An-Najah National University
Faculty of Graduate Studies

Distributed Hydrological Modeling of Semi-Arid Regions: the Case of Al-Faria Catchment, West Bank, Palestine

By

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Dedication

My great mother and father, my dear husband Ahmad, my lovely coming son or daughter.

Acknowledgment

This thesis becomes a reality with the kind of help and support of many persons but first of all praise to Allah for the wisdom, the strength, the good health and everything bestowed upon me that helped me to complete my research.

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الإقرار

أنا الموقعة أدناه، مقدمة الرسالة التي تحمل العنوان:

Distributed Hydrological Modeling of Semi-Arid Regions: the Case of Al-Faria Catchment, West Bank, Palestine

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تمت الإشارة اليه حيثما ورد، وأن هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل أية درجة علمية أوبحث علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the research's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name: **إسم الطالب:**

Signature: **التوقيع:**

Date: **التاريخ:**

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Abbreviations

AMSL	Above mean sea level
BMSL	Below mean sea level
M	Meter
Mm	Millimeter
MCM	Million Cubic Meter
km^2	Squared kilometer
GW	Groundwater
RRM	Rainfall Runoff Modeling
UH	Unit Hydrograph
NNb	Nearest Neighbor
RBF	Radial Basis Function
DEM	Digital Elevation Model
LSM	Land Surface Model

Distributed Hydrological Modeling of Semi-Arid Regions: The Case of Al-Faria Catchment, West Bank, Palestine

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Abstract

Water shortage forms a major challenge facing water managers in water scarce countries such as Palestine. As a result, great efforts should be done in order to manage the water resources optimally. Hydrological modeling is a tool among several others that is used to support water resources management. As a result, the hydrological modeling improves the understanding of the water system and provides the input data required for the water resources management models. In this regard, few researches have been carried out regarding the hydrological modeling in The Faria catchment.

This study was performed in The Faria catchment, which is located in the northeastern part of the West Bank, Palestine. The area of the catchment is about 320 km^2 which represents approximately 6% of the total area of the West Bank. Moreover, it drains its water into Jordan River in its southeastern part.

In this study, a preliminary visualization of rainfall runoff modeling was performed using HEC-HMS software which is used to simulate the rainfall-runoff response in the Faria catchment, and to understand the general hydrologic processes there. Single storm events were simulated using HEC-

HMS. The storm of February (8-9), 2009 was used for the model calibration, while the storm of February (4-8) was used for the validation. The model was statistically evaluated through the comparison of the stream observed flow data and the model simulated ones.

Furthermore, the applicability and effectiveness of a more recent hydrological model in the Faria catchment was tested. The model is WRF-Hydro (Weather Research and Forecasting model- Hydrological model extension package). Two continuous simulations were developed using the model. The first one was for January and February, 2005 and the second one was for the three years (2003-2005). Then, some calibration was performed to enhance the simulation results and to improve the model performance.

From this research, it could be concluded that the HEC-HMS model is able to simulate single rainfall events in Faria semi-arid catchment to a good acceptable degree. Moreover, WRF-Hydro model is useful for continuous simulations although it is not very feasible in our case. This is mainly because that it is used in the offline (uncoupled) mode due to the unavailability of the boundary conditions for a big enough domain.

Finally, both studied models in this research could be used as prediction tools for the Faria catchment and catchments with similar hydrological conditions. However, these models need further enhancement and calibration to improve its efficiency.

Chapter One
Introduction

Chapter One

Introduction

1.1 General Background

With two thirds of the earth's surface area covered by water and it also forms 75 percent of human body, it is apparently clear that water is one of the most essential elements responsible for life on earth. But the rapid population growth has caused an increasing demand for water in all sectors. With the increasing impacts of human on water such as pollution, increasing wastage, and deterioration of water resources, more shortage in water is expected in the coming decades (Shadeed S. , 2008).

"Scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Human health and welfare, food security, industrial development and the ecosystems on which they depend, are all at risk, unless water and land resources are managed more effectively in the present decade and beyond than they have been in the past" (ICWE, 1992). This quote was the introductory paragraph of the Dublin statement on water and sustainable development shows the responsibility for hydrologists and water resources managers to prepare management strategies and to take actions in order to save the water future from serious shortage.

In this research, a rainfall runoff hydrological modeling will be carried in the Faria catchment, West Bank, Palestine. Where tow hydrological models will be developed and applied for the catchment, the first one is using HEC-HMS software and the second using the WRF-Hydro model.

The water shortage challenge is a serious problem that is difficult to solve among this hydrological modeling research. However, the hydrological modeling is a tool among several ones that can be used to support the water resources management.

Moreover, the increased population and the resulting increased of engineered structures have caused decreasing amounts of infiltration. Thus, the probabilities of surface flash floods have been increased. All the above facts have increased the necessity for assessment and modeling of surface and groundwater resources especially in areas of limited and uncertain water supply such as Palestine.

This study is performed in the Faria catchment, which is located in the northeastern part of the West Bank with an area of about 320 km^2 and drains into the Jordan River at the south eastern part of the catchment. The HEC-HMS v4.0 software is used to develop the first model to simulate the rainfall-runoff process in the study area. In addition, the Weather Research and forecasting model Hydrological model extension package (WRF-Hydro) is the second hydrological model that is used in the Faria catchment. As an input rainfall measurements for the model, in addition to the measurements from the standard rain gages, the microwave links was planned to be used in order to provide rainfall measurements belongs to local cell phone provider (Jawwal).

This research idea came in the context of a research project entitled “Integrating MW- Link Data for Analysis of Small Scale Precipitation variability in complex terrain: Theoretical aspects and Hydrological

Applications (IMAP)" funded by German research foundation (DFG) with close corporate between ANU and Karlsruhe Institute of Technology.

1.2 Objectives

The main objective of this research is to estimate the potential runoff generation in the Faria catchment. As such, WRF-Hydro and HEC-HMS model is adopted and used. In the light of the above, the general objectives are summarized as follows:

a) To prepare rainfall data in high spatial and temporal resolution to be used as an input to the hydrological model.

b) To prepare high quality runoff data in order to be used in the evaluation of the model performance later on.

c) To prepare model relevant data including both the static data such as the topography, green fraction, longitude, latitude, land use and top layer soil information, as well as the dynamic ones including the atmospheric forcing data that varies temporally and spatially.

d) To apply HEC-HMS model for selected rainstorm events in Faria catchment.

e) To apply the WRF-Hydro model for selected rainstorm seasons in Faria catchment.

f) To assess the applicability and effectiveness of both hydrological models in the Faria catchment.

1.3 Research Importance

The Faria catchment is predominantly arid to semi-arid area, located in the northeastern part of the West Bank. It is one of the most important agricultural areas in the West Bank. So, great amounts of water are needed in this catchment for agricultural purposes. In addition, there is a relatively high population growth rate there, which means increasing water demand for domestic sector. Besides, the considerable amount of water that is being used for recreational purposes in the upper parts of the catchment at Al-Badan village. Moreover, the situation becoming worst, given the unfair Israeli's control over the Palestinians water resources (Shadeed S. , 2008). Accordingly, there is a dire need to understand and manage the availability of water resources among which the surface water in the catchment in trying to help the decision makers to develop some management strategies in order to bridge the increasing supply-demand gap in the catchment.

In the light of the above discussion, it can be concluded that the Faria catchment like the entire West Bank suffers from water stresses that need to be investigated and solved. So, the limited water resources cannot fulfill the increasing residential and agricultural water needs. This means that there is an urgent need for an assessment of the water resources availability in the catchment in order to make the most effective water management strategies, which increases the need to conduct a hydrological modeling for the catchment. The hydrological modeling improves the understanding of the water system and provides the input data required for the water resources management model.

There is a special point that gives this research a surplus importance. From the previous studies that were conducted in the Faria catchment, which are demonstrated in a separate section below, it can be noted that the latest hydrological modeling in the catchment had been conducted in 2008. This in turn means that the rainfall runoff data that was utilized in that study are only for four years (2004-2008) at most (the runoff flumes had been constructed in 2004). While now we have the rainfall and runoff data of at least twelve years (2004-2016). As a result, more rainfall events and seasons are used in the calibration and validation process of the model which will hopefully enable it to capture more climatic and hydrologic variability. So, the model will be enhanced significantly. Moreover, the other special importance of this study as was planned in the early beginnings of the IMAP project was raised from using a modern source of rainfall that is used for the first time in Palestine. This source is the Commercial Microwave Links (CML) data, from Jawwal. In order to do that, seven Microwave links (MW links) were selected in the catchment and data from these links are transformed into rainfall data that is integrated with the once from the standard rainfall stations in order to be used as an input data to the rainfall-runoff model. Unfortunately, the data from the MW links was unready to be used until this thesis was finished. However, the data will be used later to do further modifications and calibration to the developed hydrological models.

1.4 Research Questions

Following this study objectives, many questions are raised as follows:

a) What type of data to be collected to achieve the research objectives?
b) What is the quality of the available rainfall and runoff data?
c) What is the optimal parameter set that is required to apply WRF-Hydro model?
d) What are the proper domains that will be chosen for the WRF-Hydro model?
e) What is the mode under which the WRF-Hydro model will be operated (coupled or uncoupled) and why?
f) Will WRF-Hydro and HEC-HMS models be able to do continuous simulation in the Faria catchment?
g) Which one of the models is easier to use WRF-Hydro model or HEC-HMS model??

1.5 Methodology

In order to fulfill the research objectives, first of all, the objectives are defined. Secondly, the study area is characterized using many features including topography, soil, landuse, rainfall, runoff and other hydrological characteristics. Thirdly, the collected data is analyzed using both Excel and GIS. Fourthly, the model is built and the input parameters are structured. After that, the model is used to simulate some rainy events in addition to continuous rainy season simulations. Then, the model is calibrated and validated. The sensitivity analysis and uncertainty assessment will be also performed. The overall research methodology is illustrated in **Figure 1**.

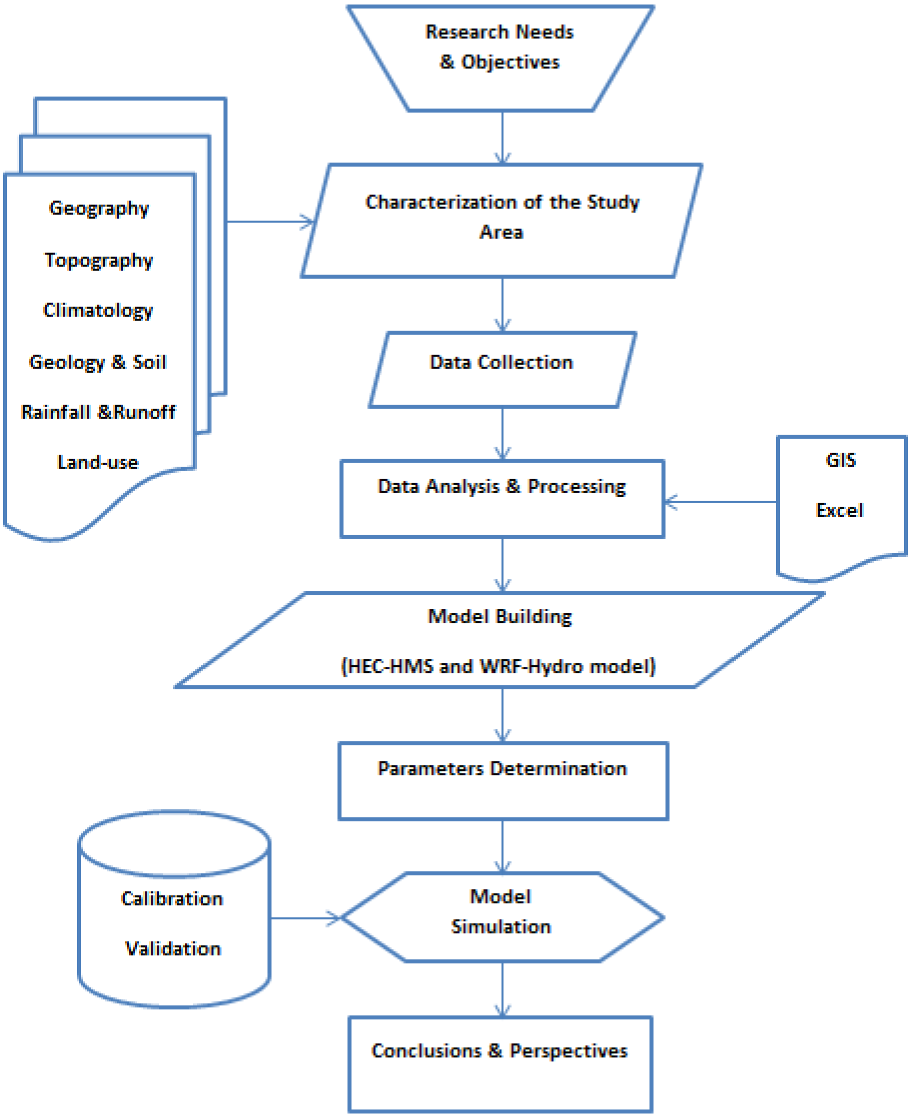


Figure (1. 1): General Methodology Flowchart

1.6 Thesis Outline

This thesis is organized as follows: chapter one is an introductory one that briefly introduces a general background about the subject, the research objectives, importance, methodology and the questions that the research raises. Chapter two provides some gatherings from the literature including the rainfall runoff modeling, the hydrological modeling in general and in arid and semi-arid regions in specific, runoff generation in these areas, and some brief information about the previous work in the study area. Chapter three discusses the study area from several aspects such as geography and topography, soil, geology, climate, water resources, and land-use patterns. In chapter four, the types of data needed for the research, its collection and analysis is discussed. Then, the models used in this research, its application, the sensitivity analysis, and a brief discussion about it are introduced. Finally, the research conclusions and recommendations are presented in chapter 6.

Chapter Tow

Literature Review

Chapter Tow

2 Literature Review

2.1 Rainfall Runoff Modeling

Hydrological modeling is a tool that simulates the surface flow and/or groundwater processes as a simplified mathematical representation. And it is essential in the controlling and management of water resources (Reed et. al., 2007). A hydrological models are concerned with the accurate prediction of the partitioning of water among several hydrologic processes including (rainfall, infiltration, evaporation, surface runoff, recharge to groundwater and baseflow) and the links between them (Dooge, 1992). It is used because of the limitations of hydrological measurements techniques (Beven K. , 2001).

The rainfall runoff modeling (RRM) is an important field of study in hydrology that aims first to understand and capture the rainfall runoff processes. RRM has an important role in water resources management and flood prediction. A large number of rainfall runoff models were introduced after the presentation of the unit hydrograph concept has been presented for the first time by Sherman in 1932. Recently, the advanced information technology indicated the importance of developing RRM process via minimizing the differences between the data observed from the different gauging method of actual runoff and the data that is obtained from the rainfall runoff model which is called the simulated data.

2.1.1 Historical Background

The history of RRM had begun about three centuries ago when P. Perreault had published his report on quantitative measures in hydrology in 1674 (Mishra & Singh, 2003). Perreault described a relationship in which he compared the measured annual rainfall (P_a) with the estimated annual streamflow (Q_a) of the Seine River near Paris. He described the relationship as $Q_a = P_a/6$. It was a major finding of his time, and the concept of computing the runoff as a percentage of rainfall is still in use after 325 years (Dzubakova, 2010).

Then, in 1850 and as a response to an engineering problem, a new hydrological model was proposed by Mulvany which is the Rational Method. It was as a response to the need of designing sewers and dam spillways in a small impervious catchment. The rational method estimates the peak flow in a small impervious catchment, in which the flow can be assimilated to kinematic process in a high degree, using the concept of time of concentration (Mulvany, 1850).

Then, Sherman (1932) had developed the Unit Hydrograph (UH) as a response for the need of determining the shape and volume of flood wave instead of the peak flow magnitude only. After that, the original triangular shape of the UH was extended to a variety of shapes as impulse responses to the causative linear dynamic system, which was started to be known as “Linear Models” (Todini, 2011).

Then, with the digital revolution in 1960’s, there were accelerated new discoveries in RRM. So, with the development of computering power, the focus was shifted from the event-based modeling to the continuous rainfall runoff simulations (Sharma et. al., 2008). As a result of the digital revolution, two other revolutions were triggered which are the “Numerical Simulations” and “Statistical Simulations” (Frevert & Singh, 2006).

In 1970’s and 1980’s the progressed computer technologies enabled the development of “Physically-based Hydrological Models” and since 1990’s new techniques have being applied in solving hydrological engineering problems (Dzubakova, 2010).

From 1960’s to 2000 the hydrological models were transformed from “Conceptual” to variable “Contributing Area models”. That was happened in order to enhance the physical interpretation of the catchment response. So the model had been consisting of individual components represented by interconnected subsystems: For example (Burnash, Ferral, & McGuire, 1973) - Sacramento, (Sugawara, 1995) - Tank, (Beven & Kirkby, 1979)- TOPMODEL.

Also as an alternative to conceptual models, the physical representation of the RRM was improved using “Distributed Area models” (1965 – Today). Nowadays, the wide availability of distributed data such as land use, soil types and radar rainfall has assisted the production of simplified physically distributed hydrological models: such as (Todini & Ciarapica, The TOPKAPI mode, 2002) - TOPKAPI, (De Roo, Wesseling, & Van Deursen, 2000) - LISFLOOD.

The age of “Data-Driven models” had started in 1970’until now, the beginnings of this age was actually Sherman’s UH and the “Linear models” which represent the first data-driven models in Hydrology. More recently, the behavior of the hydrological response of a catchment has been enhanced using various types of input-output techniques.

2.1.2 Classification of Hydrological Models

The rainfall-runoff models can be categorized depending on the model type. And it varies depending on the complexity of the model, the amount of input data needed, and the performance efficiency of the model. Mainly, the models can be stochastic or deterministic which are the data-driven models and the one that is mostly used. Within this category, the hydrological models can be divided into three sub-categories: i) lumped, ii) semi-distributed, and iii) distributed models. In the lumped models, the catchment is treated as one homogeneous unit. So, there is a limited amount of input data required for these types of models. While in the distributed models, the catchment is discretized into a large number of units depending on the catchment spatial data availability. And the semi distributed ones are intermediate type between the aforementioned two types, so it requires a medium quantity of input data. The data driven models comprises a second category, in which the hydrological models fall into three other sub-categories including: i) empirical, ii) conceptual and iii) physically-based models (Wheater et. al., 1993). The models categories are summarized in **Figure 2.1**.

In this study, the WRF-Hydro hydrological model can be categorized as deterministic distributed physically-based model.

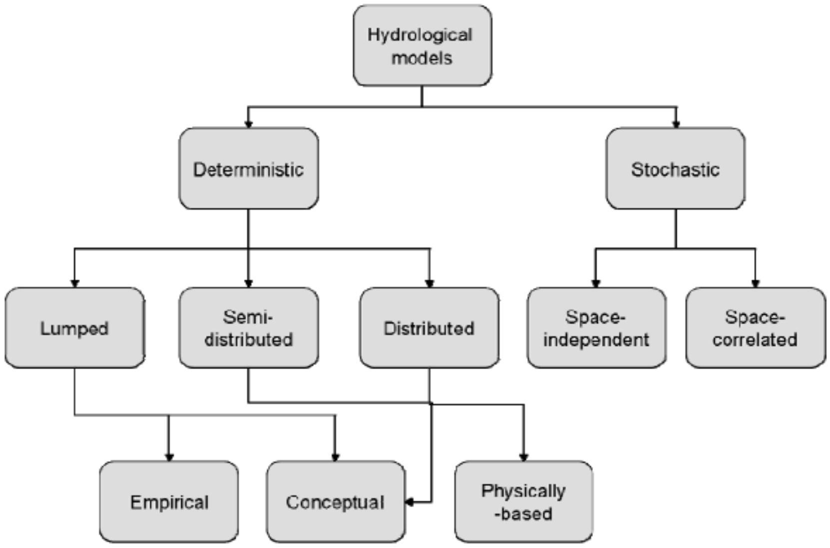


Figure (2. 1): Hydrologic models categories

2.2 Hydrology of Semi-Arid Regions

There are several types of hydrological models that simulate the hydrological processes at wide range of temporal and climatic scales. For the climatic scale, any area can be classified to specific climatic zones depending on what is called aridity index, which is the ratio of the mean annual precipitation (P) to the mean annual potential evapotranspiration (PET). This index is reclassified into one humid zone (P/ PET>=0.65) and one cold tundra mountainous zone (have more than six months of an average temperature below 0 degrees and not more than three months where the temperatures reach above 6 degree centigrade) and four main aridity zones (hyper-arid (P/PET < 0.05), arid (0.05 <= P/ PET < 0.20), semi-arid (0.20 <=P/ PET < 0.50), and dry sub-humid (0.50 <= P/ PET < 0.65)), according to (UNESCO, 1984).

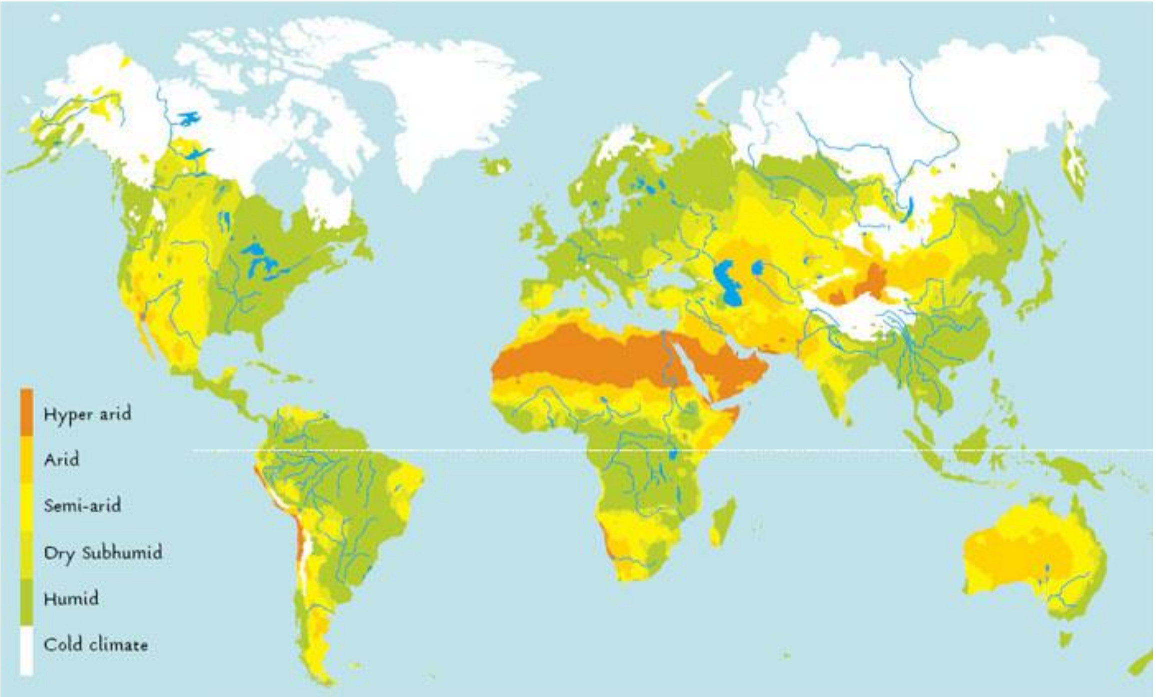


Figure (2. 2): World map of aridity zones (UNEP)

The main hydrologic difference between arid and humid zones is the high spatial and temporal variability in some climatic and hydrologic parameters such as rainfall intensity, runoff rate, and infiltration rate. Although floods are rare and infrequent in arid regions, it often causes losses in life and property (Schick et. al., 1997) and (Thormählen, 2003). The flash floods particularly affect the arid and semi-arid regions, in which the generation of Hortonian overland flow is the dominant process on the dry land in addition to the transmission losses into the dry alluvial beds of the ephemeral channels. Flash floods in these regions result from extreme, irregular rainfall events, when some conditions such as soil moisture, infiltration conditions, steep slopes (Rodier & Roche, 1987), and high rainfall intensity (Geith & Sultan, 2002) are fulfilled.

2.2.1 Rainfall and Climate

In general, the climate of the arid and semi-arid zones is characterized by excessive heat and insufficient, variable precipitation. However, there are differences in the degree of aridity, season of rainfall, temperature differences. So, the arid and semi-arid climate is classified into three major types: the continental climate, the tropical climate, and the Mediterranean climate. In the continental climate, the rainfall is distributed throughout the year, but there is a higher tendency for it in summer and the whole year is considered dry season there. For the tropical climate, approximately all the rainfall occurs during summer while the winters are long and dry. The wet season extends from the middle of June until the end of September and it is followed by 9 dry months. Moreover, the shorter the distance from the Equator, the longer the rainy season is.

In the Mediterranean climate, the rainy wet season is during winters and autumns that extends from October to April and the summers are hot dry seasons with no rain. The study area in this research, which is Al-Faria catchment, is considered to have this type of arid to semi-arid climate.

For the rainfall in arid and semi-arid regions, there are greater spatial variations than the rainfall in humid regions generally, although the variations differ in magnitude from one to another region. In addition, there is temporal variation in rainfall, which means that the rainfall statistics can vary significantly from one to another year and the monthly rainfall variations can be also greater. There is also a probability to get long sequences with very little rain in such regions.

The temporal rainfall variations in the arid regions, especially the long dry periods may affect the hydrological processes there. That might happen because the drought makes changes in the surface soil structure and in vegetation which affects the infiltration capacity and runoff production there. After the rainfall falls from the atmosphere, it is intercepted by the trees and vegetation or directly strikes the ground surface and starts to flow over the land as sheet flow or in streams (surface runoff) or under the surface as subsurface flow and groundwater flow. Much of the rainfall is returned to the atmosphere by evaporation processes from the streams or surface water bodies which is called evaporation, or from the vegetation as transpiration. This is called the hydrologic cycle which is illustrated in **Figure 2.3**. Every area has it's distinguish hydrologic cycle dynamics that is determined by the spatial and temporal nature of rainfall patterns, the soil characteristics, temperature and humidity regimes and vegetative cover types.

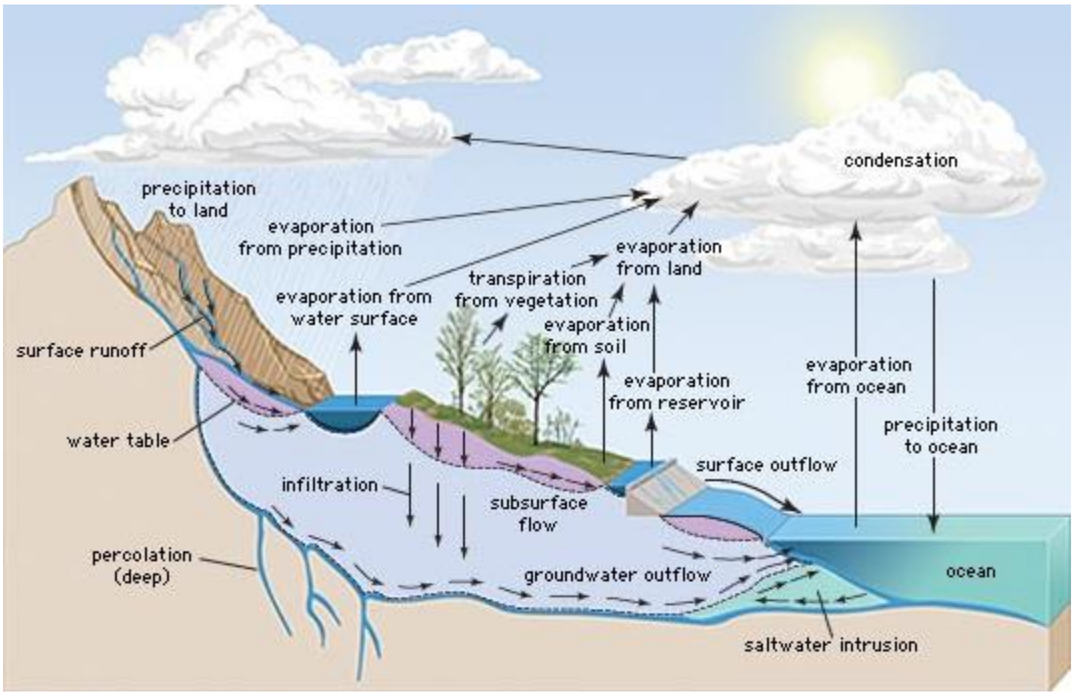


Figure (2. 3): The hydrologic cycle

2.2.2 Runoff Generation in Arid and Semi-Arid Regions

Although a large number of studies have been carried out regarding the runoff generation mechanism in the arid regions, few ones only have been done in the arid and semi-arid regions (e.g. (Yair & Lavee, 1976), (Dunne, 1978), (Yair & Lavee, 1985), (Abrahams et. al., 1988), (Wilox et. al., 1997), (Martinez-Mena et. al., 1998), (Lange, 1999), (Wheater, 2002), (Beven K. J., 2002), (Lange & Leibundgut, 2003), (Shadeed S. , 2008), and (Gunkel et. al., 2015)).

All the literature mentioned above concluded that the Hortonian or the Infiltration Excess Overland Flow (IEOF) (Horton, 1933)is the dominant runoff generation mechanism in arid and semi-arid regions. IEOF can be defined as the flow that occurs when the rainfall rate becomes higher than the soil infiltration rate, so that the excess water accumulates at the ground surface and flows as sheets on the soil surface. When the water flows as sheets over the soil surface it is called overland flow and it can be considered as the initial phase of the surface runoff in streams (Lange, 1999). There are two conditions that should be satisfied to cause the occurrence of IEOF: 1) rainfall intensity greater than the local soil infiltration capacity and 2) the rainfall duration is larger than the ponding time, the time required to saturate the soil surface for an initial soil moisture profile and the time required to fill the small depressions (Freeze, 1980), (Bonell & Williams, 1986).

On the other hand, in the humid regions, the soil allows the rainfall to infiltrate until it reaches the saturation degree. So, the flow happens because of the temporary or permanent soil saturation which is called the Dunnian or Saturation Excess Overland Flow (SEOF) (Dunne et. al., 1975).

In both humid and arid regions, the theoretical and experimental data showed that the runoff generation mechanisms including both IEOF and SEOF are highly variable due to the high variability of the soil infiltration rates (Yair & Lavee, 1985), (Loague & Gander, 1990) and (Jordan, 1994). In the arid and semi-arid regions, this variability is mainly related to the spatial and temporal variability in rainfall in addition to the chemical and physical soil surface properties (Yair & Lavee, 1976), and (Lavee & Yair, 1990). From the study of the soil properties that affects the runoff generation mechanism in the arid region, Marinez-Menta et. al. concluded that the IEOF is the dominant mechanism in the more degraded areas with fine texture and poorly permeable soils while SEOF is the dominant one in the areas in which the soil have coarser texture (Martinez-Mena et. al., 1998).

2.3 Previous Studies in the Study Area

For the hydraulic studies in West Bank, few ones only concentrated on the rainfall and runoff processes. The earliest hydraulic studies had been conducted by Rofe and Raffety (1965), who have installed a network of rainfall gages in ten wadis. They had recorded the data for 1962/1963 and found that the runoff percentage was 2.2% of the total rainfall. So, they concluded that the runoff was negligible in the North of West Bank. After the occupation of the West Bank in 1967, the Israelis started measuring the runoff through some gages that lies outside the West Bank borders. So, a more reliable runoff data had started to be collected.

In (1995), Hussary et. al. analyzed the rainfall data for the North of west Bank, and they presented the relationship between the rainfall and runoff in Hadera catchment in the period 1982/1983 to 1991/1992. They concluded that in that period the runoff-rainfall ratio was ranging between 0.1% and 16.2% with an average value of 4.5%.

Ghanem (1999) conducted a hydrological and hydrochemical investigation for the Faria catchment using GIS. He found that the runoff is 2% of the total rainfall for the upper Faria and 1% for the lower Faria.

Shadeed and Wahsh (2002) had used the synthetic models to study the runoff generation in the upper part of the Faria catchment.

Takruri (2003) had also conducted a study in the Faria catchment, in which she studied the rainfall data and derived approximate IDF curves for Beit

Dajan station there. In addition, she had used traditional methods to derive the unit hydrograph for the catchment.

Shadeed (2005) had developed GIS-based KW-GIUH hydrological model to simulate the rainfall-runoff in the Faria catchment, and he also derived the GIUH unit hydrographs for three sub-catchments there.

Jamil (2006) had developed design criteria for the construction of Retention Dams in wadi Faria in the catchment. After he had analyzed the efficiency of constructing retention dams for 2 years return period, it was found that about 90% of the storm water runoff could be used for artificial recharge.

Shadeed (2008) had developed a coupled TRAIN-ZIN model to simulate the runoff generation in the Faria catchment. In addition, he developed a runoff-generation map for the catchment from which the model parameters can be estimated for different terrain types.

In the same year, Salahat had studied the natural runoff and the infiltration system in the Faria catchment. In his study, he had developed an integrated prediction-optimization model for water harvesting, storage and utilization in the catchment.

Saleh (2009) had recognized the importance of utilizing the surplus storm and spring water in Al-Faria catchment. So, in his study, he had found and studied the feasible solution of recharging the groundwater with the surplus water there. The results of his study showed that about 3.2 MCM can be contributed artificially in the upper parts of the catchment and that 14% of the total area is very suitable for artificial groundwater recharge.

In (2013), Alawneh had assessed and modeled the water quality for Al-Faria main stream. The importance of this study is that the water quality modeling is essential for ecosystem management as well as for the stream and watershed restoration.

In the same year, Abboushi had conducted a prelimenary investigation of wadi-aquifer interaction in semi-arid regions taking Al-Faria catchment as a case study. The tracer field experiment proved that transmission losses took place and infiltrated through the wadi. The percent loss in the flow rates values in the different wadi sections ranged from 4.8% to 68.3%.

Chapter Three

Description of Study Area

Chapter Three

3 Description of Study Area

3.1 Geography and Topography

The study area considered in this research is the Faria catchment which is located in the northeastern part of the West Bank. It starts from Nablus Mountains in the west and extends to Jordan River in the South, where it drains its water (see **Figure 3.1)**. The catchment intersects three districts of the West Bank, which are Tubas, Nablus, and Jericho (see **Figure 3.1**). It has an area of about 320 km^2 which represent approximately 6% of the total area of the West Bank (5650 km^2).

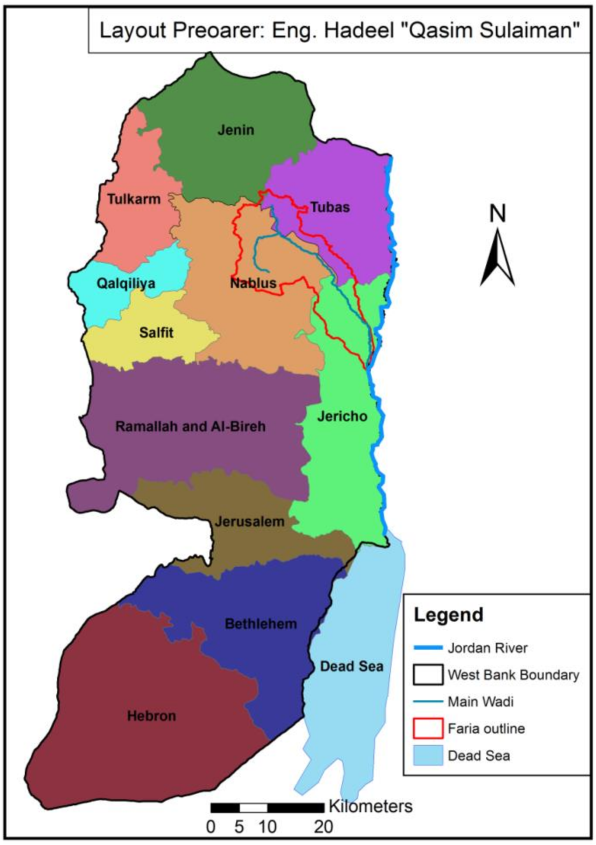


Figure (3. 1): Location map of the Faria catchment

The catchment has a unique topography since it starts at an elevation of about 920m above mean sea level at Nablus mountains in the western borders and descends to an elevation of about 360 m below mean sea level at its outlet to Jordan River in the east (see **Figure 3.1**). So, there is about 1.3 km elevation difference over a short distance of less than 35 km, which gives the catchment some distinction and importance.

3.2 Soil and Geology

There are six types of soil in the Faria catchment (see **Table 3.1**), but the main two types are the terra rossas and brown rendzinas/pale renzinas which forms about 65% of the total area of the catchment. The texture of most of the soil types are fine texture such as loam and clay, which means that it doesn't allow large volumes of infiltration. However, the texture of the main soil types in the catchment includes karstic formations such as dolomite and limestone (Ghanem, 1999) (Abboushi, 2013). These formations allow the infiltration through the soil which reduces the surface runoff volumes.

Table (3. 1): Soil types and characteristics in Faria catchment

Soil Type	Soil Texture	Hsg	Area (Km2)	Area (%)
Brown Litholsols and Loessial Arid Brown Soils	Loamy	B	16.3	5
Brown Rendzinas and Pale Renzinas	Clay Loam	D	76.9	24
Grumusols	Clay	D	46.0	14
Loessial Serozems	Sandy Loam	A	18.7	6
Regosols	Sandy Loam	A	29.8	9
Terra Rossas, Brown Rendzinas And Pale Rendzinas	Clay	D	131.3	41

The spatial distribution of the soil types through the catchment is illustrated in the following map (**Figure 3.2**).

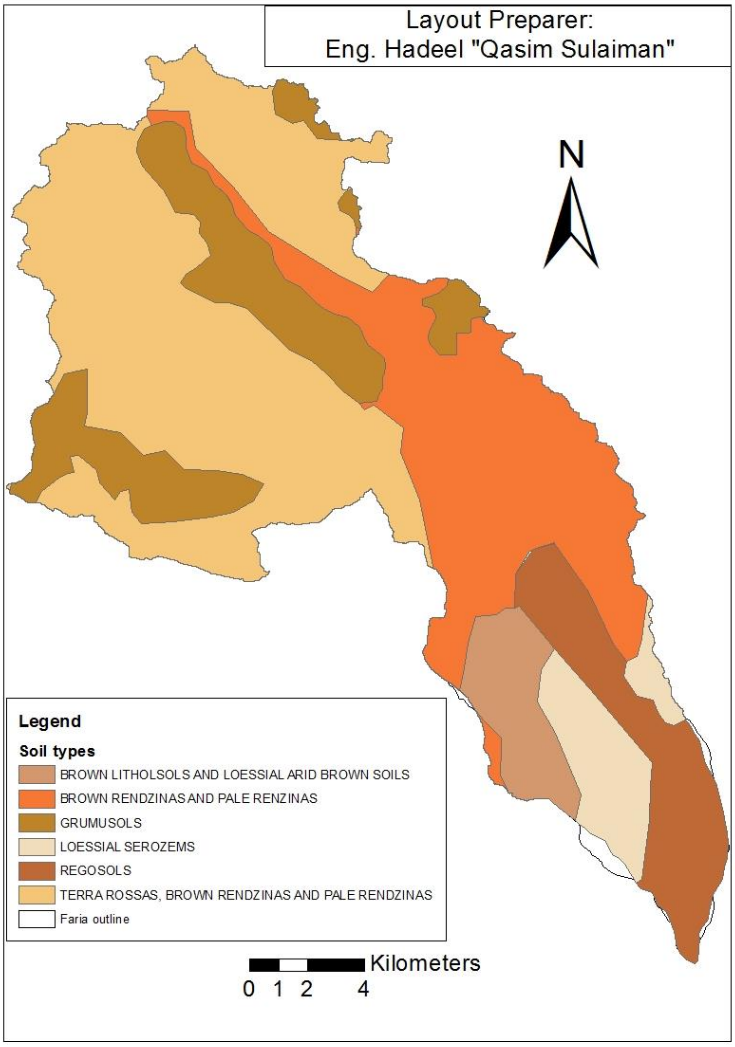


Figure (3. 2): Soil map of Faria catchment

Geologically, Faria catchment has a complex structural system with the Anticline that extends from the northeast to the southwest and represents the main controlling feature. In addition, there are many joints and faults that are perpendicular to the anticline and significantly affect the drainage water volume from the catchment. The geologic formations are composed mainly of Dolomite, Limestone, and Marl (Hijleh, 2014).

The faults and fissures in the catchment geologic formations affect the hydrology of the area by allowing huge infiltration quantities and the appearance of the springs there such as Badan, Faria, and Miska (Ghanem, 1999).

Figure 3.3 shows the geologic formations types and distribution in Faria catchment.

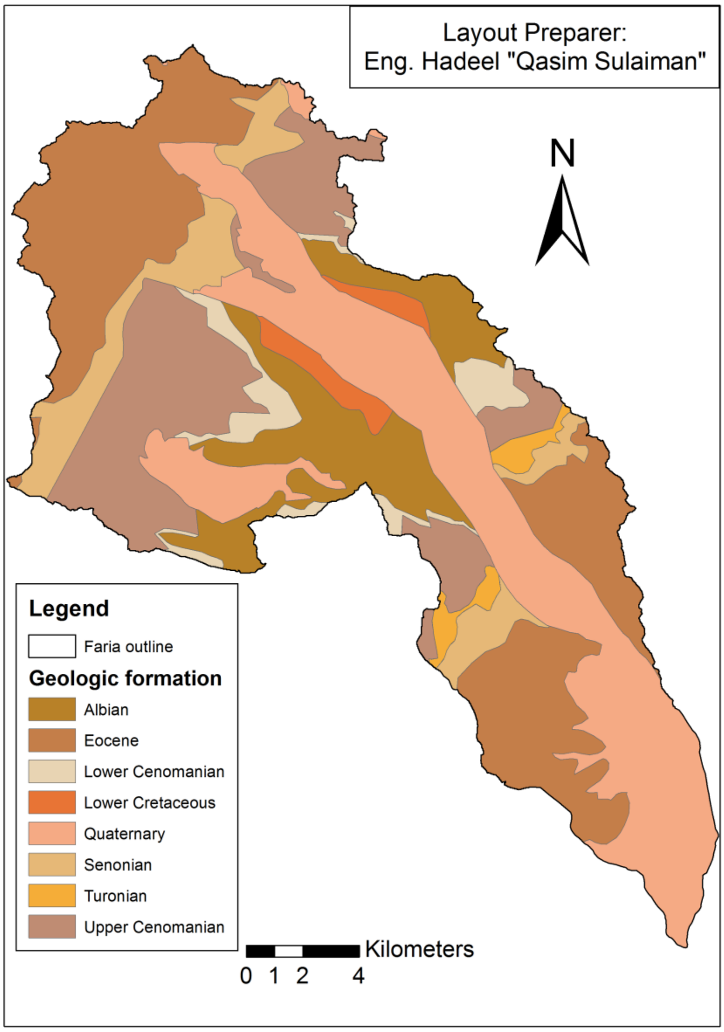


Figure (3. 3): Geologic map of Faria catchment

3.3 Climate

The Faria catchment has a Mediterranean, semi-arid climate in general, which is characterized by mild rainy winters and moderately hot dry summers. The winter season extends for six months from October to April and includes most of the annual rainfall and the other six months is mostly hot dry summer. The temperature in the catchment is variable with altitude, since it increases with decreasing altitude from northwest to east south. As such the mean annual temperature ranges from 18° C at 900 m AMSL in the upper parts of the catchment to about 24° C at an elevation of about 350 m BMSL in the catchment lower parts (Ghanem, 1999) (Abu Baker, 2007) (Shadeed S. , 2008) (Saleh, 2009) (Alawneh, 2013) (Duraidi, 2015).

There are only two climatic stations within Al-Faria catchment, one in Nablus at an elevation of about 570 m AMSL and the other is in Al-Jiftlik at an elevation of about 237 m BMSL. So, the climatic information is taken only from these two stations in addition to the rainfall stations.

Evaporation and accordingly potential evapotranspiration varies both temporally and spatially. For Nablus station, the rainfall exceeds the potential evapotranspiration in the period of five months from November to March while in Al-Jiftlik, there is a rainfall surplus only in two months in the year which are December and January, and the potential evapotranspiration exceeds the rainfall quantities during the rest of the year (Hijleh, 2014). As such, there is a need for agricultural irrigation most of the time especially in the lower parts of the catchment.

The annual average relative humidity also varies from 58% to 61% in the lower and upper parts, respectively. That affects both quality and quantity of available water in the catchment (Jarrar, et al., 2005).

The rainfall in the catchment is measured by seven rainfall gages: Tubas, Tammun, Talluza, Salim, Nablus, Al-Faria, and Beit Dajan. The first four ones are tipping buckets rainfall gages that records the time spent for every 0.2 mm rainfall depth increment. Nablus station is a regular weather station at which almost all the climatic parameters are measured from 1947 till now. Al-Faria station is located at the lower part of the catchment at Al-Jiftlik village, where it is not more reachable by Palestinians since it is under the Israeli control. The following table (see **Table 3.2**) shows the location, mean annual rainfall, and the elevation at each station.

Table (3. 2): Basic information about the rainfall stations in Al-Faria catchment

Station Name	Elevation	Period	Average Rainfall (mm)	Station Type
Al Faria Station	-237	1952-1989	198.6	Daily Gauge
Nablus Station	570	1946-2003	642.6	Daily Gauge
Tubas Staion	375	1967-2003	415.2	Daily Gauge & TBR
Tammun Station	340	1966-2003	322.3	Daily Gauge & TBR
Talluza Station	500	1963-2003	630.5	Daily Gauge & TBR
Beit Dajan Station	520	1952-2003	379.1	Daily Gauge
Salim Station	514	-	589	TBR

The following map (see **Figure 3.4**) illustrates the location of the rainfall stations and the spatial distribution of rainfall throughout the catchment. The map shows that the rainfall decreases as heading from north to south and from west to east. The rainfall has a value of 660 mm in the upper parts of the catchment at Nablus and decreases to reach a value of about 160 mm at the outlet near the Jordan River.

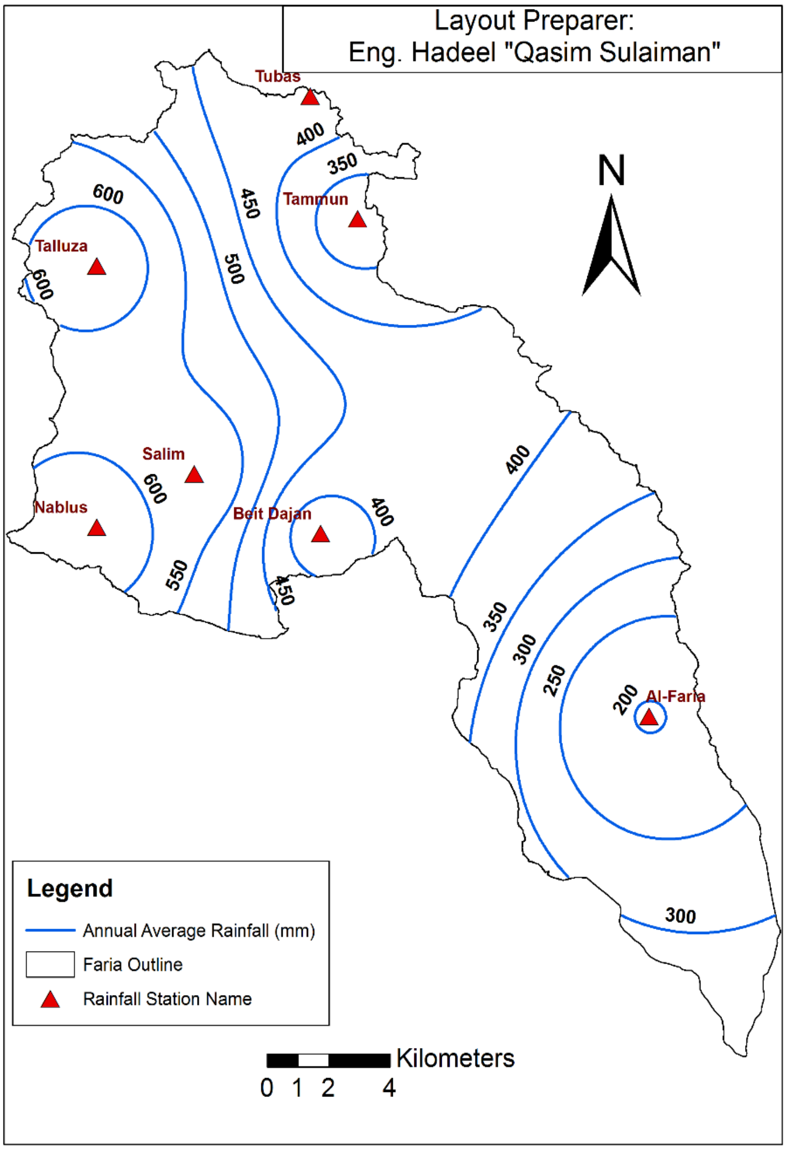


Figure (3. 4): Raingauges and average annual rainfall distribution in the Faria Catchment

3.4 Water Resources

The water resources in the Faria catchment are either groundwater or surface water. The groundwater resources are being utilized through wells and springs while the surface water is limited to winter surface runoff. The Faria catchment lies mainly over the Eastern Aquifer Basin (see **Figure 3.5**).

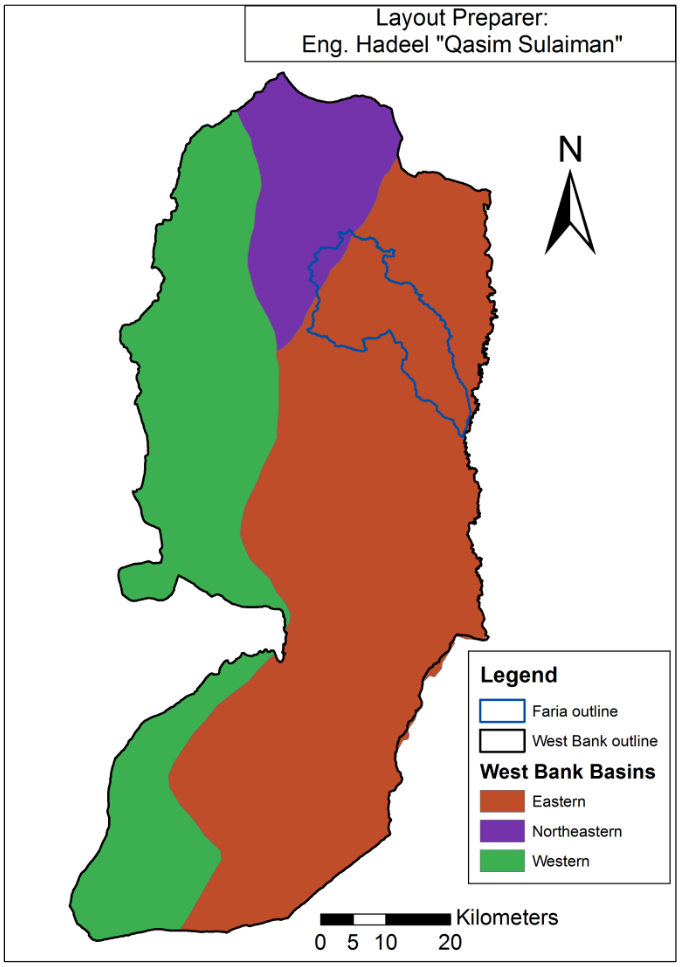


Figure (3. 5): West Bank groundwater basins

3.4.1 Wells

There are 70 wells in the catchment, 61 of it are agricultural wells, 4 are domestic, and 5 are under complete Israeli control (Shadeed S. , 2005)

(Shadeed S. , et al., 2011) (Duraidi, 2015). The total annual utilization of groundwater wells ranges from 4.4 to 11.5 MCM (Shadeed S. , et al., 2011). These amounts represent a percentage of 21 to 55 % of the annual average abstractions from the EBA for the years 2007- 2012 (PWA, 2014). The water quality of the wells in the middle areas of the catchment is negatively affected by the untreated municipal wastewater coming from the eastern Nablus.

The following map (see **Figure 3.6**) shows the locations of the groundwater springs and wells and its types within The Faria catchment.

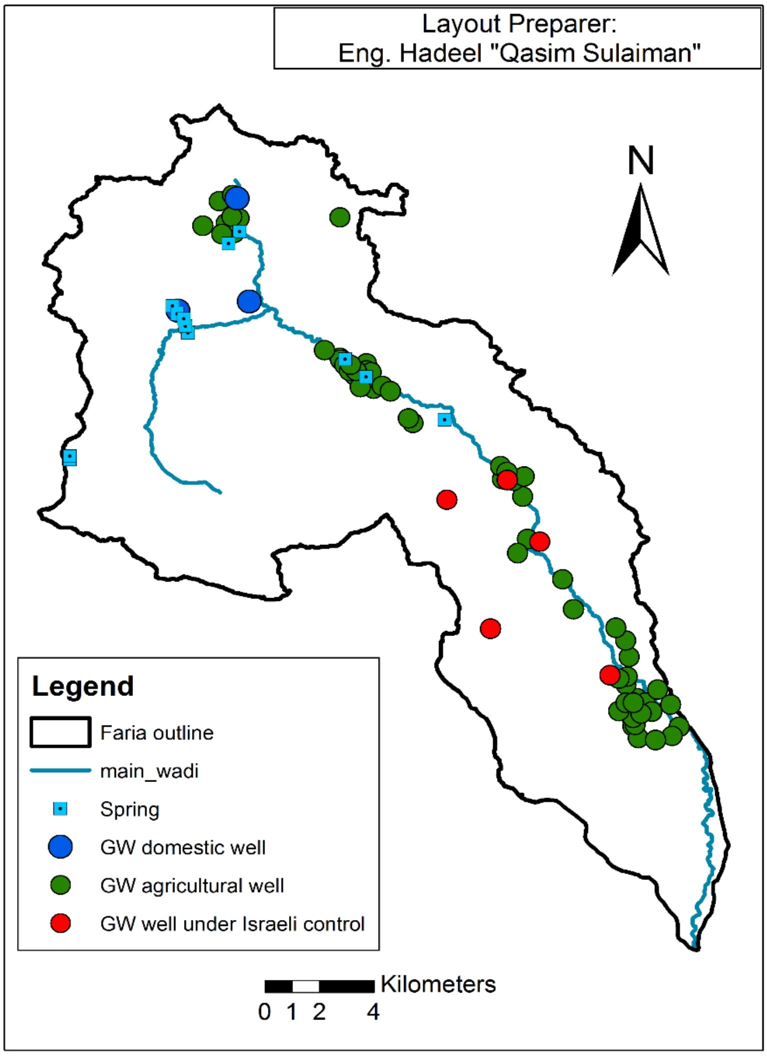


Figure (3. 6): Springs and GW wells in the Faria catchment

3.4.2 Springs

The springs represent the natural groundwater drainage outlets in the Faria catchment. There is 13 fresh water springs within the Faria catchment. Its spatial distribution in the catchment is shown in **Figure 3.6**. The annual discharge from springs varies between less than 4 and almost 40 MCM with an approximate average amount of 14 MCM (Shadeed S. , et al., 2011). Whereas the long term annual discharge of the springs in the EAB is estimated by about 33 MCM (PWA, 2014). For the water quality of the springs, the water is polluted in the upper parts of the catchment from the cesspits since they are in residential areas. In the middle areas of the catchment, the water of the springs there is increasingly polluted by the untreated municipal wastewater also. A recent research regarding the quality of the groundwater in the Faria catchment by testing the groundwater springs and wells there has concluded that the springs and wells water are suitable for drinking in terms of chemistry except for nitrates that exceeded the maximum allowed limit in some samples. On the other hand, the water there is not suitable for drinking in terms of microbiology, where it will be a source of water-borne diseases in case of absence of disinfections processes (Shadeed et. al., 2016)

3.4.3 Wadis

The surface water in the catchment is characterized by the stream flow in Al-Badan, Al-Faria and the lower streams. There is untreated domestic and industrial wastewater discharged from Nablus city to Al-Badan stream. In addition, untreated domestic wastewater is discharged from Al-Faria refugee camp to Al-Faria stream. So, the stream-flow of the Faria catchment includes:

- Surface runoff from winter storms. This includes urban runoff from Eastern Nablus and the built-up areas inside the catchment such as Tubas, Tammoun… etc. Also, the agricultural and rural runoff from the agricultural areas near to the wadi and the rural areas, respectively.
- Fresh water from the springs, which prevent the wadi from being dried in the hot summer.
- Untreated wastewater from a part of Nablus city and Al-Faria refugee camp.

Figure 3.6 shows the main wadis in the Faria catchment which are the lines in the blue color including Faria and Badan wadis in the upper parts of the catchment in addition to the lower main wadi.

3.5 Land Use Patterns

There are many land use classes in the Faria catchment. It can be divided into eight main classes: bare rocks, built up areas, natural forests, olive plantations, natural grassed hill slopes, scattered olive plantations, sparsely vegetated hill slopes, and agricultural areas. Where the last one is considered the most important one as the agriculture is the main economic activity in the catchment. The Fari catchment covers 26% of total West Bank needs from agricultural crops (Abu Baker, 2007). **Figure 3.7** shows an aerial photo for the catchment from which some patterns of land use in the catchment can be seen such (ex. the built up areas).

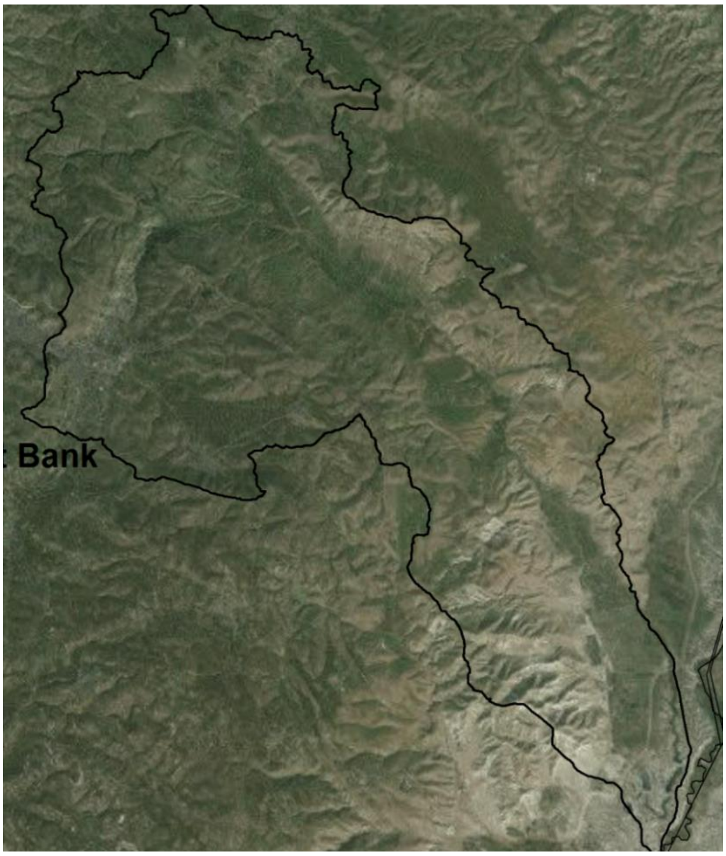


Figure (3. 7): Aerial photo of the Faria catchment

The main crops there includes: palms, olive, citrus, and many vegetable types. Some of it is irrigated and others are rain-fed and sometimes it depends on the annual rainfall amounts and timing. **Table 3.3** shows the land use classes and the areas and percentages of each one of the total catchment area.

Table (3. 3): Land use classification for Faria catchment

Land-use class	Area (m2)	Area (%)
Agricultural areas	71.0	22.1
Bare rocks	9.1	2.8
Built-up areas	15.1	4.7
Natural forests	2.8	0.9
Natural grassy hill slopes	90.8	28.3
Olive plantations	20.4	6.4
Scattered olive plantations	26.2	8.2
Sparsely vegetated hill slopes	85.2	26.6

The following map (see **Figure 3.8**) shows the spatial distribution of all the land use types through the catchment. From this figure it is obvious that the agricultural areas are concentrated around the main wadi and in its near areas since most of the irrigation water is conveyed from the wadi through agricultural canals.

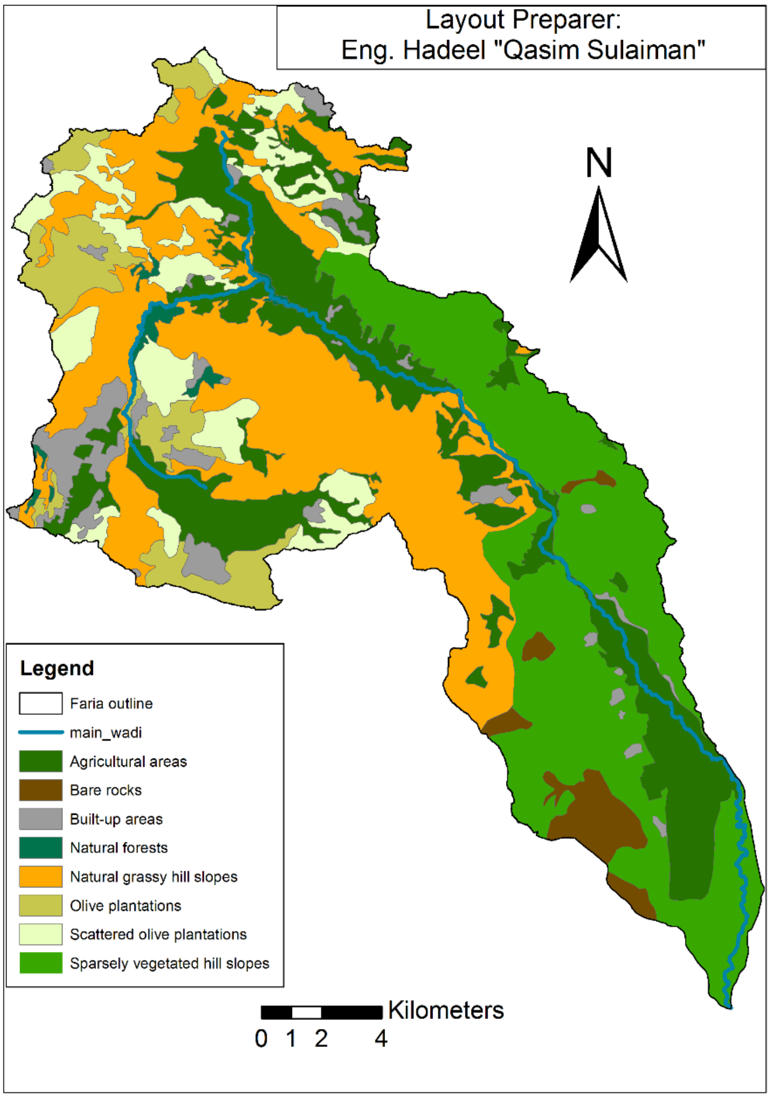


Figure (3. 8): Land use map of the Faria catchment

Chapter Four

Data Collection and Analysis

Chapter Four

4 Data Collection and Analysis

It is widely known that the efficiency of any model and its output accuracy depends on the accuracy of the input data. As such, the efficiency of a hydrological model depends mainly on the quality of the input hydrological data. So, these data should be given great care before integrating into the hydrological model.

The quality of the hydrological input data is a function of the spatial coverage of the data, which means the geographic location or area for which the data is. It is also a function of the temporal coverage that is the time period through which the data was collected or observations made. It is also regards the resolution of the data such as the cell size in the spatial data sets and the time steps in the temporal ones (Ochoa-Rodrigueza et. al., 2015).

In arid and semi-arid regions, the availability of rainfall and runoff data is very limited. This may belong to the unstable climate such as the infrequent harsh events that are sometimes damaging (Shadeed S. , 2005). This makes the arid and semi-arid areas lacking the modeling tools and data that the other regions have. Our study area in this research which is the Faria catchment, West Bank also has the same case. As such, the hydrological data is very limited and not available to the public also. So, interpolation and extrapolation in addition to some analysis for the existing data were done in order to fill the required data that had been used in the model in our case.

4.1 General Data

4.1.1 HEC-HMS Model Input Data

4.1.1.1 *Rainfall Data*

For the rainfall data applied to the HEC-HMS model, Thiessen Polygon method was used in order to find the average rainfall values overall the catchment. Then, for each sub-catchment, the gage weights method were used to find the weights of the gages which their polygons intersect that sub-catchment. After that, the total rainfall recorded by each station is multiplied by its weight for every sub-catchment. **Figure 4.1** below illustrates the distribution of the existing and the assumed rainfall stations among the catchment and Thiessen polygon for each of them. The weights of the gages for each sub-catchment are calculated according to the following equation:

$$wi,j = \frac{Ai,j}{Aj}$$

Where:

wi,j is the weight of rainfall station i in sub-catchment j;

Ai,j is the area of Thiessen polygon of station i that intersects sub-catchment j;

Aj is the area of sub-catchment j.

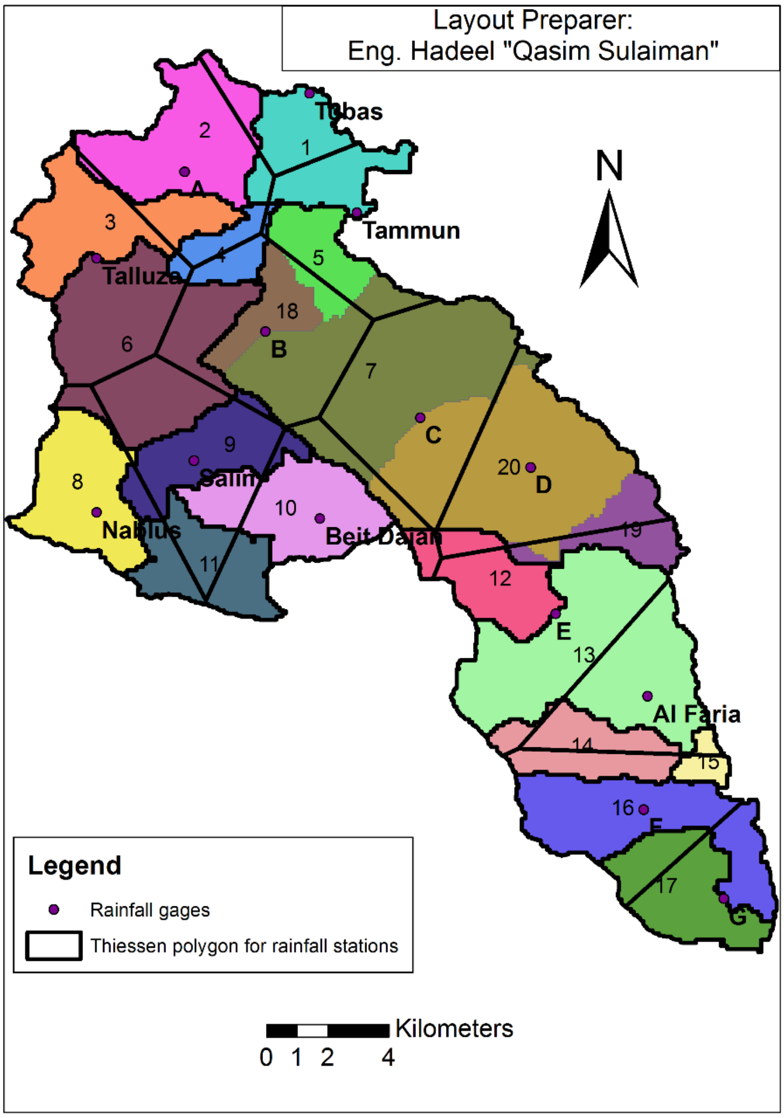


Figure (4. 1): Thiessen Polygons for the existing and assumed rainfall stations

4.1.1.2 Curve Number (CN)

The Soil Conservation Service (SCS) Curve Number (CN) loss method was used in the calibration. This method can estimate the excess rainfall as a function of many parameters, including: land use, land cover, and antecedent moisture content (Feldman, 2000). The CN in this method was computed as a weighted value according to the land use types in each sub-catchment. The following formula was used to calculate CN each sub-catchment:

$$\mathrm{CN(subcatchment)} = \frac{\mathrm{A}_i \times \mathrm{CN}_i}{\sum_{\mathrm{i=0}}^{\mathrm{n}} A_i}$$

Where:

CN(subbasin) Is the weighted average CN of the sub-catchment;

A_i Is the area of the i$^{\mathrm{th}}$ part of the sub-catchment;

CN_i Is the CN of the i$^{\mathrm{th}}$ part of the sub-catchment, where taken from standard curve number tables (Schweb et. al., 2005).

The CN values ranges from about 30 for soil with high infiltration rate to 100 for the water bodies (USDA-SCS, 1985).

4.1.1.3 Sub-catchments Initial Abstractions

SCS-CN loss method was used as stated before. So, the initial abstraction for each sub-catchment had to be entered to the model. The initial abstractions are computed according to the following formula:

$\boldsymbol{I_i = \lambda S}$ **,** where $\boldsymbol{S = \frac{25400}{CN} - 254}$

Where

$\boldsymbol{I_i}$ is the initial abstraction;

$\boldsymbol{\lambda}$ is factor varies from 0.2 to 0.4;$\boldsymbol{S}$ is the maximum potential retention;

4.1.1.4 Loss/Gain Method

For this part in the model, the constant method was selected to present the loss /gain from/to the streams in the streams network. This method uses an empirical relationship in order to calculate the channel loss using both a fixed reduction flow rate and a ratio of the flow. The fixed flow rate is subtracted from the routed flow and then the reminder is multiplied by the fixed ratio (Hydrologic Engineering Center, 2013).

4.1.1.5 Transform Method

For each sub-catchment in the model, there is a transform method that is responsible for the calculation of surface runoff. In this case, the SCS Unit Hydrograph method was selected as a transform method. Research by the SCS suggests equations by which the peak flow rate amount and timing can be calculated. In these equations the lag time for every sub-catchment is used. In this case, the lag time was computed according to the following formula (Soil Conservation Service, 1973):

$$\boldsymbol{t_l = 0.6 \times t_c}$$

Where $\boldsymbol{t_c}$ is the time of concentration in seconds. It can be expressed as:

$$\boldsymbol{t_c = \sum_{i=1}^{n} \frac{L}{v}}$$

Where:

$\boldsymbol{L}$ is the length of one segment of the longest flow path in the catchment in meters;

$\boldsymbol{v}$ is the flow velocity (m/s);

$\boldsymbol{n}$ is number of flow path elements.

4.1.2 WRF-Hydro Model Input Data

There are two types of data that are used in the hydrological model in this research, which is WRF-Hydro model. The first one is the statistic data which are time-independent information and the other one is the dynamic data, which is given within a time frame.

4.1.2.1 Static Data

This data is time-invariant or time –independent as mentioned earlier. So that it has always the same value that doesn't change with time but it may change with place. These data incudes many types as follows (Gochis, Yu., & Yates, 2015):

- Map projection information: 2D gridded latitude, longitude, map-scale factors, etc.
- Topographic information: 2D gridded elevation, green vegetation fraction, lake Mask, and soil categories.
- Routing grid: topography, flow direction, channel networks, observation points, stream order, catchments, and calibration parameters.

4.1.2.2 Dynamic Data

This type of information is the time-dependent ones. It sometimes include the initial conditions data that is the data at initial analysis time, it also may include the boundary conditions data. In addition, some programs of WRF-Hydro model such as UNGRIB and METGRID programs need such type of data. The dynamic data includes (Gochis, Yu., & Yates, 2015):

- 3D fields of horizontal winds, temperature, and relative humidity.

- 2D fields of surface or sea-level pressure, surface temperature, relative humidity, horizontal winds.
- Time-sensitive and land-surface fields: snow-cover, soil temperature, soil moisture.

4.2 Rainfall Data

4.2.1 Rainfall Stations

The rainfall in the Faria catchment is measured by seven rainfall stations which are: Tubas, Tammun, Talluza, Salim, Nablus, Beit Dajan, and Al-Faria. Tubas, Tammun, Talluza, and Salim are tipping puckets rain gages (TPR’s) that measure the time for each 0.2 mm increment of rainfall. Nablus station is a regular weather station at which most of the climatic parameters are measured. While the other two stations (Beit Dajan and Al-Faria) are simple daily stations.

The rainfall stations where controlled by the Israelis until 1994 when the Palestinian Authority had been established and been responsible for controlling these stations except Al-Faria station for which the rainfall data is available for few years only. Nablus station annual data is available for about 70 years (from 1946) while the monthly and daily data is available for about 40 years (from 1975). As such, Beit Dajan station has daily rainfall depths since 1967. While the data for the TPR’s are available since 2004.

The time resolution for the available TPR’s data is irregular since it doesn’t measure the rainfall depth every specified period of time. Instead, it measures the time spent for every tip, which happens every 0.2 mm additional rainfall depth.

Selected rainfall events and rainy periods from these data were chosen in order to test the developed HEC-HMS and WRF-Hydro models as will be discussed in chapter five.

4.2.2 Density of Rainfall Stations

As mentioned earlier, the quality of modeling results is influenced by several parameters among which the rainfall is the most important one. So, the spatial interpolation of rainfall data is a preliminary step in hydrological modeling process (Sarann et. al., 2013). Since the source of rainfall data in our case is point gauges, before doing the spatial interpolation of the rainfall data, we need to make sure that the density of these gauges is enough to represent the spatial rainfall variability in the catchment.

The simple arithmetical average method stated in the following equation is used to find the optimum number of rainfall gauges for a catchment (Eagleson, 1967):

$$N = \left(\frac{C_v}{E}\right)^2$$

Where:

N: Optimum number of rain gauges

C_v: Coefficient of variation of the rainfall values of the existing rain gauges

E: Allowable percentage of error in the mean rainfall of the catchment

To calculate the coefficient of variation, the following procedure is followed:

1) Calculate total rainfall from the existing rainfall gauges:

$$P = P_1 + P_2 + \cdots + P_7$$

2) Calculate average rainfall of the existing rainfall data:

$$\bar{P} = \frac{\sum P}{n}$$

3) Calculate sum of squares of rainfall data:

$$\sum P^2 = P_1^2 + P_2^2 + \cdots + P_7^2$$

4) Calculate mean of squares:

$$\overline{P^2} = \frac{\sum P^2}{n}$$

5) Calculate standard deviation:

$$\sigma = \sqrt{\frac{n}{n-1}\left(\overline{P^2} - \bar{P}^2\right)}$$

6) Calculate coefficient of variation:

$$C_v = \frac{100\sigma}{\bar{P}}$$

7) Calculate optimum number of rain gauges for the catchment(N):

$$N = (\frac{C_v}{E})^2$$

Based on the existing rainfall data of the seven stations and assuming for E equals 10%, the optimal number of stations in the catchment is estimated at about 14 (Shadeed S. , 2008), seven of them are already there, which means that additional 7 stations (N-n) are needed to be installed to have a better spatial representation of rainfall variation in the Faria catchment.

4.2.3 Spatial Distribution of Rainfall Stations

As can be seen in **figure 3.4**, there is great rainfall variability in the catchment. Where, the rainfall amount decreases steadily as heading from northwestern parts to southeastern ones. Also, the rainfall amount mostly decreases with decreasing elevation. For example the rainfall amount decreases from about 650 mm at Nablus Mountains in the western part of the catchment to approximately 150 mm near Jordan River in the Southeastern part. That means, in a distance of about 30 km, there is a rainfall difference of about 400 mm. The variability of rainfall amounts between stations can be notified from **Figure 4.2** that illustrates the average annual amount of rainfall for each station in the catchment.

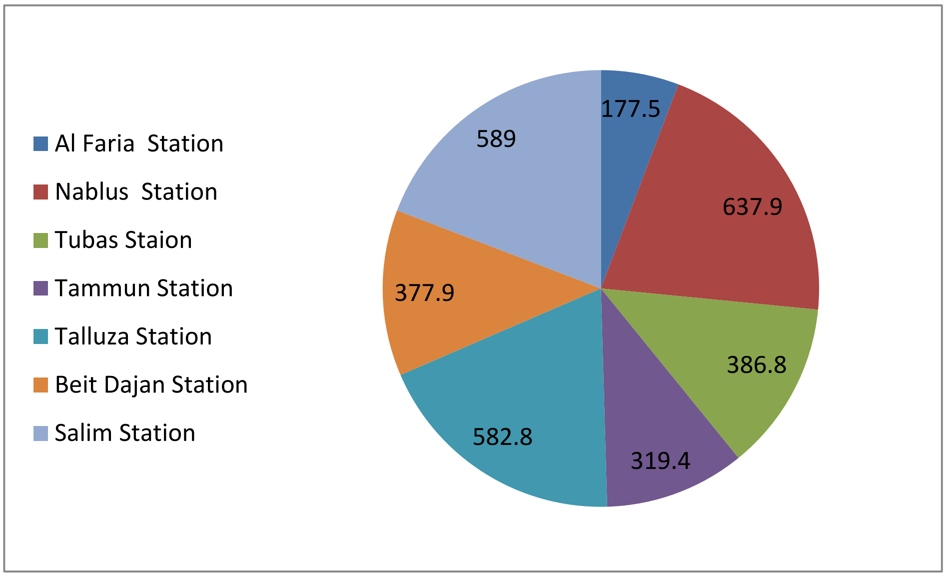


Figure (4. 2): Average annual rainfall depth (in mm)in the Faria catchment

In hydrologic modeling and especially the ones that are used for flood prediction purposes, the variability of rainfall among the catchment should be captured in high accuracy in order to get beneficial and actual results and to produce a realistic hydrograph that can be dependable to warn the public in case of floods. As a result, the additional 7 rainfall stations that proposed to be installed in the catchment to get optimum number of rainfall stations were subjectively suggested to cover the ungagged areas in the catchment. The distribution of the suggested rainfall stations together with the existing ones are illustrated in **Figure 4.3**.

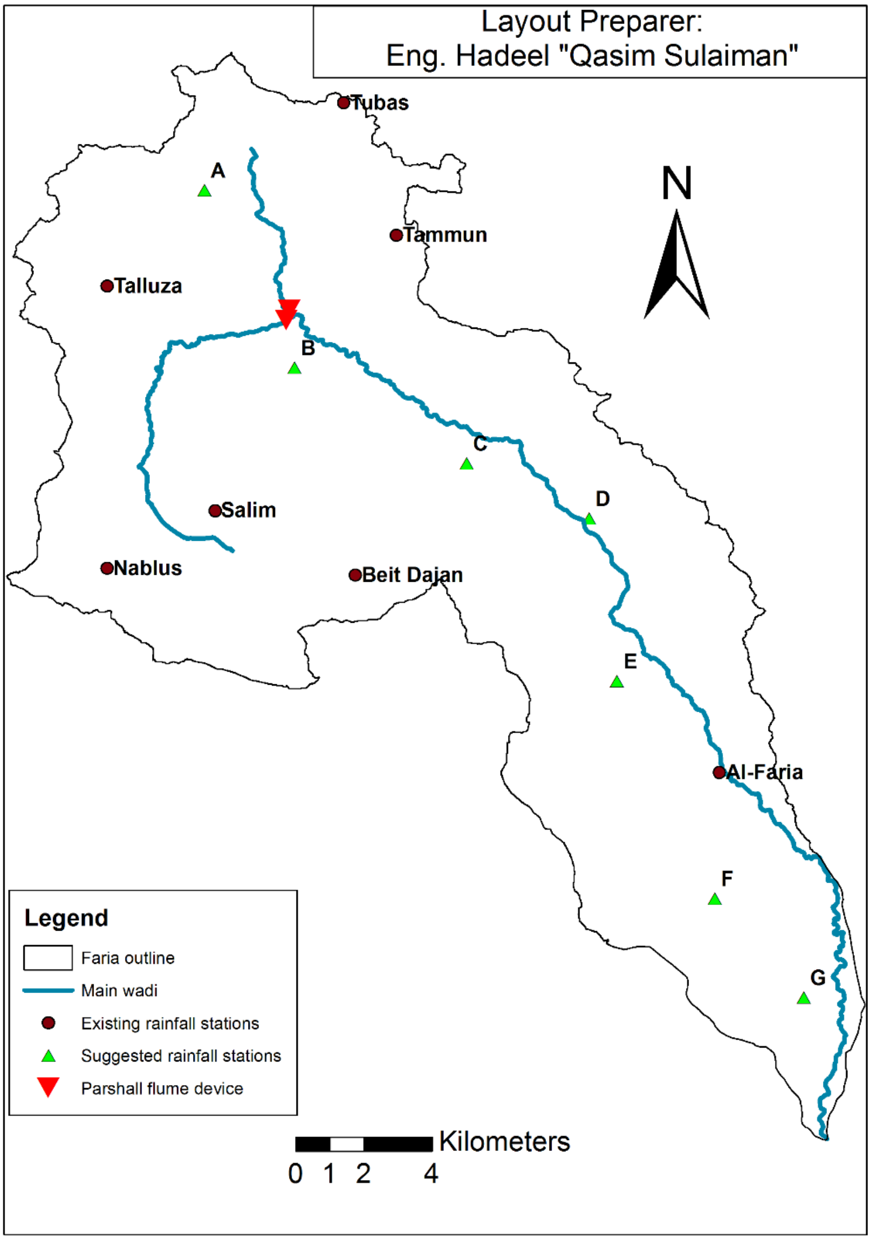


Figure (4. 3): Existing and suggested rainfall stations in the Faria catchment

The average annual rainfall value of each station of the suggested ones was found out using a spatial oriented formula that was developed by Shadeed in 2008 (Shadeed S. , 2008). The equation is developed by multiple linear regression analysis to relate the average annual rainfall value to the spatial location of the station (X and Y coordinates) and the elevation Z. It was developed and validated using the information of the existing rainfall stations in the catchment with a correlation coefficient of $r^2 = 0.99$. The equation is stated as follows:

$$R = 8285 - 39.41X - 2.46Y - 0.34Z$$

Where R is the average annual rainfall depth in mm, X and Y are longitude and latitude in km according to the Local Palestinian Grid, and Z is the surface elevation in m.

The above formula was used to calculate the average annual rainfall depth for the seven suggested rainfall stations in the catchment. The X and Y coordinates, elevation and the average annual rainfall of each station of the suggested ones are shown in **Table 4.1**.

Table (4. 1): Suggested rainfall stations information

Station Name	X (km)	Y(km)	Z(m)	Average Annual Rainfall (mm)
A	180873.0	189124.0	245.5	608.1
B	183520.0	183911.0	120.2	559.2
C	188573.0	181097.0	-20.0	414.7
D	192173.0	179477.0	112.5	308.2
E	192993.0	174687.0	-28.5	259.1
F	195873.0	168297.0	154.0	204.0
G	198486.0	165385.0	298.8	157.4

As illustrated in **Table 4.1** above, there are four tipping buckets stations in the catchment and the other three are daily ones, which are Beit Dajan, Nablus, and Al-Faria stations. So, the finest rainfall resolutions that can be taken from these stations are on daily bases. However, this resolution can do nothing in hydrologic modeling and floods forecasting, since the high major peaks of rainfall couldn't be captured in such course rainfall resolution. Moreover, the rainfall data from the suggested rainfall stations needed to be generated to be used later in the modeling. As a result, there is an urgent necessity to find a method or an equation to fill these missing data. The following formula was used to find the 1-hour rainfall data or even finer time-step using the other four tipping buckets rainfall data.

$$P_x^y = \frac{P_{avx}}{n} \sum_{i=1}^{n} \frac{P_i^y}{P_{avi}}$$

Where:

P_x^y : missing rainfall value at station x at time step y;

P_{avx} : long term annual average of station x;

P_i^y : rainfall value at station i at time step y;

P_{avi} : long term annual average of station i.

4.2.4 Rainfall Input Interpolation

The rainfall data is measured at each the existing rainfall station and estimated at the suggested ones. So, the rainfall data is available as point data only. Hence, point rainfall data are interpolated to estimate the areal rainfall extent over the catchment.

There are many several interpolation techniques that can be used in rainfall data interpolation in order to find out the rainfall data all over the catchment. For example, Thiessen polygons method, inverse distance weight method, nearest neighbor method, radial basis function and many other methods (Sergio et. al., 2003).

In this research, nearest neighbor (NNb) and radial basis function, spline (RBF) methods are the ones that were used to interpolate the rainfall data for WRF-Hydro. The NNb method is the simplest interpolation method in which the value of non-given point in the domain is approximated when the value of points around (neighboring) that point is given. The NNb algorithm selects the value of the nearest point only and doesn't consider the other points. As this method is very simple and easy to implement, it was used in the studied model to give preliminary results for the simulation periods.

The other interpolation method used is the RBF. It is one of the primary tools that are used to interpolate scattered multidimensional data. It has the ability to produce spectral accuracy that made it particularly popular in several different types of applications (Wright, 2003).

RBF model has the following form:

$$f(x) = Sum(w_i . \varphi(|x - c_i|))$$

Where, φ is a basis function, w_i are weight coefficients, c_i are interpolation centers. Interpolation centers usually coincide with the input grid, basis function is usually chosen from a set of forms include Gaussian basis function, multiquadratic basis function, and polyharmonic basis function, while the weights are calculated as solution of the linear system.

Moreover, these functions are considered as exact interpolation techniques, since it predict identical values with the ones are measured at the same points and the generated surfaces requires passing through the measured points

(Zandi et. al., 2011). Also, the major benefit of this method is that the ability to predict values higher than the maximum input value or lower than the minimum one. As the rainfall has no upper or lower limits, this method seems very suitable to use for rainfall interpolation. **Figure 4.4** shows the spatial distribution of average annual rainfall in the Faria catchment which was produced by spline interpolation from the average point annual rainfall data..

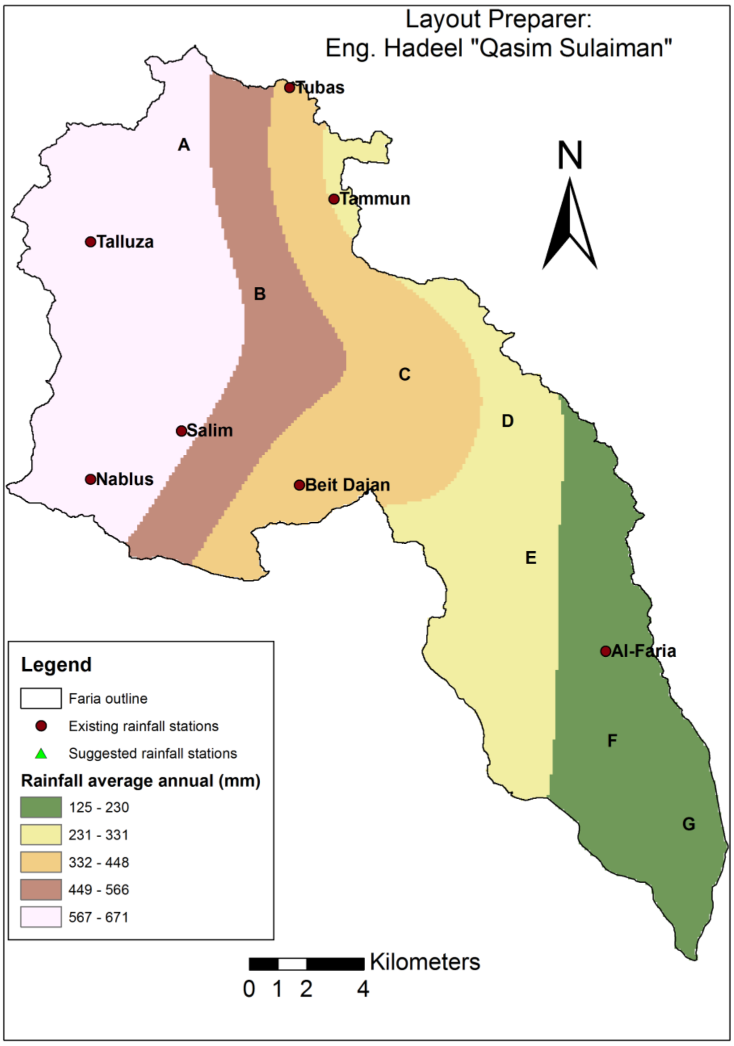


Figure (4. 4): Spatial distribution of average annual rainfall by Spline Interpolation (RBF) Method

4.3 Runoff Data

Streamflow is the amount of water in a stream moving downslope at a given time. It is a combination of both baseflow and surface water runoff. So, the streamflow can vary as these tow amounts vary.

The baseflow is the water contribution to a river or stream from ground water. It occurs as a result of the groundwater movement through geologic formations in response to gravity or other external forces (USGS, 2016).

While the surface water runoff is the part of precipitation that runs off the surface as saturated overland flow. This usually happens when the available water exceeds the infiltration capacity of the ground surface, or when the precipitation encounters relatively impermeable surfaces.

The later component enters the streams more rapidly and in higher quantities, which produces more noticeable response in the stream flow hydrographs (Rantz, 1982). As a result, the surface runoff is the most important component to be focused on and studied for RRM studies.

4.3.1 Surface Runoff Measurements

Most of the rainfall in the study region occurs during the winter and autumn seasons (October, November, December, January, February, and March) as mentioned earlier. So, the surface runoff is produced also during these months. There is a vital need to measure the runoff amounts and timing in order to quantify the rainfall and runoff trends and to compare with the results of rainfall runoff models and to do the calibration and validation of the models later on.

Runoff measuring devices should be installed/constructed at several locations among the catchment under studying in order to catch the variations in the streamflow hydrographs. In Faria catchment only two runoff measuring devices are existent there. Also, they are on the main two streams in the upper parts of the catchment only. The runoff measuring devices that are used in Faria are Parshall flumes that will be discussed in the next section.

The locations of the Parshall flumes that are used in Faria to measure surface runoff are illustrated in **Figure 4.3** using the red icons on the main wadi.

There are many types of water measuring devices that have been developed over the past several decades (Reuben, 2003). Parshall flumes are that the most commonly used streamflow measuring devices in open channels (Sooyoung & Seung Oh, 2013). This type of flumes is named by its inventor name, who is Ralph L. Parshall, since 1992.

In the Faria catchment, two Parshall flumes were constructed at the confluence of the two main streams at the outlets of the upper two sub-catchment; Al-Faria and Al-Badan. The two sub-catchments are joining at an area called al-Malaki Bridge and then daring throughout the lower sub-catchment towards the Jordan River (See **Figure 4.5**).

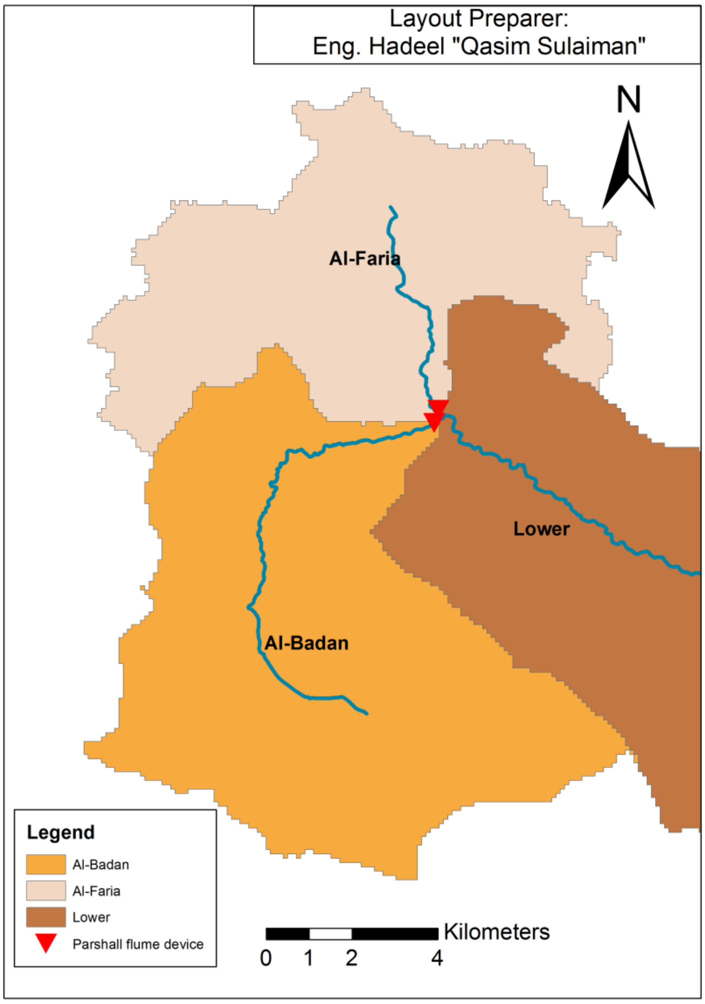


Figure (4. 5): Al-Faria and Al-Badan Parshall flumes

The depth of water inside the flumes is recorded automatically every 10 minutes (or 12 minutes in some years) using data bloggers. Then, the streamflow through the flume is estimated using Parshall empirical formula (Parshall, 1953):

$$Q = k\, H^{n}$$

Where:

Q: streamflow (m^3/s)

k: size specific coefficient

H: upstream head water elevation (m)

n: size empirical constant

Both flumes that are constructed in the catchment are standard ones. The size parameters hat were used for the design of both flumes are shown in **4.2** (Shadeed S. , 2008):

Table (4. 2): Design parameters for Parshall flumes in Al-Faria and Al-Badan sub-catchments

Design Parameter	Faria Sub-catchment flume	Badan Sub-catchment flume
Max. Discharge Q (m^3/s)	15	25
Throat width (m)	3.65	4.57
K	8.859	10.96
n	1.6	1.6

Chapter Five

Model Development

Chapter Five

5 Model Development

5.1 Introduction

Hydrological processes occur at a wide range of levels and the nature of hydrological response of a catchment depends on many reasons. The first one is the hydrological process characteristics. For example, the mechanisms of infiltration in a wet region are different from the ones in a dry region. The second one is the precipitation patterns that affect the hydrological response directly. The catchment itself also affects the type and scale of response of the catchment by its own characteristics such as soil type, land use, antecedent moisture content, slope gradients, and many other factors.

As we are in the era of scientific and technological development, the differences between the calculated and the observed catchment response should not increase very small amounts or even to be negligible. Also, the hydrologists are responsible to predict the catchment response for future events in order to help in the managing the present and future water resources and the population water demand and supply. As a result, the traditional techniques in peak flow and runoff calculations, such as the rational method, unit hydrograph, SCS curve and others, are needed to be improved and inserted to modern software that can be used for more complex catchments and hydrological processes.

In the arid and semi-arid regions, as the Faria catchment, the applicability of such traditional methods becomes more controversy. The formation of rainfall induced soil sealing, which is the altered topsoil layer, affects the water permeability through the soil and this causes the phenomenon of Hortonian runoff process in the arid and semi-arid regions. In this phenomenon, the potential abstractions may not be fully met before the runoff starts although which is not the case in the wet regions. Moreover, the evapotranspiration amounts and timing in arid regions are different from wet regions. For example, the evaporation losses are much higher in arid regions and may continue to occur during the storm which doesn't happen in the wet climates. As a result, the rainfall-runoff response is a main and central topic in hydrology that needs to be continuously developed. And as mentioned before, there is a vital need for future water availability studies, water supply and demands plans, and water management strategies. Which increase the dire need for droughts and floods prediction, and this needs the development of climate predictions and rainfall runoff modeling techniques.

Faria catchment is characterized by its complex terrain, highly temporal and spatial variable rainfall, and the short rainfall-runoff response time. So, the area had a lot of losses sometimes because of droughts and sometimes because of the unexpected high intensity rainfall. Therefore, there was a necessity for improved flood forecasting method for the area.

In this study, the applicability of coupled atmospheric and hydrological (hydro-meteorological) model system in Faria catchment is studied and some rainfall-runoff simulations are applied using the modern hydrological model WRF-Hydro.

5.2 HEC-HMS Model

Before developing the new physically-based hydrological modeling tool which is Weather Research and forecasting model-Hydrological model extension package (WRF-Hydro), it is needed to build an initial idea about the rainfall runoff response and relationships in Faria catchment and to understand the general characteristics of the main hydrologic processes there. So, a rainfall runoff semi-distributed model was developed using HEC-HMS version 4.0 software.

5.2.1 Introduction

A preliminary visualization for the RRM is needed to be done in order to understand the general processes in Faria catchment. So, The HEC-HMS was used to simulate the rainfall-runoff response in the catchment. The model was based on single storm events. GIS tools were utilized to prepare some gridded input data (e.g. land use, soil) whereas, MS excel was used to prepare some time series data (e.g. rainfall, runoff). The model performance was evaluated based on two major rainfall events. The storm of February (8-9), 2006 was used to calibrate the model while the storm of February (4-8), 2005 was used for model validation.

The observed flow data from the runoff flumes in the upper part of the catchment were used to calibrate and validate the model. The model performance was tested statistically using both the *root mean square error* (RMSE) and the *Nash-Sutcliffe efficiency* (NSE). Results showed that the model was quite good in simulating the single rainfall event response and thus it can be used for further modeling of single rainfall event in the Faria catchment specifically and in the West Bank catchments generally.

5.2.2 What is HEC-HMS?

HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) model was developed by the US Army Corps of Engineers (Feldman, 2000) and it can be used for many hydrological simulations. The hydrologic modeling system is designed to simulate the precipitation-runoff processes for dendritic watershed systems. It is a generalized modeling system that is able to represent many different watersheds. In this model, the hydrologic cycle of a watershed is divided into manageable pieces, so any mass or energy flux in the hydrologic cycle can be represented by a mathematical model.

The HEC-HMS consists of four main components. Those are:

1. The analytical model that calculates the channel routing in addition to the overland flow.
2. Storing and managing data system for time series data sets and large ones.
3. Friendly graphical user interface that illustrates the system components with interactive features, and
4. A means for displaying and reporting model results (Bajwa & Tim, 2002).

The system encompasses runoff transform, open-channel routing, losses, meteorological data analysis, parameter estimation, and rainfall-runoff simulation. HEC-HMS employs separate models for each component of the runoff, including models for computing runoff volume, direct runoff and others for base flow. Each model runs combining a basin model, meteorological model, and control specifications. Where the physical data and system connectivity of the watersheds are stored in the basin model. The precipitation data needed to simulate the hydrological processes are stored in the meteorological model.

In this study, the model is calibrated and validated for the Faria catchment with respect to the local observed stream-flow measurements. So, the model has some degree of greater confidence in its reliability (Muthukrishnan et. al., 2006).

An assortment of different loss methods are available in HEC-HMS, some are suitable for continuous simulations such as The one-layer deficit constant method and the others are intended for the event based ones like initial constant, SCS curve number and exponential loss method. In this study, the SCS curve number method was selected to simulate the excess rainfall and losses. Seven different transformation methods are also available in HEC-HMS, some of them are complicated because it needs a lot of input parameters and some are simpler. In our case, the dimensionless SCS unit hydrograph method was chosen to transform the excess rainfall to runoff. Moreover, among the six routing methods available in the software, Muskingum method was used in our hydrologic model. A brief description about the model is described in the model application and calibration sections below.

5.2.3 Data Collection

As mentioned earlier in the rainfall section, the rainfall data were collected from seven rainfall stations, four of them are tipping buckets and others are daily gauges. Another seven stations were assumed in different locations throughout the catchment in order to capture the rainfall gradient in the catchment. The average annual rainfall amounts for the assumed stations were calculated using the spatial oriented formula by (Shadeed S. , 2005) that was mentioned earlier. Then, the hourly rainfall data was computed for the ten stations rather than the four tipping buckets as explained in the rainfall input section above.

For the runoff data, it was collected from the two flumes which are located approximately at the outlets of both Al-Badan an Al-Faria sub-catchments as shown in Figure 18. So, the summation of the runoff from both streams represents the total runoff from the upper Faria catchment part. The flumes data are recorded every ten minutes, and represents the flow amount among the flume body. These data were used in the calibration process of the model simulated flows and later on it was used evaluate the model efficiency.

5.2.4 Maps Preparation

Arc GIS 10.1 software package was used in order to prepare all the spatial data required for the modeling. In addition to doing some spatial-related manipulations, the developing of the Digital Elevation Model (DEM), flow direction and flow accumulation grids, stream definition, watersheds delineation and many others were done using Arc GIS. The Digital Elevation Model, which is the most important map from which all the other maps were originated, was developed for the catchment from the contour map of the West Bank and it shows the topographic elevation all over the catchment. Then, the sinks in the DEM of Faria catchment were filled in order to derive a continuous drainage network later on. The DEM of Al-Faria catchment is shown in **Figure 5.1**.

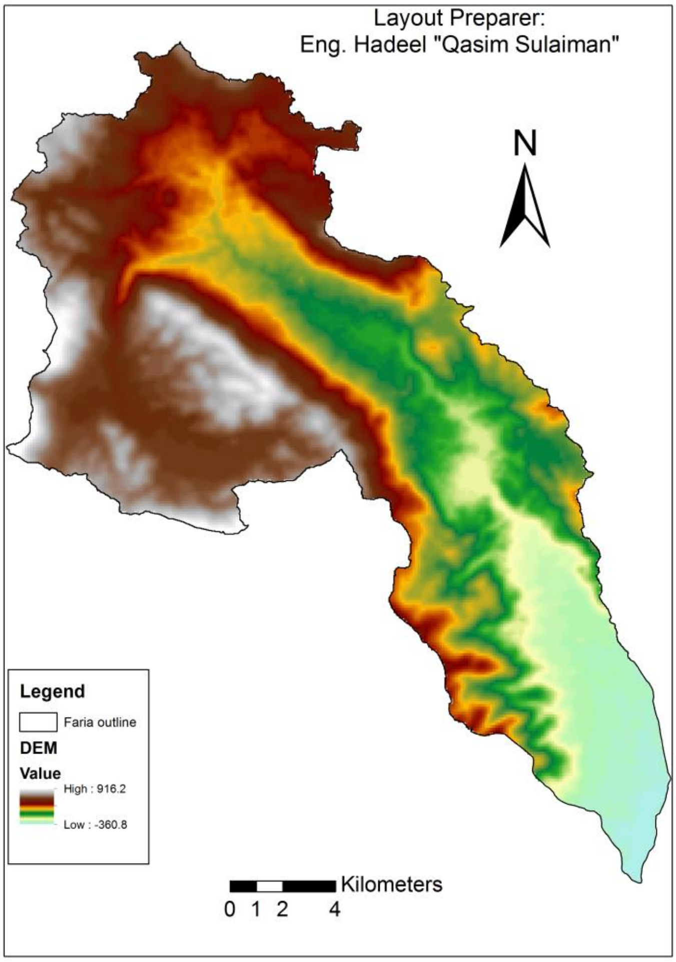


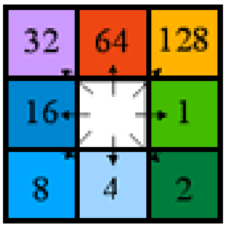
Figure (5. 1): Digital Elevation Model (DEM) of the Faria catchment.

Then, the flow direction map, which is a raster of flow direction from each cell to its steepest downslope neighbor, was also prepared. This ArcGIS tool takes a surface as an input and outputs a raster showing the direction of flow out of each cell. There are eight valid output directions relating to eight adjacent cells into which flow can travel. This approach is referred as eight direction flow model (D8) as illustrated in **Figure 5.2**.

The flow direction is determined by finding the direction of steepest descent from each cell referring to the following formula:

$$Max.drop = \frac{(change\ in\ elevation\ (z - value))}{Distance}$$

Where the distance is determined between the cells centers. The flow direction map of Faria catchment is shown in **Figure 5.3** below.



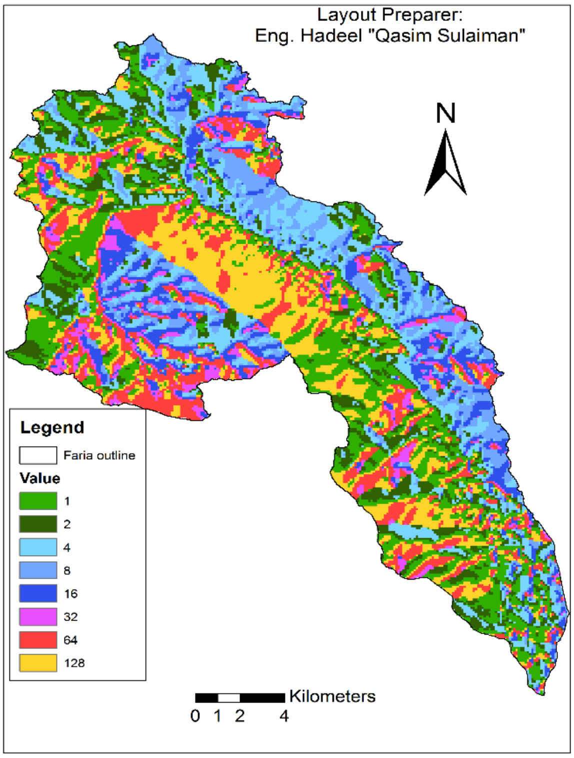


Figure (5. 2): Eight direction flow model **Figure (5. 3):** Flow Direction map of Faria catchment

After the flow direction raster calculation, the flow accumulation raster was calculated also. The flow accumulation raster is the output raster in which the accumulated weight of all cells that flowing into each downslope cell is calculated. Where a weight of 1 is assumed to each cell and each cell value in the output raster is the number of cells that flow into it.

Moreover, the stream network in the catchment was delineated using the output from flow accumulation tool. As a result, the streams and sub-streams are delineated all over the catchment.

After defining the stream network of the catchment, the catchment was divided into a number of sub-catchments, where a sub-catchment is the upslope area that is contributing flow to a given location. So, the watershed was delineated from the DEM by using the flow direction raster in the watershed function. Faria watershed was divided into 20 sub-catchments as shown in **Figure 5.4**. And from the figure it is shown that the sub-catchments number 1, 2, 3 and 4 belongs to Al-Faria sub-catchment which drains its surface runoff into Al-Faria flume and the ones having the numbers 6, 8, 9, 10 and 11 belongs to Al-Badan sub-catchment and drains into Al-Badan flume.

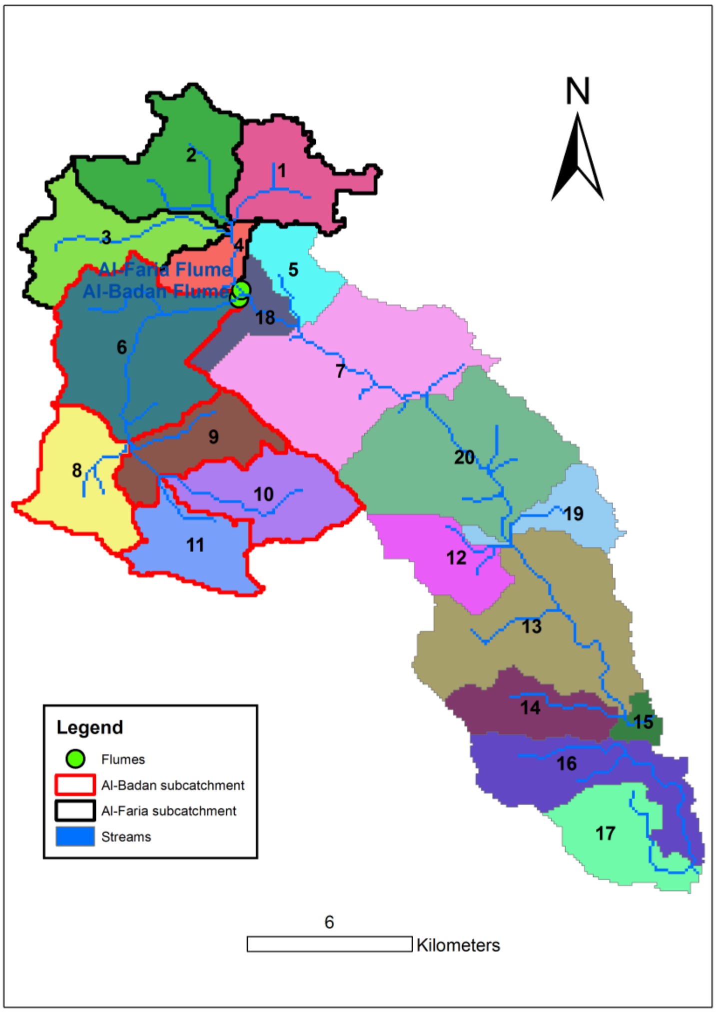


Figure (5. 4): Sub-catchments for HEC-HMS model

5.2.5 Model Application

The HEC-HMS (version 4.0) model was used in order to simulate the flood volumes, peaks and timing. The prepared maps were used in the model. In addition, the hydrologic modeling related data for the catchment were entered to the model, such as: the sub-catchments areas and land use patterns, initial losses, time of concentration, curve numbers, imperviousness, and sub-catchments initial abstractions in addition to Muskingum parameters for the routing process for the streams. These values were computed depending on the permanent soil types in the catchment. **Figure 5.5** below illustrates the developed model in HEC-HMS 4.0.

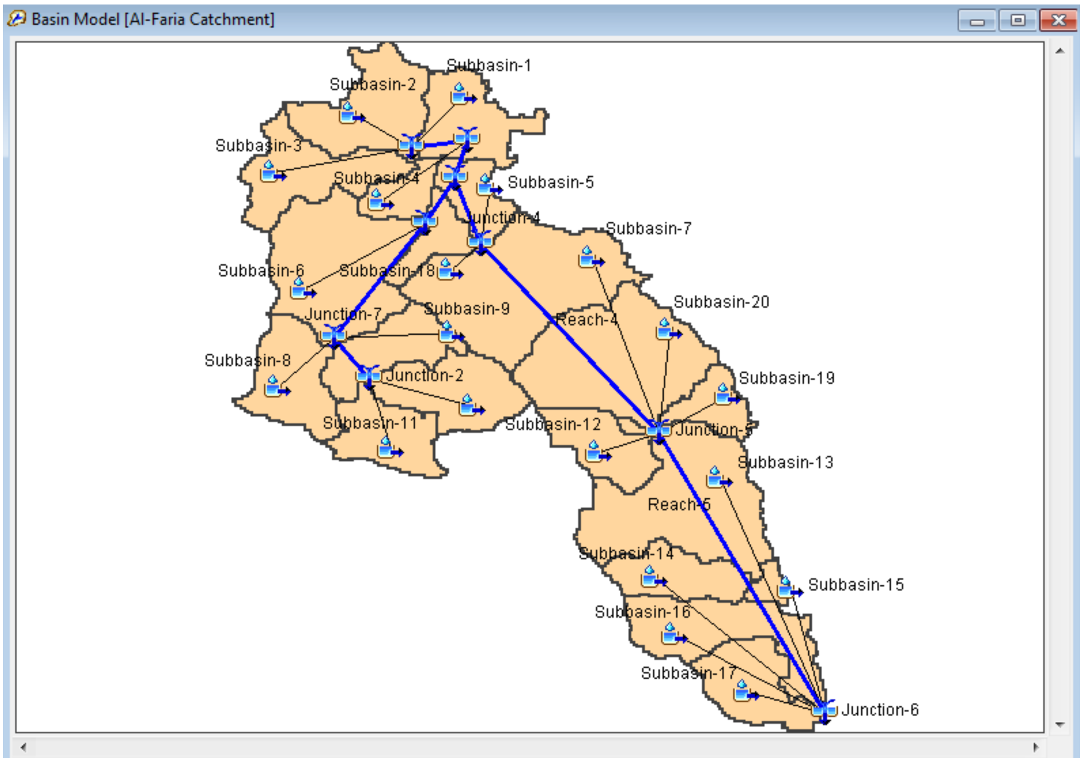


Figure (5. 5): Faria catchment hydrologic model using HEC-HMS v.4

5.2.6 Performance Evaluation

In this study, two measures of the performance of the HEC-HMS model were used. The first one is Nash-Sutcliffe efficiency (E); it is used as a predictive power of the hydrological models. It is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the same period (Nash & Sutcliffe, 1970). It is calculated as:

$$E = 1 - \frac{\sum_{i=1}^{n}(Oi - Si)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2}$$

Where *O* observed and *S* simulated values.

The value of E ranges from -∞ to 1 (perfect fit). A value of lower than zero indicates that the mean value of the observations would have been a better predictor than the model (Krause et. al., 2005).

Nash-Sutcliffe efficiency (E) implicitly compares the performance of the particular model to that of perhaps the simplest imaginable model, one that uses as its prediction the mean value of the observed target. Which means that an NSE value of 1.0 indicates that the performance of the model is perfect (the model perfectly simulates the target output), an E value of 0 indicates that the model is, on average, performing only as good as the use of the mean target value as prediction, and an E value less than 0 indicates an altogether questionable choice of a model. Therefore, it is preferred to have E values to be larger than 0·0 and approaching 1·0 (Schaefli & Gupta, 2007).

The second efficiency criteria used in this study is the coefficient of determination (r^2). This is defined as the squared ratio between the covariance and multiplied standard deviations of the observed and predicted values. So, it estimates the combined dispersion against the single dispersion of the observed and predicted series (Krause et. al., 2005). It is calculated as:

$$r^2 = \left(\frac{\sum_{i=1}^{n} (Oi - \bar{O})(Si - \bar{S})}{\sqrt{\sum_{i=1}^{n} (Oi - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (Si - \bar{S})^2}} \right)^2$$

The value of r^2 ranges from 0 to 1. A value of zero means that there is no correlation between the observed and simulated values whereas a value of one means that the dispersion of the predicted values is the same as the once of the observed values.

5.2.7 Model Calibration

The successful rainfall-runoff modeling for any catchment depends on how well the model calibration is. So, HEC-HMS catchment model was calibrated. The available runoff data at the upper parts of the catchment, which gauged by the flumes, were used mainly to calibrate the model. The model was calibrated for different parameters including: curve number, initial abstractions, loss/gain fractions and flows for the streams. The calibration process was mainly the traditional method that depends on trial and error and it continued until a good correlation between the simulated and the observed flows for both the magnitude of the peaks and time to peak had been achieved.

The storm of February (8-9), 2006 was used to calibrate the model, where a set of the input parameters as mentioned above were consecutively changed and each time the model simulation were performed until the most suitable set of input parameters were selected.

5.2.8 Model Validation

After the model calibration stage is finished, the model need to be checked if it is a good and reasonable representation of the real system. This stage is called the model validation.

For most models, there are three separate aspects that should be considered in the validation process, they are:

- Assumptions
- Input parameters
- Output values and conclusions

Although in practice, it is not easy to achieve full model validation. So, initial validation attempts concentrates on the outputs of the model, and the detailed validation is taken only if there is a problem in the results.

The storm of February (4-8), 2005 was used for model validation. Where both the runoff flow data observed from the real system and the data resulted from the model simulation at both Al-Badan and Al-Faria flumes were compared, and the resultant peak flow rate and time to peak were very close to each other.

5.2.9 Results and Discussion

The rainfall and runoff data recorded in Al-Faria catchment have been used to calibrate and validate the developed model. **Figures 5.6 and 5.7** illustrate a comparison between the observed and simulated flows for both Al-Badan and Al-Faria sub-catchments for the events of 4-8 February, 2005 and 8-9 February, 2006, respectively.

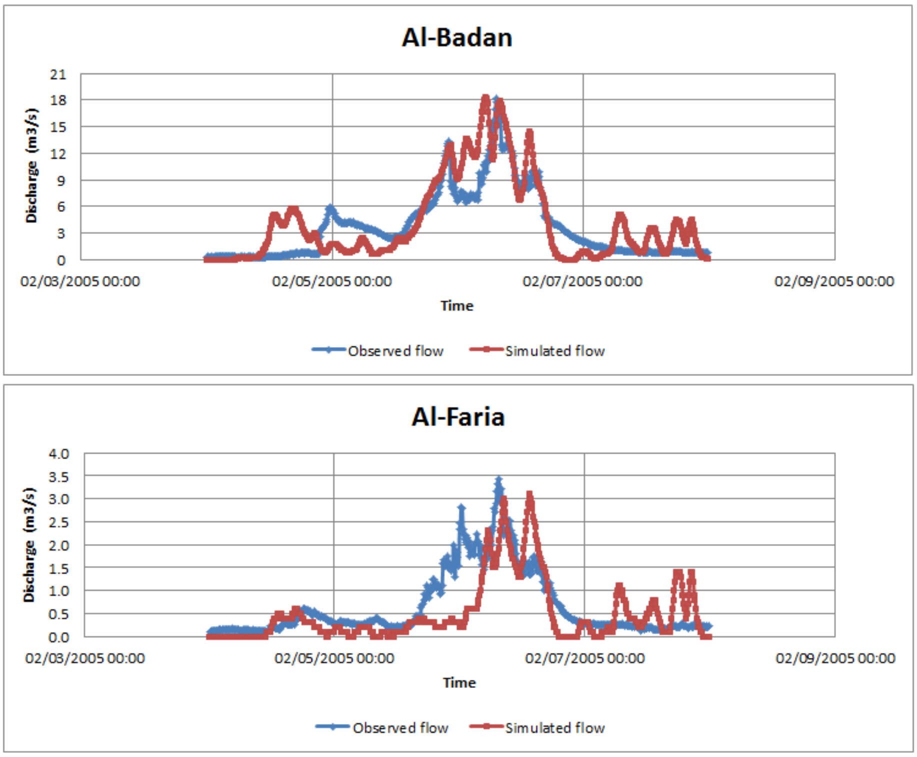


Figure (5. 6): Observed and Simulated flows for 4-8, February, 2005

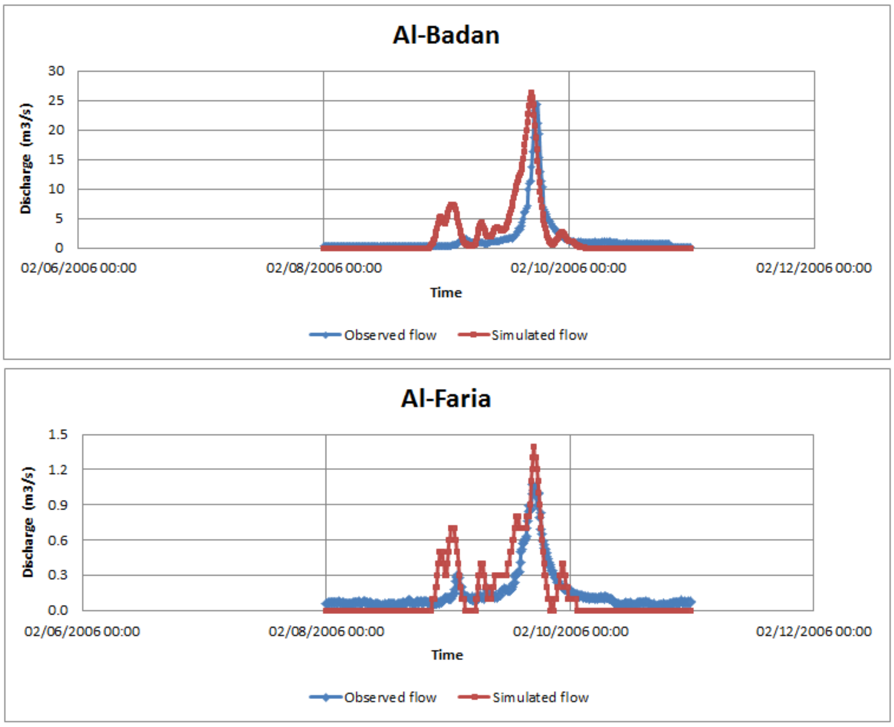


Figure (5. 7): Observed and Simulated flows for 8-10, February, 2006

Both efficiency criteria mentioned above were determined for the gauged sub-catchments, Al-Badan and Al-Faria, to check the model response efficiency for both events. The values of Nash- Sutcliffe and coefficient of determination are shown in the following tables:

Table (5. 1): Efficiency Criteria for the Event of 8-10 February, 2006

Catchment	Nash-Sutcliffe E	Coefficient of Determination r^2
Al-Badan	0.17	0.63
Al-Faria	0.71	0.52

Table (5. 2): Efficiency Criteria for the Event of 4-8 February, 2005

Catchment	Nash-Sutcliffe E	Coefficient of Determination r^2
Al-Badan	0.14	0.53
Al-Faria	-0.36	0.20

From the numbers in both tables above, it can be concluded that Nash-Sutcliffe and the Coefficient of Determination had given different impressions about the simulation for each case. For example, for the event of February, 2006, Nash-Sutcliffe efficiency coefficient for Al-Faria sub-catchment is higher than the once of Al-Badan while it is the other way round for the Coefficient of determination. Moreover, the negative value of Nash-Sutcliffe efficiency for Al-Faria sub-catchment for February, 2005 event indicates that the model predictions are weaker than the mean value of the observations.

Although the coefficient of determination r^2 reflects a good performance efficiency of the model for all cases (except the once of Al-Faria for February, 2005), Nash-Sutcliffe efficiency seems to have relatively small values. The reason may refer to the disadvantage of Nash-Sutcliffe efficiency measure, which is the differences between the observed and the simulated values are calculated as squared values (Legates & Jr., 1999). As a result, larger values are highly overestimated while the lower ones are neglected.

5.2.10 Conclusions

Based on the above results, it is fair to say that the HEC-HMS model was capable to model the single rainfall events in a semi-arid environment. In addition, the model was able to represent the different hydrological processes that take place in the catchment during a rainfall event and the resulted hydrographs. This reflects the goodness of the model and the suitability of the using of HEC-HMS as a tool to build rainfall-runoff models for single events in semi-arid climates. Overall, it can be concluded that the developed HEC-HMS model for Al-Faria catchment is a valid runoff prediction tool from rainfall data. However, it needs further modifications and calibration in order to get higher efficiency and reliability degrees.

For future work on this model, it is recommended to recalibrate the model for more events in order to get more accurate results and best simulations.

5.3 WRF-Hydro Model

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system. The model was designed for the needs of atmospheric research and operational forecasting. It consists of two dynamical cores, a data assimilation system, and a software architecture that facilitates parallel computation and system extensibility. The model serves many meteorological applications with a range of scales that vary from tens of meters to thousands of kilometers. It is also able to generate atmospheric simulations using either real data (including observations or analyses) or idealized conditions. WRF developing efforts started in late 1990's and was a collaborative partnership mainly among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration represented by the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA) (The Weather Research & Forecasting Model).

WRF model is supported (community model), which means that it is a free and shared resource, with distributed development and centralized support. It can be used by academic atmospheric scientists, who are specialized in physics, dynamics, weather, or climate research. WRF may also be used by forecast teams at operational centers who make the numerical weather predictions and meteorological case studies. In addition, WRF could be used by the applications scientists, who work in the air quality, hydrology, and utilities disciplines.

The WRF hydrological extension package is referred as (WRF-Hydro). The coupling extension package provides a mean to couple hydrological model components to atmospheric models and other earth system modeling architectures.

WRF-Hydro is a coupling architecture that is designed to simplify the coupling of terrestrial hydrological models with the WRF model. It is community based model that is designed to provide:

- An extensible, multi-scale, and multi-physics land atmosphere modeling capability for conservative, coupled and uncoupled assimilations and prediction of major components of water cycle such as precipitation, stream flow, soil moisture, and groundwater.
- Reliable and accurate stream flow predictions (from 0-order headwater catchments to continental river basins and from minutes to seasons).
- A strong land-atmosphere coupling studies framework.

The initial version of WRF-Hydro was issued in 2003 and originally called "Noah-Distributed Model". It included distributed, 3-dimentional, variably-saturated surface and sub-surface flow model. Then, the need to account for increased complexity in land surface states and fluxes and to provide physically consistent land-surface flux and stream channel information for the hydrometeorological applications had led to the implementation of terrain routing, channel and reservoir routing functions into the 1-dimentional Noah land surface model (Gochis et. al., 2015).

In 2004, the entire modeling system of the hydrological extension package known as NCAR WRF-Hydro, was coupled to the mesoscale meteorological model (WRF). As a result, a fully coupled land surface hydrology-regional atmospheric modeling capability had been ready to use in hydro-meteorological and hydro-climatological research and applications (Gochis et. al., 2015).

During late 2011 and 2012, the coding structure of WRF-Hydro was upgraded so it became easier to update and expand the WRF model and the other hydrological modeling components. Later, during 2014-2015, additional changes to the directory structure occurred in order to accommodate the coupling with the new NoahMP (multiparametarization) land surface model (Gochis et. al., 2015).

5.4 Model Physics Overview

In this section and the subsequent sections, the physics behind the main modules of WRF-Hydro (version 3.0) will be described. The modules include the Land Surface Models (LSM), sub-surface routing routines, overland flow routing routines, channel routing routines, lake/reservoir routing module, and a conceptual catchment model routine.

For the land surface models, Noah and NoahMP are the only supported LSMs within WRF-Hydro. The 1D Noah and NoahMP LSMs calculate the vertical fluxes of energy (such as sensible and latent heat, net radiation), and moisture (such as canopy interception, infiltration, excess infiltration, deep percolation), and soil moisture and thermal state. Then, the resulting data (such as infiltration excess, soil moisture, .. etc) are disaggregated form the 1D LSM coarse grid of (1-4 km) spatial grid to a high resolution routing grid (30-100

m) and repassed to the subsurface and overland flow routing modules. The WRF model pre-processing system (WPS) provides a comprehensive database of land surface data that can be used to setup the Noah and NoahMP LSMs (Gochis et. al., 2015).

In WRF-Hydro, the subsurface lateral flow is calculated before the routing of overland flow in order to add the exfiltration from the fully saturated grid cells to be added to the infiltration excess calculated from the LSM.

In subsurface lateral flow of saturated soil moisture, many methods are used to calculate it currently, such as Wigmosta et al. (1994) and Wigmosta and Lettenmaier (1999). It is affected by topography, saturated soil depth, and depth-varying saturated hydraulic conductivity values. In WRF-Hydro, typically, a minimum of four soil layers are used in a 2-meter soil column. WRF-Hydro specifies the water table depth as the depth of top saturated soil layer that is nearest to the surface.

For the overland flow routing in WRF-Hydro, the fully unsteady, spatially explicit, diffusive wave formulation is assumed for the used routing model, which is the CASC2D one developed by Julien et al. (1995) and then modified by Ogden (1997). The overland flow in this model is calculated when the depth of water on any grid cell of the model exceeds a specific retention depth. The schematic representation of the overland flow routing in the Noah LSM of WRF-Hydro is shown in **Figure 5.8**. The backwater effect and flow in adverse slopes are allowed and taken into account in the diffusive wave equation. In the overland flow routing module, the diffusive wave formulation of the momentum equation is combined with the continuity equation for an overland flow wave. And the resistance formulation for momentum in WRF-Hydro uses Manning's equation, in which the values of overland flow roughness parameters were obtained from Vieux (2001) (Gochis et. al., 2015).

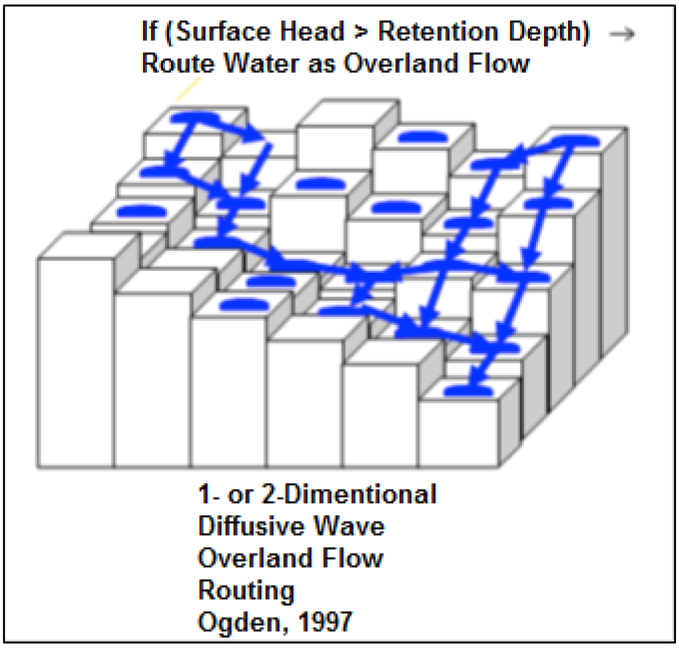


Figure (5. 8): Overland flow routing module in Noah LSM

The stream channel flow processes, lakes and reservoirs, and stream baseflow have also been represented through additional modules. The inflow into the stream network and lake and reservoir objects in WRF-Hydro v3.0 is a one-way process only. This means that the overland flow that reaches a grid cell identified as 'channel' grid cell passes a portion of surface water in excess of the local ponded water retention depth to the channel model. So, the stream and lake inflow from the land surface is always positive to the stream or lake element. Currently, there still no channel or lake loss functions where water can move back from the channel or lake to the landscape. Moreover, the channel flow in WRF-Hydro is represented by one of a few different user-selected methodologies. Water passing into and through lakes and reservoirs is routed using a simple level pool routing scheme. Baseflow to the stream network is represented using a conceptual catchment storage-discharge bucket model formulation which obtains ‘drainage’ flow from the spatially distributed landscape. Discharge from buckets is input directly into the stream using an empirically-derived storage-discharge relationship.

5.5 Land Model Description (Noah LSM)

Noah land surface model is a community, 1-dimentional LSM that simulates liquid and frozen soil moisture, soil temperature, surface temperature, snowpack depth, canopy water content, in addition to the water and energy fluxes terms at the surface of the earth (Gochis et. al., 2015).

The earliest predecessor of Noah was developed by Pan and Mahrt (1987) at Oregon State University (OSU) in the 1980’s. The original OSU model was able to calculate sensible and latent heat flux using a simplified plant canopy model and a soil model of two layers. Numerous enhancement and development had been involved to the Noah model since the first version until the current one through community participation of various agency modeling groups. The great enhancement changes to the model included a soil representation of 2m depth as four layers with consecutive thicknesses of (0.1, 0.3, 0.6, and 1.0 m) as shown in the schematic representation in **Figure 5.9**.

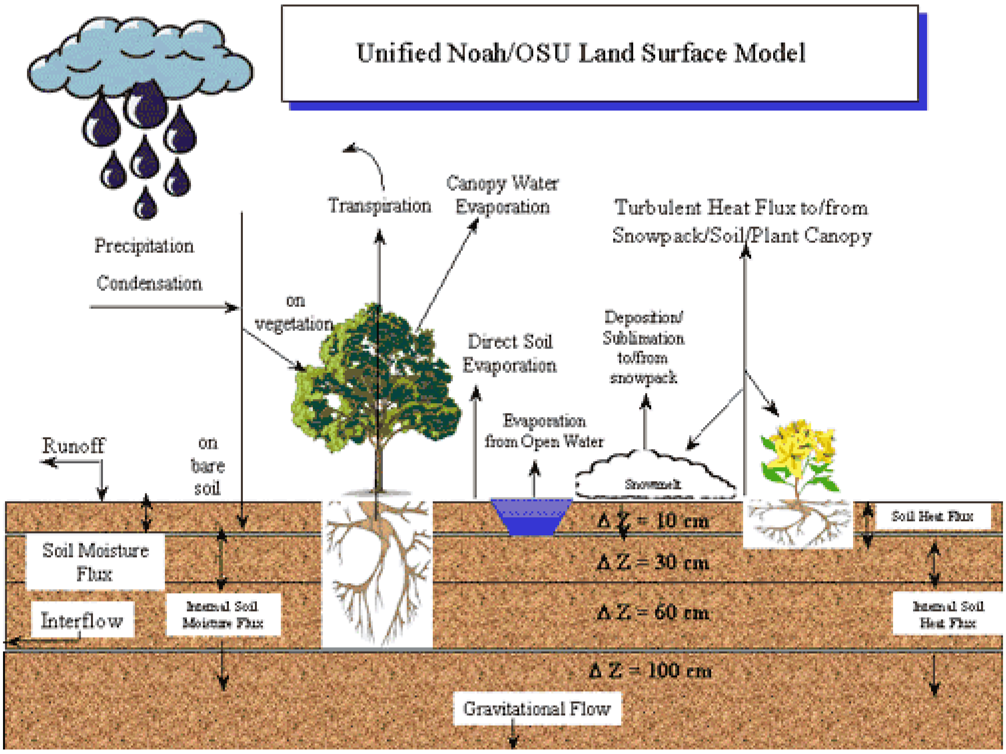


Figure (5. 9): Noah land surface model

Many other changes to Noah model had also been implemented during the last decades such as the modifications to the canopy conductance formulation (Chen et al., 1996), bare soil evaporation (Betts et al., 1997), surface runoff and filtration (Schaake et al., 1996), frozen soil processes (Koren et al., 1999), and seasonal variability of the surface emissivity (Tewari et al., 2005).

The Noah land surface model had been extensively tested in the offline (one-way) and coupled (two-way) modes. The most recent version of Noah LSM is one of the operational LSP's in NASA-NCEP real time Land Data Assimilation System (Gochis et. al., 2015). Currently, the gridded versions of Noah model are coupled to real-time weather forecasting models such as the North American Model (NAM), National Center for Environmental Prediction (NCEP), and the Weather Research and Forecasting Model (WRF).

5.6 Surface Overland Flow Routing

A fully-unsteady, explicit, finite-difference, diffusive wave formulation is being used in WRF-Hydro to calculate the overland flow (Gochis et. al., 2015). **Figure 5.10** shows the conceptual representation of overland flow in WRF-Hydro, where the flow is routed across terrain elements until it intersects a “channel” grid cell indicated by the blue line where it becomes “in-flow” to the stream channel network. The overland flow module in WRF-Hydro can be implemented in either i-dimensional (steepest descent or ‘D8’) or 2-dimensional (x and y dimensions) methods. In some complex surfaces, the 2-dimensional method provides more accurate depiction of the water movement than the 1-dimentional method. Although, the 2-dimentional method is more time consuming (Gochis et. al., 2015).

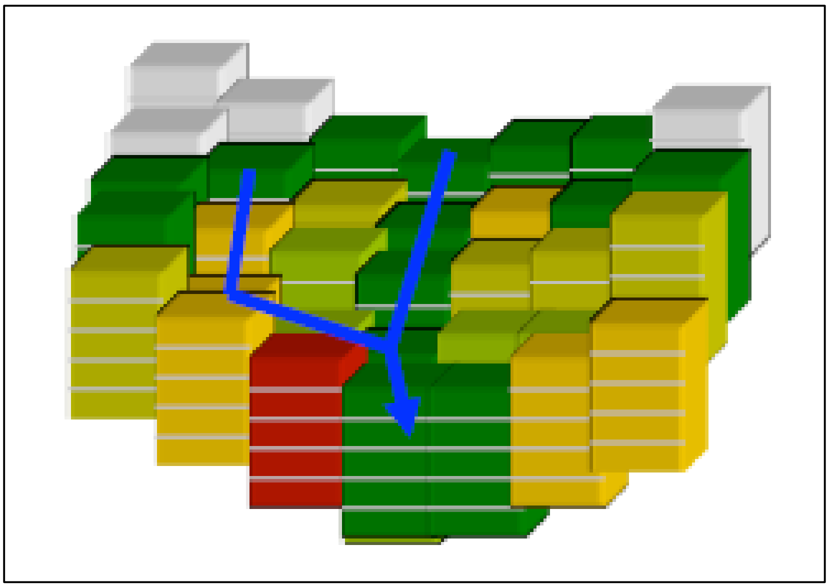


Figure (5. 10): Overland flow routing

The physics of both methods for overland flow routing are the same, but the formulation of the flow will be presented using the 2-dimentional method. The continuity equation for a flood wave flowing over the land surface in 2-dimensional method is:

$$\frac{\partial h}{\partial t} = \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial x} = i_e$$

Where,

h is the surface flow depth;

q_x and q_y are the unit discharges in the x and y directions, respectively

i_e is the infiltration excess

For the x-dimension, the momentum diffusive wave formulation is:

$S_{fx} = S_{ax} - \frac{\partial h}{\partial x}$

Where,

S_{fx} is the friction slope in the x-direction,

S_{ax} is the terrain slope in the x-direction,

$\frac{\partial h}{\partial x}$ is the change in the water depth above the land surface in the x direction

In the 2-dimention case, the flow is calculated in the x-direction, and then in the y-direction. In order to calculate q_x and q_y it is typically needed to use a resistance equation such as Manninig's equation, that contains the momentum losses expression involved in S_{fx} equation. In WRF-Hydro, the following form of Manning's equation is used:

$q_x = \alpha_x h^{\beta}$

Where,

$\alpha_x = \frac{S_{fx}^{1/2}}{n_{OV}}, \beta = \frac{5}{3}$

Where, n_{OV} is the land surface roughness coefficient and β is a unit dependent parameter expressed for the SI units.

The overland flow formulation had been used effectively for fine terrains ranging from 300-1000 m (terrain cell size). this is due to the fact that typical overland flow waves have length scales much smaller than 1000 m. Moreover, at coarse resolutions, the terrains will be smoothed since the slopes between grid cells are lowered so the resolution is decreased. As a result, in WRF-Hydro, the model time step is directly tied to the grid resolution in order to prevent simulated flood wave dissipation and dispersion. The following model time steps are suggested as a function of the size of model grid cells (see **Table 5.3**) (Gochis et. al., 2015):

Table (5. 3): Suggested model time step corresponding to model grid size in WRF-Hydro

x (m)	t (s)
30	2
100	6
250	15
500	30
1000	60

The overland flow routing option is a switch parameter in WRF-Hydro model hydro namelist, that describes all the major input, output, parameters and namelist provided files.

5.7 Channel Routing

Simple mass balance calculations are performed in order to represent the overland flow discharging into a stream channel, because until now there is no explicit sub-grid process for it. Inflow to stream channels occurs when the depth of ponded water in stream channel grid cells (surface head, 'SFHEADRT') exceeds a pre-defined retention depth ('RETDEPRT'). The depth of surface head in a grid cell is combined of the local infiltration excess, water amount flowing from the overland flow, and exfiltration from groundwater flow. As this water depth exceeds the retention depth, it is accumulated as stream channel inflow and discharged into the channel routing routine (Gochis et. al., 2015).

The channel routing module allows one-dimensional, distributed routing of streamflow across the model domain. In v3.0 of WRF-Hydro, there are many channel routing algorithms; some of them is based on grid (2-dimension) and the others on vector (1-dimention) channel network. If gridded channel routing is used, a high resolution terrain routing grid file has to be inserted to the model as an input in order to execute the routing on a pixel by pixel basis (Gochis, Yu., & Yates, 2015). A trapezoidal geometry channel reach is assumed for each channel grid cell as depicted in **Figure 5.11**.

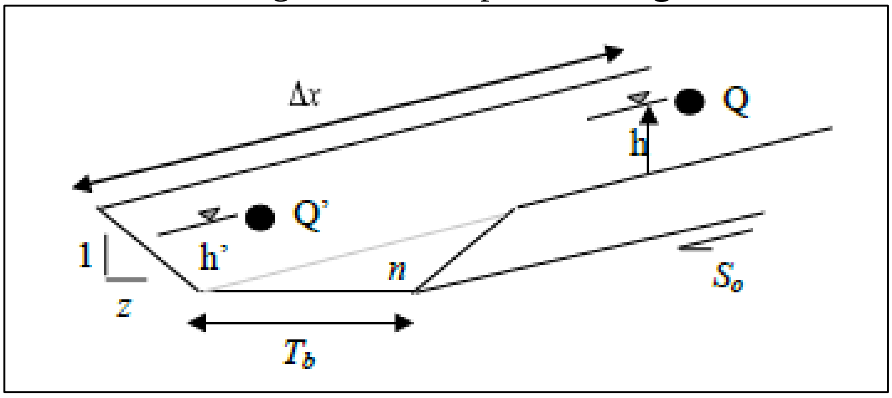


Figure (5. 11): Schematic of channel routing terms

A one-dimensional, variable time-stepping diffusive wave formulation is assumed for the channel flow through gridded channel network. The mass and momentum continuity equations used for channel routing are:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2/A)}{\partial x} + gA\frac{\partial Z}{\partial x} = -gAS_f$$

Where,

t is the time, A is the channel cross sectional area, Q is the flow rate, x is the streamwise coordinate, q_{lat} is the lateral inflow rate into the channel, β is the momentum correction factor, Z is the elevation of water surface, g is the gravity, and S_f is the friction slope which can be written as:

$$S_f = (\frac{Q}{K})^2$$

Where K is the conveyance that could be computed from Manning's equation as:

$$K = \frac{C_m}{n}AR^{2/3}$$

Where,

C_m is dimensional constant (1.0 for SI units or 1.486 for English units), n is Manning's roughness coefficient, A is the channel cross sectional area, and R is the hydraulic radius (A/P), P is the wetted perimeter.

The approximation of the diffusive wave of an open channel flow can be given by the second term of the momentum equation after ignoring the convective term. So, the momentum equation is simplified to:

$$Q = -\,\mathrm{SIGN}(\frac{\partial Z}{\partial x})K\sqrt{\left|\frac{\partial Z}{\partial x}\right|}$$

Where the friction slope had been substituted by the SIGN function, which is 1 for $\frac{\partial Z}{\partial x} > 0$ and -1 for $\frac{\partial Z}{\partial x} < 0$.

Then, if the continuity equation is discretized over a raster cell, the numerical solution will be:

$$A^{n+1} - A^{n} = \frac{\Delta t}{\Delta x}\left(Q_{i+1/2}^{n} - Q_{i-1/2}^{n}\right) + \Delta t q_{lat}^{n}$$

Where $Q_{i+1/2}^{n}$ is the flux across the cell face between point i and $i+1$, and it can be computed as:

$$\Delta Z_{i+1}^{n} = Z_{i+1}^{n} - Z_{i}^{n}$$

$$K_{i+1/2}^{n} = 0.5\lfloor(1 + \mathrm{SIGN}(\Delta Z_{i+1}^{n}))K_{i} + (1 - \mathrm{SIGN}(\Delta Z_{i+1}^{n}))K_{i+1}\rfloor$$

In WRF-Hydro version 3.0, Newton-Raphson (N-R) solver is used to implement the integration of the diffusive wave flow equations.

Variable time-stepping had been also used in diffusive wave channel routing module in order to avoid numerical dispersions and solutions instabilities and to satisfy some constraints. Moreover, the variable time-stepping methodology is used to properly characterize the dynamic propagation of flood waves in case of shallow flow depths. As mentioned in the previous section, the time step of the overland flow routing is a function of grid spacing. The initial value of the time step of channel routing is set equal to that one of overland flow routing. Then, if the N-R model convergence criterion for the stream flow of upstream-downstream discharges is not met, the time step of channel routing is decreased by a half factor and the N-R solver is called again.

5.8 WRF-Hydro Model Input Parameters

In order to apply the WRF-Hydro model, there are some groups of input parameters that should be inserted to the model as presented in the following sections:

5.8.1 Surface Physiographic

There are two input data files that need to be created to run WRF-Hydro model. The first one is the data layers of land surface model grid that is a coarse resolution grid, and the second one is the terrain routing grid which has to be in high (fine) resolution. The first grid data depends on the type of LSM used in WRF-Hydro while the terrain routing grid remains consistent for different LSM's in the model. However, both input data grids do not change whether WRF-Hydro is executed in the coupled or uncoupled mode with the WRF model.

5.8.1.1 Land Surface Model grid

The data contained within the LSM grid data file that is used for Noah LSM will be discussed here. First of all, one of the WRF preprocessing Systems (WPS) which is 'geogrid.exe' is used to build the LSM grid data file. In this preprocessor, the model space is defined and most of the land surface parameters that is required to execute the Noah and Noah MP LSM's are geo-referenced and attributed. So 'geogrid' acquires and interpolates land surface terrain, soils, and vegetation from standard, readily available data products (Ex. USGS National Elevation Dataset).

After the installation and execution of ‘geogrid.exe’ for Noah LSM, the following list of data fields will be contained in the geogrid output file:

HGT_M: Topographic elevation (units of meters) on the ‘mass grid’

XLAT_M: Latitude coordinates, in decimal degrees, on the mass grid

XLONG_M: Longitude coordinates, in decimal degrees, on the mass grid

LANDUSEF: Land use fraction, in units of fraction

SOILCTOP: Top layer soil texture category, in units of fraction

GREENFRAC: monthly mean green vegetation fraction values (units of fraction)

ALBEDO12M: Monthly mean surface albedo values (units of %) not including snow effect.

In addition, users can create their own LSM input data file without using the WPS ‘geogrid.exe’. The users can create the needed data as netcdf files containing the proper data in the proper units and specified filenames as listed above.

5.8.1.2 Terrain Routing Grid

The data required to route the water across the landscape and through streams and lakes are contained within the high resolution terrain routing grid. The data layers contained within this grid includes:

- Topography (required - in units of meters)
- Channel grid (required)
- Flow direction (required)
- Stream order (required)

- Lakes(optional)
- Groundwater basin mask (optional)
- Grid stream gauging stations (optional)
- Grid of latitudes and longitudes (required)
- Grid of overland flow roughness scaling parameters
- Grid of surface retention depth scaling parameters

A Geographical Information System (GIS) is very useful tool which is used in order to do the interpolation, georeferencing, clipping, and spatial projections for the data in order to get the proper ones.

The needed grids in our case were produced in Network Common Data Form (netcdf) format using ESRI ArcGIS system. The high resolution terrain fields that produced in netcdf format with the proper variable names for each data layer as specified by WRF-Hydro are as follows:

- LATITUDE
- LONGITUDE
- TOPOGRAPHY
- FLOWDIRECTION
- CHANNELGRID
- STREAMORDER
- LAKEGRID
- frxt_pts
- gw_basns
- OVROUGHRTFAC
- RETDEPRTFAC

5.8.1.3 Parameter Tables on Activated Options

In addition to preparing the high-resolution data layers as described in the previous section, channel routing, groundwater/baseflow basin attributing, or reservoir attributing can be performed. To achieve that, there is some tables that contains the characterizing parameters for the channel network, baseflow bucket, or reservoir must be defined. These parameters are defined in files that are placed in the run directory and called CHANPARM.TBL, GWBUCKPARM.TBL, LAKEPARAM.TBL, respectively.

5.8.2 Meteorological Forcing Data

Meteorological forcing data are required in modern land surface hydrological models in order to simulate the land-atmosphere exchanges and terrestrial hydrologic processes. Mostly, the variables used in the forcing data includes: humidity, temperature, pressure, wind speed, incoming shortwave and longwave radiations, and precipitation. Most of the models use the same variables with some changes in the units and formats. When WRF-Hydro is coupled to another modeling architecture, the specific model is the one which specify the requirements for the forcing data. In this research case, since the stand-alone version of WRF-Hydro is used, the requirements are described for this case as follows (see **Table 5.4**) (Gochis et. al., 2015):

Table (5. 4): Input forcing data for Noah LSM

Input Forcing Data Variable	Unit
Specific humidity	(kg/kg)
Air temperature	(K)
Surface pressure	(Pa)

Near surface wind speed in the u- and v- components	(m/s)
Incoming shortwave radiation	(W/m^2)
Incoming longwave radiation	(W/m^2)
Liquid water precipitation rate	(mm/s)

The forcing data in the stand-alone mode must be provided in gridded format. WRF-Hydro requires that the processing of forcing data be done external to the model as preprocessing. So, some scripts can be executed to preprocess the forcing data and get it in the proper format which is netcdf format.

When running the coupled mode of WRF-Hydro with the WRF regional atmospheric model, the forcing data is provided by the atmospheric model with a prespecified frequency in the LSM. So, there is no need to prepare the forcing data when running the WRF-Hydro coupled with WRF.

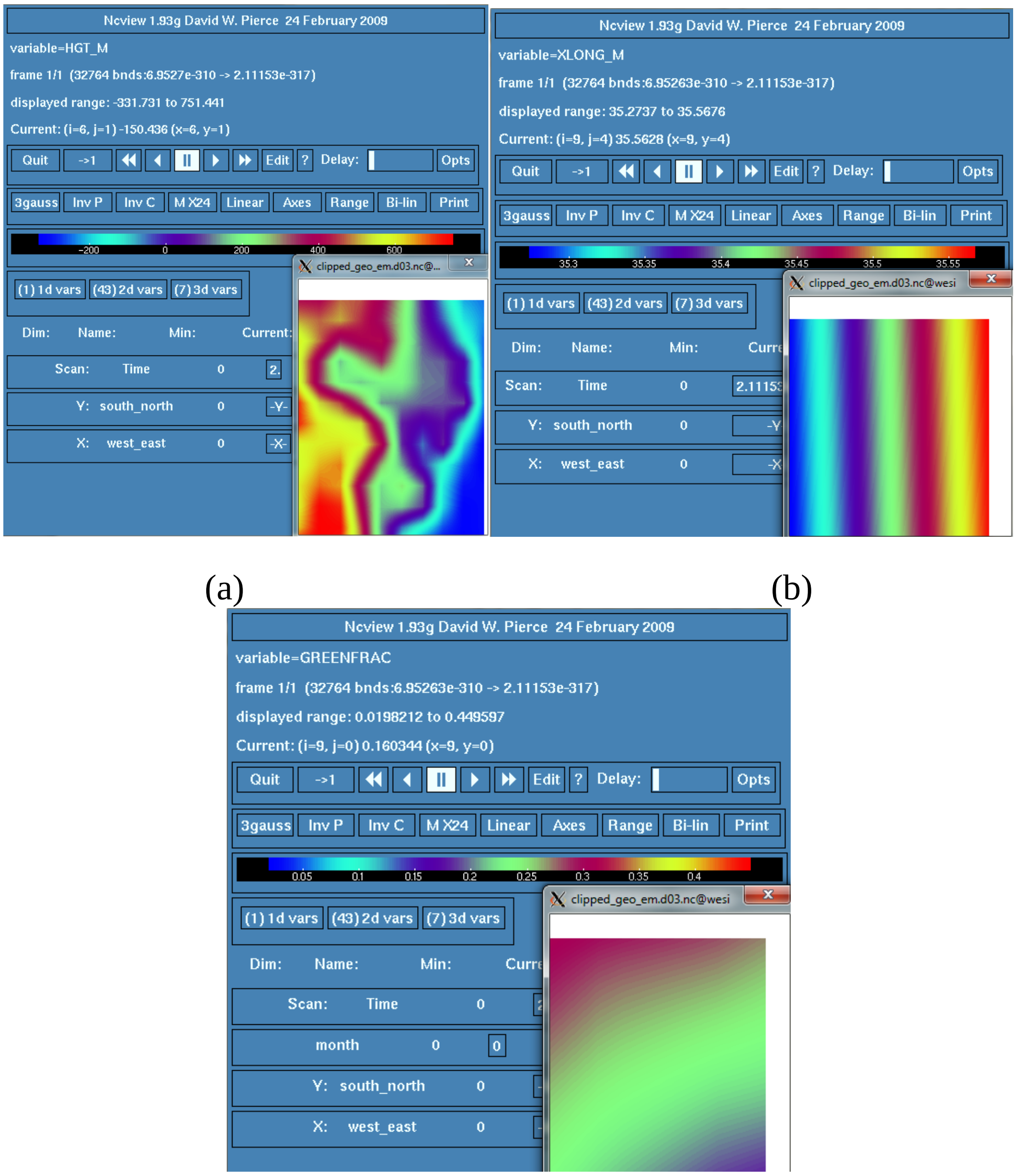
5.9 Model Application

After the domain of the WRF-Hydro model had been selected for the Faria study area catchment, the other input data for the domain including the land surface model grid, the terrain routing grid, and the meteorological forcing data were inserted to the model in order to be ready for successful run.

Two continuous simulations were developed using the model, the first one was for the first two months of 2005 (January and February, 2005) and the second one was for the three years (2003-2005). Then, some calibration for the model was performed in order to enhance the simulation results and improve the model performance.

5.9.1 Input Data Entry

The land surface model grid data resulted from the execution of the ‘geogrid’ preprocessor were saved into the right directory at the model workstation. These data includes the topographic elevation, latitude and longitude coordinates landuse fractions, soil texture categories, green fraction values, and the surface albedo values. Then, some of these data fields were replaced with more reliable ones that are available in the study area database and originated from site geostatistical techniques and site mapping. So, these data were transformed into netcdf format and saved also to the model with the proper names and units. **Figure 5.12** shows some of the input LSM grid data for the Faria WRF-Hydro model.



(a) (b)

(c)

Figure (5. 12): SLM grid data fields in WRF-Hydro including (a): Topographic elevation, (b): Longitude coordinate, and (c): Green fraction values

The terrain routing grid data layers were also preprocessed and prepared using ArcGIS software. After the data had been transformed into netcdf format, it was inserted to the WRF-Hydro model. These data includes the high resolution topography grid, flow direction, channel grid, stream order, forecast points grids (streamflow gauges), etc. Some of the terrain routing grids for the Faria catchment are shown in **Figure 5.13**.

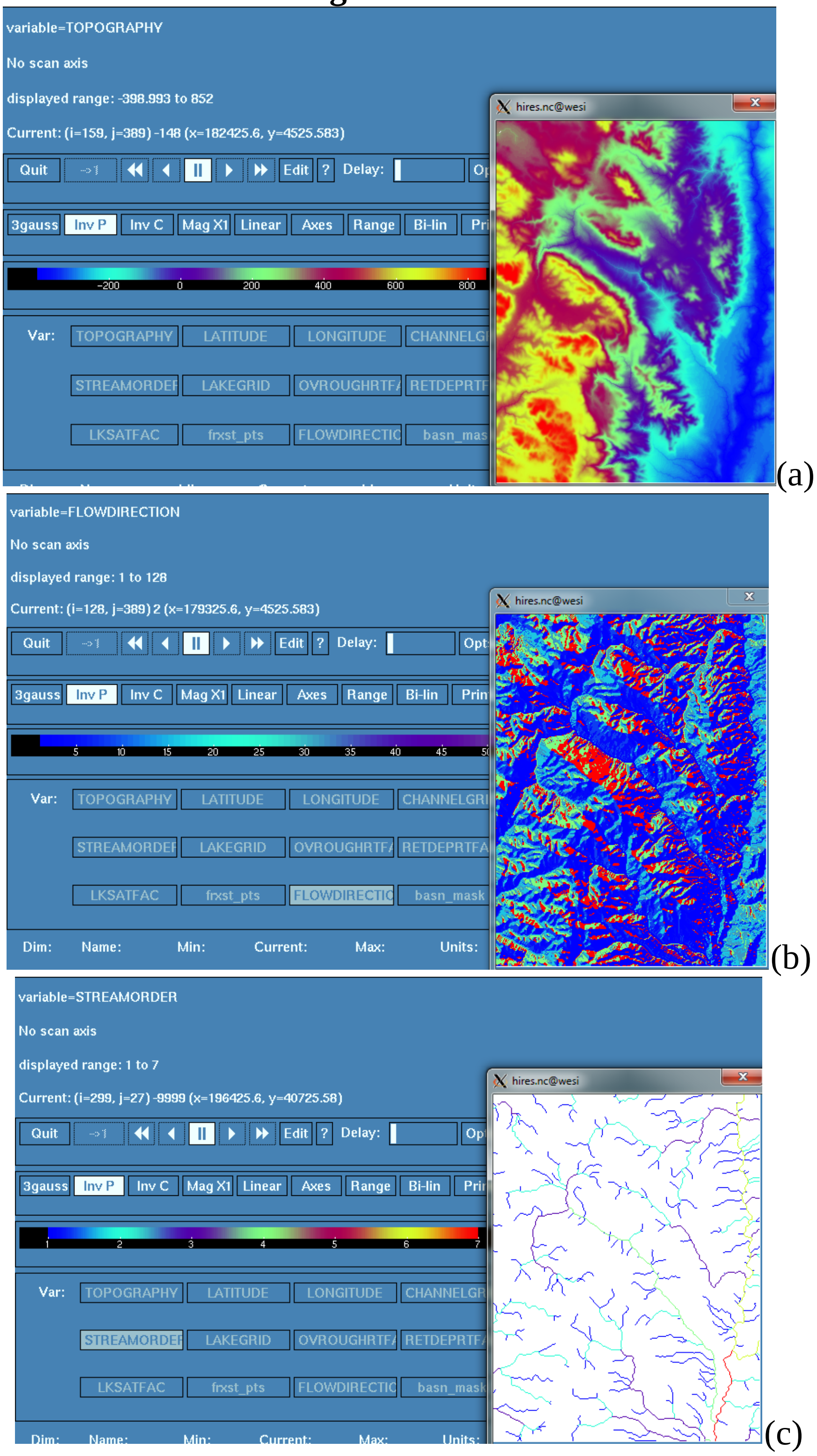


Figure (5. 13): Terrain routing data including: (a) Topography, (b) Flow direction, and (c) Stream order

After all static data above had been compiled into the model, the dynamic ones were also been inserted in order to run the offline (uncoupled) mode of the WRF-Hydro model. So, the data required to run Noah LSM evolving land surface and soil state variables over time were provided to the model. The analysis of atmospheric conditions, short and long wave radiations, and precipitation rate were provided by the High Resolution Land Data Assimilation System (HRLDAS). **Figure 5.14** show how the rain rate for a specific time can be viewed after it is forced to the model.

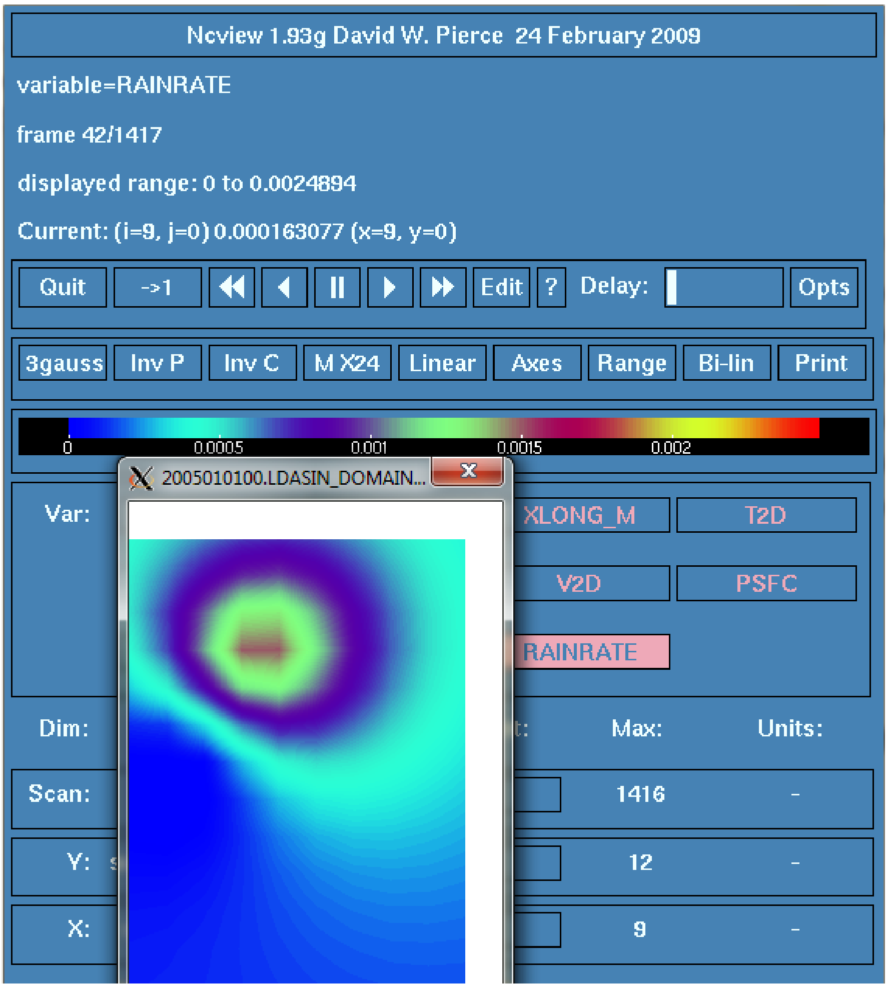


Figure (5. 14): Rain rate as example on the meteorological forcing data in WRF-Hydro

5.9.2 Simulation Results

For the simulations using WRF-Hydro model, two continuous simulations had been worked out. The model was run for both of the simulations in the uncoupled mode, which means that it is not coupled to any atmospheric model and only forced by the land surface and atmospheric data.

The first simulation was for the first two months of 2005 which are January and February as mentioned earlier. The chart in **Figure 5.15** below shows the rainfall distribution for this period.

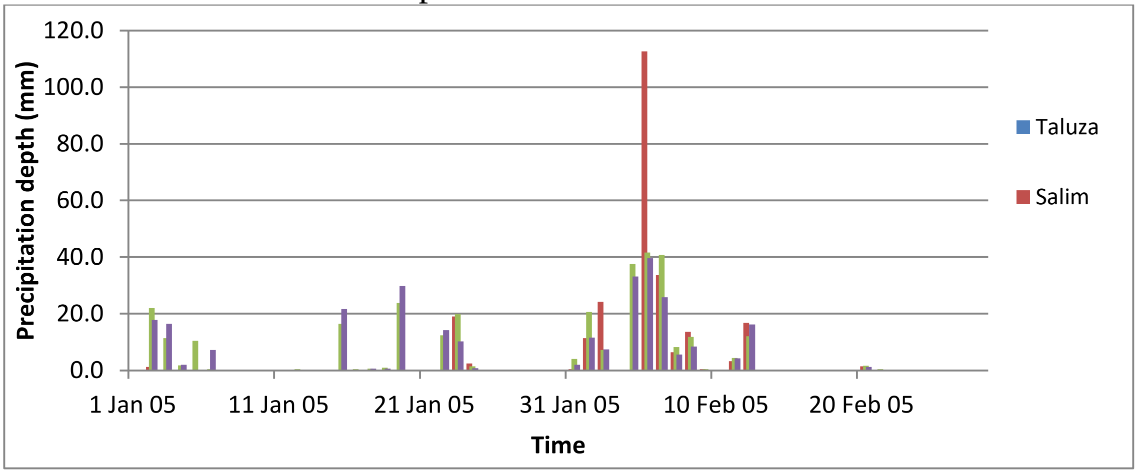
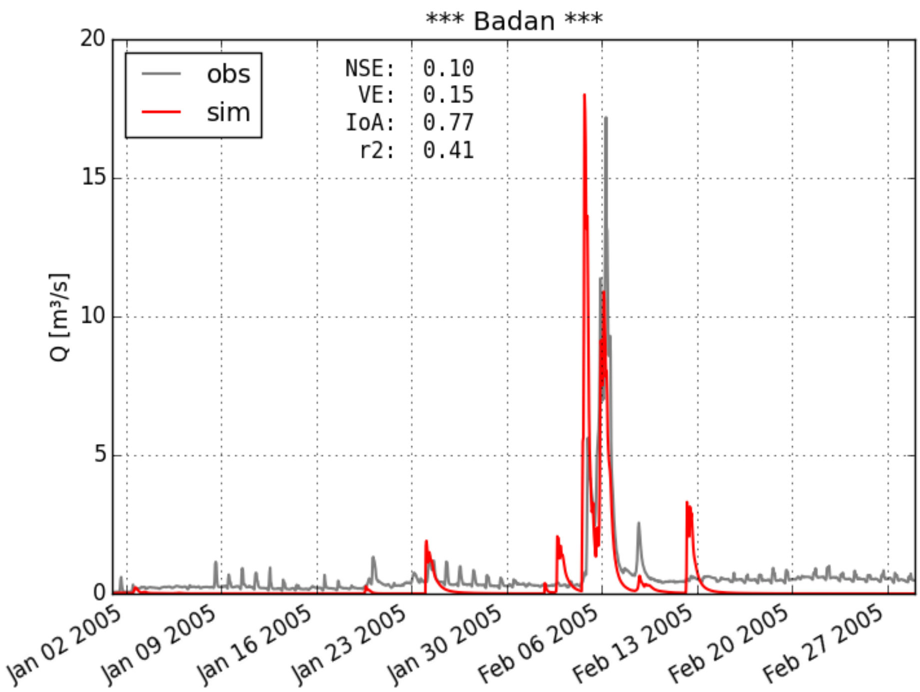
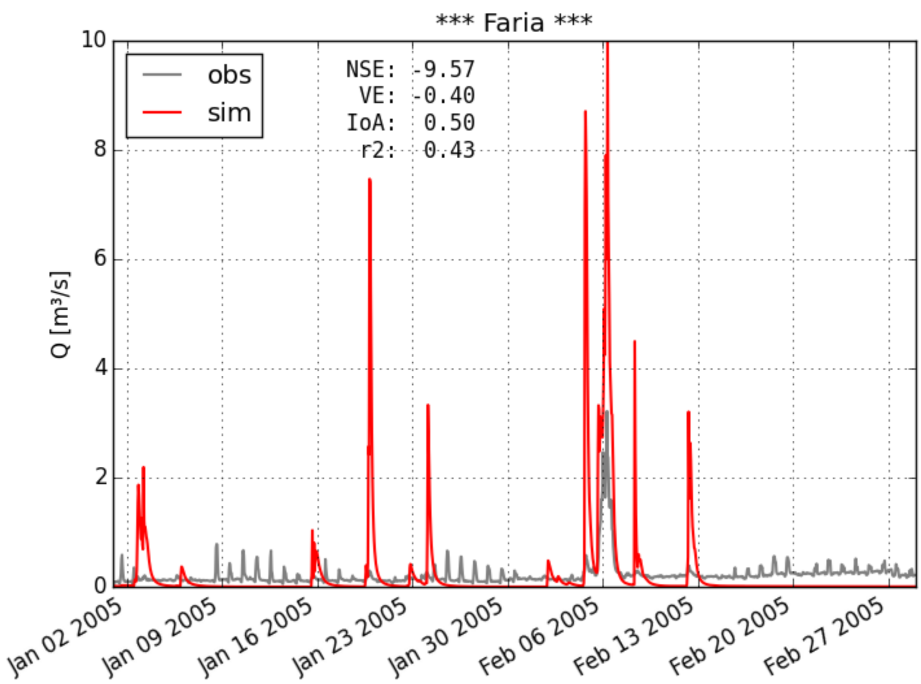


Figure (5. 15): Rainfall hyetographs for the Faria RTB's

The hydrograph for this simulation was resulted for both Al-Faria and Al-Badan sub-catchments at the flumes that exist at the outlet of each sub-catchment as mentioned before. **Figure 5.16** below shows the hydrographs for Badan and Faria sub-catchments in Figure 5.16 (a) and 5.16(b), respectively. Both runoff values that are observed at the flumes and resulted from WRF-Hydro model are represented in the figure at both sub-catchment forecasting points (flumes), where the observation values are represented by the gray lines and the simulated ones are represented by the red lines. The performance of the model had been evaluated using some parameters that were calculated, including Nash Sutcliffe Efficiency (NSE), runoff Volume Error (VE), Index of Agreement (IoA), and Coefficient of Determination (r^2).



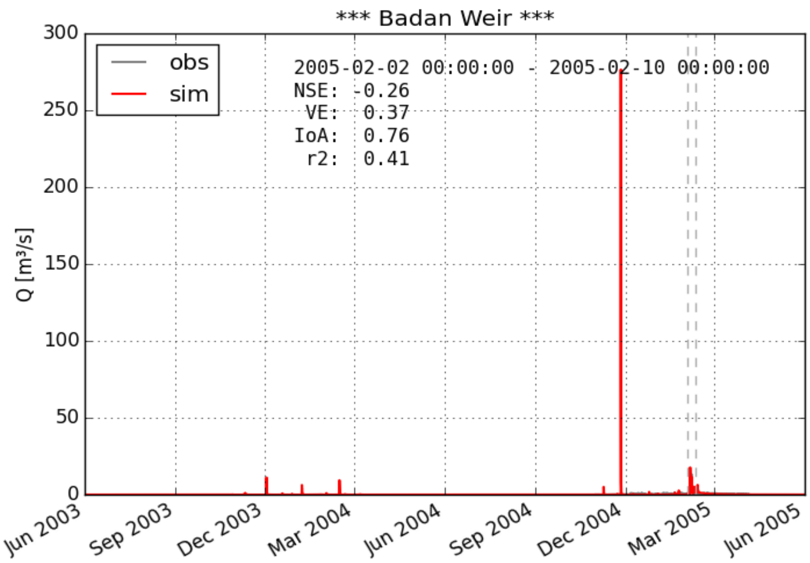
(a)



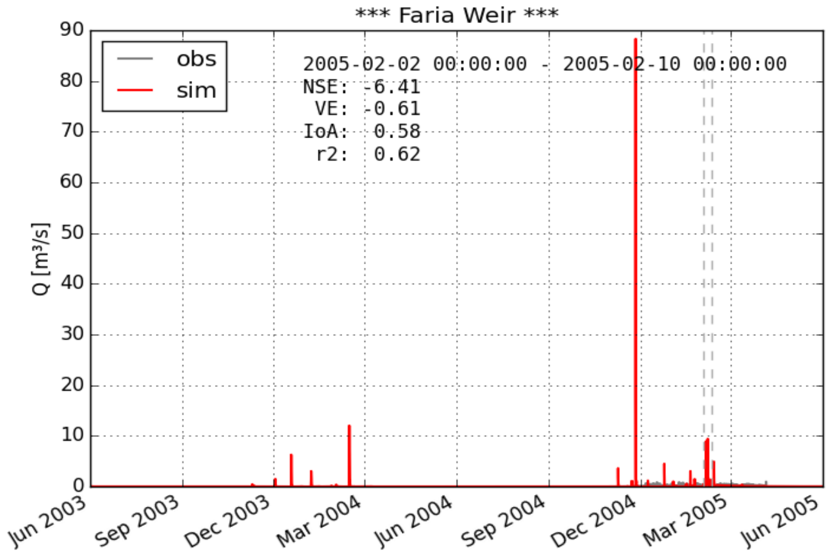
(b)

Figure (5. 16): Simulation hydrographs for the period of (Jan and Feb, 2005) for the sub-catchments of (a): Al-Badan, and (b) Al-Faria

For the second simulation, that is in the period of 2003-2005, the forcing data of this period were also inserted into the model including the rainfall data. Then, the WRF-Hydro model was run for this period. The simulation hydrographs for Al-Badan and Al-Faria sub-catchments can be seen in **Figure 5.17** (a) and (b) below, respectively. Both observed and simulated runoff values are shown in the charts in addition to the performance evaluation measures.



(a)



(b)

Figure (5. 17): Simulation hydrographs for the period of (2003- 2005) for the sub-catchments of (a): Al-Badan, and (b) Al-Faria

5.9.3 Model calibration

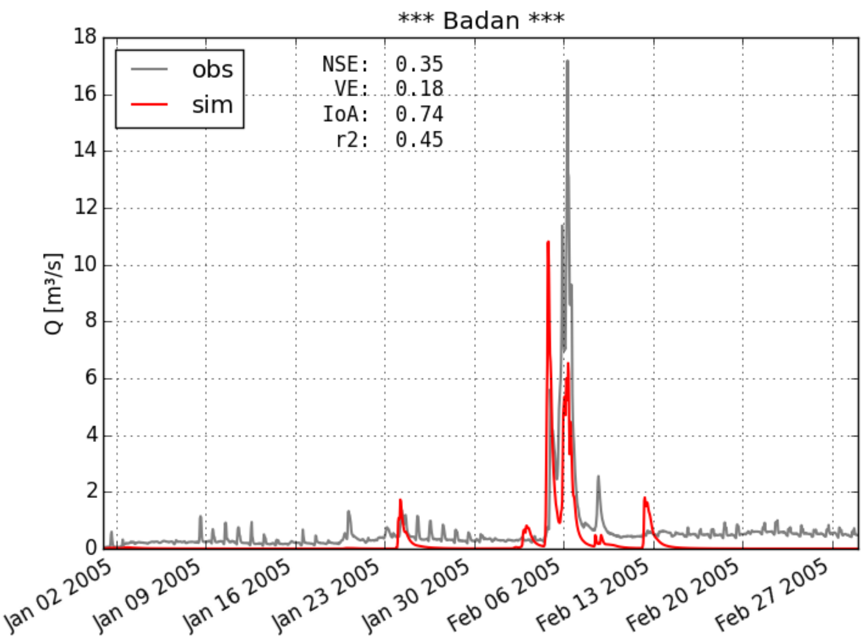
In this research the application of WRF-Hydro model was an experimental stage in order to check the applicability of the model in our region and how easy or difficult is it. So, little calibration had been only done for the model in order to minimize the differences between the simulated and observed runoff values so that the model performance is improved.

Then, the soil texture information had been updated by replacing the once from the geogrid preprocessor with a more confident once that is from the catchment database.

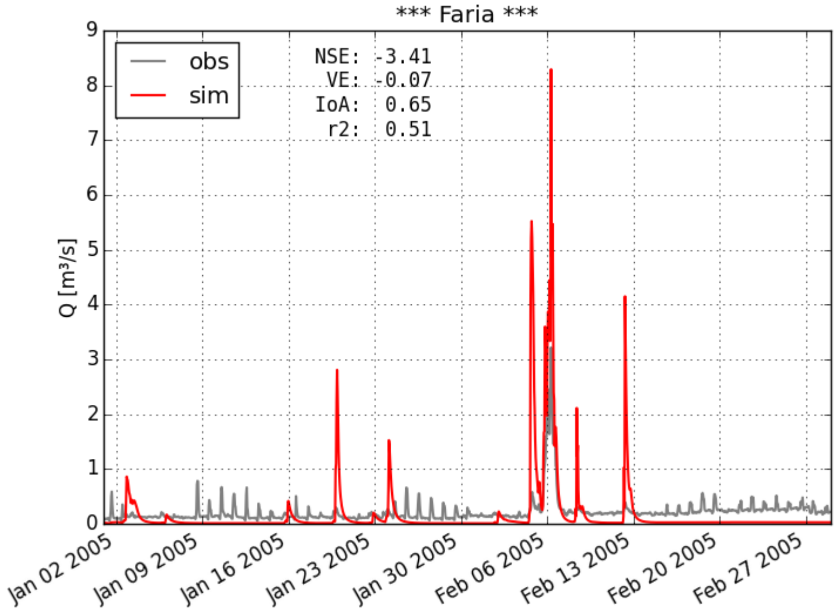
After that, the interpolation method of the rainfall data had been changed from nearest neighbor to radial basis function.

Some parameters that affect the infiltration and runoff amounts had also been changed such as the channels slopes, refDK (The soil hydraulic parameter that corresponds to the scaling of saturated hydraulic conductivity), and refKDT (the Infiltration/runoff generation parameter). The last two parameters affect the amount of baseflow that enters the groundwater bucket. For the refKDT, as it is increased, the infiltration increase and the surface runoff decrease. While for the refDK, the infiltration decrease and the surface runoff increase when it is increased.

After these modifications, the performance efficiency measures had been improved as shown in the following two charts of **Figure 5.18**. The new hydrographs for both Al-Badan and Al-Faria sub-catchments are shown in the charts in addition to the modified model performance measure.



(a)



(b)

Figure (5. 18): Simulation hydrographs for the period of (Jan and Feb, 2005) after calibration for the sub-catchments of (a): Al-Badan, and (b) Al-Faria

5.9.4 Analysis and Discussion

Form the results of the application of WRF-Hydro model in the previous section, for simulation one that is for the period of (January and February, 2005) in **Figure 5.16**, the performance is kind of good. For Badan sub-catchment, the main (higher) peak of the simulation period is very close to its observed value. In addition, the model predicts almost all the other peaks in the simulation period. As such, the main peak of the simulation period for the Faria sub-catchment is also predicted by the WRF-Hydro model. Although, its simulated value is about double the observed one. There are also other peaks that are much lower values in the reality (observations). This may be explained by the big water withdrawals amounts from the streams in Faria sub-catchment for irrigational goals.

From **Figure 5.16**, it can also be noticed that the observed low flows for both sub-catchments is always higher than the simulated ones. This could be explained as the study area is an irrigational area and it is one of the areas known as the food basket of Palestine. And a significant amount of the irrigational water is being withdrawn from the main streams (channels) there. As a result, the baseflow contributions to the channel increases, which in turn increase the water head in the channel.

For the second simulation that is shown in **Figure 5.17**, the simulation period is three consecutive years from **June 1, 2003** to **June 1, 2005**. Although, the available runoff data are for the period of 1/11/2004 to 1/6/2005 which is less than one third of the total period. So, the performance of the model can't be evaluated for the whole period. The hydrographs for both the simulated and observed values are most clear in **Figure 5.19** for Al-Badan weir.

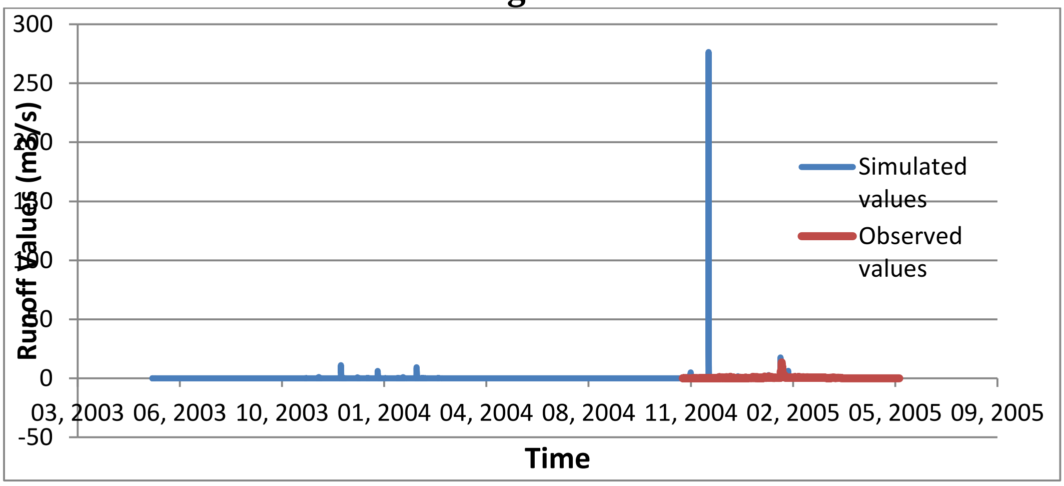


Figure (5. 19): Simulated and observed hydrographs for Badan sub-catchment

In this simulation, there is an unrealistic peak flow in November, 2004. The peak reaches about 270m^3/s for Badan weir and about 90m^3/s for Faria weir. These huge flows are supposed to remain for few hours only and it aren't notified in the observed flow. This makes a great indication that there is an error either in the rainfall data or in the execution of the model itself.

There is another peak notified in the period were the observed data from both weirs are available. This peak happens in early February, 2005 and it is about $15m^3/s$. The peak is nearly the same value predicted by the model and at the same timing which is a positive sign that the model is doing well and its results make some sense.

Chapter Six

Conclusions and Recommendations

Chapter Six

6 Conclusions and Recommendations

6.1 Conclusions

Faria catchment is characterized as a semi-arid catchment, located in the Northeastern part of the West Bank and has an area of about 320 km2. It extends from Nablus Mountains in the north to Jordan River in the east.

Since Faria catchment is an agricultural area, and there is a rapid increase in population, the available water resources within the catchment need to be managed and planned properly. For that, an accurate hydrological model for the catchment is needed.

In this research, two distributed hydrological models were developed for the Faria catchment. The first one utilizing HEC-HMS software, and the second is a primary uncoupled WRF-Hydro model.

In light of the previous chapters, the following points are the key conclusions from this research:

- The accuracy of rainfall data in Faria catchment needs to be improved in order to be used in the hydrological models since no hydrological model can produce high level accuracy output if input rainfall data is not accurate enough.
- The accuracy of the runoff data in the catchment needs to be improved in order to compare the simulated results with those observed ones. The runoff divers at the outlets of both the Faria and Badan sub-catchments need to be more accurate.
- From the application of the first hydrological model (HEC-HMS model), the following points could be concluded:

  - From the simulation results, it is fair to say that the HEC-HMS model is able to simulate the single rainfall events in Faria semi-arid catchment to a good acceptable degree.
  - The model is able to represent the different hydrological processes that take place in the catchment during a rainfall event.
  - The model is easy to use since it has a simple graphical user interface through which the data can be inserted to the model.
  - Simulations for large catchments or for long or continuous simulations using this model could be time and effort consuming.
- Using WRF-Hydro model is not very useful or feasible in our case because of the following reasons that represents some limitations for the use of WRF-Hydro in Faria catchment and similar catchments:
  - The model doesn't have a graphical user interface, instead the user inserts the data and the orders using a black screen through some programming languages such as R-language and Python scripts, which is relatively impractical at this time when modern hydrological modeling software are available.
  - There is no available data neither for the boundary conditions nor for the whole big domain, which extends from the Cyprus in the north to the Red Sea in the south and from the Mediterranean Sea in the west to Jordan and Saudi Arabia in the east to include Palestine inside the domain.
  - The model is used in the uncoupled or the offline mode. So, there is no benefit from the Weather Research and Forecasting Model (WRF). This means that there is no possibility to take the meteorological data from WRF model and link it directly to the

hydrological model (WRF-Hydro) to do the run and find out the results.

- The model can’t be used as a predicting tool when it runs on the uncoupled mode. So, it is not possible to currently use it for future events prediction.
- There is no accurate spatial rainfall data to be inserted to the model, because the number of rainfall gauging stations is low. So, the main input data to the hydrological model is not accurate.

- WRF-Hydro model is very useful for continuous simulations since all the geographic and the forcing data is available online with good accuracy that is enough to run the model.
- Both developed hydrological models could be valid prediction tools for Faria catchment. However, it needs further enhancement and calibration and validation in order to improve its performance efficiency.

6.2 Recommendations

Based on the findings of this research and the conclusions as mentioned in the previous section, the following points are recommended:

- The point rainfall gages intensity should be increased in the catchment in order to be able to catch the rainfall variability pattern. This will increase the accuracy of the output of the hydrological models simulations. Also, radar rainfall gauging stations could also be used to cover more spatial variability.
- The runoff observed data ought to be accurate in order to measure the hydrological models performance better. For that, continuous maintenance and calibrating for the divers must be done.

- Other hydrological and meteorological parameters should be also measured in the catchment including infiltration, humidity, wind speed … etc.
- More enhancement and calibration should be applied to both developed models in order to be used in managing and planning of the water resources in the catchment.
- Both hydrological models should be applied to other catchments in Palestine. To further test the applicability and usefulness of those models in management and planning of water resources.

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جامعة النجاح الوطنية

كلية الدراسات العليا

النمذجة الهيدرولوجية الموزعة للمناطق شبه الجافة: حالة حوض وادي الفارعة، الضفة الغربية، فلسطين

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قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة المياه والبيئة بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.

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الملخص

يشكل نقص المياه تحديا كبيرا يواجه مديري المياه في البلدان الشحيحة بالمياه مثل فلسطين. ونتيجة لذلك، ينبغي بذل جهود كبيرة من أجل إدارة الموارد المائية على النحو الأمثل. تمثل النمذجة الهيدرولوجية أداة من بين عدة أدوات أخرى تستخدم لدعم إدارة موارد المياه. ونتيجة لذلك، تحسن النمذجة الهيدرولوجية فهم نظام المياه وتوفر بيانات المدخلات المطلوبة لنماذج إدارة الموارد المائية.

وفي هذا الصدد، لم تجر سوى بحوث قليلة بشأن النمذجة الهيدرولوجية في حوض وادي الفارعة.

أجريت هذه الدراسة في حوض وادي الفارعة، الواقع في الجزء الشمالي الشرقي من الضفة الغربية، فلسطين. وتبلغ مساحة هذا المستجمع حوالي 320 كم^2 تمثل حوالي 6٪ من المساحة الكلية للضفة الغربية. وعلاوة على ذلك، فإنه يصب مياهه إلى نهر الأردن في الجزء الجنوبي الشرقي منه.

في هذه الدراسة، تم إجراء تصور أولي للنمذجة الهيدرولوجية باستخدام برنامج (HEC-HMS) الذي يستخدم لمحاكاة العلاقة ما بين المطر والجريان السطحي في حوض وادي الفارعة، وفهم العمليات الهيدرولوجية العامة هناك. تم محاكاة أحداث عواصف مطرية مستقلة باستخدام HEC-HMS. تم استخدام عاصفة شباط (9–8)، 2009 لمعايرة النموذج، في حين تم استخدام عاصفة شباط (8–4)، 2005 للتحقق من صحة النموذج الهيدرولوجي. تم تقييم النموذج إحصائيا من خلال المقارنة بين بيانات الجريان التي تمت مراقبتها وقياسها في الوادي وتلك الناتجة من المحاكاة النموذجية. وعلاوة على ذلك، تم اختبار إمكانية تطبيق وفعالية نموذج هيدرولوجي أحدث في حوض وادي الفارعة. النموذج هو نموذج WRF-Hydro (نموذج بحث الطقس والتنبؤ به – حزمة تمديد النموذج

الهيدرولوجي). تم تطويرمحاكاتين لمواسم مطرية كاملة باستخدام النموذج. وكان أولهما في كانون الثاني / يناير وشباط / فبراير 2005، والثاني كان للسنوات الثلاث (2003–2005). ثم تم إجراء بعض المعايرة لتحسين نتائج المحاكاة وتحسين أداء النموذج.

من هذا البحث، يمكن استنتاج أن نموذج HEC-HMS قادر على محاكاة عواصف مطرية منفصلة في حوض وادي الفارعة شبه الجاف إلى درجة مقبولة جيدة. وعلاوة على ذلك، نموذج WRF-Hydro مفيد للمحاكاة المستمرة على الرغم من أنه ليس من المجدي جدا تطبيقه في حالتنا. ويرجع ذلك أساسا إلى أنه يتم استخدامه في وضع عدم الربط مع نموذج تنبؤ الطقس(WRF (uncoupled بسبب عدم توافر معلومات لنطاق كبير بما فيه الكفاية

وأخيرا، يمكن استخدام كلا النموذجين المدروسين في هذا البحث كأدوات للتنبؤ في مستجمع وادي الفارعة ومستجمعات المياه ذات الظروف الهيدرولوجية المماثلة. ومع ذلك، فإن هذه النماذج تحتاج إلى مزيد من التحسين والمعايرة لتحسين كفاءتها.