5.04 | 7.64 | 10.67 | 0 | 0.12 | 0.9 | 2.77 | 4.72 | 7.08 |
| 26B | 0.395 | 1.8 | 2.65 | 3.61 | 5.72 | 7.86 | 10.41 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 24B | 1.496 | 7.18 | 13.5 | 18.59 | 25.78 | 31.56 | 37.58 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 35B | 1.1751 | 2.65 | 5.95 | 9.19 | 14.22 | 18.51 | 23.16 | 0.06 | 1.68 | 3.79 | 7.39 | 10.62 | 14.23 |
| 33B | 0.2536 | 8.27 | 14.96 | 20.24 | 27.65 | 33.55 | 39.7 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 148B | 4.8049 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 146B | 2.2701 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 143B | 1.9591 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 138B | 1.8783 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 139B | 2.6633 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 137B | 3.7171 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 132B | 4.9676 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 126B | 2.3504 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 120B | 1.2748 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 112B | 2.2559 | 0.22 | 2.58 | 5.28 | 9.73 | 13.63 | 17.94 | 0.06 | 1.68 | 3.79 | 7.39 | 10.62 | 14.23 |
| 92B | 1.0834 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 82B | 1.8557 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 133B | 1.7275 | 1.52 | 5.94 | 10.01 | 16.11 | 21.2 | 26.61 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 128B | 0.3142 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 124B | 1.3041 | 0.22 | 2.58 | 5.28 | 9.73 | 13.63 | 17.94 | 0.06 | 1.68 | 3.79 | 7.39 | 10.62 | 14.23 |
| 119B | 1.251 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 115B | 0.7242 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 114B | 1.7646 | 2.27 | 6.94 | 11.14 | 17.39 | 22.57 | 28.07 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 106B | 0.2973 | 0.09 | 0.13 | 0.32 | 1.45 | 2.89 | 4.76 | 0 | 0 | 0.01 | 0.6 | 1.56 | 2.92 |
| 95B | 0.8718 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 81B | 1.6255 | 2.81 | 7.67 | 11.97 | 18.33 | 23.57 | 29.12 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 70B | 0.9088 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 64B | 2.5734 | 3.09 | 8.03 | 12.39 | 18.79 | 24.07 | 29.65 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 60B | 0.2186 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 53B | 2.1209 | 1.99 | 6.58 | 10.73 | 16.93 | 22.07 | 27.54 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 135B | 3.835 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 134B | 3.6656 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 125B | 3.0409 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 121B | 0.2978 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 118B | 1.0738 | 0 | 0.68 | 2.18 | 5.09 | 7.88 | 11.1 | 0 | 0.29 | 1.31 | 3.52 | 5.72 | 8.31 |
| 107B | 1.2422 | 0.01 | 1.47 | 3.56 | 7.22 | 10.56 | 14.32 | 0 | 0.84 | 2.39 | 5.27 | 7.98 | 11.07 |
| 100B | 0.7086 | 3.36 | 8.4 | 12.8 | 19.26 | 24.57 | 30.18 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 90B | 1.9034 | 0.36 | 2.78 | 5.51 | 9.99 | 13.92 | 18.25 | 0.06 | 1.68 | 3.79 | 7.39 | 10.62 | 14.23 |
| 105B | 1.2359 | 0.3 | 1.88 | 4.03 | 7.77 | 11.16 | 14.97 | 0 | 0.84 | 2.39 | 5.27 | 7.98 | 11.07 |
| 96B | 1.1489 | 2.81 | 7.67 | 11.97 | 18.33 | 23.57 | 29.12 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 88B | 0.7905 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 78B | 0.3924 | 8 | 14.59 | 19.83 | 27.18 | 33.05 | 39.17 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 68B | 1.5066 | 6.91 | 13.14 | 18.18 | 25.32 | 31.06 | 37.05 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 62B | 0.5669 | 4.18 | 9.49 | 14.04 | 20.66 | 26.06 | 31.77 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 54B | 1.2036 | 4.18 | 9.49 | 14.04 | 20.66 | 26.06 | 31.77 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 45B | 1.8909 | 3.5 | 8.58 | 13.01 | 19.49 | 24.82 | 30.45 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 37B | 0.375 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 36B | 0.0028 | 15.81 | 23.3 | 28.56 | 35.65 | 41.19 | 46.89 | 0 | 0 | 0.35 | 1.65 | 3.17 | 5.09 |
| 43B | 1.1619 | 9.09 | 16.05 | 21.48 | 29.04 | 35.05 | 41.28 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 44B | 2.6042 | 15.1 | 24.07 | 30.58 | 39.29 | 46.04 | 52.91 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 58B | 1.9306 | 0.29 | 0.43 | 0.94 | 2.54 | 4.33 | 6.55 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 50B | 0.5786 | 8.27 | 14.96 | 20.24 | 27.65 | 33.55 | 39.7 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 113B | 1.5131 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 103B | 0.7923 | 6.23 | 12.23 | 17.14 | 24.15 | 29.81 | 35.73 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 79B | 1.1621 | 8.14 | 14.78 | 20.04 | 27.41 | 33.3 | 39.43 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 75B | 0.5162 | 10.19 | 17.51 | 23.14 | 30.91 | 37.05 | 43.4 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 67B | 0.1608 | 10.06 | 14.8 | 17.94 | 22.25 | 25.82 | 29.64 | 0 | 0 | 0 | 0.15 | 0.71 | 1.66 |
| 130B | 1.4709 | 0 | 0.68 | 2.18 | 5.09 | 7.88 | 11.1 | 0 | 0.29 | 1.31 | 3.52 | 5.72 | 8.31 |
| 122B | 0.9697 | 0.22 | 2.58 | 5.28 | 9.73 | 13.63 | 17.94 | 0.06 | 1.68 | 3.79 | 7.39 | 10.62 | 14.23 |
| 117B | 1.0958 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 111B | 0.3421 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 101B | 1.346 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 87B | 1.0798 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 76B | 0.5871 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 72B | 0.0458 | 7.19 | 10.63 | 13.43 | 17.69 | 21.32 | 25.26 | 0 | 0 | 0.35 | 1.65 | 3.17 | 5.09 |
| 158B | 8.6151 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 156B | 8.0341 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 153B | 9.1105 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 155B | 8.7948 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 152B | 7.0215 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 145B | 7.1077 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 151B | 17.3146 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 150B | 14.0098 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 144B | 5.1585 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 141B | 8.497 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 140B | 6.6374 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 136B | 4.6672 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 109B | 5.5099 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 104B | 0.237 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 94B | 0.2222 | 1.45 | 5.85 | 9.9 | 16 | 21.07 | 26.48 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 85B | 0.8635 | 0.43 | 0.64 | 1.19 | 2.84 | 4.66 | 6.91 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 108B | 2.2204 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 97B | 0.5778 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 84B | 0.577 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 77B | 0.3375 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 170B | 40.1262 | 0 | 0 | 0.43 | 1.91 | 3.62 | 5.76 | 0 | 0 | 0.12 | 1.04 | 2.27 | 3.88 |
| 165B | 30.4792 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.8 | 0 | 0 | 0.12 | 1.06 | 2.29 | 3.92 |
| 163B | 21.3692 | 0 | 0 | 0.43 | 1.93 | 3.64 | 5.8 | 0 | 0 | 0.12 | 1.06 | 2.29 | 3.92 |
| 169B | 25.5197 | 0 | 0 | 0.42 | 1.9 | 3.6 | 5.74 | 0 | 0 | 0.12 | 1.04 | 2.25 | 3.86 |
| 166B | 25.8628 | 0 | 0 | 0.43 | 1.92 | 3.64 | 5.79 | 0 | 0 | 0.12 | 1.05 | 2.29 | 3.92 |
| 162B | 21.1643 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.8 | 0 | 0 | 0.12 | 1.06 | 2.29 | 3.92 |
| 157B | 49.3678 | 0 | 0 | 0.42 | 1.9 | 3.6 | 5.74 | 0 | 0 | 0.12 | 1.04 | 2.25 | 3.86 |
| 183B | 30.1552 | 0 | 0 | 0.42 | 1.91 | 3.61 | 5.75 | 0 | 0 | 0.12 | 1.04 | 2.26 | 3.87 |
| 182B | 34.4272 | 0 | 0 | 0.42 | 1.88 | 3.56 | 5.67 | 0 | 0 | 0.11 | 1.02 | 2.21 | 3.8 |
| 176B | 39.2619 | 0 | 0.01 | 0.48 | 2 | 3.7 | 5.84 | 0 | 0 | 0.15 | 1.1 | 2.32 | 3.93 |
| 172B | 24.3078 | 0.38 | 3.13 | 6.11 | 10.88 | 15.03 | 19.57 | 0.15 | 2.13 | 4.47 | 8.37 | 11.83 | 15.65 |
| 180B | 26.6437 | 0 | 0 | 0.42 | 1.89 | 3.59 | 5.72 | 0 | 0 | 0.12 | 1.03 | 2.24 | 3.85 |
| 177B | 23.3298 | 0 | 0.07 | 0.76 | 2.59 | 4.56 | 6.96 | 0 | 0 | 0.31 | 1.54 | 3 | 4.85 |
| 167B | 35.184 | 0 | 0.05 | 0.65 | 2.28 | 4.04 | 6.21 | 0 | 0 | 0.25 | 1.31 | 2.58 | 4.22 |
| 181B | 27.4686 | 0 | 0 | 0.43 | 1.92 | 3.63 | 5.78 | 0 | 0 | 0.12 | 1.05 | 2.28 | 3.91 |
| 179B | 18.9538 | 0 | 0 | 0.43 | 1.92 | 3.64 | 5.79 | 0 | 0 | 0.12 | 1.05 | 2.29 | 3.92 |
| 178B | 37.8221 | 0 | 0 | 0.43 | 1.93 | 3.64 | 5.8 | 0 | 0 | 0.12 | 1.06 | 2.29 | 3.92 |
| 175B | 39.617 | 0 | 0 | 0.43 | 1.91 | 3.62 | 5.76 | 0 | 0 | 0.12 | 1.04 | 2.27 | 3.88 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 174B | 31.8271 | 0 | 0 | 0.43 | 1.92 | 3.63 | 5.78 | 0 | 0 | 0.12 | 1.05 | 2.28 | 3.9 |
| 171B | 25.6624 | 0 | 0 | 0.42 | 1.88 | 3.56 | 5.68 | 0 | 0 | 0.11 | 1.02 | 2.22 | 3.81 |
| 168B | 55.7798 | 0 | 0 | 0.42 | 1.89 | 3.58 | 5.71 | 0 | 0 | 0.12 | 1.03 | 2.24 | 3.84 |
| 173B | 33.8457 | 0 | 0.57 | 1.94 | 4.65 | 7.27 | 10.32 | 0 | 0.22 | 1.12 | 3.14 | 5.19 | 7.62 |
| 164B | 77.8097 | 0 | 0.17 | 1.07 | 3.17 | 5.34 | 7.95 | 0 | 0.02 | 0.51 | 1.98 | 3.62 | 5.66 |
| 160B | 63.7179 | 0 | 0.03 | 0.63 | 2.33 | 4.2 | 6.5 | 0 | 0 | 0.23 | 1.35 | 2.71 | 4.47 |
| 161B | 49.0023 | 0.06 | 1.8 | 4.08 | 7.97 | 11.47 | 15.37 | 0 | 1.08 | 2.79 | 5.88 | 8.73 | 11.96 |
| 159B | 33.0438 | 0 | 0 | 0.43 | 1.91 | 3.62 | 5.76 | 0 | 0 | 0.12 | 1.04 | 2.27 | 3.89 |
| 154B | 62.6803 | 0 | 0.01 | 0.49 | 2.05 | 3.81 | 6 | 0 | 0 | 0.15 | 1.14 | 2.41 | 4.08 |
| 147B | 49.0482 | 0 | 0 | 0.43 | 1.91 | 3.62 | 5.76 | 0 | 0 | 0.12 | 1.04 | 2.27 | 3.88 |
| 149B | 28.199 | 0 | 0 | 0.43 | 1.92 | 3.64 | 5.79 | 0 | 0 | 0.12 | 1.05 | 2.29 | 3.91 |
| 142B | 43.1966 | 0 | 0 | 0.43 | 1.93 | 3.64 | 5.8 | 0 | 0 | 0.12 | 1.06 | 2.29 | 3.92 |
| 131B | 36.0601 | 0 | 0.43 | 1.67 | 4.26 | 6.8 | 9.77 | 0 | 0.14 | 0.93 | 2.84 | 4.82 | 7.19 |
| 99B | 59.8997 | 0 | 0.03 | 0.63 | 2.35 | 4.24 | 6.56 | 0 | 0 | 0.23 | 1.37 | 2.75 | 4.54 |
| 91B | 0.2743 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 123B | 3.8218 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 110B | 1.921 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 98B | 0.5563 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 83B | 0.3139 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 89B | 1.757 | 2.68 | 7.49 | 11.77 | 18.09 | 23.32 | 28.86 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 86B | 1.3683 | 0.03 | 0.04 | 0.48 | 1.99 | 3.72 | 5.88 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 73B | 1.6112 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 69B | 2.1616 | 8 | 14.59 | 19.83 | 27.18 | 33.05 | 39.17 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 63B | 1.2002 | 11.01 | 18.6 | 24.38 | 32.31 | 38.55 | 44.98 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 74B | 1.4545 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 66B | 0.9881 | 2.59 | 3.81 | 5.01 | 7.39 | 9.71 | 12.43 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 65B | 1.3722 | 4.5 | 8.53 | 12.18 | 17.66 | 22.24 | 27.15 | 0.06 | 1.68 | 3.79 | 7.39 | 10.62 | 14.23 |
| 59B | 0.1298 | 5.75 | 8.52 | 10.91 | 14.7 | 18.01 | 21.65 | 0 | 0 | 0.35 | 1.65 | 3.17 | 5.09 |
| 56B | 0.5628 | 7.18 | 13.5 | 18.59 | 25.78 | 31.56 | 37.58 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 57B | 1.4587 | 11.01 | 18.6 | 24.38 | 32.31 | 38.55 | 44.98 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 51B | 1.0943 | 6.77 | 12.95 | 17.97 | 25.08 | 30.81 | 36.79 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 102B | 3.7358 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 93B | 3.0409 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 129B | 9.1497 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 17B | 3.6187 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 16B | 11.9334 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 15B | 3.3999 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 9B | 8.3752 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 10B | 5.9787 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11B | 2.4255 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 14B | 8.6058 | 0 | 0.03 | 0.61 | 2.31 | 4.19 | 6.5 | 0 | 0 | 0.22 | 1.34 | 2.72 | 4.5 |
| 127B | 5.0935 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 116B | 2.662 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 80B | 3.684 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 71B | 0.8197 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 61B | 0.533 | 3.09 | 8.03 | 12.39 | 18.79 | 24.07 | 29.65 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 55B | 0.8555 | 5.54 | 11.31 | 16.11 | 22.99 | 28.56 | 34.41 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 49B | 0.2367 | 8.27 | 14.96 | 20.24 | 27.65 | 33.55 | 39.7 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 46B | 0.9601 | 15.1 | 24.07 | 30.58 | 39.29 | 46.04 | 52.91 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 41B | 1.1212 | 14.38 | 21.19 | 26.04 | 32.66 | 37.88 | 43.29 | 0 | 0 | 0.35 | 1.65 | 3.17 | 5.09 |
| 32B | 1.252 | 13.74 | 22.25 | 28.52 | 36.97 | 43.54 | 50.27 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 25B | 0.8876 | 11.28 | 18.97 | 24.79 | 32.77 | 39.05 | 45.51 | 0.91 | 4.38 | 7.72 | 12.85 | 17.18 | 21.83 |
| 40B | 4.0839 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 48B | 7.7355 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 13B | 6.7319 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 7B | 11.7629 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 5B | 7.1587 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 4B | 14.1483 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 2B | 9.3768 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 1B | 16.1698 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 3B | 7.5703 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 6B | 10.8653 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 8B | 15.9222 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 12B | 14.8199 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 47B | 2.6791 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 39B | 1.67 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 28B | 3.0484 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 27B | 0.4867 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 21B | 1.6133 | 0.16 | 1.68 | 3.8 | 7.5 | 10.86 | 14.64 | 0 | 0.84 | 2.39 | 5.27 | 7.98 | 11.07 |
| 20B | 0.6806 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |
| 18B | 2.5866 | 0 | 0 | 0.43 | 1.93 | 3.65 | 5.81 | 0 | 0 | 0.12 | 1.06 | 2.3 | 3.94 |

# APPENDIX IV

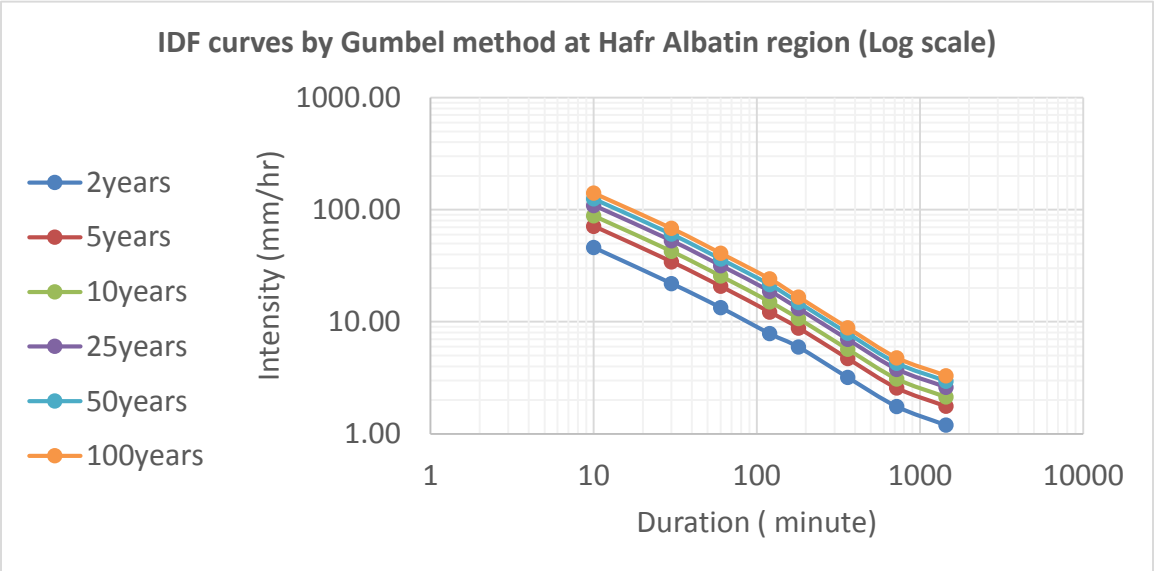
# Peak discharge used in HEC-RAS

| No. | Stream | Reach | RS | Peak flow | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Q2 | Q5 | Q10 | Q25 | Q50 | Q100 |
| 1 | 1 | reach_1 | 13628.3 | 0.0001 | 0.01 | 0.71 | 2.78 | 5.15 | 8.25 |
| 2 | 10 | reach_20 | 2353.18 | 9.07 | 18.48 | 27.4 | 62.96 | 108.23 | 163.94 |
| 3 | 11 | reach_22 | 1981.89 | 12.52 | 23.99 | 34.38 | 63.51 | 108.9 | 164.73 |
| 4 | 12 | reach_24 | 1030.46 | 17.61 | 38.94 | 59.88 | 93.18 | 123.57 | 174.22 |
| 5 | 13 | reach_26 | 2253.26 | 18.6 | 40.65 | 62.21 | 96.47 | 127.66 | 174.65 |
| 6 | 14 | reach_30 | 4740.13 | 19.61 | 42.72 | 65.55 | 102.33 | 136.63 | 190.81 |
| 7 | 2 | reach_3 | 21887.6 | 0.0001 | 0.01 | 1.62 | 6.39 | 11.83 | 18.92 |
| 8 | 3 | reach_5 | 10399.3 | 0.2 | 1.7 | 7.9 | 24.16 | 41.58 | 63.2 |
| 9 | 4 | reach_7 | 24798.3 | 0.2 | 1.71 | 8.61 | 26.66 | 46.04 | 70.09 |
| 10 | 5 | reach_9 | 6367.11 | 0.24 | 3.2 | 12.68 | 36.53 | 61.8 | 92.9 |
| 11 | 6 | reach_11 | 7231.68 | 0.24 | 3.21 | 15.01 | 45.78 | 78.84 | 119.94 |
| 12 | 7 | reach_13 | 12657.2 | 0.24 | 3.21 | 15.7 | 48.4 | 83.62 | 127.51 |
| 13 | 8 | reach_15 | 4626.45 | 0.25 | 3.6 | 17.59 | 53.92 | 93.16 | 142.01 |
| 14 | 9 | reach_17 | 2396.07 | 4.4 | 10.08 | 18.76 | 59.15 | 102.31 | 155.44 |
| 15 | L1 | reach_12 | 15154.8 | 0.0001 | 0.0001 | 0.43 | 1.71 | 3.17 | 5.06 |
| 16 | L2 | reach_19 | 13777.8 | 0.03 | 0.15 | 1.37 | 5.03 | 9.74 | 16.28 |
| 17 | L3 | reach_21 | 4319.04 | 0.46 | 0.75 | 1.04 | 1.54 | 2.03 | 2.62 |
| 18 | L4 | reach_23 | 6825.64 | 0.69 | 1.5 | 2.3 | 3.73 | 7.26 | 12.16 |
| 19 | L5 | reach_25 | 1131.16 | 0.82 | 1.46 | 2.01 | 2.81 | 3.45 | 4.13 |
| 20 | L6 | reach_32 | 754.31 | 0.0001 | 0.02 | 1.59 | 5.84 | 11.36 | 19.01 |
| 21 | LL8 | reach_33 | 5725.81 | 0.0001 | 0.02 | 1.59 | 5.82 | 11.32 | 18.96 |
| 22 | LR7 | reach_31 | 4532.65 | 0.09 | 0.13 | 0.2 | 0.49 | 0.9 | 1.44 |
| 23 | R1 | reach_4 | 26623.4 | 0.0001 | 0.0001 | 0.44 | 1.7 | 3.16 | 5.07 |
| 24 | R2 | reach_6 | 26588.4 | 0.0001 | 0.02 | 0.54 | 1.9 | 3.42 | 5.32 |
| 25 | R3 | reach_8 | 23058.6 | 0.2 | 1.83 | 4.3 | 9.91 | 15.77 | 22.83 |
| 26 | R4 | reach_10 | 21399.9 | 0.06 | 1.5 | 3.61 | 7.76 | 11.75 | 16.41 |
| 27 | R5 | reach_14 | 11209.6 | 0.0001 | 0.0001 | 0.27 | 1.04 | 1.93 | 3.11 |
| 28 | R6 | reach_16 | 4706.2 | 0.0001 | 0.35 | 1.19 | 3.07 | 5.03 | 7.39 |
| 29 | R7 | reach_18 | 5570.81 | 0.24 | 1.82 | 3.69 | 6.86 | 9.67 | 12.76 |
| 30 | R8 | reach_28 | 4641.6 | 3.26 | 11.95 | 21.45 | 37.1 | 51.27 | 67.21 |
| 31 | RL10 | reach_27 | 5412.53 | 1.41 | 6.92 | 12.98 | 22.94 | 31.96 | 42.1 |
| 32 | RR9 | reach_29 | 5311.28 | 1.56 | 4.03 | 6.76 | 11.36 | 15.58 | 20.38 |

# APPENDIX V

# Rainfall intensity for different duration and return period

| Frequency (Years) | Duration(minutes) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 10 | 30 | 60 | 120 | 180 | 360 | 720 | 1440 |
| 2 | 46.002 | 21.998 | 13.391 | 7.849 | 5.955 | 3.198 | 1.756 | 1.198 |
| 5 | 71.414 | 34.382 | 20.757 | 12.213 | 8.818 | 4.706 | 2.564 | 1.762 |
| 10 | 88.239 | 42.581 | 25.635 | 15.101 | 10.713 | 5.704 | 3.099 | 2.136 |
| 25 | 109.497 | 52.940 | 31.797 | 18.751 | 13.107 | 6.965 | 3.774 | 2.608 |
| 50 | 125.268 | 60.626 | 36.368 | 21.459 | 14.883 | 7.901 | 4.276 | 2.958 |
| 100 | 140.922 | 68.254 | 40.906 | 24.147 | 16.647 | 8.829 | 4.773 | 3.306 |



# Vitae


| | | |
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