A HYDROLOGIC CLIMATE STUDY FOR AN ARID REGION

BY

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A dissertation submitted in partial fulfillment of the requirement for the

Doctor of Philosophy

Major in Civil Engineering

South Dakota State University

2021

DISSERTATION ACCEPTANCE PAGE

Ali Alsubeai

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This dissertation dedicated to my father, my mother, my sisters, my wife and to my son.

ACKNOWLEDGEMENTS

In January 2018, I started my PhD studies with a general idea of what are my objectives and why. Since then, I have learned a lot: deepened my knowledge in the geospatial filed, developed new skills, and built up my capacity to conduct a scientific research, which summed up to this dissertation. This achievement would not have been realized without the help and support of several nice people:

First, I gratefully acknowledge my advisor Dr. Suzette R. Burckhard for her inspiration, competent guidance, patience, and encouragement through all the different stages of this research. Suzette was and remains my best role model for a scientist, mentor, and teacher. Suzette was the reason why I decided to go to pursue a career in research. Her enthusiasm and love for teaching is contagious. Suzette, you are the best!

Second, I would like to thank the members of my committee which includes, Dr. Guanghui Hua, for his giving suggestions and comments on how to improve this paper. Also, I would like to thank Dr. Michael D. Pawlovich, for all good questions and discussions that led to improve the quality of my research. Also, I would like to thank Dr. Péter Kovács, for his commitment and participations.

I would like to thank my parents for many reasons. I would like to thank my dad, Mohammed Alsubeai for motivating me to study abroad. This accomplishment would not be real without you. I am forever indebted to my mother for her understanding, endless patience, and encouragement when it was most required throughout the study-period. Also, I am thankful for my wife who is been supportive and encouraging me to achieve this goal. Also, I would like to thank my sisters and my brothers for all the good wishes. I am deeply indebted for not having spent much time with them throughout my study in the United States.

My thanks also go to Abdullah Alzaydani who started this journey with me from the beginning. Also, I would like to thank my colleagues, Philip Adalikwu, Angelina Rasoeu and Abdoul Aziz Kouanda for all good discussions and making me enjoy coming to the graduate office.

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ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
CN	Curve Number
Esri	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
GPCP	Global Precipitation Climatology Project
GSMAP	Global Satellite Mapping of Precipitation
GUI	Graphical User Interface
HEC	Hydrological Engineering Center
HEC-HMS	HEC Hydrological Modeling System
HEC-RAS	HEC River Analysis System
IHACRES	Identification of unit Hydrograph And Component flows from Rainfall, Evaporation and Stream flow
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
RFC	River Forecast Centers

SAC-SMA	Sacramento Soil Moisture Accounting
SCS	Soil Conservation Service
SWAT	Soil & Water Assessment Tool
TMPA	TRMM Multi-satellite Precipitation Analysis
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States of America
USACE	United States Army Corps of Engineers
	Artificial Neural Networks
USDA	United States Department of Agriculture
WMO	World Metrological Organization

ABSTRACT

A HYDROLOGIC CLIMATE STUDY FOR AN ARID REGION

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2021

Water is the most precious natural resource in arid regions due to the limitation of water resources, expanding population, and increasing volumes of industrial and domestic waste. The purpose of this research was to evaluate methods to estimate water quantity in an arid region. The research consisted of three separate studies.

In the first study, hydrologic models used to estimate water quantity were evaluated for suitability of use in arid regions. Most hydrologic models that have been used in arid regions were originally developed for humid regions. Rainfall events in arid regions can be characterized as short-term, high intense rainstorms causing severe runoff in arid regions. This study provides an assessment various rainfall-runoff models and a comparison of methods and/or modifications used by researchers to adapt these models to arid regions. Mike 11, Sacramento, Pitman, and the IHACRES models have been used in arid regions with mixed results.

The second study evaluated the annual rainfall for the Tabuk region obtained from observed datasets for the period 1978–2013. The objective of this study was to determine Tabuk catchment climate characteristics in terms of precipitation. The Tabuk region has common aridity characteristics in terms of the small precipitation amounts and high temperature rate. There is a drop in the annual rainfall from (25-30) mm to (5-10) mm

(1978-2004). The lowest annual rainfall (0-6.0 mm) occurred in the year 2004, which is the driest year in 35-year period. The mean annual rainfall is less than 33.5 mm.

The third study analyzed flash floods caused by short-intense rainstorms. The objective of this study was to determine flood risk related to identified precipitation depths. The project quantized the runoff corresponding to different design storms and used hydraulics and geospatial data to determine flood elevations. The study constructed hydrologic and hydraulic models to quantify flood hazards in the adjacent area of Wadi Abu Nashayfah. Peak discharges for the wadi were computed by using observed rainfall data, and the output of this process was applied to compute water surface elevations within the flow channel. The depth of precipitation at which the channel was overtopped was determined in several locations. The predicted overtopping was compared to historic events with good agreement.

CHAPTER 1: INTRODUCTION

"A drop of water, if it could write out its own history, would explain the universe to us" (Larcom 1824 - 1893).

1.1 Background

Understanding, measuring, and forecasting rainfall spatial patterns and quantities may be useful for a variety of human, social, economic, hydrological, and ecological practices such as agricultural planning, water supply management, flood control, groundwater recharge, forest management, industry, and the health of the human community and the national economy. The annual and seasonal patterns, as well as the overall amount of precipitation, are critical components of any water balance study. Human activities affect runoff characteristics. Specifically, declines in base flow, erosion, changes in floodplain area, peak flow rate and runoff amounts, are all changes seen in areas that have experienced urbanization, with flooding being the most destructive outcome (Niemczynowicz 1999).

Urbanization in arid regions requires the design of storm water runoff quantity control structures because of the high-intensity, short-duration rain spells in these regions. Such high-intense storms, combined with the poor drainage potential of desert soils, can contribute to floods, property damage and loss of life. As a result, storm water control systems were built in the 1960s to handle flooding in arid regions (Baxter 1985). Flooding regimes in arid and semi-arid regions are heavily influenced by climate change and water shortage, water regulations, and increased water demands.

Floods are very rare and infrequent in arid regions, are hard to predict and can cause severe harm to people lives and infrastructure as well. The low amount of annual precipitation due to the desert climate may lead to false estimations of flooding hazards. Rainfall events in arid regions is characterized as short term-high intensity events where there is a shortage of time for water to enter soil layers, so most of water generates surface flow or runoff.

1.2 Surface Runoff

Early hydrologists have measured a surface runoff with minimal data and basic analytical techniques. The first commonly used runoff method was the Rational Method, which used the precipitation rate, the drainage area, and the runoff coefficient to calculate the peak discharge in the drainage basin (Xu 2002). The rational method equation is as follows (Dooge 1957).

$$Q = kCiA \qquad (1)$$

Where:

Q = Peak discharge (cfs)

k = 1.008 account for unit conversions

C = runoff coefficient

i = rainfall intensity (inch/hr)

A = watershed area (acres)

The method has many limitations and is based on the following assumptions:

(1) Rain falls evenly through the drainage area.

(2) The rainfall level averaged over a time span equal to the time of concentration of the drainage area will represent the peak rate of runoff.

(3) The time taken for flow to hit the point in question from the hydraulically most distant point is referred to as the time of concentration.

(4) The frequency of runoff is equal to the frequency of rainfall in the equation.

Runoff coefficient (C) variable represents the ratio of runoff to rainfall (Table 1.1). It is the most difficult input variable to estimate. It represents the interaction of many complex factors, including the storage of water in surface depressions, infiltration, antecedent moisture, ground cover, ground slopes, and soil types. The coefficient may vary with respect to prior wetting and seasonal conditions.

Table 1.1 Rational method runoff coefficient (Chin 2000).

Ground Cover	**Runoff Coefficient**
Lawns	0.05 - 0.35
Forest	0.05 - 0.25
Cultivated land	0.08-0.41
Meadow	0.1 - 0.5
Parks, cemeteries	0.1 - 0.25
Unimproved areas	0.1 - 0.3
Pasture	0.12 - 0.62
Residential areas	0.3 - 0.75
Business areas	0.5 - 0.95
Industrial areas	0.5 - 0.9
Asphalt streets	0.7 - 0.95
Brick streets	0.7 - 0.85
Roofs	0.75 - 0.95
Concrete streets	0.7 - 0.95

The rational method is based on assumptions that have been made where humid climate is more likely dominating. Runoff coefficient have been assumed to be based on several climatic factors that vary from one region to another. For example, average temperature, precipitation amount, duration and intensity are not the same in humid and arid regions.

Even though this method has frequently come under academic criticism for its simplicity, no other practical drainage design method has evolved to such a level of general acceptance by the practicing engineer.

Another technique used to estimate runoff is the curve number method established by USDA in 1954 (Rallison 1980). The curve number is based on the area's hydrological soil group, land use, and hydrologic condition. The method was developed for the estimation of direct runoff from storm rainfall. Curve number method is widely used because of its convenience, its simplicity, its authoritative origins, and its responsiveness to four readily grasped catchment properties: soil type, land use, surface condition, and antecedent condition. The SCS runoff equation is as follows:

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

Where:

Q = direct runoff (in)

P = rainfall (in)

The initial abstractions I_a is a percentage of S as follows:

$$Ia = 0.2\,S \qquad (3)$$

Noting that S is the potential max retention which can be computed as:

$$S = \frac{1000}{CN} - 10 \qquad (4)$$

The curve number method has been widely used in different regions for a variety of purposes, but there are concerns in using this model, which was developed for humid regions, in arid regions. This method was designed based on one climate dataset, taking into consideration the natural characteristics of a humid region. With this bias, the CN procedure is less accurate when runoff is less than 0.5 in., which is the case in arid regions, where precipitation is typically low with exceptions for some high intensity events.

The Initial Abstraction parameter accounts for all losses prior to runoff and consists mainly of interception, infiltration, evaporation, and surface depression storage. This parameter is assumed as 0.2 of potential maximum retention based on watersheds studied in humid regions. Accordingly, vegetation cover in humid regions is larger compared to arid regions which have a lower potential of intercepting high runoff volumes which may lead to flooding.

1.3 Surface Runoff Impacts on Arid Regions

In arid regions, rainfall is sporadic and varies spatially and temporally. Short but intensive thunderstorms of highly intense rainfall usually take place early in the rainy season and at the end of the season (Pilgrim 1988). Therefore, flash flooding occurs quickly on a timescale of minutes to a few hours usually over small drainage areas on the order of a few hundred square kilometers. These are the most dangerous floods because they can occur with little or no warning and are often associated with fast-moving waters that can negatively impact human life, urban infrastructures, and agriculture.

Floods affect large areas, particularly in arid regions, with thousands of human casualties causing significant damage. For example, it has been recorded in Jordan that a flash flood occurred in March 1966, leading to around 200 deaths and 250 injuries. Approximately half of the houses in the town of Ma'an were demolished, in addition to 3,000 residents being left homeless (Al-Qudah 2011). In addition, more than 113 people have lost their lives in Saudi Arabia and 10,000 homes have been destroyed in the last 5 years because of devastating flash flood events (Youssef. 2016). In 2013, Sudan experienced flash flood events causing 48 deaths and over 210,000 affected people (UNOCHA 2013).

Urban projects such as transportation networks are impacted by flash flooding. Heavy rainfall and devastating floods may cause road closure, traffic volume growth, damages to road structure and destroy bridges. For instance, the expressway between two large cities in Saudi Arabia, Jeddah and Makkah, was closed on Nov 25, 2009, due to extreme flooding. The highway remained close on the following day, Nov 26 amid fears that the Jamia “University” bridge would collapse completely (Daoudi 2019).

Agricultural industries are affected differently by flash floods. Certainly, Sudan has been extremely affected by floods that have caused agricultural losses. According to the Food and Agriculture Organization of the United Nations almost one-third of cultivated land has been flooded, affecting three million people in agricultural households. FAO estimates that 108,000 head of livestock have been destroyed and 5.4 million acres (2.2 million hectares) of cropland have been flooded (FAO 2017).

1.4 Research Objectives

This study discusses how hydrological models can be used to simulate rainfall-runoff in arid regions where there is a lack of historic data. The essential research question is: *Due to a lack of historic data in arid regions, what are the applicable hydrological models that can be used to assess flood risk potential and how can a flood risk study be carried out?*

Furthermore, some concerns and questions addressed by this PhD research:

- What is the prevalence of rainfall-runoff modeling in arid regions?
- Do existing rainfall-runoff models sufficiently estimate arid regions streamflow?
- How has climate variability impacted precipitation trends at annual and monthly scales?
- What approach is necessary to determine flood risks in arid regions?

1.5 Overview of Dissertation

This dissertation is comprised of five chapters. Chapter One is the overall introduction and includes the background and research objectives of the study. Chapter Two is the literature review of relevant topics in hydrological modeling in arid regions. This chapter includes a literature review of runoff models for arid regions. Chapter Three covers the climate study of a specific arid region which is Tabuk region. Chapter Four includes assessments of flood risks produced from extreme events to actual channel characteristics. Chapter Three and Four, with their respective abstracts, research questions, materials and methods, results and discussions, and conclusions, are related to the overall goal of evaluating methods to estimate water quantity in an arid region by determining the effects of climate variability on generating extreme floods. Chapter Five is a summary of the overall conclusions and suggestions for further research, respectively.

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Chapter 2. Rainfall- Runoff Modelling in Arid Regions: case study Middle East

Abstract

Developing models relating the rainfall incident upon a watershed to the stream flow originating from the watershed has been a major focus of surface water hydrology for years. Models' configuration was originated to work with limited input parameters, so not necessarily valid unless the model has been tested in different situations. Most models were designed for humid regions that receive high amounts of precipitation compared to arid regions as well as other differences. For instant, vegetation cover is extensive in humid areas compared to arid areas. In addition, there are very intense rainfall events that occur during the year causing runoff in both humid and arid regions but the nature of the events in arid regions is different compared to humid regions in terms of timing and vegetation conditions. This chapter will provide an assessment and demonstration of the suitability of using rainfall-runoff models particularly in arid regions. The ideal location representing arid lands is the Middle East which is characterized by very low precipitation, poor vegetation, and high rates of evaporation.

Introduction

A scientific approach for the management of natural resources like water requires a periodical revision of the database. Revision involves checking and changing information to reflect the situation in the field. Modeling enables a quantitative assessment of the consequences of heterogeneity in ecological systems over a broad range of spatial and temporal scales. Integration of several surface features that indicate groundwater potentialities in a systematic way is an important aspect in water management studies.

A database designed to support water resource decisions must contain a variety of thematic information because of the interdisciplinary nature of water problems. Geographic Information Systems (GIS) technology provides a means of integrating information and knowledge from other data sources into the decision-making process and helps to handle and analyze remotely sensed data (Adinarayana 1996).

Some researchers have shown that the application of multi-thematic Earth charts, remote sensing and GIS is useful for the detection of reliable water zones for exploration and for the creation and management of water supplies. (Sidhu 1989, Mattikalli 1995, Kamaraju 1996).

Hydrological runoff- rainfall model was developed by using GIS and remote sensing (Lynn 1989). Numerous studies have been conducted to show the capabilities of remote sensing and GIS systems in natural resource applications and growth planning. Wherefore, improving water management is a necessary mission to conserve water especially for places where there is existed water scarcity (Smith 1980, Hellden 1982, Trotter 1991, Kushwaha 1993).

The purpose of this chapter is to be providing an assessment and demonstration of how suitable of using rainfall-runoff models particularly in arid regions. Middle East region (Figure 2.1) represents the true case of water shortage and poor management. Middle East contains 18 countries divided into four major subregions, Arabian Peninsula, Cacaos, Iran, and Near East.

Figure 2.1 Middle East geography region (ESRI 2017).

2.1 Desertification in Middle East

Water cycle impacts environment components in various ways. The circulation of humidity and heat between the atmosphere and Earth's surface has a significant influence on the dynamics and thermodynamics of climate system. Even though, water can occur in three states, vapor, liquid and gas, the transition between the three states impacts heating and cooling the climate. Water vapor is the largest contributor to the Earth's greenhouse effect (Evans 2012).

However, the temperature of the planet is not regulated by water vapor, but instead by temperature pressure. This is because the temperature of the ambient atmosphere restricts the overall volume of water vapor that the atmosphere can contain. As well as clouds regulate the atmosphere by changing the Earth's radiation budget.

Rainfall generation is generally seen as the beginning of the Earth's hydrological cycle. Rainfall can be in the form of rain or snow. However, rain or melt water may be intercepted by vegetation cover, or may penetrate soil layers, or run over the surface of the soil into streams.

Accordingly, infiltrated water may be deposited in the soil as soil moisture or may percolate to deeper levels to be stored as groundwater. Along with a portion of the water intercepted by vegetation, deposited in soil surface depressions and stored in the soil profile, water can return to the atmosphere because of evaporation. Plants remove a large amount of soil moisture from the root zone and evaporate much of this water from their roots.

Desertification is the diminution or destruction of the biological potential of the land and can lead ultimately to desert-like conditions. This global problem has received a great amount of attention in the past few decades since many countries in the world have suffered its effects and consequences (UNCOD 1977).

Desertification responds to both long-term climatic conditions and human impact. High temperature, low humidity, and high values of evapotranspiration, as well as the impact of overgrazing and woodcutting have contributed to the reduction of biological productivity and the spread of arid zones. The combination of human activities and the occasional series of dry years has led to vegetation reduction in arid environments (Goudie, 1986).

Water is the most precious natural resource in arid regions due to the limitation of water resources, expanding population, and increasing volumes of industrial and domestic waste. Rainwater, surface water, and groundwater are the main natural resources of water. Many hydrologists have investigated the impact of temperature and precipitation change on hydrology. Average temperature and precipitation both increased during the 20th century, mostly due to an increase in intense rainstorms (Muttiah 2002).

The increasing pressure on water resources in those regions could lead to severe situations. For instance, arid regions are highly affected by drought phenomena since they have limited water resources. Drought is defined as the period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance (WMO 1992).

There are nine countries listed as the poorest places with natural resources of water located in Middle East. Middle East receives the lowest average annual precipitation comparing to other regions and Kuwait state recorded the lowest precipitation rate (Table 2.1).

Table 2.1 Middle East water resources, by subregion (FAO 2003).

	Annual Precipitation		**Annual Internal Renewable Water Resources**		
Subregion	**Height (mm)**	**Volume (Million m^3)**	**Volume (Million m^3)**	**% Of Middle East**	**Per Inhabitant 2005 (m^3)**
Arabian Peninsula	117	362,041	6,110	1	108
Caucasus	702	130,582	73,104	15	4,597
Iran	228	397,894	128,500	27	1,849
Near East	439	673,531	276,376	57	1,964
Total region	238	156,4048	484,090	100	1,711

Subregions in Middle East receive variant amount of precipitation, Arabian Peninsula has highly potential of drought occurrences due to the total population, and area covered comparing to average precipitation, which is the lowest. As mentioned earlier, population growth continues, energy use increases, and standard of living increases all requiring more water. Therefore, establishing ways and techniques to preserving water resources in arid and semi-arid is essential for sustainability and life quality.

Growth in population has led to rapid urbanization, marked by agricultural, manufacturing, and residential land grading; vegetation removal; and soil compaction. Such landscaping changes improve the impervious surface area and greatly affect the quality and quantity of storm water runoff. (Foley 2005; Hatt 2004; Walsh 2000). In turn, the hydrological impacts of urbanization include declines in base flow and erosion and changes in floodplain area, peak flow rate and runoff level, with flooding being the most destructive outcome (Niemczynowicz 1999).

Urbanization in arid regions requires the use of storm water runoff quantity control structures because of the high-intensity, short-duration rain spells in these regions. Such high-intense storms, combined with the poor drainage potential of desert soils, can contribute to floods, property damage and loss of life. As a result, storm water control systems were built in the 1960s to handle flooding in arid regions (Baxter 1985). Flooding regimes in arid and semi-arid regions are heavily influenced by climate change and water shortage, water regulations, and increased water demands.

Accordingly, most potential of water scarcity due to shortage of resources is assimilate in Middle East. By far, countries in good financial stand can provide drinking water to its people but with high operation cost which rise a concern of the ability of the existed process of dissention to stay or sustain.

2.2 Water Resources and Use in Middle East

Middle East has suffered from poor water resources and water management over past years. The Middle East is the first region of the world to effectively run out of water. Countries such as Saudi Arabia, Iraq, Jordan, and Yamen are facing serious issues, which require immediate attention from world community (Allan 2001).

Middle East contains six percent of world's population and keeps raising (Table 2.2), (Figure 2.2), yet just one percent of freshwater resources locates in the region (World Bank 2017).

Table 2.2 Population growth in Middle East (2005-2020) (FAO 2003).

	Total Area		**Population (millions) (2005 & 2020)**		
Subregion	**km^2**	**% Of Middle East**	**2005**	**2020**	**% Change**
Arabian Peninsula	310,029,0	47	56.8	87.3	53.69
Caucasus	186,100	3	15.9	16.7	5.0
Iran	174,515,0	27	69.5	83.4	20
Near East	153,303,0	23	140.8	171.4	21.7
Total region	656,457,0	100	283.0	358.8	-

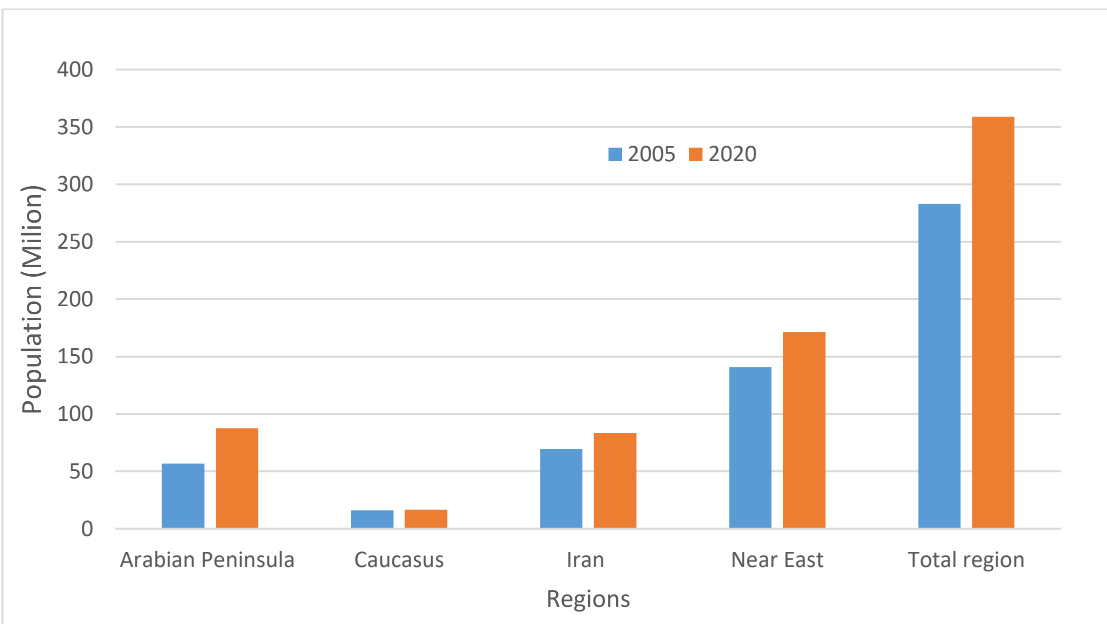

Figure 2.2 Population growth (million) in Middle East 2005-2020 (FAO 2003).

Countries suffer from absolute water scarcity when their annual water supply from natural sources drops below 500 cubic meters per person to satisfy household, agricultural and industrial needs (FAO 2003).

Accordingly, the lack of agriculture lands lead to serious problem, which is increasing desertification in the region. In addition, wastewater treatment production grows slowly in Middle East. The annual volume of wastewater discharged in untreated form in Middle East and North Africa countries are 7.5 km^3, which is 57% of the total wastewater produced in the region. In addition to about 83% of treated wastewater used in agriculture, urban and peril-urban farmers to grow a range of crops use most of the partly treated, diluted or untreated wastewater (FAO 2003).

On the other hand, Gulf countries depends on the desalination to cover up the shortage in water supplies but as mentioned earlier misusing seawater could lead to severe issues to environment and health in long run. Middle East and North Africa accounts for almost half of the total world's desalination capacity. With the fact of water shortage and lack of sustainability there must be reconsider of the existed water management in the region and suggest proper solution could reduce harm to water resources (World Bank 2017).

2.3 Modeling of Watershed Hydrology

A watershed describes an area of land that contains a common set of streams and rivers that all drain into a single larger body of water, such as a larger river, a lake, or an ocean. There are elements affecting watershed processing such as climate, topography, geology, soils, land cover, and land use and are related to the basin size. Many smaller watersheds are included within larger watersheds. It all depends on the outflow point; the watershed for that outflow area includes all of the land that drains water to the outflow point. Watersheds are critical because what happens in the land area "above" the river's outflow point affects the streamflow and water quality of the river.

Watersheds may be classified by its cover. The form and pattern we see in the landscape are the product of extensive human activity. Analyzing land use, patterns, and developments is standard practice in all areas of environmental conservation, particularly watershed protection. Since multiple uses exist in many places and some land uses are not recognizable landscape features in and of themselves, mappers often use the word land cover to characterize the delineation of landscape structure and pattern created by dominant land uses and residual vegetation groups. Urban land (residential, agricultural, manufacturing, mixed), farmland (row crops, field crops, pasture), transportation (roads, railroads, airports), rangelands, silviculture, and mining/extractive areas are several typical land cover categories. Land use patterns in a watershed, including plant patterns, may be analyzed using GIS data or maps.

Watershed models are representations of natural water system by using mathematical equations providing assessment technique for planners and designers. They are, for example, used to evaluate the quantity and quality of streamflow, maintain certain level in water reservoir, provide sustainability to groundwater, surface water and groundwater conjunctive use management, water distribution systems, water use, and a range of water resources management activities (Wurbs 1998).

Accordingly, human activity’s paly role in defining parameters such as biological population, and economic response. In addition, Models are helping to estimate the value of instream water use that allows tourism, ecological and biological issues to compete with conventional use uses, irrigation, hydropower, communities, and industry (Hickey 1999).

2.4 Floods Simulation in Arid Regions

Flood is resulting of high-intense rainfall events when water flows from upstream to downstream in natural or constructed channel. Upstream is the source when water flows from high elevated places such as mountains towards places with lower elevations which defined as downstream. The water collected in the stream channel flows to lakes, seas, and oceans. In the global hydrological cycle, the primary mechanism is the circulation of water in between the atmosphere, the surface, and the oceans. In this situation, precipitation on land and seas, evaporation from land and oceans, and drainage from land to oceans are the main components.

The flow of water through the hydrological cycle is related to the degradation and transfer of sediments and chemicals. The erosion and depositional effects of streams, tides, and ice have created a variety of Earth's landscapes that make the Earth's surface distinct from any other planet.

Floods are very rare and infrequent in arid and semi-arid regions, which are hard to predict, and can cause severe harm to people lives and infrastructure as well. Floods are divided into four categories depending on the features of the flood occurrence: flash floods that last a few hours, single-event floods that last longer, multiple event floods, and seasonal floods. Flash flooding are most common in small headwater basins during short-duration convective, frontal, or orographic storms with high-intensity rain cells.

The economic, social, and environmental consequences of flash floods are close to those of other forms of "river floods," with the only exceptions being that flash floods often occur with little, if any, notice and are usually confined to comparatively small areas. The consequences of flash flooding, on the other hand, are often devastating and depending on construction and land use in the affected basins, may result in significant loss of life due to the abrupt onset of the flood events.

Modeling methods have been widely used for over 40 years for a variety of purposes, but almost all modeling tools have been primarily developed for humid area application. Accordingly, there are concerns in using models, which were developed for humid areas in arid areas due to increasing differences in climate conditions, and parameters, which have been developed in the models (Wheatear 2008).

Rainfall- runoff relations play a major role in any hydrological study examining or evaluating effects on a catchment area, drainage basin or watershed. Rainfall is the primary hydrological input, but rainfall in arid areas is commonly characterized by extremely high spatial and temporal variability. However, in arid, the runoff generation is extremely high due to the combination between intense rainfall events and the lack of vegetation cover (Wheatear 2008).

The disparity in precipitation rate, which is minimal in arid regions due to desert conditions, is characterized as harsh climate (Table 2.3). Arid hydrology has recently become an important topic of research. With half the countries of the world facing problems of aridity. There is an increasing demand of developing hydrological parameters occurring in catchments located in arid regions (UNESCO 1979).

Accordingly, lack of water resources and high-water consumption could lead to sever impact in long term. One of the most important and immediate effects of global warming would be the changes in local and regional water availability since the climate system is interactive with the hydrologic cycle.

Table 2.3 worldwide climate conditions.

Climate classification	**Precipitation High - Low**	**Average Temp °F**
Tropical	60 – 160 inch/ year	64.4
Temperate	30 – 60 inch/ year	27 – 64.4
Continental	24 – 47 inch/ year	25 – 71
Dry	< 14 inch/ year, mostly in summer & spring	68
Polar	< 10 inch/ year, mostly in summer	< 50

Such effects may include the magnitude and timing of runoff, the frequency and intensity of floods and droughts, rainfall patterns, extreme weather events, and the quality and quantity of water availability; these changes, in turn, influence the water supply system, power generation, sediment transport and deposition, and ecosystem conservation. Table 2.4 summaries the similarities and differences between arid and non-arid regions in terms of rainfall, runoff, evaporation, transpiration, time of concentration, and data availability.

Table 2.4 Arid and non-arid regions hydrological similarities and differences.

	Arid Regions	Non-Arid Regions
Rainfall	Intensive short events, with low annual rainfall amount. Rainfall tends to be more variable than other regions.	Low intense rainfall events occur evenly through the year.
Runoff	Extreme rainfall events cause severe stream flows with irregular infiltration capacity.	Occurrence when rain falling on saturated areas. Uniform infiltration capacity
Evaporation and Transpiration	High evaporation rate from bare soil and low transpiration due to low vegetation cover. Most of rainfall occurs in summer.	Potential Evatranspiration is less than arid regions cause rainfall occurs when temperature is low (Winter).
Time of concentration	Both can be measured by 1) SCS Method 2) Velocity Method	
Data availability	Very rare	Widely available

Not all of these effects are negative, but due to progression of water consumption which affect other natural resources they need to be studied and revised in soon future. In addition, vegetation cover is extensive in humid regions compared to arid regions. Definitions of aridity depend on the purpose of the classification. They may relate to features of the Earth's surface, such as geomorphology, soil science or natural vegetation, which are effects of climate and tend to correspond with common perceptions of aridity. Most formal definitions are in terms of the causes of aridity and are often based on comparisons between precipitation and some measure of potential evaporation.

2.5 Summary

Rainfall-runoff models have parameters that been created for specific climate set. Most models are based on estimated parameters where the humid climate is dominating. Time of concentration, rainfall intensity, soil and land cover are tools help predicting flow intensity and direction. These parameters could differ from region to another.

Climate variability impacts hydrological modeling performance. Rainfall events are more intense and occurring in short duration in arid regions than humid regions. Some models are designed to analyze continuous event of precipitation, which is contrasting of what occurring in arid lands. Accordingly, vegetation cover is variant in both humid and arid regions.

However, plans in arid lands featuring with ability of water retention. The evaporation rate mostly is high in arid regions, which represent huge amount of the precipitation due to the high rate of temperature and soil group. Presenting data through hydrograph in both regions is very similar but rainfall intensity and short duration occurrence makes it flashier in arid regions.

Streamflow simulations and predictions, physical-based hydrological models have been widely applied. Among the numerous types of physically based models, fully distributed hydrological models, which can account for the geographic variability of the watershed landscape as well as its atmospheric forcing, are regarded the gold standard for hydrological modeling and have been used in ungauged basins. Physically based distributed hydrological models, on the other hand, have high computational costs and require high levels of hydrological expertise for modelers and users due to their complex model structures and extensive calculation requirements, limiting their application in water resource management.

2.5.1 Mike 11

The MIKE 11 is an implicit finite difference model for one-dimensional unstable flow computing that may be extended to looping networks and quasi-two-dimensional floodplain flow simulation. The model was created to undertake extensive river modeling, including the treatment of floodplains, road overtopping, culverts, gate openings, and weirs. MIKE 11 is a modelling package for the simulation of surface runoff, flow, sediment transport, and water quality in rivers, channels, estuaries, and floodplains (Mike 11 2005).

Mike 11 model parameters include: surface, root zone, snow melt data, ground water data, initial conditions, and irrigated area. MIKE 11 can solve vertically integrated mass and momentum equations that are kinematic, diffusive, or completely dynamic. The implicit finite difference approach is used to solve the continuity and momentum equations. This technique is designed to be independent of the wave description provided. Boundary types include water level (h), Discharge (Q), Q/h relation, wind field, dam break, and resistance factor. In the model, the water level boundary must be applied to either the upstream or downstream border condition. The discharge boundary can be used to define either the upstream or downstream boundary condition, as well as the side tributary flow. Runoff is represented by the lateral inflow. Only the downstream boundary can be used with the Q/h relation border. (Mike 11 2005).

2.5.2 Sacramento

SAC-SMA theoretically describes the hydrologically active zone of the soil as two layers, a thin top layer and a considerably larger bottom layer. Each layer consists of tension and free water storages that interact to generate soil moisture states and a total of five components of runoff. The free water components are mostly driven by gravity forces, whereas the tension water (slow) components are mostly driven by evapotranspiration and diffusion. (Burnash 1995).

The partitioning of rainfall into surface runoff and infiltration is limited by upper layer soil moisture levels and lower layer percolation potential. There is no surface runoff before the top layer's tension water capacity is filled. The content of the upper layer free water storage, as well as the insufficiency of lower layer tension water and free water storages, then influence surface runoff production.

The tension water component storages of SAC-SMA are related to plant-extractable soil moisture, while free water components are related to gravitational soil moisture (Koren 2000). Occurrence of these soil properties directly in SSURGO data is unpredictable (data records in these fields are frequently unpopulated), so the assumption made by Koren is used frequently. They estimated these properties by using STATSGO dominant texture grids available for eleven soil layers (Miller 1998).

2.5.3 Pitman

The modeling component's primary goal is to establish the hydrological baseline river basin discharge. The Pitman model includes explicit procedures for simulating interception, infiltration of surplus surface runoff, soil moisture (or unsaturated zone) runoff, groundwater recharge and drainage to stream flow, evaporative losses from the unsaturated zone, and groundwater storage (in the vicinity of the river channel). As a result, the model has a rather high number of parameters, and it is often hard to build parameter sets that provide unique results using traditional calibration methods (Kapangaziwiri 2008).

The model's potential benefit is that it can assess the various contributions to stream flow and should be responsive to changes that occur within sub-basins. Climate, land use, and land cover changes, as well as different forms of abstractions and water consumption, may all be affected by these changes (Kapangaziwiri 2008).

2.5.4 IHACRES

The IHACRES model is a simple model for simulating rainfall-runoff that requires 5 to 7 parameters to calibrate the results. This model runs simulations over a wide range of regions (up to 5000 square kilometers) and time frames. The IHACRES model, according to the majority of studies which applied the model, is an efficient and simple model for rainfall-runoff simulation that requires little data (Croke 2007).

The performance of IHACRES revealed certain flaws, although the flow comparison between calibrated stream flow findings and actual stream flow data in HEC-HMS fits well.

2.6 Impacts of Climate Variability on Hydrological Models

The fundamental problem in the simulation of rainfall-runoff in arid and semi-arid regions is due to climatic conditions. Models been used in arid lands are lacking some parts affect the accuracy and reliability of outcome results. Such as using models been created in mostly humid area with unfit parameters as an analyzing tool in arid area. There are models that have been widely used for simulating rainfall-runoff in arid regions. For instance, Mike 11 Nam was originally developed in Denmark, where the climate describes as temperate (moderate). However, this model has been applied in three different countries, Turkey, Iraq, and Iran where the climate varies. In addition, Sacramento, Pitman and IHACRES are models that been applied in many countries in middle east with lacking modification in parameters. Table 2.5 summaries four common rainfall-runoff models, their origins, where they are been applied and in which climate classification.

Table 2.5 Models widely used in different climates and locations.

Rainfall-Runoff Models	**Developed at: (Climate Region)**	**Studies and Locations (2004-2021)**	**Climate Classifications**
Mike 11 NAM	Mike 11 NAM was originally developed in Denmark, where the climate describes as temperate (moderate)	* Turkey (Keskin et al. 2008) * Iraq (Kamel. 2008) * Iran (Hafezparast et al. 2013)	* Mediterranean * Subtropical aridity * Semi-arid
Sacramento	Sacramento model was developed in Sacramento, CA, USA, where the Mediterranean climate dominates.	* Jordan (Abdulla et al. 2007) * Thailand (Yang et al. 2020) * Greece (Bournas et al. 2021)	* Hot Dry * Tropical * Mediterranean
Pitman	Pitman model was mostly developed and applied in South Africa where the climate is temperate.	* Nigeria (Owolabi et al. 2012) * Angola (Hughes et al. 2006) * Zambia (Mwelwa. 2004)	* Warm tropical * Tropical * Arid or semi-arid
IHACRES	IHACRES model was originally developed by the Australian National University	* Australia (Wheater et al. 2008) * Jordan (Abushandi et al. 2011) * Iran (Ahmadi et al. 2019)	* Tropical * Hot Dry * Semi-arid

The presented models demonstrating models were developed in humid regions, yet they have been used in arid and semi-arid widely regardless of the different parameters may or may not be suitable for those regions as mentioned earlier. In addition, the complexity of arid climate and its phenomena of precipitation intensity and land use and cover lead to put contribution in developing parameters to be used in models fitting with arid conditions.

2.7 Conclusions

This paper demonstrated that there is a process been applied for years to analyze data in arid regions that does not lead to the right results. Due to population growth with water shortage, different climate set, extreme nature of land use/cover, and rainfall intensity/duration. Modeling in arid regions is a challenge due to shortage of significant data and lack of suitable simulation software. The causes presented could be beneficial to engineers who are responsible for runoff prediction, the design of arid modeling tool, and maintenance and improvement projects in Middle East region.

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Chapter.3 Analysis of Precipitation over Tabuk Region, Saudi Arabia

Abstract

In this chapter, rainfall over Tabuk, Saudi Arabia is analyzed using data from available meteorological stations. The data obtained displaying the annual rainfall climatology over the Tabuk region (1978 - 2013); this period is chosen due to the high-quality observed rainfall data being available. This data set period is divided into three main groups as wet, average, and dry based on annual rainfall occurs periodically over the Tabuk region. The analysis of these data shows that the highest amount of rainfall occurs during the wet years was in January over Tabuk area. Whereas the highest amount of rainfall occurs during dry years was in January over the same area. The month of the lowest amount of rainfall over Tabuk during the dry years was June, when the amount of rainfall is very small. The objective of this chapter is to present Tabuk catchment climate which has common aridity characteristics in terms of the small precipitation magnitudes and temperature rate that been analyzed annually and monthly over 35-year period.

Introduction

Hydrology is a study of the process of the hydrological cycle, its temporal and spatial variations, and the interaction between water and other subsystems, such as ecology, the environment and society, in the Earth system. Construction engineering for water conservation, energy sources and transport is also essential. Hydrological phenomena are the products of interactions between atmospheric processes and land surface conditions (McCuen 2005).

Water is the most precious natural resource in arid regions due to the limitation of water resources, expanding population, and increasing volumes of industrial and domestic waste. Rainwater, surface water, and groundwater are the main natural resources of water. Preserving current resources from water depletion and limiting usage are challenge task for governments and people live in the region.

In addition to facing water resource shortages on both ground and surface water, the Kingdom of Saudi Arabia faces the issue of flash flooding almost every year. One of the main aspects of maintaining the water sector in the kingdom is excess water management. Tabuk, like many other cities in Saudi Arabia, suffers from flash floods as it belongs to an arid climate, which is exacerbated by surface water scarcity.

With its associated high demand for agricultural water, unexpected floods and strong population growth would increase the pressure on water supplies, in Tabuk, on groundwater. Water supplies are limited, however, and therefore a comprehensive understanding of potential flooding scenarios in Tabuk is a key to sustainable future management of water resources. Furthermore, a method for spatially distributed surface flow estimation for the Tabuk region is still lacking.

Actions to minimize flood risk in the Kingdom of Saudi Arabia, especially in urbanized cities such as Tabuk, require accurate predictions. In addition, accurate flash flood forecasts are crucial to surface water harvesting, which is a promising, although difficult, approach to sustainable management of water supplies in the Kingdom of Saudi Arabia.

Accurate flash flood predictions in the Tabuk area are challenging for several reasons, such as, recorded rainfall data and topographic information, which are inputs to flood prediction models, are often not available in the required spatial-temporal resolution due to a sparse observation network. Spare and unknown precipitation knowledge greatly decreases the predictive efficiency of flood prediction models.

The present-day climate of the desert and semi-desert areas is known to have changed on various temporal (interannual, interdecadal multidecadal and intersessional) and spatial scales (particularly for rainfall), which represents a major challenge for the climate forecasting and modelling of these climatic variables in these areas (Lioubimtseva 2004).

In Saudi Arabia, some areas receive their total annual rainfall in only a few days, from intense bursts of rain over a short duration such as 3 to 5 h in a day. In addition, Tabuk area, Saudi Arabia has heterogeneous hydrological characteristics that are different from those of humid and even other arid areas, particularly in terms of topography, rainfall, and flash flood patterns. The objective of this chapter is to present Tabuk catchment climate which has common aridity characteristics in terms of the small precipitation magnitudes and temperature rate that been analyzed annually and monthly over 35-year period.

3.1 Water Resources in Middle East

The Middle East has suffered from poor water resources and water management over past years. The Middle East is the first region of the world to effectively run out of water. Countries such as Saudi Arabia, Iraq, Jordan, and Yamen are facing serious issues which require immediate attention from world community (Allan 2001).

Middle East contains six percent of world's population yet just one percent of freshwater resources locates in the region. Countries suffer from absolute water scarcity when their annual water supply from natural sources drops below 500 cubic meters per person to satisfy household, agricultural and industrial needs (World Bank 2017).

The lack of agriculture lands lead to serious problem, which is increasing desertification in the region. In addition, wastewater treatment production grows slowly in Middle East. The annual volume of wastewater discharged in untreated form in Middle East and North Africa countries are 7.5 km3, which is 57% of the total wastewater produced in the region. In addition to about 83% of treated wastewater used in agriculture, most of the partly treated, diluted or untreated wastewater is used by urban and peril-urban farmers to grow a range of crops.

On the other hand, Gulf countries depends on the desalination to cover up the shortage in water supplies but as mentioned earlier misusing seawater could lead to severe issues to environment and health in long run. Middle East and North Africa accounts for almost half of the total world's desalination capacity. With the fact of water shortage and lack of sustainability there must be reconsider of the existed water management in the region and suggest proper solution could reduce harm to water resources (World Bank 2017).

3.2 Study Area, Tabuk, Saudi Arabia

3.2.1 Geography and Location

The Tabuk region is located in the extreme northwest of Saudi Arabia, with Jordan bordering on the north and the Gulf of Aqaba and the Red Sea bordering on the west (Figure 3.1). Surrounding it are three other administrative regions; Al Jouf, Hael, and Madinah. Evidently, the strategic position of the region is considered to be one of the most significant elements of economic growth due to its long sea front in the Red Sea.

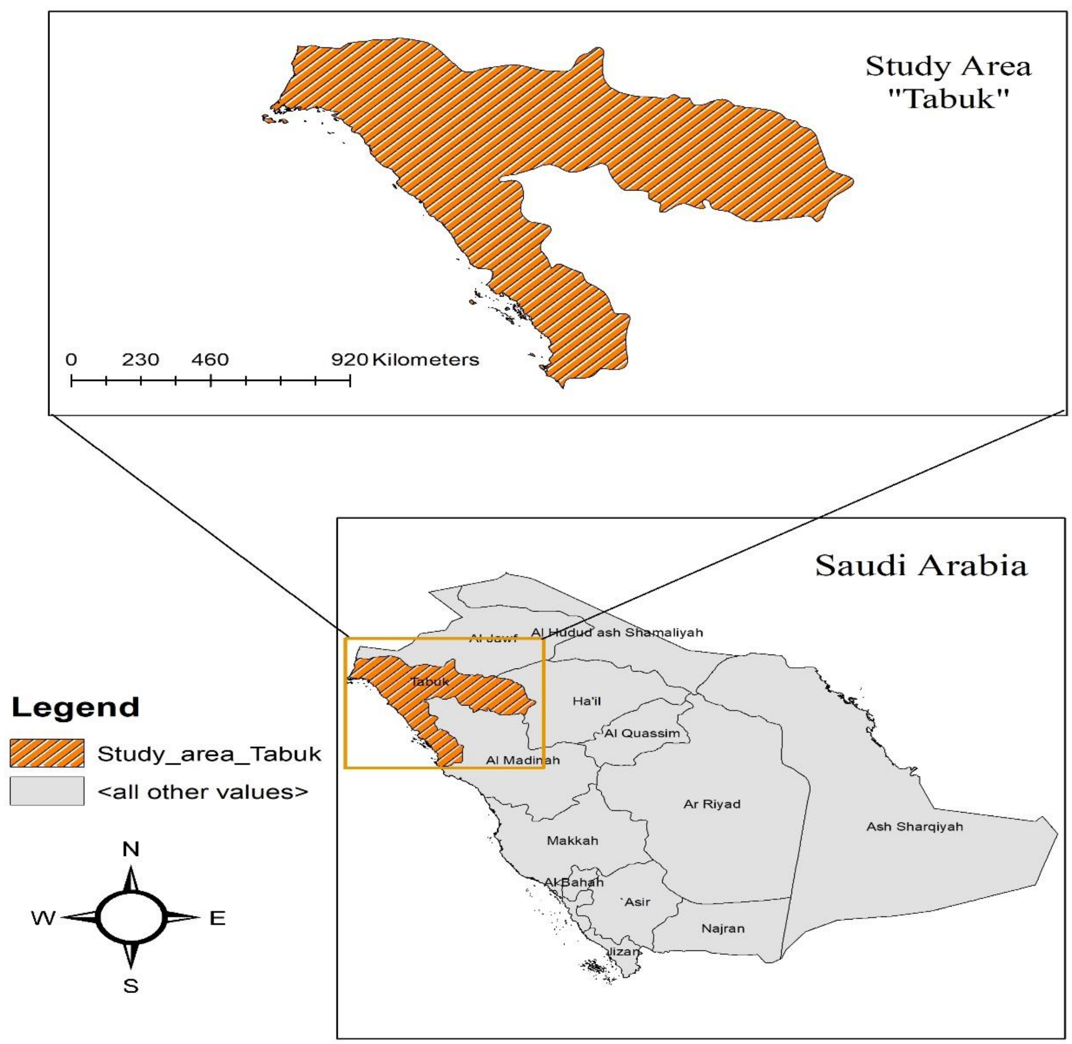

Figure 3.1 Tabuk geography region (Esri 2017).

In addition, being a border area allows a large proportion of trade access to Egypt, Jordan, Syria, Lebanon, and Turkey, as well as the movement of passengers and pilgrims from those countries and other countries in North Africa. The area of the Tabuk Region is 139,000 square kilometers or about 6.2% of the total area of the Kingdom. The Tabuk Region stretches from North to South covering over 580 kilometers and extends over 480 kilometers from East to West (UN-Habitat 2019).

3.2.2 Demographic background

According to the estimations of the Central Department of Statistics and Information, the total population of the region was projected at 887,000 people, representing about 2.88% of the total population of the Kingdom, in 2014. The Saudi population in the region is estimated to be 732,000 and 155,000 are made up of non-Saudis. The Tabuk Governorate has 72% of the total population of the region, followed by Amlaj with 7.7%, Diba with 6.6%, Wajeh with 5.6%, Taima with 4.6%, and finally Haql governorate with 3.5% of the total population. In 2004, the urbanization rate for the region was 85%, noting that this rate differs from one governorate to another (UN-Habitat 2019).

3.2.3 Land use

Land use plans were proposed based on the Regional Development Plan selected until the target year 1450H, which was the basis on which detailed studies of the Regional Sectoral Plans for services, infrastructure, and the economic base of the Tabuk Region were developed. The general framework of land use for the Regional Plan for the

Tabuk Region in 1450H noted that agricultural areas would increase to 156% of the current area of agricultural areas. For urban agglomerations, it will increase to 90% of the current status.

For industrial zones, there are two industrial cities in Duba and Tabuk as well as the industrial areas in each of the cities of Tabuk, Wajh, Dabaa, Tayma, and Amlaj. As for the tourist areas, it is spread in Tabuk and the five governorates of the region. The plan was supported by a regional road network and a head to serve the main development axes, linking the National Growth Centre with Regional Growth Centers and Local Growth Centers while supporting sub-development hubs to link regional and local growth centers with rural growth centers.

3.2.4 Environmental Aspects

Tabuk City lies at the junction of the Hejaz Mountains and the plains in the North. It is settled at an altitude of 778 meters bordered by large mountainous systems to the South as well as large areas of agriculture to the South, East, and North, and protected areas and hunting reserves further east. All these elements make Tabuk´s immediate natural surroundings a varied and characteristic environment. The region, as well as the rest of the country, has a semiarid to hyper-arid climate, characterized by high temperatures, deficient rainfall, and extremely high evapotranspiration (Saudi Ministry of Information, 1992).

Tabuk region is also characterized by its northerly cooling influences and by having the lowest winter temperature average in the country. Winter temperatures usually range between 6°C and 18°C, occasionally dropping below zero at night, and summer temperatures vary from 28°C to 40°C. Prevailing winds coming from the West also influence these temperatures.

3.2.5 Climate and Topography

The Kingdom of Saudi Arabia represents 80% of the Arabian Peninsula. Environmentally, the country is mainly formed by large sandy and rocky deserts with big mountainous systems. It also has many structural features such as 2,410 kilometers of seacoasts, 2.7 million hectares of forest land, over 171 million hectares of rangelands, 35 square kilometers of mangroves, and 1,480 square kilometers of coral reefs. These ecosystems have an incalculable value; not only do they structure the territory, but they are also key elements for the national economy and welfare of the population. Saudi Arabia has a mid to high rate of population growth, one of the few in the world, standing at 2.52% by the year 2017. If not well managed, this growth can impact and deteriorate natural systems, affecting biodiversity and ecosystems' dynamics (Saudi Ministry of Information, 1992).

In the case of both the Tabuk Region and the city of Tabuk different drivers of environmental degradation have been identified. On the one hand, unsustainable growth patterns and inadequate infrastructure are challenging future economic development and compromising existing natural resources. On the other hand, the burden on the environment is exacerbated by climate change, which is currently driving the already severe climate to more extreme conditions (UN-Habitat 2019).

3.3 Precipitation

The dominant contribution to the low annual average rainfall in arid regions is short, high intensity rainstorms. Rainfall in the Tabuk region (Figure 3.2) appears to differ considerably from year to year, with an erratic distribution in time and space.

As an illustrative example of the extreme yearly variability, Tabuk rain gauge measured the annual rainfall to be 6.8, 13.70, 21.90, 13.00, 39.60, 51.10, and 13.50 mm over seven years. On one single day, 76.60 mm of rainfall occurred, even though the total annual rainfall in the same year was 92.20 mm observed data from Tabuk rain gauge. These types of rainfall events can lead to substantial surface runoff, resulting in severe soil erosion. Weather behavior and topographical characteristics play important roles in this variation. Around 70% of the total annual rainfall occurs during November, December, January, February, and March.

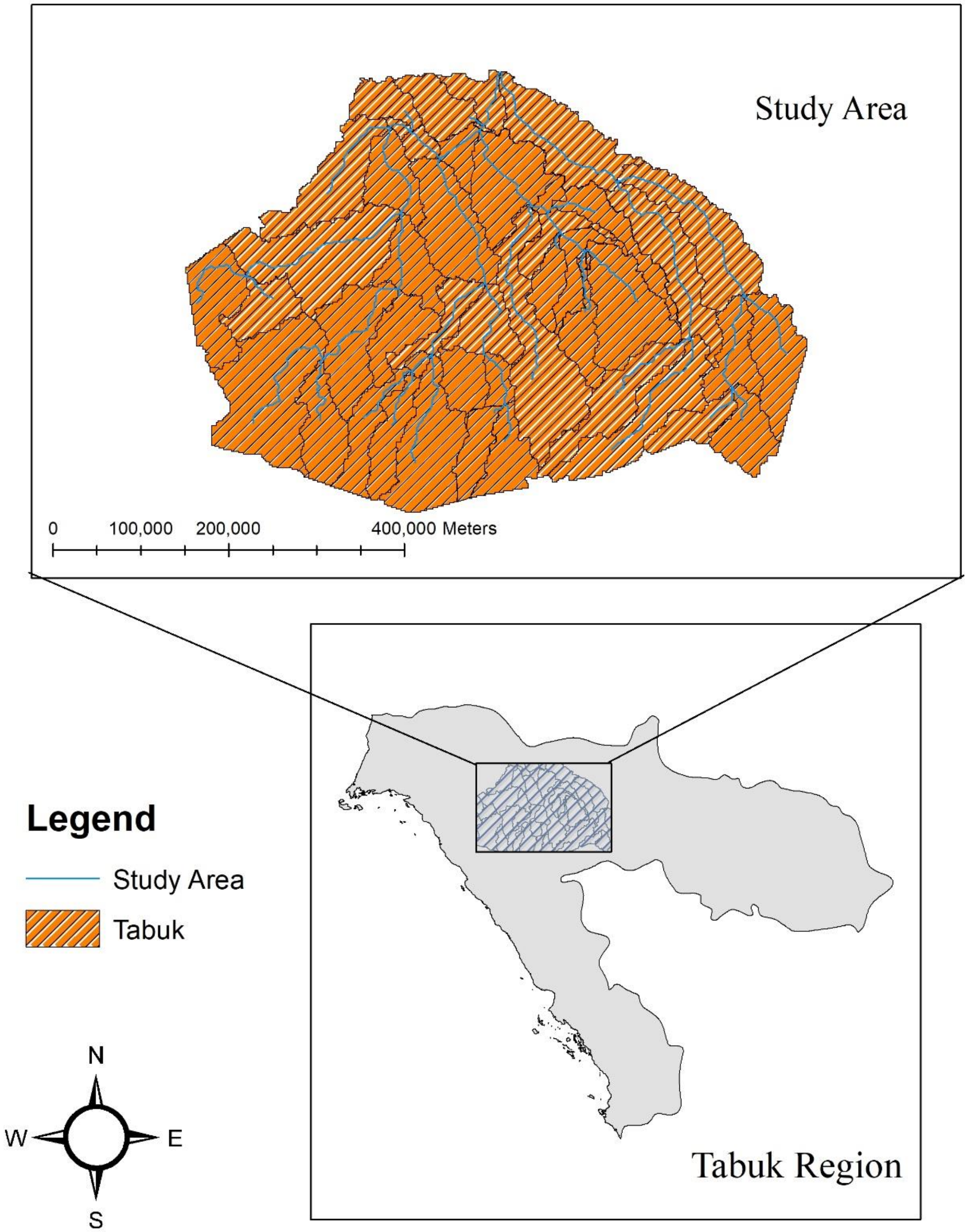

Figure 3.2 Tabuk watershed area and stream flows (Esri 2017).

3.4 Temperature

The entire Tabuk region investigated here currently has one climatic station. Tabuk station, that has complete climatic data, is located in Tabuk City. Tabuk climate is characterized by warm and dry summers (May to September) with mean degree 28.54, 32.43, 34.48, 34.67, and 31.26 °C respectively. In addition to moderate cold and wet winters (October to April) (Table 3.1). The average annual temperature is 23.52 °C (1999–2018).

Table.3.1 Temperature description for the period of 1999–2018 (Tabuk Meteorological Station).

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Average °C	10.59	13.40	17.96	23.66	28.54	32.43
Month	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Average °C	34.48	34.67	31.26	25.64	17.31	12.25

3.5 Surface runoff

Tabuk catchment is exemplified by ephemeral wadis, where a stream runs fully for a short period of time, usually during and after heavy rain events, and is dry most of the year. Flash floods events fill desert dams and may recharge groundwater resources. The complex relationship between rainfall and streamflow is influenced by many factors, such as catchment slope, land cover type and density, soil type and infiltration rate, and evapotranspiration. Moreover, the quality and quantity of streamflow are strongly affected by urbanization and agricultural activity.

3.6 Methodology

Define precipitation data between the years 1978 and 2013 at daily time intervals have been gathered, including historical and real-time observations. In addition, daily data for the selected years were available. Detection and filtering of abnormal and missing data were automated using statistical routines. The data set includes annual and monthly precipitation were provided by Tabuk meteorological station. However, the application of any climate model requires a validation process to make sure that the results are in an acceptable range.

3.7 Statistical Analysis

Statistics are used to display and analyze the remote sensing data. The remote sensing data of this study consist of the Tabuk watershed for 1978 and 2013. The objective of using these statistics in this research is to provide the descriptive analyses to identify the general magnitude of all observations in a data set. The mean or average was the statistical measure used in this study. The standard deviation, also an important measurement, can be used to measure how closely the values of a data set are near the mean. In addition, the minimum, maximum, and range are a group of measurements that help in describing the data set.

3.7.1 Mean

The mean of a list of numbers is the sum of the list divided by the number of items in the list (Yamen 1967). The mean is the most commonly used type of average and is often referred to as simply the average. The mean (μ) is defined as:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The mean calculation is used to calculate the average monthly rainfall. In Microsoft® Excel, the function '= AVERAGE (N1:N2)' is used to calculate the mean for a list of data.

3.7.2 Standard Deviation

The standard deviation measures the degree to which data are concentrated around the mean. A small standard deviation means that the values in a statistical dataset are close to the mean of that dataset, on average. The standard deviation (σ) of a data set is the square root of its variance.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{1} (x_i - \mu)^2}$$

The standard deviation was used to define the climate classification for the annual analysis. In Microsoft® Excel the function '= STDEV (N1:N2)' is used to calculate the standard deviation for a list of data.

3.7.3 Coefficient of Variance

The coefficient of variance was applied, using the following formula:

$$\mathrm{CV} = \frac{\sigma}{\mu}$$

Where o is the standard deviation and p. is the mean of the data set (Mann, 1998). This equation reveals the relative variability of the rainfall data and the many differences of rainfall values.

3.7.4 Skewness

In probability and statistics, skewness is a measure of the degree of asymmetry of a distribution (Yamane 1967). A distribution is considered to be skewed if the tail on one side of the distribution is longer than the tail on the other side. If the data is skewed in the direction of higher values, it is positive skewed. If the opposite is true, it has a negative skewness. In a perfect distribution there will be no skewness and the skew value will be zero. The skewness was used to determine whether the data fit a normal or log normal distribution. In Microsoft® Excel the function '= SKEW (N1:N2)' is used to calculate the skewness for a list of data.

3.8 Climate Classification

In this study, climate classification divides climates into three main climate groups, with each group being divided based on annual precipitation. The three main groups are wet, average, and dry. The mean and standard deviation are two statistical tools involved in cataloging climate. The parameters listing below (Table 3.2) demonstrating how data is shifting form its mean which creates the three groups of climate classification.

Table 3.2 Boundaries for climate classification Based on Precipitation (Ruppert 2019)

	Parameter	**Classification**
Above	Average + 0.5* Standard Deviation	Wet
Between	Average + 0.5xStandard Deviation & Average - 0.5xStandard Deviation	Average
Below	Average - 0.5* Standard Deviation	Dry

3.9 Results

This study evaluated the annual rainfall for the Tabuk region obtained from observed datasets for the period 1978–2013. Over the region (1978-2004), there is a drop in the annual rainfall for the observed datasets, from approximately 25-30 mm to approximately 5-10 mm (Figure 3.3). The lowest annual rainfall (0 – 6.0 mm) occurs over the Tabuk region in the year 2004, which is mainly the driest year in 35-year period. Across the region, the mean annual rainfall is less than 33.5 mm, thus classifying the climatic conditions of the Tabuk region.

However, rainfall in the year 2013 of the region ranges from 90 -100 mm which is the highest recorded in the dataset. These results for annual rainfall in the Tabuk region are consistent with the available reported information. Table 3.3 displays the annual rainfall climatology over the Tabuk region for the period 1978 - 2013; this period is chosen due to the high-quality observed rainfall data being available.

Similarly, the period 1978–2013 discussed earlier, the data set period (year) is divided into three main groups as wet, average, and dry based on annual rainfall occurs periodically over the Tabuk region. The dry years (1978, 1981, 1983, 1990, 1995, 1998, 2002, 2003, 2004, 2008, 2011) and wet years (1979, 1982, 1985, 1986 1987, 1988, 1989, 1991, 1994, 2010, 2013) representing the first degree of shifting the data from its mean. Thus, the results produced by the observed rainfall patterns over Tabuk region encourage the use of these datasets for studying the rainfall characteristics of the region. The average rainfall for Tabuk over different time scales is obtained from the observational datasets and are summarized (Tables 3.5, 3.6, and 3.7).

3.9.1 Annual Analysis

The plot in Figure 3-3 presents the annual rainfall of the Tabuk, Saudi Arabia from 1978 to 2013. Note that the total rainfall in the figure is observed data from Tabuk metrological gauge.

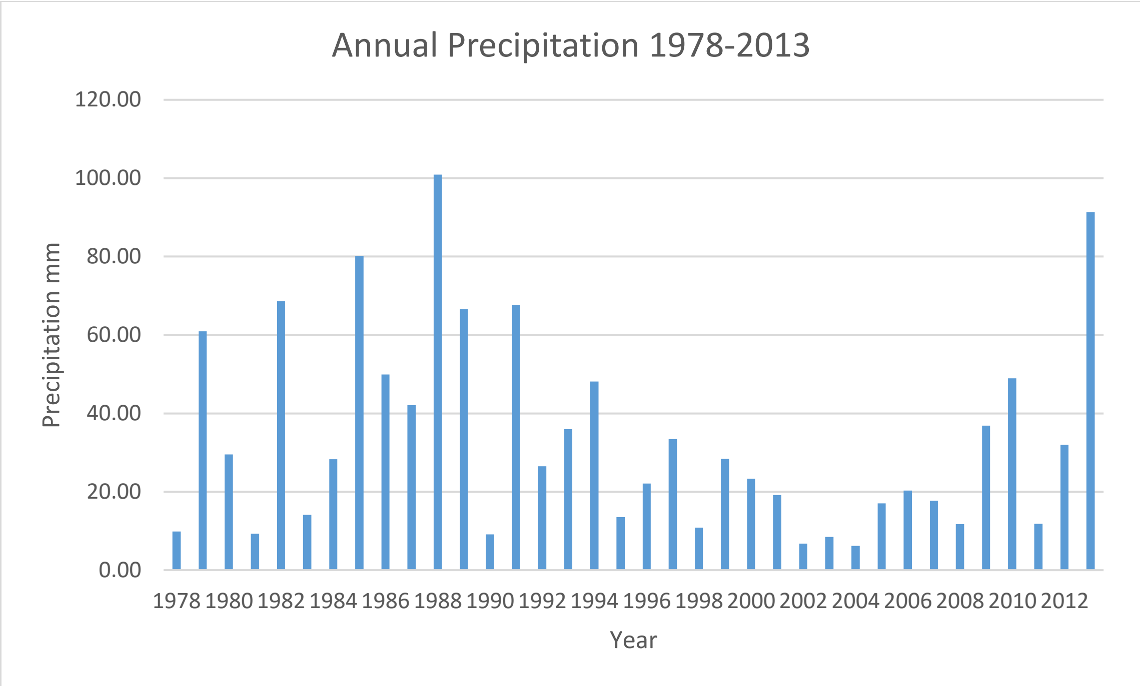

Figure 3.3 Annual precipitation data for Tabuk region over 35 year.

The results indicate that the year with the highest annual rainfall was 1988, with a total annual rainfall of 100.90 mm. whereas, 2004 had the lowest total annual rainfall of 6.20 mm.

The average annual rainfall was 33.54 mm and standard deviation was 25.33. Any year with average annual rainfall higher that the average plus a half times the standard deviation is considered to be a wet year. Years with average annual rainfall that falls between the average plus half the standard deviation and the average minus half the standard deviation are considered average years. Years with average annual rainfall that fall between the average minus half the standard deviation are considered to be dry years. Table 3.3 shows the years sorted into the climate classifications and Table 3.4 shows the cut-off values used in the analysis.

Table 3.3 Wet, Average, Dry, Climate Classification.

Climate Classification (Years)		
Wet	**Average**	**Dry**
1979	1980	1978
1982	1984	1981
1985	1992	1983
1986	1993	1990
1987	1996	1995
1988	1997	1998
1989	1999	2002
1991	2000	2003
1994	2001	2004
2010	2005	2008
2013	2006	2011
	2007	
	2009	
	2012	

Table 3.4 Cutoff Values for the Climate Classification of Annual Precipitation (1978-2013)

Analysis of Annual Rainfall of the Tabuk (1978-2013)		
Parameter	**Log Transformed (mm)**	**Non-Log Transformed (mm)**
Average - 1/2 STDEV	1.27	20.83
Average	1.41	32.11
Average + 1/2 STDEV	1.56	43.38

3.9.2 Monthly Analysis

From the information gained in the annual analysis of annual rainfall, the monthly analysis (Figure 3.4) could then be conducted. The main information needed from the annual analysis was the climate classification of wet, average, dry for each year (Table 3.3). Each year was normally distributed into 12 months a year. Month of the year in order from January to December were presented in the graphs. The years were separated into 3 different tables depending on their climate classification (wet, average, dry) and then the average and total rainfall for each month was found, along with the standard deviation for each group (Tables 3.5, 3.6, and 3.7).

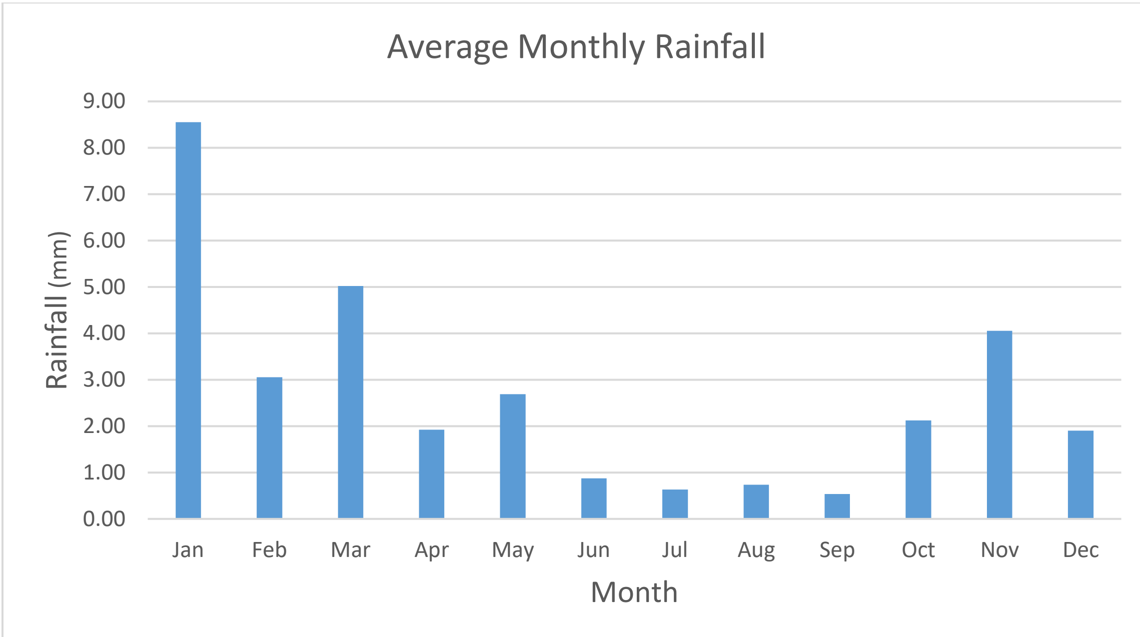

Figure 3.4 Monthly Rainfall Record for Tabuk 1978-2013.

Table 3.5 Total, Average, Standard Deviation and Coefficient of Variance for each year Classified as Wet Year.

Wet Years												
Rainfall mm												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979	0.10	24.60	0.10	0.10	13.60	0.10	0.00	0.00	0.00	17.50	0.30	4.50
1982	2.00	2.10	0.50	25.60	20.90	0.00	0.00	0.00	1.00	1.00	15.50	0.00
1985	0.30	1.50	3.10	4.30	0.60	0.00	0.00	0.00	0.00	0.10	10.90	59.40
1986	0.70	0.00	18.50	12.70	0.00	0.00	0.00	0.00	0.00	1.00	17.00	0.00
1987	0.00	0.50	0.40	0.00	0.20	0.00	0.00	0.30	0.00	26.30	0.00	14.40
1988	9.50	0.20	1.10	13.00	2.20	0.00	0.00	0.00	0.00	52.70	0.00	22.20
1989	21.00	0.00	6.00	1.50	0.50	0.00	0.00	0.00	0.00	0.00	19.50	18.10
1991	36.20	0.20	24.20	0.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00	1.10
1994	5.20	0.60	0.00	0.20	1.50	0.00	0.00	0.00	1.90	25.00	13.40	0.30
2010	38.80	0.00	0.70	0.10	5.00	0.00	0.00	0.00	0.00	0.00	0.00	4.30
2013	75.60	5.50	0.00	0.00	0.50	0.00	0.00	0.00	0.10	0.00	0.00	9.80
Total	189.40	35.20	54.60	57.50	45.00	0.10	0.00	0.30	3.00	129.60	76.60	134.10
Mean	17.22	3.20	4.96	5.23	4.09	0.01	0.00	0.03	0.27	11.78	6.96	12.19
STDEV	24.15	7.28	8.39	8.40	6.86	0.03	0.00	0.09	0.62	17.06	8.21	17.49
CV	1.40	2.28	1.69	1.61	1.68	3.32	0.00	3.32	2.26	1.45	1.18	1.43
Max	75.60	24.60	24.20	25.60	20.90	0.10	0.00	0.30	1.90	52.70	19.50	59.40

Table 3.5 presents that January had the highest average rainfall for wet years with an average rainfall value of 17.22 mm. The highest monthly rainfall value for January was 75.60 mm in 2013 and it approximate represents 65.0% of the total rainfall occurred in January during the wet years. The lowest January monthly rainfall occurred in 2009, 2014, 2015, 2017 and it was zero. The month with the lowest average annual rainfall for wet years was September with an average rainfall value of 0.33 mm. In wet years, there is one dominating rain season (Oct-Jan) with total rain of 529.70 mm which is 73% from

the total rain 725.30 mm while the total rain in period of (Feb-May) is set to be 192.30 which is only 26%.

Table 3.6 Total, Average, and Standard Deviation and Coefficient of Variance for each year Classified as Average Year.

Average Years												
Rainfall mm												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980	0.80	13.80	0.80	0.10	0.50	0.00	0.00	0.00	0.10	4.10	2.20	7.10
1984	0.10	0.10	2.60	0.00	0.00	0.00	0.00	0.00	0.00	18.70	6.80	0.00
1992	2.00	1.40	0.00	0.00	0.00	0.00	0.00	20.00	0.00	0.00	2.40	0.70
1993	1.40	1.40	0.30	4.80	0.90	0.00	0.00	0.00	0.00	9.50	0.00	17.70
1996	0.70	0.00	1.40	0.10	0.00	0.00	1.60	1.00	1.00	0.00	12.10	4.20
1997	21.10	0.10	2.50	0.00	2.80	0.00	0.00	0.00	0.00	6.60	0.00	0.30
1999	2.60	14.00	11.40	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.20
2000	7.60	2.50	0.00	0.00	0.20	0.00	0.20	0.00	0.00	1.10	7.70	4.00
2001	2.30	0.20	1.90	12.60	1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.40
2005	7.90	2.00	4.10	1.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2006	0.00	6.00	8.40	0.00	5.70	0.00	0.00	0.00	0.00	0.10	0.10	0.00
2007	7.50	2.30	3.00	1.20	2.40	0.00	0.00	0.00	0.00	1.30	0.00	0.00
2009	0.00	1.30	0.00	0.00	23.50	8.00	0.00	0.00	0.00	0.00	4.10	0.00
2012	0.10	5.30	0.10	8.50	0.00	0.00	0.00	0.00	0.10	16.80	1.10	0.00
Total	54.10	50.40	36.50	28.30	40.00	8.00	1.80	21.00	1.20	58.20	36.50	34.60
Mean	3.86	3.60	2.61	2.02	2.86	0.57	0.13	1.50	0.09	4.16	2.61	2.47
STDEV	5.76	4.73	3.40	3.92	6.15	2.14	0.43	5.33	0.27	6.47	3.78	4.90
CV	1.49	1.31	1.31	1.94	2.15	3.74	3.32	3.55	3.10	1.56	1.45	1.98
Max	21.10	14.00	11.40	12.60	23.50	8.00	1.60	20.00	1.00	18.70	12.10	17.70

However, in Table 3.6, Jan had the highest average rainfall for the average years with an average rainfall value of 3.86 mm. The highest monthly rainfall value for the Jan was 21.10 mm and it approximate represents 39% during the average years. The lowest Jan rainfall occurred in 2006 and 2009. These years having an average rainfall of zero. The month with the lowest average rainfall for average years was the Sep with an average rainfall value of 0.09 mm. 1996 had the highest Sep rainfall with a value of 1.00 mm.

Table 3.7 Total, Average, Standard Deviation and Coefficient of Variance for each year Classified as Dry Year.

Dry Years												
Rainfall mm												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1978	0.00	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	8.40
1981	0.00	1.00	2.20	0.60	2.00	0.00	1.00	2.20	0.00	0.30	0.00	0.00
1983	2.00	3.00	1.90	0.00	3.60	1.00	0.00	0.10	0.00	0.00	0.00	2.50
1990	2.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00	3.20	0.00	1.90
1995	0.20	0.40	10.90	0.20	1.00	0.00	0.00	0.00	0.10	0.10	0.20	0.40
1998	3.40	1.60	3.20	0.20	2.20	0.00	0.00	0.10	0.00	0.00	0.10	0.00
2002	1.70	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	2.60	0.00
2003	1.00	0.00	0.00	0.00	3.00	0.00	0.00	3.00	0.00	0.10	0.00	1.20
2004	5.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.10	0.10
2008	8.50	1.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.50
2011	3.80	3.20	0.20	4.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	27.60	13.20	18.60	7.60	11.80	1.00	1.00	5.40	0.10	5.70	4.50	15.00
Mean	2.51	1.20	1.69	0.69	1.07	0.09	0.09	0.49	0.01	0.52	0.41	1.36
STDEV	2.57	1.07	3.26	1.43	1.38	0.30	0.30	1.06	0.03	0.99	0.85	2.49
CV	1.02	0.89	1.93	2.06	1.29	3.32	3.32	2.16	3.32	1.91	2.08	1.82
Max	8.50	3.20	10.90	4.60	3.60	1.00	1.00	3.00	0.10	3.20	2.60	8.40

January had the highest average rainfall in dry years with an average rainfall value of 2.51 mm (Table 3.7). The highest monthly rainfall value for the January was 8.50 and it represents 30% of the total rainfall during the dry years. The lowest January rainfall occurred in 1978 and 1981 having a rainfall value of zero. In addition, Sep was the month with the lowest average rainfall for dry years with an average rainfall value of

0.01 mm. 1995 had the highest Sep rainfall with a value of 0.10 mm. The lowest rainfall value was with a rainfall value of zero. In dry years, there are two equal rain seasons with 52.80 mm (Oct-Jan) and 51.20 mm (Feb-May). These two seasons equally represent 50% of the total rainfall during dry years.

3.10 Discussion

Tabuk climate behavior has wide rang in both space and time, thus causing and affecting the precipitation magnitudes. For this reason, Tabuk arid catchments are more open to simplified models.

The results have wide-ranging practical and scientific significance. First of all, they will provide a modelling framework for a regional climate classification in the Tabuk Region, based on a detailed observed data presented monthly and annually. The modelling framework may assist future water resource management, which will face increasing water scarcity in the study region. In addition, this study successfully tested the existing applicability of climate and precipitation models in arid regions, which are usually not in the focus of hydrological model development (Wheater 2008).

To explore the links between climate and rainfall intensity in Tabuk region, this study analyzed 35-year of detailed rainfall data monthly measured from a meteorological station. In Tabuk catchment, most rainfall events are based on one or two incidents which contains high percentage of the total rainfall recorded. Those short and intense events are mainly the reason of flash flooding besides lacking vegetation cover and poor infrastructure facilities.

The total annual rainfall showed an increase above the normal occurring once in four or five years. Also, total annual rainfall is an excellent indicator of whether the year experienced an acute rainfall deficiency (less than 60 mm). For the past four decades rainfall has been recorded in the study area (Figure 3.3). Rainfall was considered as the main factor in dealing with understanding whether the study area has suffered an above or below normal receipt of atmospheric moisture.

Initially, climatic analysis of rainfall showed that the study area has climatic characteristics of an extreme arid environment. Nevertheless, the study area has the advantage of rainfall occurring in the winter season, which increases moisture effectiveness and the availability of existing vegetation to maximize the life-supporting impact of small amounts of water. However, the summer season receives little rainfall comparing to winter season.

The Tabuk area has the typical arid environment, characterized by low rainfall that may cause temporary and long-term deterioration in the natural landscape. Rainfall, prior to the 1988 was much higher or above normal, compared to the last twenty years of data set, which means that the wet condition was dominating in that period. On the other hand, the rainfall data for the period between 1990 and 2010 indicates that the Tabuk area has been subjected to limited rainfall.

The preliminary analysis of rainfall data revealed that the annual average rainfall in the region varies from 6 mm/year to 100 mm/year, with a weighted average rainfall of 33.54 mm/year for the entire command area. A total of 60% of total annual rainfall occurs in the wet years.

Most of wet years were placed in the first 20-year of the data set. This divided data into two subjected pattern which represents a series of wet years occurrence with total annual precipitation above the average. As expected, we found that statistically defined wet years have occurred more frequently in more earlier decades relative to recent decades. With this pattern evident nine years of the total wet years occurred in (1979-1994). No such decadal patterns were evident in the occurrence of extreme dry years. Furthermore, when each climate classification was analyzed separately, differences among years in these precipitation regimes also were significant. When comparing wet vs. dry years, the total amount of precipitation that was most important for distinguishing these two types of years.

The variability of annual and seasonal rainfall and rainy days was evaluated using the CV. The Coefficient of Variation indicated the relative variability of annual rainfall is higher for 1978, 1984, 1985, 1987,1992, 1995, 2004, 2008, 2010, and 2013 and these years have showed great variability in rainfall for all months. The CV for weighted mean seasonal rainfall of the command area is approximately 2.04. A data series with smaller variation will have lower CV, and the numerical value of the CV depends on the value range of the data series. Ideally annual rainfall or seasonal rainfall should not show any variation; however, the annual or seasonal rainfall does exhibit variation.

In wet years, there are high variations in June and August (3.32). whereas January and November calculated as 1.40 and 1.18 respectively which are the lowest. This shows that there is high variation during summer season which may be due to some intense rainstorms. These rainstorms are the primary cause of generating floods during summer season in wet years.

Average years have similar case to wet years when high variations occur in June and August. whereas February and March were calculated as 1.31 which is the lowest. This shows that there is high variation during summer season which may cause some intense rainstorms. These rainstorms are the primary cause of generating floods during summer season in average years.

In dry years, there are high variations in June and August (3.32) which the case in wet years. whereas January and February calculated as 1.02 and 0.89 respectively which are the lowest. This shows that there is high variation during summer season which may cause some intense rainstorms. These rainstorms are the primary cause of generating floods during summer season in wet years.

Overall, there is a significant variation in wet and dry years during summer season when there is high potential of flooding occurrence compared to average years. This sort of floods is difficult to predict and can cause severe harm to people lives and infrastructure as well. The low amount of annual precipitation due to the desert weather may lead to false estimation of flooding hazards. Rainfall events in arid regions is characterized as short-high intense which means most of water turns to generate surface flow.

This chapter presents a hydrologically motivated alternative to traditional climate classification schemes, accounting for gradual changes in climate and the influence that has on flow regimes and streamflow signatures. We find that the wide range and high variation in wet years are the primary cause of generating floods during winter season while the variation in average and dry years extended to cover the summer in addition to the winter.

3.11 Conclusion

In this chapter, the climatology of monthly and annual rainfall in the Tabuk region has been analyzed using the available data from Tabuk meteorological station. The mean amount of annual rainfall seems to be homogeneous.

Analysis of these data shows that the highest amounts of rainfall occur during November in the wet years. While the highest amounts of rainfall occur during the average years in March. Dry years are the lowest annual rainfall in Tabuk, when the climate is harsh and temperature degree gets to its maximum in Jun, July, and August.

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Chapter.4 Assessment of Flood Hazards over Tabuk City, Saudi Arabia

Abstract

In this Chapter, flooding phenomena over Tabuk, Saudi Arabia was analyzed using rainfall data from available meteorological stations. The data obtained displaying the daily, monthly, and annual rainfall climatology over the Tabuk region (1978 - 2013); this time period is chosen due to the high-quality observed rainfall data being available. This paper constructed hydrologic and hydraulic models to quantify flood hazards in the city of Tabuk. The catchment was divided into sub-catchments in the urban portion of the catchment. The hydrologic/hydraulic model simulations quantified the runoff corresponding to different storms and helped delineate the resulting flood inundation maps. The results of this study can be utilized for planning purposes and in the design of flood control project as it has quantized the runoff corresponding to different design storms and used hydraulics and geospatial data in delineating the flood zones.

Introduction

Annually, the Kingdom of Saudi Arabia experiences flash flooding risks in addition to confronting water resource limitations in both surface and groundwater. Flooding regime generates from short intense precipitation events in arid region where Tabuk is located.

Floods are a climatic phenomenon that can occur at any time. Compared to riverine floods, which occur when water levels increase to the point that they overflow riverbanks and inundate floodplains, flash floods are more severe since they occur suddenly and with violent water motions, resulting in more deaths of unprotected citizens. (Montz 2002; Ruin 2008; Pollak 2009; Ruin 2009; Calianno 2013).

The degree of urbanization and growth of the built environment; the demographic, social, cultural, and political economic circumstances of its people; and its political ecology and government action plan on climate governance, as well as measures for coping, adaptation, and prevention of hazards determine a city's vulnerability to flash flooding. (Hewitt 1983; Liverman 1990; Blaikie 1994; Bohle 1994; Liverman 2015).

Tabuk's flash flooding is not an exception to this pattern. Rapid population development, urbanization, and the transformation of vast areas of sandy desert into concrete constructed impervious surfaces that delay rainwater runoff have significantly increased the risk of dangerous flash flooding events in Tabuk for the next 25 years due to the lack of a river and drainage outlets to the sea (Sharif 2014). Hence, flash flood mitigation has now become a major challenge for the Tabuk’s city planners (Nahiduzzaman 2015). It is critical to recognize the city areas and residents that are vulnerable to flash flooding in order to prepare effective flood mitigation plans for the city. (Ewea 2010; Alamri 2011; Saud 2012). The purpose of this study is providing an assessment and evaluating flood hazards for Tabuk region.

4.1 Flood modeling in arid region

Rainfall- runoff relations play a major role in any hydrological study examining or evaluating effects on a catchment area, drainage basin or watershed. Rainfall is the primary hydrological input, but rainfall in arid and semi-arid areas is commonly characterized by extremely high spatial and temporal variability (Wheater 2008).

However, in arid region, the runoff generation is extremely high due to the combination between intense rainfall events and the lack of vegetation cover. Flow regime from a catchment is the result of a dynamic combination of climatologic and catchment characteristics, and this interaction affects runoff's spatial and temporal variability. Furthermore, watershed attributes such as area, catchment size, slope, channel network, soil, vegetation cover, and underlying geology are all influencing runoff generation.

Understanding the spatial and temporal variance of model inputs and controls, as well as their use in distributed modeling, improves our understanding and ability to simulate diverse hydrological processes. The remote sensing and Geographic Information System (GIS) developments are now well-established methods for producing and interpreting spatially dispersed data for use in distributed hydrological models.

Runoff modeling clarify different components of hydrologic phenomena and how changes affect the hydrological cycle (Xu 2002). Runoff models visualize what occurs in water systems due to changes in pervious surfaces, vegetation, and meteorological events. Runoff model is defined as a set of equations that aid in the estimation of the amount of rainfall that turns into runoff as a function of various parameters used to describe the watershed (Devi 2014).

Modeling surface runoff can be difficult, for the calculation is complex and involves many interconnected variables. General components of a model include inputs, governing equations, boundary conditions or parameters, model processes, and outputs (Singh 1995). Surface runoff modeling is used to understand catchment yields and responses, estimate water availability, changes over time, and forecasting (Vaze 2012).

Most rainfall–runoff models are developed primarily for scientific purposes in order to formalize information about hydrological processes. The demonstration of such awareness is a crucial step in the development of a scientific field. We normally benefit the best when a model or hypothesis is found to be in disagreement with accurate evidence, necessitating a change in the interpretation upon which the model is based. However, the ultimate goal of prediction using models must be to enhance decision making regarding a hydrological issue, whether in water supply preparation, flood control, pollution prevention, abstraction licensing, or other fields.

4.2 Study area

The Tabuk Region is located in Saudi Arabia's extreme northwest, with Jordan to the north and the Gulf of Aqaba and the Red Sea to the west (Figure 4.1). The area of the Tabuk Region is 139,000 square kilometers or about 6.2% of the total area of the Kingdom. The Tabuk Region stretches from North to South covering over 580 kilometers and extends over 480 kilometers from East to West (UN-Habitat 2019). The region, as well as the rest of the country, has an arid climate, characterized by high temperatures, deficient rainfall, and extremely high evapotranspiration.

Tabuk region is also characterized by its northerly cooling influences and by having the lowest winter temperature average in the country. Winter temperatures usually range between 6°C and 18°C, occasionally dropping below zero at night, and summer temperatures vary from 28°C to 40°C. Prevailing winds coming from the West also influence these temperatures.

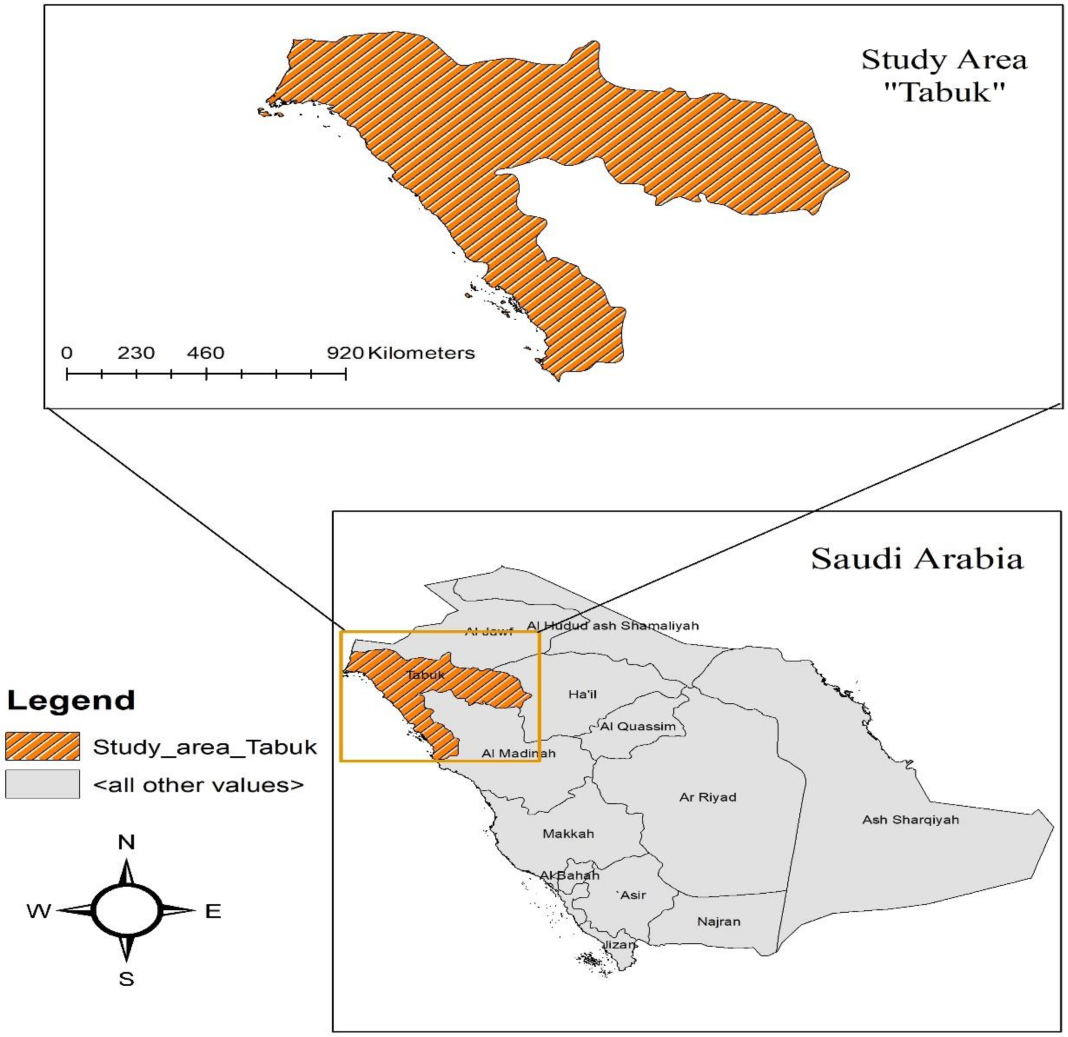

Figure 4.1 Tabuk geography region (Esri 2017).

Tabuk catchment is exemplified by ephemeral wadis, where a stream runs fully for a short period of time, usually during and after heavy rain events, and is dry most of the year. Flash floods events fill desert dams and may recharge groundwater resources. The complex relationship between rainfall and streamflow is influenced by many factors, such as catchment slope, land cover type and density, soil type and infiltration rate, and evapotranspiration. Moreover, the quality and quantity of streamflow are strongly affected by urbanization and agricultural activity.

In Tabuk, precipitation events are generated by short, high intensity rainstorms which account for the dominant contribution to the low annual total rainfall in arid regions. Rainfall in Tabuk region tends to vary markedly from year to year with an irregular distribution in time and space. As an illustrative example of the extreme yearly variability in Tabuk region. (Figure 4.2).

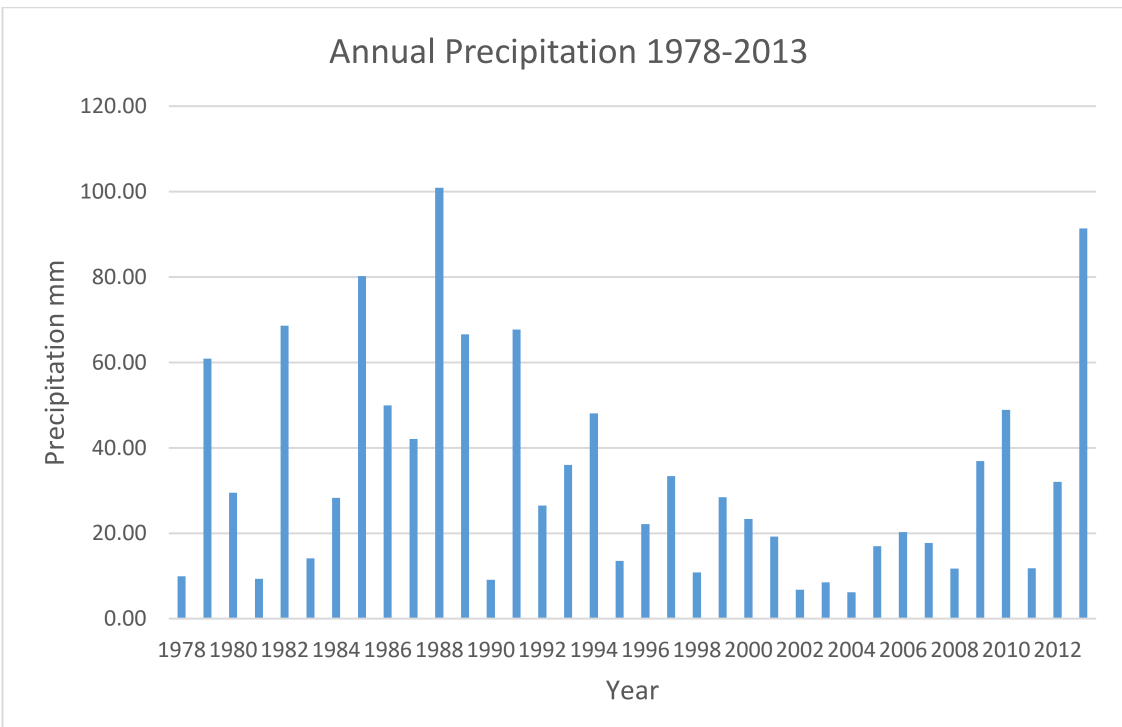

Figure 4.2 annual precipitation data for Tabuk region over 35 year (1978-2013).

The annual and seasonal patterns, as well as the overall amount of precipitation, are critical components of water balance equation. With harsh climate in arid regions, when there is a serious scarcity of available water, preserving natural resources is essential for the continuation of life. For this reason, modeling the real water system by combining these two sciences, geography and hydrology is important to observing water movement and distribution on earth.

Tabuk has several rainy seasons which can be investigated from annual observed data. There are three scenarios describing Tabuk precipitation occurrence pattern. First, in wet years when the annual total rainfall is above 40 mm, the potential of rain occurrence is starting from October and ending in January which representing one heavy rain season. The potential of having two rainy seasons (Oct-Jan and Feb-May) is high where the mean of annual rainfall is below 36 mm which classified as average and dry years.

4.2.1 Wadi Abu Nashayfah

The downstream control point is located at Wadi Abu Nishayfah, which is the longest wadi crossing the city of Tabuk at 25 km long (Figure 4.3). This wadi has an arid climate. The city of Tabuk's culverts and bridges are specifically designed to avoid ephemeral flash flood incidents. Wadi Abu Nishayfah was measured and divided into three essential sections based on cross sectional characteristics mainly the width of channel (Wadi). This channel is 25 km long. This channel was divided into three sections based on channel width. First section is 90 m width at upstream along with second section 130 m and last section 160 m at downstream (Figures 4.4, 4.5, and 4.6).

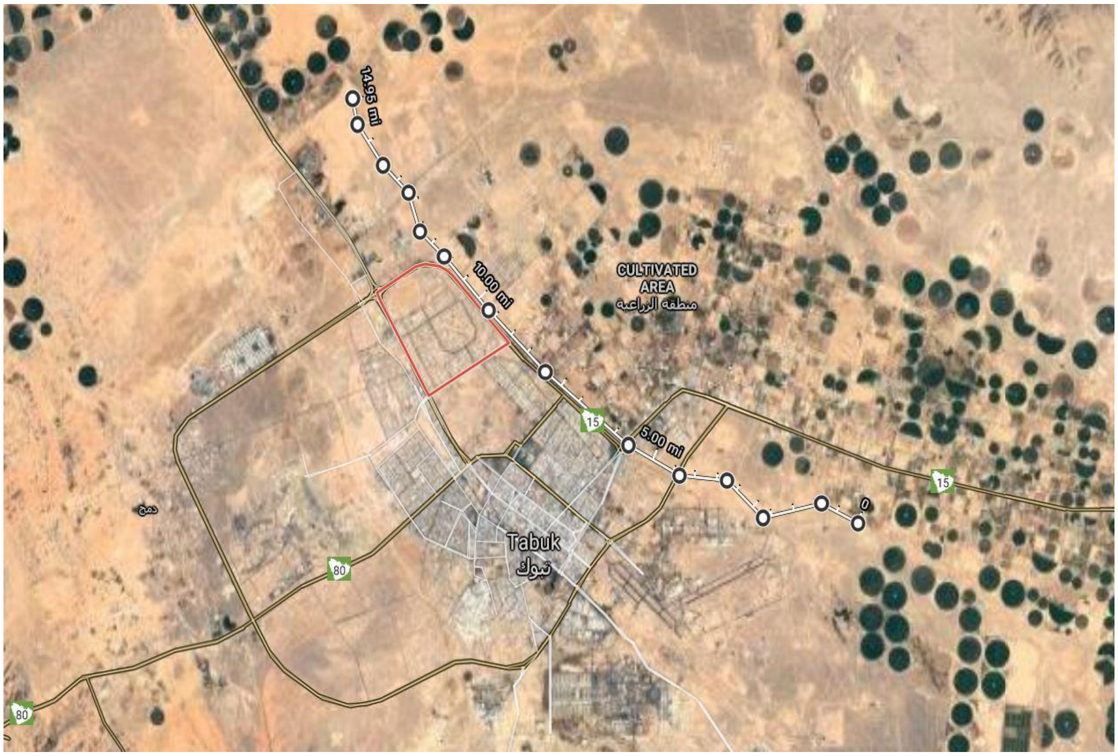

Figure 4.3 Wadi Abu Nishayfah path from upstream to downstream (Google Map 2017)

Figure 4.4 Aerial photo of first section (channel width is 90 m).

Figure 4.5 Aerial photo of second section (channel width is 130 m).

Figure 4.6 Aerial photo of third section (channel downstream width is 160 m).

4.3 Methodology and Data collection

Defined precipitation data between the years 1978 and 2013 at daily time intervals have been gathered, including historical and real-time observations. In addition, daily data for the selected years were available. Detection and filtering of abnormal and missing data were automated using statistical routines. The data set includes annual and monthly precipitation were provided by Tabuk meteorological station. However, the application of any climate model requires a validation process to make sure that the results are in an acceptable range (Figure 4.7).

4.3.1 ArcGIS

Fitting spatial statistical models to stream network data is challenging because it requires multidisciplinary skills in aquatic ecology, geographic information science, and spatial statistics. In addition, specialized geographic information system in ArcGIS tools is needed to generate the spatial information needed to fit spatial models to stream network data. ArcGIS different versions geoprocessing toolboxes have been provided to help users generate these spatial data: the functional linkage of water basins and stream flows toolbox and the spatial tools for the analysis of river systems. The flows toolbox is a set of graph theoretic-based analysis tools that functionally link aquatic and terrestrial components of the landscape based on hydrologic processes. These tools provide an efficient framework for navigating throughout the network, which makes it possible to calculate a variety of attributes related to network distance, flow direction, and terrestrial contributing areas.

4.3.2 HEC-HMS

HEC-HMS is the updated version of the USACE rainfall-runoff model USACE-HEC 1998. It utilizes a graphical user interface to build a watershed model and to set up the precipitation and control variables for simulation. The watershed model created in HEC-HMS follows the form of the Sacramento District Corps office HEC-1 forecast model of the basin USACE 1987. This model utilizes one sub basin above designated reservoir that provides runoff into the reservoir. Below the reservoir, there is a routed channel reach and another sub basin that provides runoff to downstream.

4.3.3 HEC-RAS

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

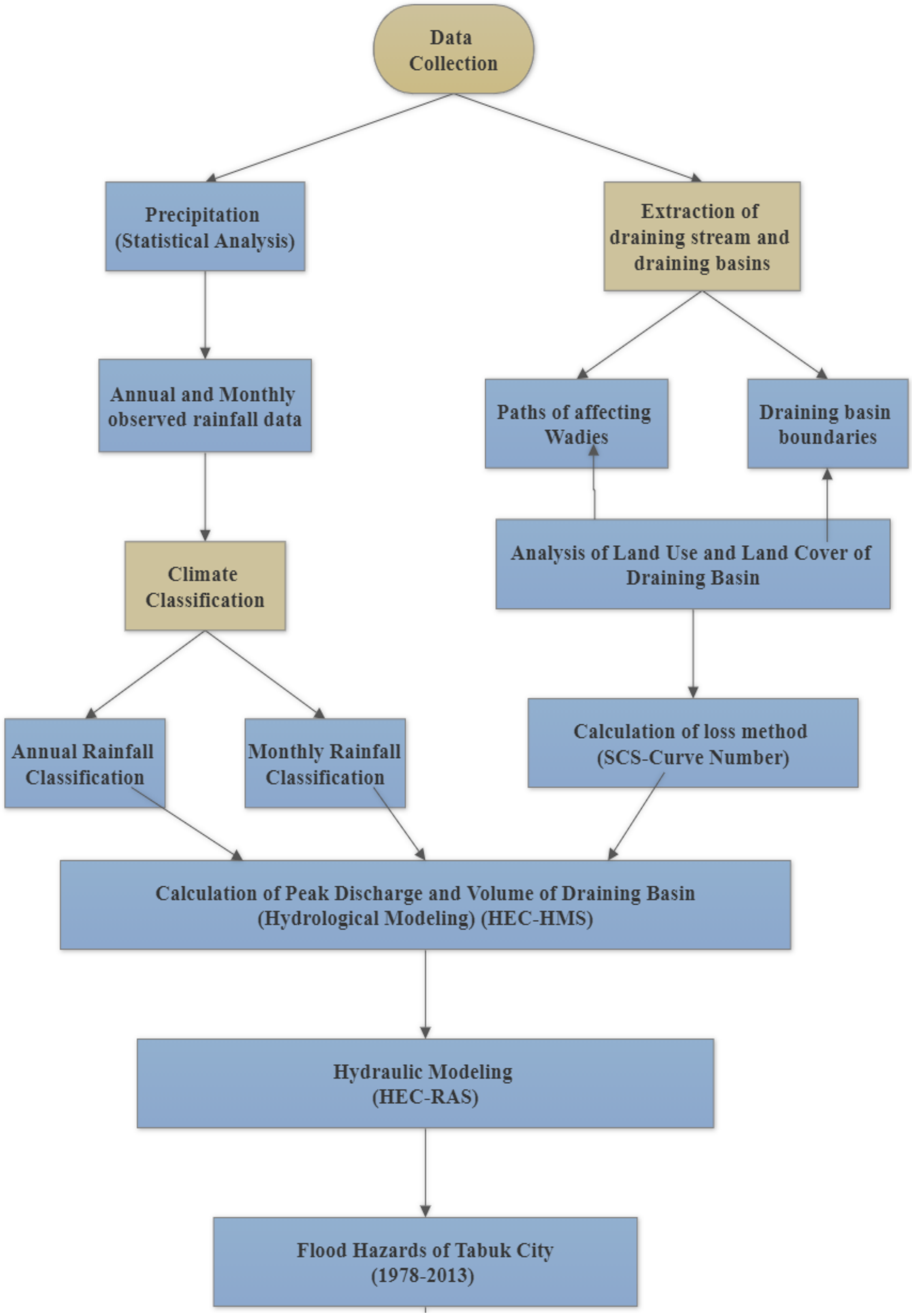

Figure 4.7 Flowchart showing the process applied in this study.

The hydrologic, hydraulic, and floodplain models in this study were built using HEC-HMS and HEC-RAS. Accordingly, HEC-HMS is the updated version of the USACE rainfall-runoff model USACE-HEC 1998. It employs a graphical user interface to build a watershed model as well as to configure the precipitation and control variables for simulation. This model was created to simulate rainfall-runoff processes in a variety of watershed forms. HEC-HMS employs a number of sub-models to describe various components of the runoff process, including neuromas penetration methods, unit hydrographs, and flood routing techniques (USACE 2010). The SCS curve number method is the most commonly used method for estimating infiltration potential and runoff for different configurations of soil land use/cover type (US. SCS 1986).

HEC-RAS is a window-based hydraulic model also developed by the U.S Army Corps of Engineers and the Hydrologic Engineering Center. The model calculates and analyzes floodplain hydraulics using the output hydrograph from HEC-HMS as an input. (USACE 2010). A hydraulic analysis, which is often conducted after a hydrologic analysis, determines water elevation. The model is used to simulate steady, gradually varied, rapidly varied and unsteady one-dimensional flow and to delineate flood zones, which is the most common application of the model. This computation makes use of the continuity, momentum, energy, and Manning equations.

The major steps followed in this study include generating a digital elevation (DEM) for the study area, delineate the watershed, use HEC-HMS to develop a hydrological model for the watershed, and use HEC-RAS model to develop one dimensional (1D) hydraulic model and generate flood risk maps for Wadi Abu Nashayfah.

4.4 Basin model input parameters

Basin characteristics such as area, CN number, and streams parameters were extracted from ArcGIS. The required input parameters for basin and streams are shown in Table 4.1.

Table 4.1 HEC-HMS model parameters

Model	Method	Parameters
Loss	SCS Curve Number	Initial abstraction (mm), CN, Imperviousness (%)
Transform	SCS Unit Hydrograph	Lag time (min)
Routing	Muskingum	Channel length (m), Slope, Manning's n, Channel width

4.5 Losses calculations

There are many options available for loss calculations, including initial and constant loss rate, and SCS curve number method. In this analysis, the SCS curve number approach is used to calculate runoff losses. The rainfall excess is calculated using the SCS formula as a function of total precipitation, soil cover, land use, and antecedent moisture content.

The SCS runoff equation is as follows.

$$Q = \frac{(P-Ia)^2}{(P-Ia)+S} \qquad (1)$$

Where:

Q = direct runoff (in)

P = rainfall (in)

The initial abstractions I_a is a percentage of S as follows:

$$Ia = 0.2\,S \qquad (2)$$

Noting that S is the potential max retention which can be computed as:

$$S = \frac{1000}{CN} - 10 \qquad (3)$$

Initial Abstraction is a parameter that accounts for all losses prior to runoff and consists mainly of interception, infiltration, evaporation, and surface depression storage. This parameter assumed as 0.2 of potential max retention based on watersheds studied in humid regions. Accordingly, vegetation cover in humid regions is larger compered to arid regions which low the potential of intercepting flooding in arid regions. Another example, evaporation rates are higher at higher temperatures because as temperature increases. In sunny, warm weather the loss of water by evaporation is greater than in cloudy and cool weather.

The CN method involves CN values, initial abstraction, and impervious area details. Using the soil map, as well as the land use and land cover maps, the CN layer was generated in GIS. The soil layer has four major hydrological groups such as A, B, C, and D and interpreted in GIS for developing the CN layer. After developing the CN map in GIS, it was found that the CN varies at different locations from a maximum of 81 to minimum of 58 (Table 4.2). The average CN for the sub basins is 72 which represent the majority of Wadi Abu Nashayfah catchment curve number.

Table 4.2 Curve number calculated for subbasins in study area.

Tabuk Watershed								
Subbasin	**Area km^2**	**Curve Number**	**Subbasin**	**Area km^2**	**Curve Number**	**Subbasin**	**Area km^2**	**Curve Number**
470	3.98	77	630	19.11	73	780	9.92	77
480	4.28	74	640	6.6	78	790	9.98	70
490	5.72	80	650	3.87	73	800	13.1	71
500	5.51	80	660	12.73	73	810	21.36	66
510	14.72	81	670	3.99	75	820	4.85	69
520	11.58	78	680	4.34	79	830	23.37	71
530	6.68	81	690	13.68	76	840	7.98	70
540	2.93	75	700	4.91	75	850	13.97	58
550	11.73	75	710	9.44	75	860	7.7	58
560	17.41	80	720	5.68	66	870	6.02	58
570	12.38	76	730	4.7	70	880	5.98	58
580	13.91	72	740	6.42	71	890	4.87	72
590	14.52	72	750	11.43	65	900	6.59	72
600	6.25	75	760	6.29	70	910	4.52	59
610	11.72	71	770	6.68	79	920	6.1	59
620	19.17	71						

4.6 Direct runoff calculation

There are many different methods to calculate the direct runoff. In this study, SCS Curve Number was implemented for finding the direct runoff in Tabuk basin. The lag time is the input parameter required for direct runoff measurement. Lag time for SCS unit hydrograph for each sub-basin was calculated by Eq.4 as follows:

$$Lag = \frac{L^{0.8}(S+1)^{0.7}}{1900 * Y^{0.5}} \quad (4)$$

where,

Lag = basin lag time (hours)

S = maximum retention

L = hydraulic length of watershed (longest flow path)

Y = basin slope (%)

4.7 Estimation of flow losses

The total flow losses in the stream network of the catchment are the sum of flow losses per stream. The total discharge exiting the catchment is the sum of routed flows originating at the upstream side and is calculated as:

$$Q = \sum_{i=1}^{n} Q_i \qquad (5)$$

Where,

Q = total discharge exiting the catchment,

Qi= routed discharge of stream i the individual discharge

Qi for each stream is estimated from the contributing drainage area of that stream and is computed as:

$$Q = \frac{A_i}{A} Q \qquad (6)$$

Where,

Ai = drainage area of stream i,

A = total catchment area.

4.8 Results and Discussion

Table 4.3 presents the runoff volumes and peak discharge at the outlet of Wadi Abu Nashayfah watershed. Figure 4.8 shows the relationship between precipitation and peak discharge for the watershed. This trend shows increasing in peak discharge and runoff volume following the raising of precipitation depth which reflect the natural relationship between rainfall and runoff. Precipitation values ranged between 0 to 50 mm which is the dominating case in arid region and certainly Wadi Abu Nashayfah. While peak discharge and runoff volume ranged in 0.10-120 m^3/s and 0.02-13.8 m^3 respectively.

Table 4.3 Runoff volumes and peak discharges at the outlet for Tabuk watershed.

N	**Precipitation (mm)**	**Runoff Volume (x1000 m^3)**	**Peak Discharge (m^3/s)**
1	0.10	0.02	0.10
2	0.20	0.03	0.30
3	0.50	0.08	0.70
4	1.00	0.17	1.50
5	2.00	0.34	3.00
6	3.00	0.51	4.40
7	5.00	0.85	7.40
8	8.00	1.36	11.80
9	10.00	1.69	14.80
10	15.00	2.55	22.20
11	20.00	3.50	30.50
12	25.00	4.67	40.60
13	30.00	6.08	52.90
14	35.00	7.72	67.20
15	40.00	9.57	83.30
16	45.00	11.60	101.00
17	50.00	13.81	120.20

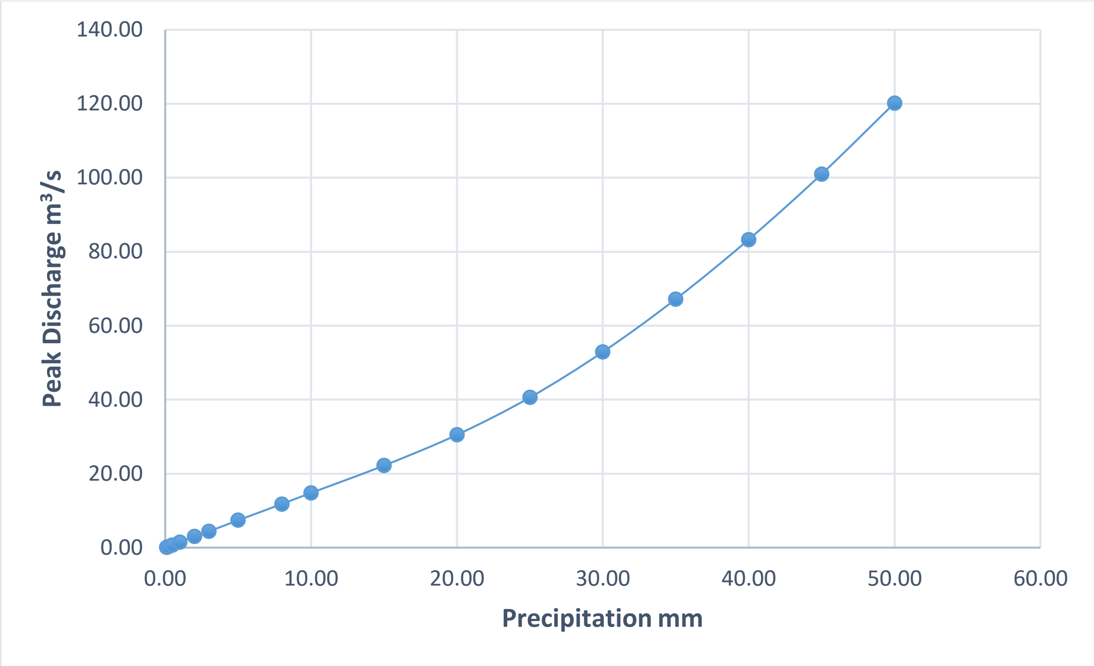

Figure 4.8 Peak discharge interacting with precipitation over Wadi Abu Nashayfah.

HEC-RAS was run to compute water surface elevation corresponding to the peak discharge computed by HEC-HMS at the defined cross sections. There are three types of cross sections applied in this 1D simulation. As a matter of fact, channel cross sections have several dimensional measurements which can be categorized into three main shapes. Accordingly, W 90, W 130, and W 160 are sorted based on variations on channel width (Table 4.4).

Peak discharges for Wadi Abu Nashayfah were computed by using observed precipitation data from Tabuk metrological station, the output of this process was applied to compute water surface elevation. At upstream, there is high potential of flooding when Wadi Abu Nashayfah receives minimum of 25 mm of rain which generates 40.60 m^3/s of peak discharge, thus, at this point the stream will overtop its banks and risking the adjacent area. In second case, flow will overtop its banks when the channel receives at least 35 mm of rain and peak discharge level to 67.20 m^3/s. While flow will reach bank full point if wadi Abu Nashayfah receives 10.00 mm of rain and generates 14.80 m^3/s of streams at downstream. The high flow depth is within this channel is essentially based on the topography of the channel and location of Tabuk city which is located at low elevation.

Table 4.4 Precipitation, Peak Discharge, and Water Surface Elevation for Wadi Abu Nashayfah Catchment.

Tabuk Watershed					
N	**Precipitation mm**	**Peak Dis m^3/s**	**WS Elevation (Section 1)**	**WS Elevation (Section 2)**	**WS Elevation (Section 3)**
1	0.10	0.10	792.18	755.14	735.14
2	0.20	0.30	792.30	755.22	735.23
3	0.50	0.70	792.45	755.33	735.34
4	1.00	1.50	792.64	755.47	735.48
5	2.00	3.00	792.89	755.65	735.66
6	3.00	4.40	793.06	755.78	735.79
7	5.00	7.40	793.35	755.99	736.01
8	8.00	11.80	793.68	756.24	736.25
9	10.00	14.80	793.87	756.37	**736.39**
10	15.00	22.20	794.26	756.66	
11	20.00	30.50	794.63	756.93	
12	25.00	40.60	**795.01**	757.21	
13	30.00	52.90		757.50	
14	35.00	67.20		**757.80**	
15	40.00	83.30			
16	45.00	101.00			
17	50.00	120.20			

*Marked values are bank full points.

Table 4.4 summaries HEC-RAS and HEC-HMS results corresponding to precipitation data. Again, water surface elevation ranges between 735-795 m in different sections of Wadi Abu Nashayfah (Table 4.4). Elevation levels were obtained from 10m -DEM. Stream flow direction downhill from upstream where mountains are dominating, flowing along to downstream which is location at lower elevation.

To develop the flood hazard map, the peak flows for each sub-catchment simulated by HEC-HMS were inputted into HEC-RAS and the solution generated by

HEC-RAS model was imported and read by Geographic Information System (GIS). The process was repeated for different cross section shapes. Each time, a new scatter point file containing the water depths resulting from the HEC-RAS simulation was read into GIS as Two-dimensional scatter points that are connected to delineate the flood inundation.

By analyzing the flooding and the water surface elevation for the different hydraulic modelling results (Table 4.4), some selection criteria can be set up for determining the type of DEM to be used. The 10-meter DEM has a low resolution; however, the effectiveness for its use in hydraulic modelling has been illustrated for the Tabuk study. The model improves as precipitation depth and peak discharge data are added, making it more expensive but also introducing the variation between cross-sections.

Modeling first section (Figure 4.9) shows that the results (water surface elevation) are affected by cross section variations. Water surface elevations were obtained from DEM and they vary from 792.18 to 796.84 m. While peak discharge has a range of 0.10-120.20. The result of this simulation indicates that the channel bank is full when watershed receives 25 mm or above and peak discharge is 40.60 m^3/s. At this point the channel reaches its maximum capacity and the stream overtop to reach the adjacent area.

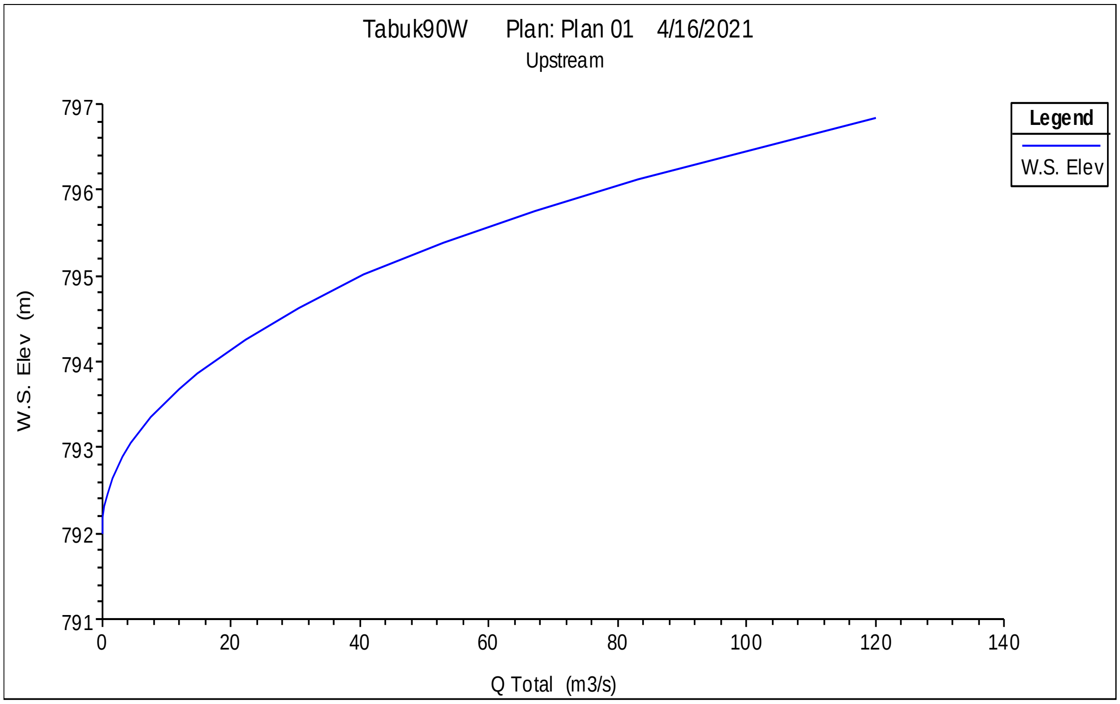

Figure 4.9 Water surface corresponding to peak discharge for section 1.

Similarly, modeling second section (Figure 4.10) shows that the results (water surface elevation) are affected by cross sections variations. Water surface elevations were obtained from DEM and they vary from 755.14 to 758.65 m. While peak discharge has a range of 0.10-120.20. The result of this simulation indicates that the channel bank is full when watershed receives 35 mm or above and peak discharge is 67.20 m^3/s. At this point the channel reaches its maximum capacity and the stream overtop to reach the adjacent area.

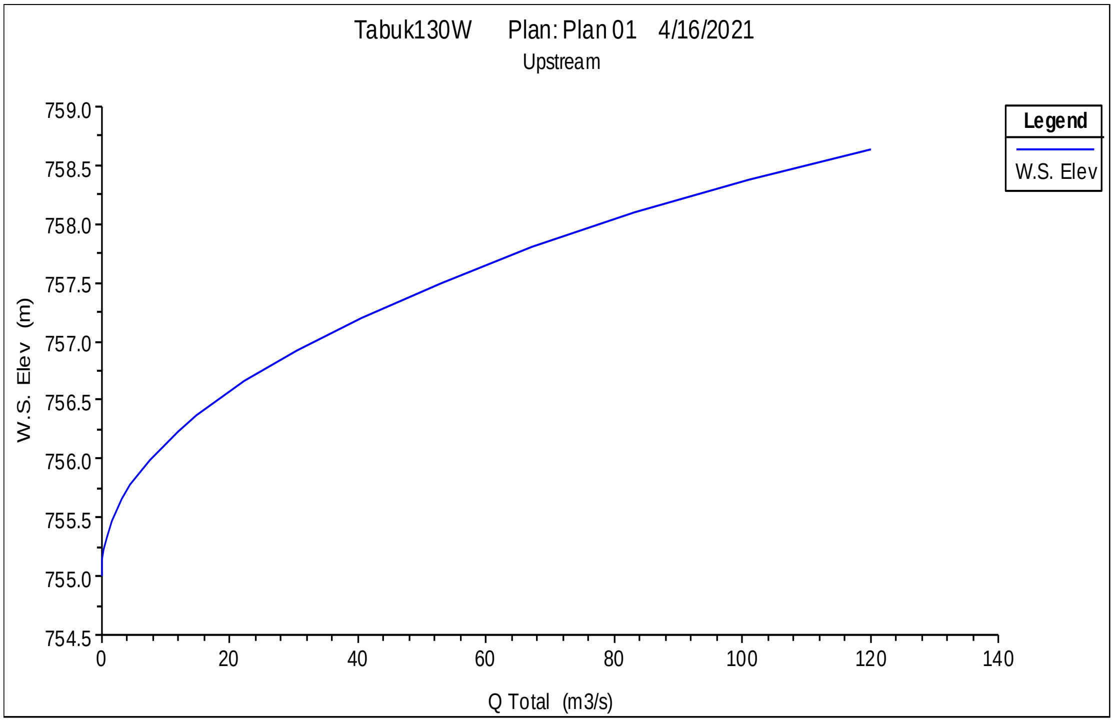

Figure 4.10 Water surface corresponding to peak discharge for section 2.

Modeling third section (Figure 4.11) shows that the results (water surface elevation) are affected by cross sections variations. Water surface elevations were obtained from DEM and they vary from 735.14 to 738.67 m. While peak discharge has a range of 0.10-120.20. The result of this simulation indicates that the channel bank is full when watershed receives 10 mm or above and peak discharge is 14.80 m^3/s. At this point the channel reaches its maximum capacity and the stream overtop to reach the adjacent area.

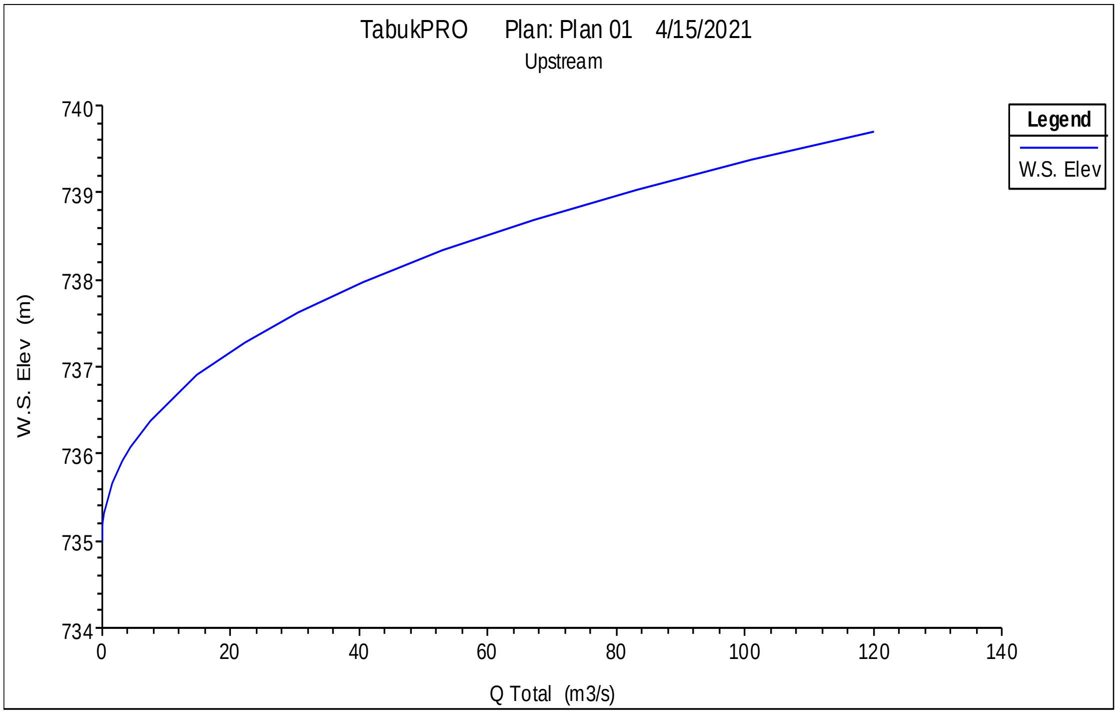

Figure 4.11 Water surface corresponding to peak discharge for section 3.

Wadi Abu Nashayfah watershed was delineated form DEM by using ArcGIS. The delineated DEM was exported HEC-HMS to calculating peak discharges at different points on the watershed. HEC-RAS was mainly used for simulation stream data to locate at which point the channel exceeds its capacity and their high potential of flooding occurrence.

This influence increases as precipitation data and peak discharges are incorporated into the model and leads to greater water level variations. The variation in cross sections based on width, depth and length of channel produce larger variability but they are maintained when DEM data are added. For each precipitation depth, the smaller variations are for the lowest discharges. In general, it can be noted that for any discharge, the more detailed the water surface model represented, the greater sensitivity of the hydraulic results to roughness coefficient variations. The analysis of the water surface model at 10-meter DEM resolution shows variations of between three sections, indicating little significant difference between them.

First and second section were affected by channel width showing increasing in water surface elevation along with precipitation death and peak discharge. On the other hand, third section simulation presents decreasing in water surface elevation while the channel is characterized with 160 m width which is the maximum width for Wadi Abu Nashayfah basin. This downstream section has the maximum possibility of flooding when it receives only 10 mm of rain. The adjacent area of this downstream section is mainly characterized as open spaces where there are significant dangers of occurring flash flooding to the transportation system, agriculture lands, and wildlife.

Section 3 has the least elevation when channel bank is full after receiving 10 mm of precipitation. At this point, streamflow overtops the channel edges to the adjacent area which is mostly urban area including residential houses, roads, and properties. Tabuk has suffered from high intense storm events in last decades. Those events are the primary cause of generating severe floods.

Storms of high intensity and varying durations occur from time to time. However, the probability of these heavy rainfalls varies with locality. The first step in designing engineering projects dealing with flood control, and gully control is to determine the probability of occurrence of a particular extreme rainfall. This information is determined by the frequency analysis of point rainfall data.

Weibull formula is the most commonly used plotting position formula. Having calculated P and T for all the events in the series, the variation of rainfall magnitude is plotted against the corresponding T on semi-log or log-log paper. The rainfall magnitude for any recurrence interval can be determined by extrapolating the plot between magnitude and recurrence interval. Empirical procedures can give good results for small extrapolations, but the errors increased with the amount of extrapolation. For more accurate results, analytical methods using frequency factor are used.

However, the 36 annual total rainfall depths were subsequently ranked from high to low and the corresponding probabilities of exceedance were estimated with Weibull method (Table 4.5) (Weibull 1939).

Table 4.5 Probabilities of recurrence flooding events exceeded 10 mm estimated with Weibull method.

Rank	**Max Rainfall (mm)**	**Weibull Prob %**
1.00	48.30	2.70
2.00	38.80	5.41
3.00	38.00	8.11
4.00	36.00	10.81
5.00	34.50	13.51
6.00	26.10	16.22
7.00	23.70	18.92
8.00	22.20	21.62
9.00	18.10	24.32
10.00	18.00	27.03
11.00	17.10	29.73
12.00	12.80	32.43
13.00	12.60	35.14
14.00	12.40	37.84
15.00	12.20	40.54
16.00	11.40	43.24
17.00	11.00	45.95
18.00	10.30	48.65
19.00	9.80	51.35
20.00	9.50	54.05
21.00	9.00	56.76
22.00	8.00	59.46
23.00	7.70	62.16
24.00	7.40	64.86
25.00	6.50	67.57
26.00	5.80	70.27
27.00	4.90	72.97
28.00	4.50	75.68
29.00	4.10	78.38
30.00	3.30	81.08
31.00	3.20	83.78
32.00	2.50	86.49
33.00	2.50	89.19
34.00	2.00	91.89
35.00	1.20	94.59
36.00	1.10	97.30

It can be noted that all of the relationships give similar values near the center of the distribution but may vary somewhat in the tails. The probability of events that exceeded 10 mm is 50% which means that half of rainfall events in Tabuk may cause flooding over the wadi channel (Figure 4.12).

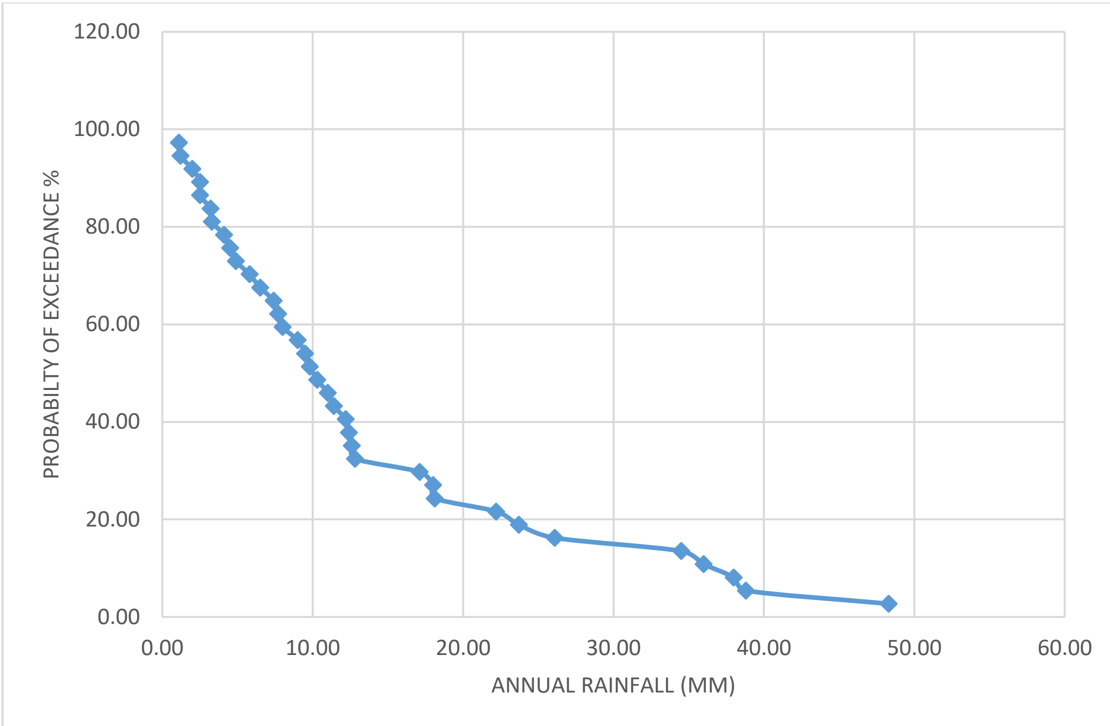

Figure 4.12 Probability plot of the total annual rainfall for Wadi by using linear scales for both axes.

This plot (Figure 4.12) is showing that half of rainfall events probability occurring is above 10 mm with high risk of generating floods. The section 3 which has the lowest capacity and high potential of flooding would reach its maximum when the rainfall depth is 10 mm which represent 50% of all events in 35-year period.

Tables 4.6 and 4.7 summarize precipitation events that are above 10 mm in last three decades (1978-2013). Those precipitation events were the main cause of flooding. From the information gained in the annual analysis of annual rainfall (Table 3.3), Tabuk climate has three climate classifications as wet, average, and dry. The years sorted into the climate classifications base on criteria shown in Table 3.4.

Table 4.6 History of precipitation events above 10 mm in 35 years corresponding with peak discharge and climate classification.

N	Date	Precipitation mm	Peak Dis m^3/s	Climate Classification
1	02/08/1979	12.2	16.4	Wet
2	05/04/1979	12.6	16.6	Wet
3	04/26/1982	23.7	35.0	Wet
4	05/09/1982	16.0	24.0	Wet
5	11/09/1982	15.3	22.5	Wet
6	10/31/1984	12.4	16.5	Average
7	12/17/1985	11.0	15.3	Wet
8	12/18/1985	48.3	145.0	Wet
9	04/25/1986	12.4	16.5	Wet
10	11/28/1986	12.8	17.0	Wet
11	10/17/1987	26.1	43.6	Wet
12	10/16/1988	34.5	65.2	Wet
13	10/17/1988	18.2	28.2	Wet
14	12/24/1988	12.7	16.8	Wet
15	11/05/1989	15.0	22.2	Wet
16	12/26/1989	18.1	28.0	Wet
17	01/01/1991	36.0	70.0	Wet
18	03/22/1991	16.6	25.2	Wet
19	05/10/2009	22.2	33.2	Average
20	01/18/2010	38.8	80.3	Wet
21	01/27/2013	38.0	79.2	Wet
22	01/28/2013	26.0	42.0	Wet

Most precipitation events that cause flooding were occurred in this period (1979-1991). This period was dominated by wet climate which represents the natural correlation between rainfall and runoff. In other words, high intense rainstorms during wet years are likely to generate severe flooding which can lead to danger the around area of Wadi Abu Nashayfah.

Table 4.7 Number of events above 10 mm correlating with climate classification (1978-2013).

Year	# Of events above 10 mm	Climate Classification	Year	# of events above 10 mm	Climate Classification
1978	0	Dry	1996	0	Average
1979	2	Wet	1997	0	Average
1980	0	Average	1998	0	Dry
1981	0	Dry	1999	0	Average
1982	3	Wet	2000	0	Average
1983	0	Dry	2001	0	Average
1984	1	Average	2002	0	Average
1985	2	Wet	2003	0	Dry
1986	2	Wet	2004	0	Dry
1987	1	Wet	2005	0	Average
1988	3	Wet	2006	0	Average
1989	2	Wet	2007	0	Average
1990	0	Dry	2008	0	Dry
1991	2	Wet	2009	1	Average
1992	0	Average	2010	1	Wet
1993	0	Average	2011	0	Dry
1994	0	Wet	2012	0	Average
1995	0	Dry	2013	2	Wet

Most floods events occur in years classified as wet years. There is a correlation between wet years and flooding. In Tabuk, flooding events occurred in (1979,1982,1985,1986,1987,1988,1989,1991,2010, and 2013). These years are representing wet years in 35-year data set with exception to 1994 when there was no flooding event in that particular year. The maximum occurring of flooding events was in 1982 and 1988 with 3 events recorded. While 1984 and 2009 were classified as average years, there was single event recorded in each year. Dry years are insignificant in case of analyzing flooding in this watershed due to there is no event occurring in those years.

However, the first and second WS cross sections are located in high residential area (Figure 4.13). Stream flow in this channel has intercepted by some built up areas. These areas need to be removed due to the high potential of flooding and prevents properties from washing away.

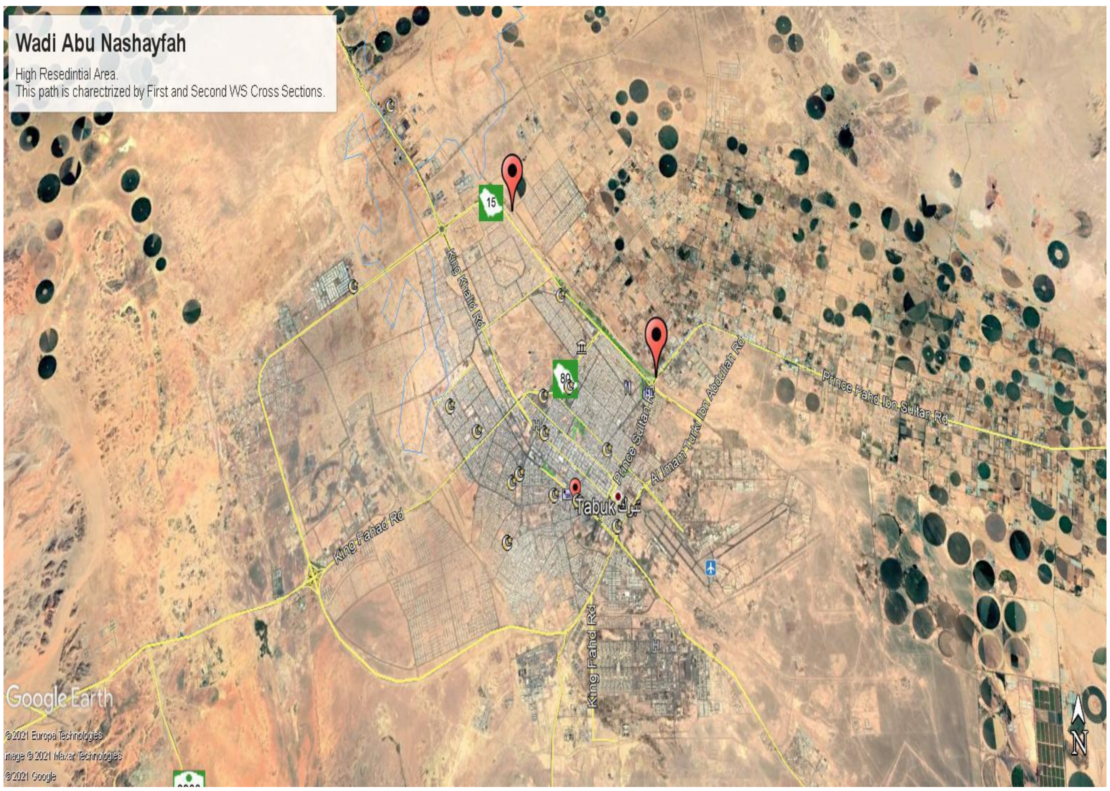

Figure 4.13 A path of Wadi Abu Nashayfah cross Tabuk City (Google map 2017).

This critical area is highly affected by different intense rainstorm in the past. For instance, Wadi Abu Nashayfah received 38.8 mm/day in Jan 18, 2010. This amount of rain exceeded water surface elevation for the wadi which allow water to overtop its banks. This extreme event has generated sever flood which harm the adjacent area. Such event caused economic loss, property damages because the adjacent area of Wadi Abu

Nashifah is mostly residentials. Flash floods created damages to properties such as, homes, businesses, vehicles, belongings, equipment (Figures 4.14 and 4.15).

Figure 4.14 The adjacent area of Wadi Abu Nashayfah after a storm event (01/18/2010).

Figure 4.15 Road collapse and one vehicle was sent off the road after intense rainstorm (01/18/2010).

These photos are showing how severely flash floods can be in Tabuk city. When rain depth exceeded the water surface elevation as shown in Table 4.4. This kind of tragedy can be occurring in short time right after rain occurring.

A major key to protecting properties is to maintain, stabilize, and expanding channel capacity in most critical spots. This wadi edge is the bulwark that stands in the soil and prevents properties from washing away and can be supported by some constructed walls. It is an essential part of the whole channel ecosystem.

Bank degradation leads to property damage or loss, sedimentation of in-stream structures, water quality deterioration, aquatic habitat damage, channel widening, and more. In Tabuk, floods are infrequent but severely damaged when they occur. It is understood that current built-up stock of flood-prone areas must be protected against flood disasters. A rigorous flood disaster prevention strategy will include steps such as limiting additional construction or operations in the flood plain, removing some physical infrastructure from the floodway, and regulating land use patterns within the basin.

Furthermore, a comprehensive catchment planning strategy for flood adaptation is needed. The basin must be used as the primary planning unit for reducing flood damages. To that end, constructive collaboration between local/regional governments and water agencies is a top priority. This collaboration must be made possible by establishing a regulatory system that incorporates natural hazards into the spatial planning process. The key consequences of the presented strategy can be divided into two categories. First category, it makes ex-ante flood risk mapping as a result of urban growth easier. another factors, Changes in the occurrence and severity of extreme flooding, for example, may also be implemented. Second, it will aid in the practical evaluation of urban development activities that are synergized with spatial and technological flood control strategies.

4.9 Conclusion

This chapter constructed hydrologic and hydraulic models to quantify flood hazards in the city of Tabuk. The catchment was divided into sub-catchment in the urban portion of the catchment. The hydrologic/hydraulic model simulations quantified the runoff corresponding to different storms and helped delineate the resulting flood inundation maps.

The results of this study can be utilized for planning purposes and in the design of flood control project as it has quantized the runoff corresponding to different design storms and used hydraulics and geospatial data in delineating the flood zones.

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Chapter 5. Summary and Conclusions and Recommendations

5.1 Summary and Conclusions

The Tabuk area has the unique spatial location of being at the north gate of Saudi Arabia. Several geographic factors have played a major role in forming the environmental ensemble of the Tabuk area. By using multiple geographic techniques in describing, analyzing, and interpreting the data, this study significantly reveals that intense rainstorms causing flash floods have been occurring there. These rainstorms have been caused by several processes; each process has received considerable attention in this research.

This study clearly demonstrates that annual rainfall decreasing is one of the main desertification indicators in arid environments. A combined methodology, consisting of remote sensing methods, climatic analysis, disturbance analysis, fieldwork, and statistical analysis was adopted for this study. Models in the study area was studied and analyzed based on where it was originally created and designed. Noting that most of existed models were programmed for humid climate, yet they have been used in arid climate.

Rainfall variability was the main factor presenting climate variability in the study area. Several statistical techniques were used to measure its variability and similarity. The Tabuk area has the typical arid environment, characterized by low rainfall that may cause temporary and long-term deterioration in the natural landscape. Rainfall, prior to the 1988 was much higher or above normal, compared to the last twenty years of data set, which means that the wet condition was dominating in that period. On the other hand, the rainfall data for the period between 1990 and 2010 indicates that the Tabuk area has been subjected to limited rainfall. The Coefficient of Variation indicated the relative variability of annual rainfall is higher for 1978, 1984, 1985, 1987,1992, 1995, 2004, 2008, 2010, and 2013 and these years have showed great variability in rainfall for all months.

This study constructed hydrologic and hydraulic models to quantify flood hazards in the city of Tabuk. The catchment was divided into sub-catchment in the urban portion of the catchment. The hydrologic/hydraulic model simulations quantified the runoff corresponding to different storms and helped delineate the resulting flood inundation maps. Peak discharges for Wadi Abu Nashayfah were computed by using observed precipitation data from Tabuk metrological station, the output of this process was applied to compute water surface elevation. At upstream, there is high potential of flooding when Wadi Abu Nashayfah receives minimum of 25 mm of rain which generates 40.60 m^3/s of peak discharge, thus, at this point the stream will overtop its banks and risking the adjacent area. In second case, flow will overtop its banks when the channel receives at least 35 mm of rain and peak discharge level to 67.20 m^3/s. While flow will reach bank full point if wadi Abu Nashayfah receives 10.00 mm of rain and generates 14.80 m^3/s of streams at downstream. The high flow depth is within this channel is essentially based on the topography of the channel and location of Tabuk city which is located at low elevation.

5.2 Recommendations for future research

The approaches utilized in this study, as well as the results given, give potential worth studying in the future. Following the examination of rainfall distribution, further research should concentrate on rainfall intensity trends in the basin. This information would be valuable in better understanding recharge patterns and the likely occurrence of floods and drought events.

In terms of water resource components, future research should concentrate on characterizing the lag time between rainfall and water level response, intermittent recharging, and water table forecasting in the context of climate change.

Data shortage from two perspectives was a key issue encountered throughout this investigation. The data needed was available yet unreachable. In contrast, the required data was available but of poor quality. Future study in the region should explore high quality data gathering efforts throughout the basin as well as building methods for data collecting, quality assurance, and archiving. Researchers should have access to data.