Up To Date Hydrological Modeling in Arid and Semi-arid Catchment, the Case of Faria Catchment, West Bank, Palestine

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بسم الله الرحمن الرحيم

أَنزَلَ مِنَ السَّمَاءِ مَاءً فَسَالَتْ أَوْدِيَةٌ بِقَدَرِهَا
فَاحْتَمَلَ السَّيْلُ زَبَدًا رَّابِيًا وَمِمَّا يُوقِدُونَ
عَلَيْهِ فِي النَّارِ ابْتِغَاءَ حِلْيَةٍ أَوْ مَتَاع زَبَدٌ
مِّثْلُهُ كَذَلِكَ يَضْرِبُ اللّهُ الْحَقَّ وَالْبَاطِلَ فَأَمَّا
الزَّبَدُ فَيَذْهَبُ جُفَاءً وَأَمَّا مَا يَنفَعُ النَّاسَ
فَيَمْكُثُ فِي الأَرْضِ كَذَلِكَ يَضْرِبُ اللّهُ الأَمْثَال
(القرآن13:17)

صدق الله العظيم

He sends down water (rain) from the sky, and the valleys flow according to their measure, but the flood bears away the foam that mounts up to the surface, and (also) from that (ore) which they heat in the fire in order to make ornaments or utensils, rises a foam like unto it, thus does Allah (by parables) show forth truth and falsehood. Then, as for the foam it passes away as scum upon the banks, while that which is for the good of mankind remains in the earth. Thus Allah sets forth parables (for the truth and falsehood, i.e. Belief and disbelief). (Al-Qur'an 13:17)

I dedicate this dissertation to:
My Parents
My wife, Heba
My daughters, Muna and Masa

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Contents

Abstract

Extreme events, such as severe storms, floods, and droughts are the main features characterizing the hydrological system of a region. In the West Bank, Palestine, which is characterized as arid to semi-arid region; little work has been carried out concerning hydrological modeling. However some rainfall-runoff studies were done in the region using simple lumped models. The present research study deals with the hydrological modeling in Faria catchment under limited hydro-meteorological and spatial data. The goal has been to obtain reliable estimates of naturally available, surface water resources in arid to semi-arid environment of the West Bank, Palestine. For this purpose, an up to date physically-based and spatially distributed hydrological model (the newly coupled TRAIN-ZIN model) has been applied. Advances in geographical information system (GIS) made it possible to enhance the spatial model parameters estimation. Thus this study has been the first attempt of its kind in the Faria catchment which started from basic database development to adoptive model parameters identification and application. Understanding the processes of runoff generation is prerequisite to enhance the evaluation and quantification of water resources in the Faria catchment. Consequently such evaluation can be utilized in the development of best management practices that can be adopted to manage the scarce water resources in the catchment.

The Faria catchment dominates the north eastern slopes of the West Bank and is a catchment of about 320 km^2. It has arid to semi-arid characteristics with a Mediterranean climate which is characterized by hot and dry summers and mild and wet winters. The catchment receives a mean areal rainfall of 412 mm per annum falling during October to April. Rainfall events are highly variable in space and in time. Generally, they are of local extent with high intensities. Hence flood events of short duration occur mainly during winter months. Spring discharges are the direct contact between surface water and groundwater in the catchment. Wadi Faria is considered as a perennial Wadi since 11 springs provide the baseflow for the Wadi and preventing it from drying up during hot summers.

The coupled TRAIN-ZIN model is used for runoff simulation. TRAIN simulates long term vertical fluxes between soils, vegetation and atmosphere whereas ZIN simulates short term runoff generation processes. The coupling layer of both models is the soil storage. During times of rain, ZIN model is active describing the filling of the soil storage and runoff generation by infiltration excess overland flow (IEOF) and/or saturation excess overland flow (SEOF) in time steps of minutes. During times of no-rain the soil module of TRAIN is active and calculates the emptying of the soil storage by evapotranspiration using the Penman-Monteith equation. Van-Genuchten method was integrated into the model to simulate water losses through deep percolation with a dynamical function. These calculations are important for modeling the next event, as they describe initial filling of the soil storage. With time steps of one day, TRAIN provides the missing long term simulation of soil moisture to ZIN. This modifies the ZIN model to a combined model that can be run on a continuous mode instead of single event oriented.

A runoff generation map (terrain types) was developed for the Faria catchment with the help of aerial photographs. Based on this map, the model parameters for various terrain types are estimated. The terrain types represent the sub-units for the model's runoff generation routine according to hydrologically relevant surface characteristics. For runoff concentration 1088 tributary catchments (model elements) were delineated whereas for channel routing the

channel network was cut into 544 channel segments denoted by two nodes. Runoff delivery from model elements to the adjoining channel segment was timed by a uniform time lag. Small scale variability is not represented as a uniform time lag has been taken for all model elements. In the case of Faria catchment which was divided into 1088 sub-catchments with an average area of about 0.295 km^2 scale variability can be neglected. Channel routing has been done using Muskingum-Cunge flow routing technique in which the Green-Ampt infiltration model was integrated to simulate the transmission losses. The parameter values for the three basic components in the coupled TRAIN-ZIN model, namely the runoff generation component, channel flow and transmission losses components and evapotranspiration component (climatic data for TRAIN part), were measured directly in the field (infiltration capacity and channel geometry), estimated from the literature (e.g. hydraulic conductivity, porosity, channel roughness, field capacity and others) and recorded (climatic parameters).

Rainfall data from four tipping bucket rain-gauges and runoff data from two Parshall Flumes for three consecutive rainy seasons (2004-2007) were collected for the purpose of this study. The inverse distance weight (IDW) method was applied to estimate the spatial rainfall data from the pointwise raingauge stations in a five minute time step. Four considerable single rainfall events with different rainfall and runoff characteristics were used for model calibration and validation. The runoff simulation of event 1 with mainly SEOF and event 2 with more IEOF was used for model calibration. With the determined set of parameter values event 3 and event 4 were simulated for model verification. The traditional method of calibration which is based on a trial-and-error process was used. This method was carried out sequentially by adjusting the non measured model input parameters until the simulated values approximate the observed values. After the successful calibration and validation of the coupled TRAIN-ZIN model, continuous simulation of the entire rainy seasons 2004/05, 2005/06 and 2006/07 from October to April were achieved. This facilitated accurate assessments of seasonal water balances in the entire Faria catchment. Results of both events based and continuous simulations were optimistic to assume the applicability of the coupled TRAIN-ZIN model to the Faria catchment.

The simulation results have been characterized by uncertainties of natural, data, parameter and model structure. In this study, parameters of the coupled TRAIN-ZIN model were determined through physical measurements carried out directly in the field (e.g. infiltration capacity) or from topographic maps (e.g. channels slope), from aerial photographs (e.g. channels geometry) or from information in the literature (e.g. hydraulic conductivity, porosity, Manning n, etc). Hence a certain amount of uncertainty is involved in parameter determination. These parameters usually may differ over years and even during various events of the same year. Therefore uncertainty assessment was carried out in this study to examine the sensitivity of the coupled TRAIN-ZIN model to the range of parameters uncertainty.

To evaluate how much and to what extend hydrological modeling can contribute to a quantitative analysis of the effects of land use and climate changes on catchment hydrology, the validated TRAIN-ZIN model was used to run land use and climate change scenarios to predict their effects on runoff characteristics as well as the overall availability of water resources in the Faria catchment. Consequently and in the face of the outstanding difficulties and challenges for managing the water resources in the Faria catchment, a set of proper management options were developed under the existing and future conditions.

Zusammenfassung

Extremereignisse, wie große Hochwässer und schwere Dürren, charakterisieren zu einem großen Teil das hydrologische System einer Region. In der West Bank (Palästina), eine aride bis semi-aride Region, fanden bislang nur wenige hydrologische Modelle Anwendung. Es gab einige wenige Studien zu Niederschlags-Abfluss-Beziehungen flächenzentrierten Ansätzen. Die vorliegende Studie beschäftigt sich mit hydrologischer Modellierung im Faria Einzugsgebiet mit begrenzt verfügbaren hydrologischen und meteorologischen sowie räumlichen Daten. Das Ziel war es die natürlich verfügbaren Oberflächenwasserressourcen in der ariden bis semi-ariden West Bank verlässlich abzuschätzen. Zu diesem Zweck wurde ein physikalisch basiertes und flächendetailliertes hydrologisches Modell (TRAIN-ZIN) angewendet. Fortschritte in geographischen Informationssystemen (GIS) ermöglichten eine verbesserte Abschätzung der räumlichen Modellparameter. Diese Studie ist also der erste Versuch seiner Art im Faria Einzugsgebiet. Die Studie begann mit der Entwicklung von grundlegenden Datenbanken bis hin zur Identifizierung und Verwendung geeigneter Modellparameter.

Das Wissen um die Entstehung von Oberflächenabfluss ist eine Grundvoraussetzung für die Verbesserung der Bewertung und Quantifizierung der Wasserressourcen im Faria Einzugsgebiet. Folglich kann solch eine Bewertung für die Entwicklung eines bestmöglichen Managements knapper Wasservorräte im Einzugsgebiet verwendet werden.

Das Faria Einzugsgebiet liegt in den nordöstlichen Hängen der West Bank. Es erstreckt sich über eine Fläche von etwa 320 km² und weist die ariden bis semi-ariden Merkmale eines mediterranen Klimas auf. Das bedeutet heiße und trockene Sommer und milde, feuchte Winter. Niederschlagsereignisse sind sowohl zeitlich als auch räumlich hochvariabel. Der mittlere Einzugsgebietsniederschlag von 412 mm pro Jahr fällt zwischen Oktober und April. Daher treten Abflussereignisse von kurzer Dauer hauptsächlich in den Wintermonaten auf. Quellabflüsse im Einzugsgebiet bilden den Übergangsbereich von Oberflächenwasser und Grundwasser. Wadi Faria wird als perennierend angesehen, weil 11 Quellen einen Basisabfluss garantieren und das Wadi vor Austrocknung im Sommer bewahren.

Das gekoppelte TRAIN-ZIN Modell wird für die Abflusssimulation verwendet. TRAIN simuliert länger andauernde Vertikalflüsse zwischen Böden, Vegetation und Atmosphäre, ZIN unmittelbare Oberflächenabflussprozesse. Der Bodenspeicher ist das Bindeglied der beiden Modelle. Bei Regenereignissen beschreibt das ZIN-Modell im Minutentakt wie sich der Bodenspeicher füllt und Abfluss durch Infiltrationsüberschuss (IEOF) oder/und Sättigung (SEOF) bildet. Zwischen Regenereignissen berechnet das Bodenmodul von TRAIN die Entleerung des Speichers durch Evapotranspiration mit der Penman-Monteith Gleichung. Die Van-Genuchten-Methode ist in das Modell integriert, um Wasserverluste durch tiefe Perkolation mit einer dynamischen Funktion zu simulieren. Diese Berechnungen sind wichtig, um das nachfolgende Ereignis zu modellieren, da sie das anfängliche Wasservolumen im Boden beschreiben. TRAIN liefert ZIN die fehlende Langzeitsimulation der Bodenfeuchte. So ist ZIN nicht mehr am Einzelereignis orientiert, sondern kann kontinuierlich modellieren.

Eine Karte der Abflussbildung im Faria Einzugsgebiet wurde mithilfe von Luftbildern erstellt. Basierend auf dieser Karte wurden die Modellparameter für die verschiedenen Böden abgeschätzt. Die Bodentypen repräsentieren Untereinheiten für die Routine der Abflussbildung im Modell und entsprechen wichtigen Oberflächenmerkmalen. 1088

Einzugsgebiete von Nebenflüssen (Modellelemente) wurden für die Abflusskonzentration beschrieben. Für das Channelrouting wurde das Fließnetzwerk in 544 Segmente unterteilt, die jeweils durch zwei Punkte begrenzt sind. Der Beitrag der Modellelemente zum Abfluss in das anliegende Segment wurde durch eine einheitliche Verzögerung beschrieben. Durch diese einheitliche Verzögerung, die für alle Modellelemente gleich ist, werden kleinmaßstäbliche Variabilitäten nicht berücksichtigt. Im Fall des Faria Einzugsgebiets, das in 1088 Einheiten aufgeteilt wurde, die eine mittlere Fläche von etwa 0.295 km² aufweisen, wird die räumliche Variabilität aber adäquat beschrieben. Das Channelrouting wurde mit der Muskingum-Cunge-Methode modelliert, in die das Infiltrationsmodell von Green und Ampt integriert wurde, um zusätzlich Transmission losses zu simulieren. Die Parameterwerte für die drei Hauptkomponenten im gekoppelten TRAIN-ZIN, die Komponente der Abflussbildung, des Gerinneflusses und der Transmission losses sowie der Evapotranspiration (Klimadaten für TRAIN) wurden direkt im Gelände gemessen (Infiltrationskapazität, Gerinnegeometrie), durch Literaturwerte abgeschätzt (z. B. hydraulische Leitfähigkeit, Porosität, Rauigkeit des Gerinnes, Feldkapazität und andere) oder direkt gemessen (Klimaparameter).

Niederschlagsdaten von vier Niederschlagsmessstationen (Wippen) und Abflussdaten von zwei Parshall-Gerinnen für drei aufeinander folgende Regensaisons (2004-2007) wurden für diese Studie gesammelt. Mit der Methode der inversen Distanzwichtung (IDW) wurden die Niederschlagsmessungen räumlich in einem Fünf-Minutenabstand interpoliert. Vier größere Regenereignisse mit verschiedenen Niederschlags und Abflussmerkmalen dienten zur Kalibrierung und Validierung des Modells. Die Abflusssimulation von Ereignis 1 mit hauptsächlich Sättigungsflächenabfluss (SEOF) und Ereignis 2 mit mehr Horton-Abfluss (IEOF) wurden zur Kalibrierung verwendet. Die Werte von Ereignis 3 und 4 wurden simuliert, um das Modell zu validieren. Die Kalibrierung erfolgte visuell bis gemessene Abflüsse durch die simulierten Modellergebnisse gut beschrieben wurden. Nach der erfolgreichen Kalibrierung und Validierung des gekoppelten TRAIN-ZIN Modells wurden kontinuierliche Simulationen über die gesamten Niederschlagssaisons 2004/05, 2005/06 und 2006/07 von Oktober bis April erstellt. Dies ermöglichte genaue Abschätzungen der saisonalen Wasserbilanz für das gesamte Faria Einzugsgebiet. Die Ergebnisse von sowohl ereignisbasierter als auch kontinuierlicher Simulation waren so gut, dass man von der Anwendbarkeit des gekoppelten TRAIN-ZIN Modells auf das Faria-Einzugsgebiet ausgehen kann.

Die Simulationsergebnisse waren gekennzeichnet von natürlichen Unsicherheiten, Unsicherheiten in Daten und Parametern und Unsicherheiten in der Modellstruktur. In dieser Studie wurden die Parameter des gekoppelten TRAIN-ZIN Modells durch pysikalische Messungen direkt aus dem Gelände (z. B. Infiltrationskapazität) von topographischen Karten (z. B. Gerinneneigung), von Luftbilden (z. B. Gerinnegeometrie) oder aus der Literatur (hydraulische Leitfähigkeit, Porosität, Manning n usw.) bestimmt. Daher ist ein gewisser Anteil der Unsicherheit an die Parameterbestimmung geknüpft. Modellparameter ändern sich über Jahre hinweg auch während unterschiedlicher Ereignisse im gleichen Jahr. Daher wurde die Abschätzung der Unsicherheit in dieser Studie ausgeführt, um die Sensitivität des gekoppelten TRAIN-ZIN Modells auf die Reihe an Parameterunsicherheiten zu betrachten.

Um zu bewerten, wie gut eine hydrologische Modellierung eine quantitative Analyse der Effekte von Landnutzungs und Klimaänderungen auf Einzugsgebietshydrologie ermöglicht, wurden verschiedene Szenarien mit TRAIN-ZIN berechnet. Somit sollte es die Effekte der Szenarien auf Abflussprozesse sowie auf die gesamte Verfügbarkeit der Wasserressourcen im Faria Einzugsgebiet vorhersagen. Basierend hierauf und in Anbetracht der ausstehenden

Schwierigkeiten und Herausforderungen, die Wasserressourcen im Faria Einzugsgebiet zu bewirtschaften, wurde ein Set geeigneter Managementstrategien für derzeitige und zukünftige Zustände entwickelt.

1 Introduction

1.1 General

Water means life and it is a basic source in all human activities. All ancient civilizations flourished only near water sources and then probably collapsed when the water supply failed. Water is a finite resource, essential for agriculture, industry and human existence. Without water of adequate quantity and quality, sustainable development is impossible. Water is becoming scarce in quantity and inadequate in quality in many areas around the world. There is a worldwide consensus that the need for water and water supply systems are increasing rapidly as a direct result of human population growth, improved standards of living and industrial expansion as well as escalating need for food in dry climate regions. Water resources management is essential to ensure the availability of water, when and where it is needed, and to safeguard its quality.

Hydrology was defined by Penman (1961 in Singh et al., 2002) as the science that attempts to answer the question, "what happens to the rain"? This sounds like a simple enough question, but experience has shown that quantitative descriptions of the land phase of the hydrologic cycle may become very complicated and are subject to a great deal of uncertainty. The term "catchment hydrology" is defined as that branch of hydrology that deals with the integration of hydrologic processes at the catchment scale to determine the catchment rainfall response.

Hydrologists and water engineers are always concerned with discharge rates resulting from rainfall. Not only measuring rainfall and the resulting runoff are of interest, but also the process of transforming the rainfall hyetograph into runoff hydrograph. Peak flow rate and time to peak are the two important hydrograph characteristics that need to be estimated for any catchment. Unfortunately, the classic problem of predicting these parameters is usually difficult to resolve because many catchments are ungauged, especially those in developing regions or isolated areas. Even in cases where catchments are gauged, the period of record is often too short to allow accurate estimates of the different hydraulic parameters.

Hydrological models are increasingly used in hydrology and play a fundamental role in many aspects of catchment management, for example determining the availability and sustainability of water resources, design of flood protection works and operational aspects of flood and water resources management. Hydrological models are powerful tools to describe and to understand the behavior of the natural systems. Due to continuous improvements and developments in hydrological modeling and computing power, the applicability and the benefit of hydrological models have grown in importance. They have contributed extremely to the scientific understanding and support decision making in water resources management. Hydrological models are in general designed to gain a better understanding of the hydrologic behaviors of a catchment and of how changes in the catchment may affect these behaviors. They also provide valuable information for studying the potential impacts of changes in land use or climate.

In catchment modeling, if we consider water quantity and water availability, traditionally, simulating the relation between precipitation and discharge at the catchment's outlet should be carried out. Rainfall-runoff modeling is a major part of this job. Therefore, rainfall-runoff modeling is considered a standard tool routinely used today for the investigation and application in catchment hydrology.

Worldwide, water resources availability in arid and semi-arid regions is limited and under severe conditions. This is caused by high population growth rate, increasing urban development and increasing use of water for irrigation. Hydrology plays an important role to overcome the water shortage related problems in arid and semi-arid regions through reliable assessment of usable water volumes that leads to sustainable water resources management. Water resources assessment is the key issue for integrated water resources management. Correct and detailed assessment of water resources is of great importance to plan, design, realize and manage any water resources development project. The results of the assessment are the basis for any decision making process, since they can lead to large investments and serious consequences on the environment. Water resources assessment consists of determining their quantity, quality and availability for sustainable development and coherent management.

Water resources in the West Bank, Palestine are scarce. This is due to the fact that, geographically, the West Bank is located in arid to semi-arid region. Therefore, societies in the West Bank (one of the developing countries) are very vulnerable to variability of water resources availability. This vulnerability is caused by the strong constraints on the use of natural resources due to limited and low reliable water resources availability in addition to an often high population density and growth rate. The population is strongly dependent on these resources with few short-term options to reduce such dependency. The existing political situation adds another constraint to the availability of water resources in the West Bank.

In arid and semi-arid regions storm water drainage and hydrological modeling are important because it is not only a drainage problem but also a water resources management and planning problem. Hydrological modeling in the West Bank has not been given enough care and no intensive studies have been done. Runoff generation in the West Bank catchments is limited to a few hours only, following single rainstorms and is highly variable in space and time. Dominating runoff processes are saturation excess in Mediterranean areas and infiltration excess in arid parts. Runoff generation can be directly linked to rainfall, through assessments of catchment rainfall.

This research study aims to gain an understanding of the hydrological processes in arid and semi-arid catchments. This is achieved through the modeling of rainfall-runoff process in the Faria catchment, which is characterized as arid to semi-arid region located in the northern West Bank, Palestine. Nowadays rainfall-runoff modeling is considered a standard tool normally used for the investigation and application in catchment hydrology. In this study, up to date, process-oriented modeling techniques (coupling the models TRAIN and ZIN) integrating existing scientific results have been applied.

This research study is jointly supervised by the Institute of Hydrology of Freiburg University, Germany and the Institute of Water and Environmental Studies Institute of An-Najah National University, Nablus, Palestine in the context of project 5 of GLOWA-JR Project. GLOWA-JR is an interdisciplinary study addressing the vulnerability of water resources and adaptation of different management options to global climatic changes of the Jordan River Basin (JRB). Project 5, of GLOWA-JR project deals with the hydrological modeling and assessing of water availability for the JRB. This study applies the newly coupled TRAIN-ZIN model in the Faria catchment, a focus area, West Bank, Palestine.

1.2 Objectives

The objective of this research is to obtain dependable estimates of naturally available, water resources in arid and semi-arid environment of the West Bank, Palestine. Faria catchment which is one of the catchments contributing to the Lower Jordan River Basin (LJRB) is the focus study area in this research study. The coupled TRAIN-ZIN model is to be used in this research to evaluate the availability of surface water resources in the Faria catchment. Such evaluation can be utilized in the development of best management practices that can be adopted to manage the scarce water resources in the Faria catchment and lead towards understanding and managing the regional water resources in the LJRB. In light of the above, the general objectives of this research can be summarized as follows:

1. To collect high quality rainfall and runoff data in high temporal and spatial resolution for hydrological modeling;
2. To collect relevant model parameters for the coupled TRAIN-ZIN model. These include infiltration characteristics of different terrain types and GIS-parameters for the runoff generation routine and channel routing routine of the model;
3. To apply the coupled TRAIN-ZIN model for selected single rainstorm events followed by continuous simulation for the entire rainy seasons;
4. To assess the total available water resources in the Faria catchment. These also include discharging springs from the regional karst aquifer that make up the main contribution to stream baseflow; and
5. To develop proper water resources management options for the most efficient water use under present and global change induced conditions based on the assessment of total available water resources in the Faria catchment.

1.3 Research Questions

Follow up to the above objectives, a few questions are raised.

1. What are the active runoff generation processes in arid and semi-arid regions?
2. What is the best hydrological model that can be used to assess the runoff generation process in arid and semi-arid regions?
3. Which data should be collected and how to acquire data in the fieldwork period? What is the quality of the data (spatial data and attribute data)? If data availability is insufficient, how to generate synthetic data?
4. How can we provide improved estimations of catchment initial conditions (e.g., soil moisture, infiltration rate, Manning coefficient, hydraulic conductivity)?
5. What is the optimal set of the input model parameters required to apply the coupled TRAIN-ZIN model?
6. What is the potential for the spatially distributed TRAIN-ZIN model set up for catchment outlet simulations to generate hydrographs at interior locations for flood forecasting?

7. How do we characterize the coupled TRAIN-ZIN model uncertainties?
8. How can we use the coupled TRAIN-ZIN model in assessing the runoff generation under land use and climate changes scenarios?
9. What are the total available water resources in the Faria catchment?
10. What are the proper water resources management options for the most efficient water use in the Faria catchment?

1.4 Research Needs and Motivations

Water shortage is not a new phenomenon in arid and semi-arid regions. What is new, however, is that it is occurring in an increasingly changing environment and this makes it more serious and long-lasting (Hamdy et al., 1995). West Bank, Palestine is under arid to semi-arid conditions as characterized by its natural water resources scarcity, low per capita water allocation and conflicting demands on its shared water resources. This scarcity has led to the limited availability of water resources and the dire need to manage these resources.

Faria catchment is an arid to semi-arid catchment located in the northeastern part of the West Bank, Palestine. The drought that took place several times in the catchment and the high population growth rate in addition to other artificial constraints marked a turning point that highlighted the vulnerability of the existing obtainable surface water and groundwater resources. The available water resources in the Faria catchment are limited and are not sufficient to fulfill the agricultural and residential water demand. The water crisis is endemic or permanent in the Faria catchment as one of the most important agricultural areas in the West Bank. In the Faria catchment the shortfall in water supplies quantity has been compounded by a decrease in quality owing to the contamination of surface water as well as groundwater resources. Water shortage threatens to spread and become a permanent feature in the Faria catchment due to the increasing demographic and agricultural growth that exacerbates demand and jeopardizes the quality of the water resources in the catchment. A management strategy is urgently needed to be adopted to stop the water crisis in the Faria catchment.

There are many interrelated reasons that have contributed to water crisis in the Faria catchment. These are inefficient management, water shortages, environmental pollution, and Israeli occupation. The major water crisis of the Faria catchment can be summarized as follows:

1. Lack of proper management of water resources causes over utilization of the scarce water resources;
2. The water is not properly allocated between upstream and downstream communities and thus water use rights need to be well established and institutionalized;
3. More than 40% of the people in the catchment lacks water supply for drinking purposes. In addition to that, the annual water gap between water needs and obtainable water supply is increasing rapidly with time;
4. There is lack of storage capacity e.g. reservoirs to capture flood water during the rainy season in order to be used later;

5. Unbalanced utilization of groundwater causes increasing salinity especially in the south eastern part of the catchment in the proximity of the Jordan River;
6. Water losses through evaporation and infiltration from the agricultural canals are high and thus large quantities of water are not fully utilized;
7. Water pollution is an ongoing problem. For instance fresh surface water originating from the springs mixes with wastewater coming from Nablus City and Al-Faria Refugee camp;
8. Cesspools, unbalanced use of fertilizers and pesticides has led to the pollution of the scarce water resources;
9. Unmanaged solid waste dumping in some areas adds additional complexity to the pollution problems; and
10. Lack of permits to rehabilitate and remediate the deteriorated shallow Palestinian wells, while the Israeli wells are pumping properly and largely from deep aquifers and thus lowering the water table.

From the above it can be inferred that like the entire West Bank, Faria catchment faces a severe water crisis that needs to be investigated to develop sound mitigation strategies. Due to the fact that the available water resources in the Faria catchment are limited and cannot suffice for increasing water demand to fulfill the agricultural and residential requirements, reliability assessment of water availability in the catchment is of great importance in order to optimally manage the local water resources. This situation has compelled the motivation for conducting a hydrological modeling to better understand and to evaluate the water resources availability in the Faria catchment. This modeling is essential to provide input data for a management system and to enable the development of optimal water allocation policies and management alternatives to bridge the gap between water needs and obtainable water supply under the present and forecasted future changes, in land use and climate conditions.

1.5 Methodology

To achieve the objectives of this research study, firstly research needs and objectives were defined. Characterization of the study area included geography, topography, climate, geology, soil, land use, rainfall, runoff, infiltration and hydrological network. Data collection was conducted depending on literature review and field experiments for outlining and understanding the hydrological processes in arid and semi-arid environments. The collected data were analyzed and processed using Excel and GIS. This leads to setup of the GIS-based database, mainly the runoff generation map and hydrological network, which had been prepared as required for the coupled TRAIN-ZIN model. The channel network is divided into segments which are adjoined by small sub-catchments (model elements) delineated according to topography. For this purpose, a detailed topographic map supported by a DEM was made available and used within the GIS system.

A land use map in addition to a runoff generation map were developed with the help of aerial photographs that were incorporated into the GIS. Field experiments were done to estimate the infiltration capacity of the different terrain types from the runoff generation map. The data collected were arranged and the GIS-based database was compiled.

The structure of the coupled TRAIN-ZIN model was built and input parameters were estimated. The TRAIN model is a physically-based, spatially distributed approach which has been designed to simulate the spatial pattern of long term water budget components with a special focus on evapotranspiration. The ZIN model is a single event, hydrological model which concentrates on dominant flood generation processes (i.e. infiltration and saturation excess runoff) and can be fully parameterized using existing information from catchment topography and field measurements.

The coupled TRAIN-ZIN model was used and applied for different rainfall events to simulate the runoff generation in the Faria catchment. Calibration, validation, sensitivity analysis and uncertainty assessment of the model using the observed runoff data and model optimization were achieved. Having done the model calibration and validation, the impacts of land use and climate changes on water availability were studied.

Water resources management options for the most efficient water use was developed based on the assessment of total available water resources in the Faria catchment. Finally, conclusions and perspectives were presented. The overall methodology followed in this study is illustrated in **Fig. 1.1**.

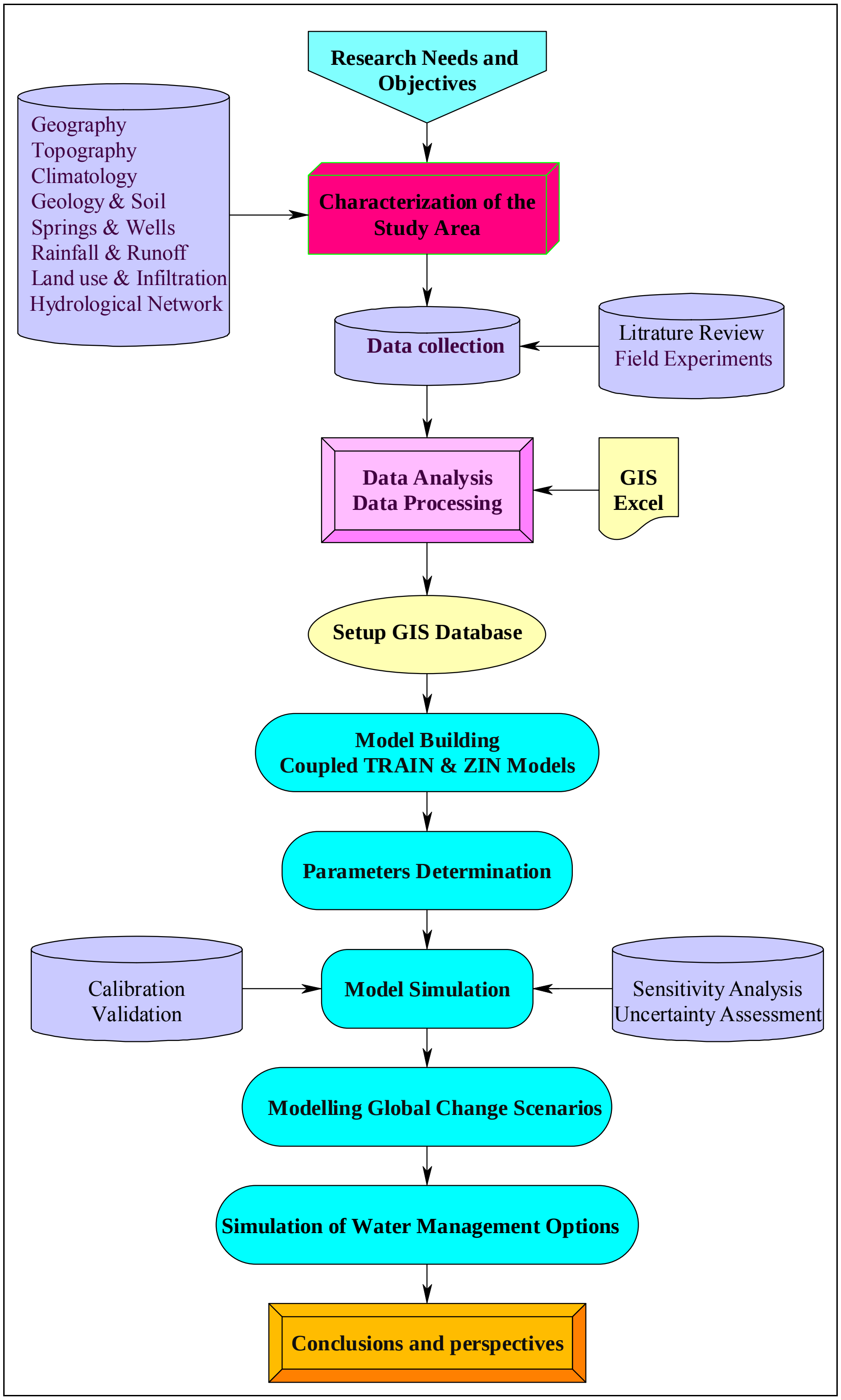

Fig. 1.1 **A Flow Chart Depicting the General Methodology Followed in this Research Study**

1.6 Expected Outcomes

The expected outcomes of this study can be summarized as follows:

1. A GIS-based format map of the spatial distribution of the land use practices will be one of the major outputs that will lead to understand the hydrological characteristics of the Faria catchment;
2. Assessing the hydrological characteristics and modeling the rainfall-runoff process in the Faria catchment as arid to semi-arid catchment; simulated flow versus observed flow;
3. Future potentials and vulnerabilities of the Faria catchment, arising from climate change and human pressure (urbanization) and their implications for the availability of water resources;
4. Different water resources management options will be finalized based on different climate and land use changes scenarios to develop and realize strategies for sustainable development of water resources in the Faria catchment as one of the catchments contributing to the LJRB; and
5. Knowledge transfer to follow up research focused on the hydrology of arid and semi-arid regions. This includes data processing techniques, data use, selecting of the proper rainfall-runoff models, interpretation of results and integration of results into a management strategy.

1.7 Dissertation Organization

This dissertation is organized as follows. Chapter 1 introduces the objectives, research questions, research needs and motivations and the expected outcomes. Literature review of hydrological processes of arid and semi-arid regions in addition to the rainfall-runoff models are provided in Chapter 2. The research area characteristics, field work activities and data collection are described in Chapter 3. Chapter 4 presents the analysis of the rainfall and runoff data. Hydrological modeling and the structure of the coupled TRAIN-ZIN model is the topic of Chapter 5. In Chapter 6 the model parameterization is included. Chapter 7 presents the application of the coupled TRAIN-ZIN model in Faria catchment for both event based and continuous simulations. Sensitivity analysis and model uncertainty are provided in Chapter 8. Chapter 9 deals with scenario modeling for both climate and land use changes. A set of surface water management options are presented in Chapter 10. Chapter 11 gives the conclusions and perspectives out of this research study. Following Chapter 11 are the references and annexes.

2 Literature Review

2.1 Hydrological Processes in Arid and Semi-arid Regions

2.1.1 Introduction

The arid and semi-arid regions of the world are under severe and increasing pressure due to expanding populations, increasing per capita water use, and limited water resources. Point and diffuse pollution, increasing volumes of industrial and domestic waste and over abstraction of groundwater provide a major threat to those scarce resources. Floods are infrequent, but extremely damaging, and the threat from floods to lives and infrastructure is increasing due to urban development. Added to these pressures is the uncertain threat of climate change. Effective management is essential and this requires appropriate understanding of the hydrological processes in these areas, including modeling tools (Wheater, 2002).

The hydrological processes of arid and semi-arid regions are significantly different from that in more humid regions (Simmers, 2003). The main hydrological difference between humid areas and arid to semi-arid regions is a high variability in both space and time of all hydrological parameters (e.g. rainfall intensity, infiltration rates and runoff generation processes) (Schick et al., 1997).

Broad hydrological features that characterized arid and semi-arid regions are given by FAO (1981), Wheater (1996, 2002) and Simmers (2003) to be:

- High levels of incident solar radiation;
- High diurnal and seasonal temperature variations;
- Evaporation is prominent in the hydrological cycle;
- Low humidity at short distance from the sea;
- Strong winds with frequent dust and sand storms;
- Sporadic rainfall of high temporal and spatial variability;
- High rainfall intensities;
- Significant difference between potential and actual evaporation;
- Extreme variability of short duration runoff events in ephemeral drainage systems;
- High rates of infiltration loss in dry channel alluvium;
- High erosion and sediment transport rates;
- Relatively large groundwater and soil moisture storage changes;
- Distinctive geomorphology, with poorly developed soil profile, and
- Deep groundwater tables.

From the aforementioned hydrological features of arid and semi-arid regions, there is a dire need to go deeply to gain an understanding of the unique features of arid and semi-arid zones hydrological systems and the nature of the dominant hydrological processes. This provides an important opportunity to develop appropriate methodologies for flood and water resource management strategy which are fitting to the specific hydrological characteristics of arid and semi-arid regions and the associated management needs.

2.1.2 Geographical Distribution

The world's extensive "drylands" areas generally lie between latitudes 10-35^{o} N and S, immediately north and south of the major tropical convergence zone (Landsberg and Schloemer, 1967, cited by Simmers, 2003). Typical areas include southwest USA, south central South America, South Africa, North Africa extending into central and southern Asia and most of Western Australia.

One third of the world's land surface has been classified as arid and semi-arid and approximately half of all countries are directly affected in some way by problems of aridity (FAO, 1981, Rodier, 1985 and Simmers, 2003).

One way to define aridity is the moisture deficit, or the aridity index, which is the ratio of mean annual precipitation (P mm) to Penman mean annual potential evapotranspiration (PET mm). This index is then reclassified into four main aridity zones and one humid zone and one cold tundra mountains zone, according to the ranges defined by UNESCO (1984).

These zones are: (1) Hyper-arid ($P/PET < 0.05$), (2) Arid ($0.05 \leq P/PET < 0.20$), (3) Semi-arid ($0.20 \leq P/PET < 0.50$), (4) Dry sub-humid ($0.50 \leq P/PET < 0.65$), (5) Humid ($P/PET \geq 0.65$) and (6) Cold, which are areas that have more than six months of an average temperature below 0^{o}C and not more than three months where the temperature reaches above 6^{o}C. The six arid regions around the world are shown in **Fig. 2.1**.

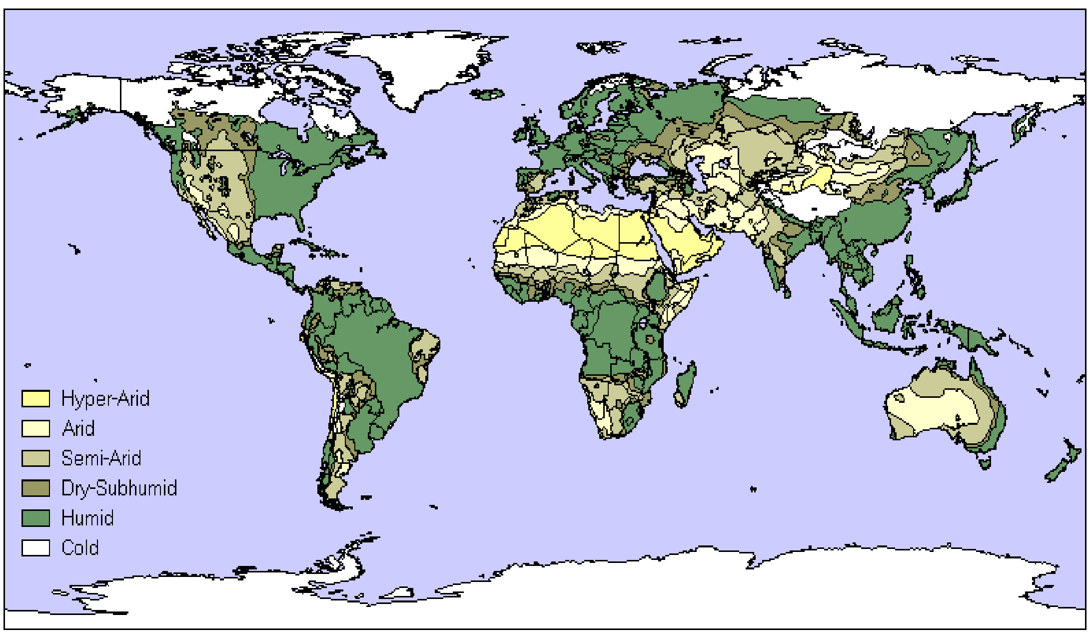

Fig. 2.1 Arid Regions around the World (UNESCO, 1984)

2.1.3 Climate and Rainfall

Arid and semi-arid regions are associated with dry climate which are dominated by low annual rainfall, low soil moisture conditions and very high potential evapotranspiration levels (Graf, 1988). Climate conditions of arid and semi-arid regions frequently lead to serious water deficits and drought conditions (Kalma and Franks, 2003). Understanding the role of climate is vital in any assessment of the nature of the dominant hydrological processes in arid and semi-arid regions, as it is the main determinant of rainfall and runoff. Arid and semi-arid regions are characterized by highly variable degrees of aridity with aridity being promoted by various factors. Most of the world's drylands are located in the subtropics where they are under the influence of dry, stable and high pressure air masses that inhibit the diffusion of rain bearing weather systems for a significant part of the year (Nanson et al., 2002). The main climatological feature of arid and semi-arid regions is the short-lived and often localized nature of precipitation usually associated with vast variations in space and time (Lange, 1999).

Rainfall is the primary hydrological input required for successful hydrological modeling. In arid and semi-arid regions, rainfall is commonly characterized by extremely high spatial and temporal variability (Wheater, 2002). A semi-arid region is subject to seasonal rainfall, with little or no rainfall in other parts of the year. Rainfall patterns vary widely from region to region and within a certain region (Ponce, 1989).

For a majority of tropical areas rainfall is concentrated in summer months (e.g. southern Sahara, semi-arid India, Australia and Mexico), elsewhere it is mainly concentrated in winter (e.g. China, Asia). In comparison with humid zones, there are several unique arid and semi-arid zone rainfall characteristics which can be summarized as (Wheater, 2002):

- Rain storms are random events with a small frequency of occurrence;
- The more intense the drought conditions, the lower the magnitude of frequent storms;
- In tropical arid regions rain storms result from short duration convective events which usually last from 15 minutes to two hours, with a maximum intensity in excess of 100-150 mm hr^{-1}; and
- The areal extent of storms in tropical arid regions is variable, commonly 30-60 km^2 in the Sahel, whereas in the mountainous regions this is much smaller and the localized nature of storms is very significant.

It is true that recorded rainfall intensities in arid and semi-arid regions are very high. It is noted that 264 mm in 10 hours recorded in the Nimes, southern France; 556 mm in 48 hours in the Spanish Pyrenees in the 1992; 650 mm in 18 hours in 1982 in Valencia and 866 mm in 72 hours in 1940 in Catalonia (Beven, 2002; Wainwright, 1996 and references quoted therein). In the Vaison-Ia-Romaine, southern France, the peak intensity of the flood event recorded in 1992 is 200 mm hr^{-1} over 6 minutes period, while the catastrophic event of 1996 at Biescas in the Aras basin in the Spanish Pyrenees had a maximum recorded intensity of the 153 mmh^{-1} over a 10 minutes period (White et al., 1997; Gutierrez and Sancho, 1998). More than a 330 mm hr^{-1}, with rapid changes in intensity and volume over relatively short distances (**Fig. 2.2**), were recorded inside the semi-arid Walnut Gulch catchment, Arizona, USA (Goodrich et al., 1997).

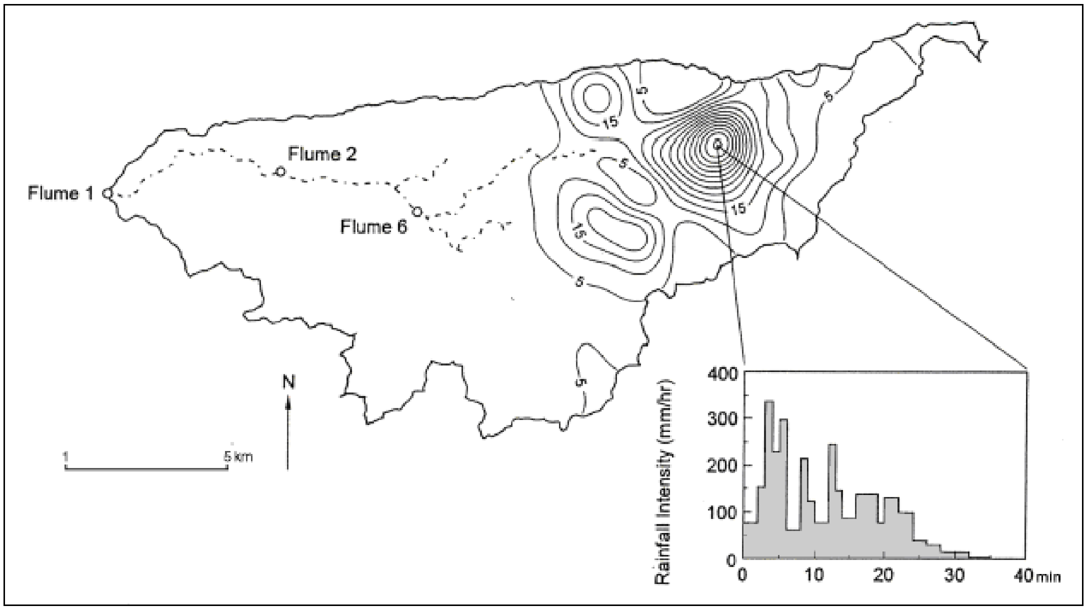

Fig. 2.2 Pattern of Rainfall Intensities Recorded during an Event on the Walnut Gulch Catchment, Arizona (Goodrich et al., 1997)

Rainfall regimes in historic Palestine were studied in detail by Kalma Franks (2003). The climate of Palestine historically as a whole is Mediterranean with a mild, rainy season and a dry, hot summer. Climatic regionalization across the country is difficult mainly because of the abrupt differences in climate across relatively short distances. Annual rainfall decreases from 1000 mm in the far north down to about 25 mm in the extreme south of the country. There are significant west-east differences across the country that are controlled by distance from the Mediterranean Sea and the blocking effects of the region's mountain ranges. On the basis of annual rainfall; the country can be divided into three important zones. These are: (1) a sub-humid zone with annual rainfall of 400-1000 mm; (2) a semi-arid zone with annual rainfall of 200-400 mm; and (3) an arid zone with an annual rainfall of 25-200 mm. The semi-arid and arid zones occupy most of the southern half of the country. The ZIN model that is used in this study was developed by Lange (1999) in Negev (Nagab) region that is entirely located in the arid zone.

In Faria catchment which is characterized as a semi-arid region located in the northern West Bank, Palestine, annual rainfall variability is marked spatially and temporally. The rainfall varies from 650 mm at the headwater in Nablus station to 150 mm at the outlet to the Jordan River, while the annual rainfall varies between 315 and 1387 mm at a certain location in the catchment, at Nablus station (Shadeed, 2005).

The rainfall that falls is either intercepted by trees, shrubs, and other vegetation, or it strikes the ground surface and becomes overland flow and groundwater flow. Regardless of its deposition, much of the rainfall eventually is returned to the atmosphere by evapotranspiration processes from the vegetation and soil or by evaporation from streams and other bodies of water into which overland, subsurface, and groundwater flow move (Chow et al., 1988).

Evaporation is affected by several climatic elements (e.g. air temperature, relative humidity, net radiation). It is necessary to distinguish between actual rates of evaporation and potential rates. The concept of the potential evaporation assumes that water is not limited and is at all times sufficient to supply the requirements of the dry air and the transpiring cover. Obviously, in arid and semi-arid regions, the value for actual evaporation seldom equals the potential evaporation, but is much lower. Generally in arid and semi-arid farm lands there is large gap between potential evaporation and rain depth (Thormählen, 2003).

Evaporation plays a decisive role in arid and semi-arid regions, as it dominates the long-term water balance. Water balance approach under extreme arid conditions was studied in Saudi Arabia. As a result, the authors found that evapotranspiration losses make up 95% of the rainfall. For the short term, water balance evaporation losses from the surface or open water tables are generally negligible, due to very short durations of the rainfall events. Furthermore, cloudiness, low air temperatures and relatively high humidity during storm events prevent high values of potential and actual evaporation (Abdulrazzak et al., 1989).

2.1.4 Runoff Generation Mechanisms

Understanding the mechanisms involved in the hydrological response has motivated several studies that have been carried out during the last two decades. There is an extensive body of literature describing runoff generation mechanisms in humid regions (e.g. Betson, 1964; Hewlett and Hibbert, 1967; Whipkey, 1969; Dickenson and Whiteley, 1970; Dunne and Black, 1970; Weyman, 1975; Dunne et al., 1975; Harr, 1977; Dunne, 1978; Mosley, 1979; Pearce, 1986; Bonell et al., 1990; Bonell, 1993; Genereux et al., 1993; Allan and Roulet, 1994; Quinton and Marsh, 1999; Ward, 2000; Putty and Prasad, 2000a, b; Sidle et al., 2001; Levia, 2004), on the other hand, relatively few studies have been carried out in arid and semi-arid regions (e.g. Yair and Lavee, 1976; Dunne, 1978; Yair and Lavee, 1985; Abrahams et al., 1988; Lavabre et al., 1993; Abrahams et al., 1994; Wilox et al., 1997; Martinez-Mena et al., 1998; Lange, 1999; Wheater, 2002; Beven, 2002; Lange et al., 2003; Lange and Leibundgut, 2003).

The aforementioned literatures concluded that, the Hortonian or Infiltration Excess Overland Flow (IEOF) (Horton, 1933) is generally assumed to be the dominant mechanism of runoff generation in most arid and semi-arid regions. IEOF is defined as the flow of water from a catchment that occurs when the rainfall rate exceeds the ability of the soil to allow water to infiltrate, resulting in the accumulation of excess water at the ground surface and overland flow in sheets. In contrast, in humid regions different runoff generation mechanisms (e.g. runoff from saturated areas and slow outflow of large groundwater bodies) deliver more or less permanently water to perennial rivers. The overland flow is the mechanism by which rainfall is transported downslope as a sheet flow over the soil surface and it is described as water that flows over the ground surface towards a stream channel as the initial phase of surface runoff (Lange, 1999). Two conditions must be satisfied for the IEOF: first, delivery of rainfall at intensity greater than the local infiltration capacity of the soil, causing ponding of water at the surface; and secondly, the rainfall duration longer than ponding time, the time required to saturate the soil surface for a given initial soil moisture profile and to fill the small surface depression storage. The excess water accumulates at the soil surface, if the infiltration capacity of the soil surface is exceeded, where some of this water is lost via evaporation and infiltration (Freeze, 1980; Bonell and Williams, 1986). IEOF depends on the simultaneous action of a multitude of factors which can be classified into two groups: 1) abiotic factors:

relief and geomorphological characteristics, parent rock and soil composition, and climate (primarily the intensity and amount of rainfall), and 2) biotic factors: vegetative cover of the slope, land use, anthropogenic factors, etc (Hernandez et al., 2000).

In many humid zones, the soil is capable of allowing essentially all of the incident rainfall to infiltrate. In such catchments overland flow develops not because rainfall intensity exceeds the infiltration rate, but because it falls on temporarily or permanently saturated areas (wetlands) with no capacity for water to infiltrate. Flow developing under these conditions is known as Dunnian or Saturation Excess Overland Flow (SEOF), (Dunne et al., 1975). SEOF mechanism combines a return flow of subsurface water, infiltrated water which returns to the land surface having flowed for a short distance in the upper soil horizon, with direct rainfall onto the saturated discharge area (Kirkby, 1969, Beven, 2001). The areas of a catchment where the SEOF is expected tend to be in valley bottom areas, near stream saturated areas, particularly headwaters hollows where there is convergence of flow and a gradual decline in slope towards the stream (Beven, 2001), or where groundwater discharge areas occur (Dunne et al., 1975). SEOF may also occur on areas of thin soils where small amounts of water are required to saturate the soil and induce emergence of return flow or in permeable and low slope areas that tend to stay wet during recession periods (Beven, 2001).

Deduction from field data which show that runoff generation may be more related to antecedence conditions and rainfall volumes more than rainfall intensities prompted, Beven, (2002 and references quoted therein) to suggest that SEOF may occur in semi-arid regions. In such areas, SEOF mechanism doesn't imply that the soil profile is completely saturated, only that the primary control on infiltration into the soil profile may not be at the surface but at some depth into the soil, perhaps associated with the tillage layer. As in more humid regions, SEOF mechanism requires that rainfall volumes will be greater than the effective storage deficit in the soil above the controlling layer. Areas of saturated soil will therefore tend to occur first where the antecedent soil moisture deficit is smallest prior to an event, but significant saturation may only occur when there has been antecedent wetting (Taha et al., 1997). This may be more related to variations in soil characteristics than to the topographic controls that are important in humid areas (Beven and Kirkby, 1979). The area of saturated soil will tend to expand with increased wetting during a storm and reduce again after rain stops at a rate controlled by the supply of water from upslope (Beven, 2001). Thus the effective contributing area for both types of surface runoff generation mechanisms, IEOF and SEOF, should be expected to be dynamic during the storm (Coles et al., 1997). This is known as the dynamic contributing area concept (Beven, 2001). **Fig. 2.3** illustrates both IEOF and SEOF runoff generation mechanisms.

In both humid and semi-arid regions, theoretical and field studies have found that the spatial generation of runoff is strongly non-uniform and highly variable, due to the high variability in soil infiltration capacity (Yair and Lavee, 1985; Loague and Gander, 1990; Jordan, 1994). In humid regions this variability is mainly attributed to spatial differences in soil moisture (Troendle, 1985), whereas, in arid and semi-arid regions it is mainly controlled by the variability of rainfall both in time and space and the physical and chemical properties of the soil surface (Yair and Lavee , 1976; Lavee and Yair, 1990). Marinez-Mena et al. (1998) studied the effects of the physical and chemical properties of the soil surface that influence runoff generation in semi-arid regions and concluded that IEOF mechanism occurred pre-dominantly in the more degraded areas with fine texture and poorly permeable soils. In soils with courser texture, SEOF is the dominant runoff generation mechanism.

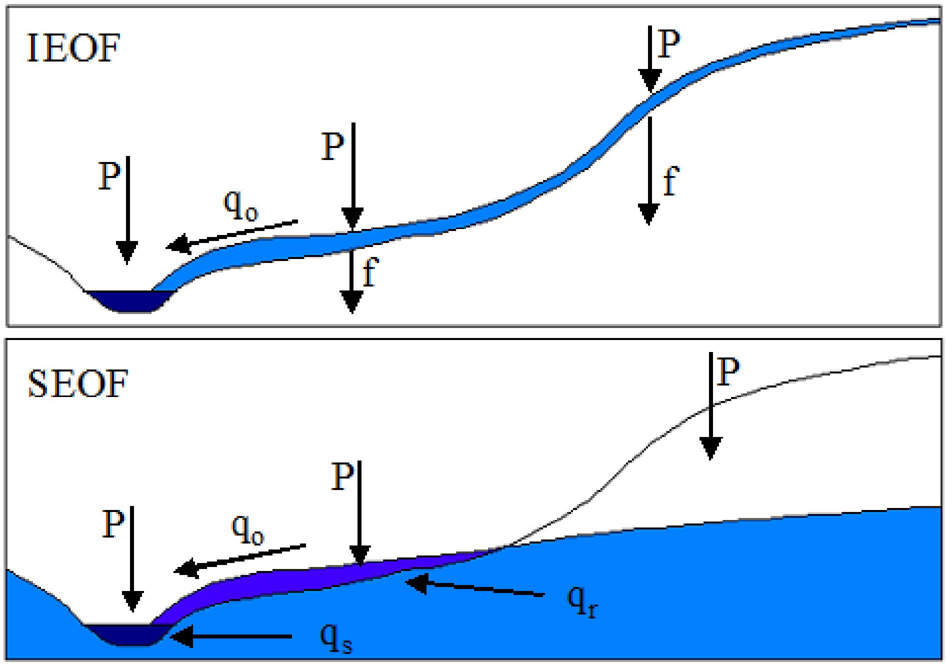

Fig. 2.3 Illustration of the IEOF and SEOF Runoff Generation Mechanisms (Beven, 2001)

2.1.5 Infiltration Process

Infiltration is the process of water entry into the soil through the soil surface. Infiltration capacity is the maximum rate at which water can infiltrate into a soil under a given set of conditions. Infiltration rate is the rate at which water penetrates the surface of the soil (Ward and Robinson, 1990).

The infiltration process plays an important role in determining the water balance by partitioning rainfall between soil water gain and overland flow (Cerda, 1997). The relationship between rainfall intensity and duration with the infiltration capacity determines the amount of surface runoff, subsurface runoff, groundwater recharge and soil moisture (Cerda, 1996).

Infiltration rates are affected by soil texture and structure, macroporosity and permeability, soil bulk density and compaction, vegetation cover and land management, raindrop impact and surface crusting, chemical effects controlling disaggregation and clay dispersion, drought and fire, stone cover, the pattern of rainfall intensities at the soil surface in time and space, slope, landscape position and topography (Beven, 2002). The infiltration rate decreases rapidly over the storm time as a result of pore saturation by water or clogging by sediment, crust formation and swelling of the clays (Romkens et al., 1990; Cerda, 1997; Beven, 2002).

Crust formation is the controlling factor for runoff generation in semi-arid catchments. The direct impact of raindrops on the surface is the cause of crust formation with a corresponding decrease in the infiltration rate (Seginer and Morin, 1970; Morin and Cluff, 1980). The susceptibility of crust formation is common in many arid and semi-arid regions, where soil surface is characterized by low organic matter, high silt contents and low aggregate stability

(Arshad and Mermut, 1988; Abu-Awwad, 1997; Akasheh and Abu-Awwad, 1997; Abu-Awwad and Shatanawi, 1997; Vandervaere et al., 1997; Smith et al., 1999).

In arid and semi-arid regions, there is an important constructive response between infiltration rates and vegetation cover where vegetation growth is controlled by water stress. Growth of vegetation will tend to protect the soil surface from rain splash and crust formation as well as improve the soil structure and porosity, thereby enhancing infiltration rates (Beven, 2002). Many studies, using both artificial and natural rainfall, have concluded that vegetation is a major control on runoff generation in arid and semi-arid areas (Yair and Lavee, 1985; Wilox et al., 1988; Lavee et al., 1991; Snelder and Bryan, 1995; Nicolau et al., 1996; Sole-Benet et al., 1997).

Stone cover may have both positive and negative impacts on infiltration rates (Brakensiek and Rawls, 1994). Stone fragments at the soil surface intercept rain-water and reduce the surface area available for infiltration (Abrahams and Parsons, 1991). On the other hand, stones will protect the surface from rain splash and crusting, with a tendency to increase infiltration rates (Poesen and Bunte, 1996).

2.1.6 Channel Transmission Losses

Transmission losses are one of the main features that separate ephemeral channels from perennial channels. Transmission losses are abstractions of water volume along the flow path in the channel bed. Especially in ephemeral channels, the amount of transmission losses can be very significant and a major part of the runoff volume does not reach the catchment outlet but is lost along its way through the channel (Butcher and Thornes, 1978; Shannon et al., 2002; Leistert, 2005).

Transmission losses are affected by a complex interaction of variables such as: (1) soil moisture characteristics of the channel sediments and bank material; (2) initial moisture distribution in the channel sediments; (3) physical structure of the channel materials, including the presence of a surface crust, cracks, and\or stratification; (4) depth of streamflow and its rate of change with time; (5) duration of streamflow; (6) surface area wetted by the flow; (7) sediment content of the flow; (8) channel erosion and deposition; (9) chemical composition of surface and subsurface water and channel sediments; and (10) temperature of surface and subsurface water (Freyberg, 1983).

Transmission losses are caused by different processes such as evaporation, artificial withdrawal, bank storage, depression storage and infiltration; however the infiltration into the channel bed is the major abstraction (Külls, 1994). Flooded overbank increases rapidly the rate of transmission losses. This is due to the other processes that take place like temporary storage in waterholes and evaporation as well the infiltration (Lange, 2005).

Generally, flood flows move down the channel network as a flood wave, moving over a bed that is either initially dry or has a small initial flow. Channel bed transmission losses, mainly infiltration, are an important factor in reducing the flood volume as the flood moves downstream (Wheater, 2002).

In arid and semi-arid regions where the alluvial fills of ephemeral channel beds are usually dry, they can absorb large volumes of water from runoff events (Sorman and Abdulrazzak, 1993). A fraction of the infiltrated water can percolate through the unsaturated zone and recharge aquifers when the channels are hydraulically connected to deeper aquifers (Shentsis et al., 2001). The remaining fraction (interception and soil moisture) evaporates back into the atmosphere, leaving space that can be refilled from subsequent runoff events (Ben-Zvi and Shentsis, 2001). The Namibian experience (Wheeler et al., 1987) suggests that managing transmission losses to alluvial material can be used as an effective alternative water resource development strategy to conventional surface water storage, which is subject to large evaporative losses.

Transmission losses may possibly fluctuate during a flood event in ephemeral channels. This is because various modifying processes (e.g. air entrapment, scour and fill) are active and take place. The process of scour and fill plays an important role in ephemeral channels. Silt carried by flood waters can effectively seal the alluvial surface during flood events even at relatively high flow velocities (Crerar et al., 1988). Another process which reduces infiltration rate under ponded conditions is the entrapment of air. When the air cannot escape ahead of the infiltrating water, or even when it can, air movement offers an appreciable resistance to downward water flow at high soil water contents near saturation (Morel-Seytoux and Bilica, 1985).

Depending on the flood volume the transmission losses behave very differently from event to event. Sorman and Abdulrazzak (1997) note that transmission losses were highly correlated to the inflow volume. The antecedent moisture content depends on the alluvial characteristics and the time between two rainstorm events. It influences the losses as it directly affects the infiltration rates (Serrano, 2001) and determines (together with the porosity and the geometry of the alluvial body) the total possible volume that the alluvium can absorb (Lado et al., 2004).

It can be concluded that the quantification of transmission losses are of great important in arid and semi-arid regions to assess the hydrographs accurately at the catchments outlet and to quantify the replenishment of groundwater aquifers.

2.2 Rainfall-Runoff Modeling

2.2.1 Introduction

A model is a simplified representation of a real world system, and consists of a set of simultaneous equations or a logical set of operations contained within a computer code. Models have parameters which are numerical measures of a property or characteristics that are constant under specified conditions (Wheater, 2002). A hydrological model is an approximation of the actual system; its inputs and outputs are measurable hydrologic variables and its structure is a set of equations linking the inputs and outputs (Chow et al., 1988).

Hydrologic models are concerned with the accurate prediction of the partitioning of water among the various components of the hydrological cycle (rainfall, interception, evaporation, infiltration, surface runoff, groundwater recharge and baseflow) and the links between them (Dooge, 1992). The components and the links of the hydrological cycle are represented by mathematical functions that are built into a model by using computer-programming languages. The models are built to simulate catchment conditions, to generate long-term data and to enhance further understanding of the hydrological behavior of catchments. They are further used for assessment of the impacts of various changes and activities within the catchment (Savadamuthu, 2004).

Hydrological modeling requires a clear understanding of the hydrological cycle at catchment scale. The catchment hydrological cycle involves many processes. Several hydrologists investigated this cycle by a number of studies. A summary of the hydrological cycle is given by Chow et al (1988).

Catchment models are essential to water resources assessment, development and management. They are used for several practical purposes; to analyze the quantity and quality of streamflow, reservoir system operations, groundwater development and protection, surface water and groundwater conjunctive use management, water distribution systems, water use and a variety of water resources management activities (Wurbs, 1998). Furthermore, catchment models are to be used to inspect a flood disaster; during the flood event a model may help to predict when and where there is a risk of flooding. After the flood, models may be used to quantify the risk that a flood of similar or larger magnitude will occur during the coming years and to decide what measures of flood protection may be needed for the future (Lundin et al., 1998). Selecting of the model should be adapted to achieve the purpose for which the model is to be used. The simplest model capable of producing information adequate to deal with the scope of issues should be selected (Viessman et al., 2003).

Runoff generation processes in arid and semi-arid regions described in the previous section are not straightforward to quantify because most hydrological systems are extremely complex. Pilgrim et al. (1988) reviewed the problem of rainfall-runoff in arid and semi-arid regions, in the light of experience in humid regions, and summed up the difference and difficulties briefly. They noted that in particular that the whole nature of the vegetation and hydrology in semi-arid regions can change as a result of a prolonged wet and dry spell; the variability of rainfall in time and space; the importance of channel transmission losses and the complex controls on the soil surface properties that affect infiltration rates. A major conclusion of this review was that there is a lack of data for catchment responses in arid and semi-arid regions that could be used for the calibration and evaluation of modeling approaches. Therefore seeking to find a conception of the processes instead of comprehending them in all details is the goal. Rainfall-runoff modeling is a tool for this purpose. The rainfall-runoff model is a hydrological model that determines the runoff signal that leaves the catchment from the rainfall signal received by this catchment.

The tasks for which rainfall-runoff models are used are varied, and the scale of applications ranges from small catchments, of the order of a few hectares, to that of global models. Typical tasks for hydrological simulation models include (Wheater, 2002):

1. Modeling existing catchments for which input-output data exist, e.g. extension of data series for flood design of water resource evaluation, operational flood forecasting or water resource management;
2. Runoff estimation on ungauged catchments;
3. Prediction of effects of catchment change e.g. land use change, climate change;
4. Coupled hydrology and geochemistry e.g. nutrients, acid rain; and
5. Coupled hydrology and meteorology e.g. global climate models.

The rapid development of technology has promoted the creation of mathematical models based neither on adequate theory nor on adequate data. Therefore a hydrological model should be considered as a mathematical tool for hydrological science. This tool should be based on sound data and should include the dominant hydrological processes of the catchment it is applied to (Lange, 1999).

2.2.2 Classification, Selection and Application of Rainfall-Runoff Models

A general classification of hydrological models can be useful for giving an indication of model structure or complexity. The modeling literature is replete with different ways of classifying hydrological models. Chow et al. (1988), Todini (1988) and Refsgaard (1996) present an excellent description of model types and basic definitions relevant to modeling. Singh (1995) discusses classifications in terms of how processes are represented, what time and space scales are used and what methods of solution to equations are used. **Fig. 2.4** provides a general overview of the hydrological models using the classification criteria randomness, spatial discretization and model structure.

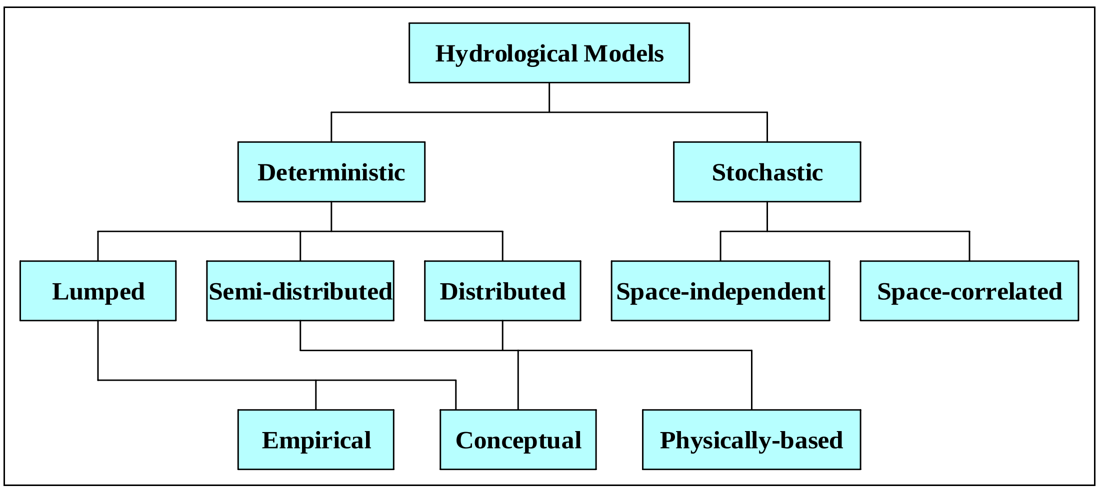

Fig. 2.4 Classification of Hydrological Models (Chow et al., 1988, modified)

The first question in classification is whether any attempt is made to represent the basic processes. Empirical "black-box" models are simply calibrating a relationship between inputs and outputs. They are based on input-output relationships without any attempt to describe the behavior caused by individual processes. Empirical models do not explicitly consider the governing physical laws of the processes involved. They only relate input through some empirical transformed function. The next step in complexity is conceptual-empirical models where, in the case of catchment modeling, the basic processes such as interception, infiltration, evaporation, surface and subsurface runoff etc. are separated to some extent. However, the equations that are used to describe the processes are essentially calibrated input-output relationships, formulated to take off the functional behavior of the process in question (Series on Model Choice, 2006). As the mission for deeper understanding of hydrological processes has progressed, models based on the fundamental physics and governing equations of water flow over and through soil and vegetation have been developed. These are often called physically-based or process-based models. They are intended to minimize the need for calibration by using relationships in which the parameters are, in principle, measurable physical quantities. In practice these parameters can be difficult to measure so these models are best thought of as complex conceptual models (Beven, 1989). Physically-based models reproduce the rainfall-runoff process only by physical principals on the conservation of mass and momentum (Chow et al., 1988).

Another basic distinction between models is whether stochastic or deterministic representations and inputs are to be used. In the stochastic models, the chance of occurrence of the variable is considered thus introducing the concept of probability. In the deterministic models, the chance of occurrence of the variables involved is ignored and the model is considered to follow a definite law of certainty but not any law of probability (Raghunath, 1985).

In stochastic models, some or all of the inputs and parameters are represented by statistical distributions, rather than single values. A range of values is defined instead of a single value. There is then a range of output sets, each derived from different combinations of the inputs and parameters and/or each of them associated with a certain probability of occurrence. Stochastic modeling generally requires the model to be run many times, each with different combinations of parameters or model inputs that are, perhaps, resulting in many outputs that can be analyzed to define a probability distribution of outputs. Stochastic modeling can be very useful, particularly when we are uncertain about the exact values of model parameters or model inputs, but running a model many times can be time consuming (Series on Model Choice, 2006). Stochastic models are termed space-independent or space-correlated according to whether or not random variables at different points in space influence each other (Chow et al., 1988).

In a deterministic model, randomness is not considered. This means that a single set of input values and a single parameter set are used to generate a single set of outputs; a given input rainfall always produces the same output runoff (Chow et al., 1988). In terms of spatial domains in catchment modeling, deterministic models can be classified as lumped, distributed or semi-distributed ones. The lumped model ignores spatial distribution of the catchment characteristics; values are spatially averaged and a single value is used for the entire catchment. It may either be conceptual or empirical. Since hydrological processes generally are space dependent, spatial lumping always includes rough conceptualization. In contrast, a distributed model considers the hydrological process taking place at various points in space, in which parameters, inputs and outputs vary spatially. It captures the system by partitioning the catchment into a number of smaller units. It may either be physically-based or conceptually-based. A semi-distributed model is something in between the lumped and distributed models that means the catchment is partitioned but in a coarser unit as compared with distributed models. A semi-distributed model may adopt a lumped representation for individual sub-catchments.

Among the numerous hydrological models available within the research community, selecting the best hydrological model is a challenging issue for rainfall-runoff modelers. Many hydrological models are site specific; therefore it appears to be very difficult to select an appropriate model which could efficiently provide the answers to the all addressed questions. General guidelines for model selection have been presented by Singh (2004) and references quoted therein. The model selection problem was viewed by Baker and Carder (1976) as an interactive question-choice process. This process was quoted by Singh (2004) as follows:

1. **Ease of use:** skill required, ease of interpreting results, assumption required by model.

2. **Availability of data:** ability to use readily available data, ability to handle small and variable time increments, data accuracy and data resolution.
3. **Availability of models:** cost to operate in terms of computing time and hardware system.
4. **Application to management activities:** number of parameters predicted, sensitivity to change in management activities.
5. **Broad regional coverage:** ability of a model to operate in diverse hydrological areas, extrapolation of model.
6. **Accuracy of prediction:** ability to predict relative change and absolute effects needed to calibrate model, repeatability of model predictions, error between actual and predicted values for volumes.

In terms of selection the desired hydrological model according to its type, Lange (1999) proposed the following questions:

1. Is there a need to consider randomness?
2. Is there a need to consider spatial variations of model input or parameter?
3. To what extent do the governing physical laws have to be considered?

A general procedure for applying rainfall-runoff models was proposed by Refsgaard (1996) (**Fig. 2.5**). The purpose of the model application should be defined firstly by considering type and accuracy of the desired model output. Based on this purpose the user should establish a conceptual picture comprising the key hydrological processes in the catchment and corresponding limits of simplification and accuracy assumed to be acceptable at the hydrological model. This is followed by the selection of a suitable modeling system (computer codes and software packages for rainfall-runoff modeling). A model building has to be made from the modeling code in a catchment with collected field data, in case of no suitable modeling system solutions obtained. The next step is to define performance criteria that should be achieved in subsequent calibration and validation steps. Preliminary parameter values are manipulated, comparing model simulation with gauged streamflow data, during model calibration to reproduce catchment response within the range of accuracy specified in the performance criteria. Model application is possible if a gauging station exists in a catchment. Model validation implies that the model is applied to another period or a site not used for calibration without changing the calibrated model parameters. Then the model may be used for process studies and predictions. Finally, several years after the modeling study, a postaudit is possible to evaluate the model prediction in other catchments.

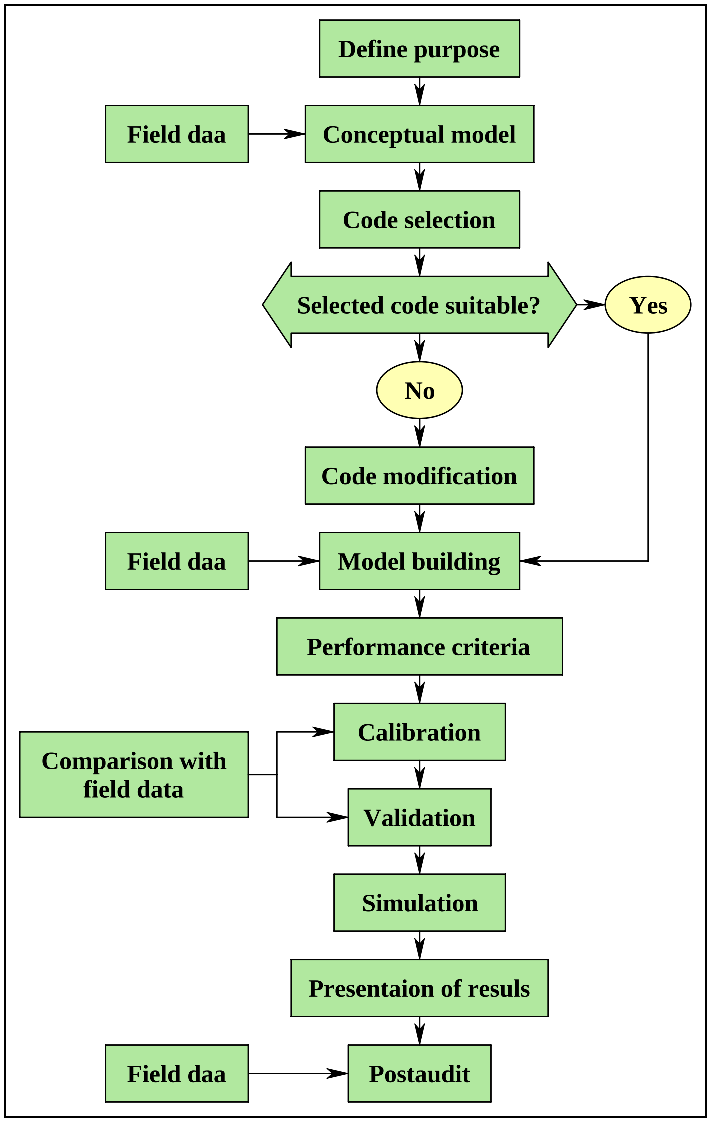

Fig. 2.5 **Schematic Modeling Protocol** (Refsgaard, 1996, modified)

2.2.3 Development of Rainfall-Runoff Models

In order to simulate the transformation from rainfall to runoff, rainfall-runoff models have been developed and reference is made to the work of Chow et al. (1988), Todini (1988) and Leavesley (1994) for historical reviews of rainfall-runoff modeling. Singh and Woolhiser (2002) reviewed more than 100 catchment models that have been used worldwide. With respect to development over the past decade, Beven (2001) wrote "It is now virtually impossible for any person to be aware of all the models that are reported in the literature" indicating that many efforts have been devoted to this issue.

The development and application of hydrological models have gone through a long time period. The origins of rainfall-runoff modeling in the broad sense can be found in the middle of the 19th century, when Thomas Mulvaney presented a paper which can be considered as the origin of the so-called rational method for flood peak estimation. A major step forward in hydrological analysis was the concept of the unit hydrograph introduced by Sherman in 1932 on the basis of superposition principle. The use of the unit hydrograph made it possible to calculate not only the flood peak discharge (as the rational method does) but also the whole hydrograph (the volume of surface runoff produced by the rainfall event). About the same time, Horton (1933) developed a theory of infiltration to estimate rainfall excess and improve hydrograph separation techniques. These two methods are the first basic rainfall-runoff models, as they introduced a rainfall-runoff transfer function. The real breakthrough came in the 1950s when hydrologists became aware of system engineering approaches used for the analysis of complex dynamic systems (Todini, 1988). This was the period when conceptual linear models originated; solutions of simplified differential equations yielded the shape of the rainfall-runoff transfer function describing the outflow of a single reservoir or a cascade of reservoirs (e.g. Nash, 1958). Many other approaches to rainfall-runoff modeling were considered in the 1960s.

A large number of conceptual rainfall-runoff models appeared thereafter including the famous Stanford Watershed Model-SWM (now HSPF), which is one of the first conceptual, hydrological models for continuous streamflow simulation which was developed to assess the increase of the capacity of one of the water supply reservoirs of Stanford University (Crawford and Linsley, 1966).

Increased computing power advanced development of conceptual rainfall-runoff models. Such models include the HBV model (Bergström and Forsman, 1973) in Sweden, the XIANJIANG model (Zhao et al., 1980) in China, the SATT-I model in Finland (Vakkilainen and Karvonen, 1982), the TANK model (see e.g. Franchini and Pacciani, 1991) in Japan, the MODHYDROLOG model (Chiew and McMahon, 1994) in Australia and the ARNO model in Italy (Todini, 1996). A great variety of these conceptual hydrological models has appeared up to the present date.

Advances in computing technology not only played a significant role in the development of conceptual rainfall-runoff models, they certainly also promoted emergence of physically-based distributed models. Physically-based distributed models tend to have a clearly formulated physical basis underlying their process descriptions which are based on physical laws that include a set of conservation equations of mass, momentum and energy to describe the real world physics that governs nature (Kokkonen, 2003). Well documented physically-based distributed rainfall-runoff models include the SHE model (Abbott et al., 1986a, b) developed as a joint European effort, the IHDM model (Rogers et al., 1985) in the United Kingdom, the DHSVM in the United States (Wigmosta et al., 1994), the model of Kuchment et al. (2000) in Russia, the THALES model (Grayson et al., 1992) in Australia and the REW model (Reggiani and Rientjes, 2005; Reggiani, and Schellekens, 2005) in Belgium.

Computational difficulty, along with the difficulties of measuring hydrological variables and parameters in the field, has compelled the introduction of the semi-distributed modeling schemes. TOPMODEL which was developed in the late 1970s (Beven and Kirkby, 1979) is one of the most cited of such semi-distributed models. The model is based on the idea that topography applies a dominant control on flow routing through upland catchments. The TOPMODEL has received a substantial amount of attention in the form of model applications (e.g. Durand et al., 1992; Ambroise et al., 1996; Holko and Lepistö, 1997; Coles et al., 1997).

Geomorphological Instantaneous Unit Hydrograph (GIUH) which was introduced by Rodriguez-Iturbe and Valdes (1979) is a semi-distributed rainfall-runoff model used for the simulation of runoff hydrograph, especially for ungauged catchments. During the last two decades, several hydrologist focused on the development and applications of the GIUH model (e.g. Gupta et al., 1980; Rodriguez-Iturbe et al., 1982; Kirshen and Bras, 1983; Karlinger and Troutman, 1985; Agnese et al., 1988; Chutha and Dooge, 1990; Lee and Yen, 1997; Yen and Lee, 1997; Berod et al., 1999; Brooks and McDonnell, 2000, Hall, 2001; Lee and Chang, 2005).

2.2.4 Rainfall-Runoff Models for Arid and Semi-arid Regions

Rainfall-runoff models have been widely used over 40 years for a variety of purposes, but almost all modeling tools have been primarily developed for humid area applications. Arid and semi-arid areas have particular challenges that have received little attention (Wheater, 2002). Lange (1999) reviewed the rainfall-runoff models for drylands. While the application of different hydrological models that have been developed specifically for arid and semi-arid regions of South Africa have been reviewed by Hughes (2005). A number of rainfall-runoff models of arid and semi-arid catchments appear in the body of literatures particularly in USA, Africa, Australia, India, Saudi Arabia and Israel (Historical Palestine) are presented herein.

In the semi-arid experimental catchment of Walnut Gulch, Arizona, USA, the long history of research provides good runoff records, which facilitated the successful application of calibrated models (Renard et al., 1993 and Goodrich et al., 1997). KINEROS model (Smith et al., 1995); a complex non-calibrated distributed model developed for semi-arid catchments was applied and calibrated in Walnut Gulch. The Walnut Gulch has received a great amount of interest from several hydrologists, like (e.g. Lane, 1982; Grayson et al., 1992; Scoging et al., 1992; Karnieli et al., 1994; Michaud and Sorooshin, 1994; Wheater et al., 1997; Hernandez et al., 2000). In general several studies have been focused on the hydrology of ephemeral streams of southwest USA (e.g. Drissel and Osborn, 1968; Renard and Laursen, 1975; Burkham, 1976; Graf, 1983).

Few studies of rainfall-runoff modeling have been focused semi-arid regions of Africa. The Pitman monthly time-step model, developed in the 1970s (Pitman, 1973) has undergone a number of revisions since then. The model is an explicit soil moisture accounting model representing interception, soil moisture and groundwater storages, with model functions to represent the inflows and outflows from these. This model has been more widely applied within the southern African region than any other hydrological model (Wilk and Hughes, 2002). The NAMROM model developed and designed specifically for use in Namibian basins (de Bruine et al., 1993; Mostert et al., 1993) and therefore includes components to simulate processes that were identified as important in this arid region. The model has been applied with a reasonable degree of success to a number of basins in Namibia, it has not been applied elsewhere and therefore its general applicability is largely untested (Hughes, 2005). The ACRU model, developed by the Bioresources and Environmental Engineering Hydrology School of the University of KwaZulu-Natal (Schulze, 1994), is a daily time-step model designed around a multi-layer soil moisture accounting scheme and has a large number of parameters that require quantification. It is designed to be used in ungauged basins on the basis of parameters evaluated through default relationships with measurable catchment properties (soils, vegetation, management practices, etc.) (Schulze, 2000). Very little documentation of the success of its application in arid and semi-arid basins was found (Hughes, 2005). The Variable Time Interval (VTI) model was developed at the IWR, Rhodes University as part of a detailed study of the catchment response characteristics of a medium sized semi-arid basin (670 km^2) in the Eastern Cape Province of South Africa (Hughes and Sami, 1994). It has subsequently been applied to a wide range of basins in South Africa with poor to moderate output results.

Kotwicki (1987) applied the conceptual lumped rainfall-runoff model RORB3, developed by Laurenson and Mein (1983), to the 450,000 km^2 arid Lake Eyre catchment in Australia. Because of short streamflow records available for calibration only rough estimates about past inflows into the lake were possible. The flow behavior and transmission losses in a small flow event in an Australian desert stream were studied by Dunkerley and Brown (1999). Coles et al. (1997) used the TOPMODEL on modeling experiments for a number of small experimental agricultural catchments in the eastern wheatbelt of Western Australia (0.14-0.41 km^2). Their study was focused on the effect of conversion of land to agriculture on rising of the water table and consequently an increase in the SEOF. Zhua et al. (1999) modified TOPOG model, developed in Australia, by adding model representations of some of the predominant features and processes on a semi-arid agricultural catchment in the Loess Plateau of China. The modified model enabled the simulation of both slowly changing hydrologic states during interstorm periods and fast-responding overland and tunnel flows during stormflow periods. Considerable variability in simulation accuracy was found among storm events and within the catchment.

Sharma and Muthy (1996) studied the ephemeral flow modeling in arid regions of India. Sharma et al. (1996) incorporated remotely-sensed data into a GIS-based rainfall-runoff model for a small arid catchment in India. In 1998, Sharma and Muthy, developed a package of simulation models to predict flow hydrographs in the arid zones of India. Seventy-nine gauged hydrographs enabled model applications to nine different study catchments.

The GIUH model introduced by Rodriguez-Iturbe and Valdes (1979) has been used by Allam (1990), Nouh (1990) and Al-Turbak (1996) to develop unit hydrograph for several catchments in the Kingdom of Saudi Arabia. Shadeed (2005) used the GIUH model to develop the unit hydrograph for 320 km^2 of the semi-arid Faria catchment in Palestine. Two rainfall events were simulated and compared with the recorded discharges, and reasonable matching was obtained.

Abdulla et al. (2002) developed and applied a single event watershed model for simulating runoff hydrograph in the western Iraqi desert region. The single event watershed model is based on the water balance equation. The inputs to the model are rainfall, evaporation, and soil properties data. The available rainfall and runoff data in focused region has been used in calibrating and testing the model. The results of the simulated runoff hydrograph are in good agreement with observed data.

A lumped parameter model was developed by Shanan and Schick (1980) for runoff plots and a 3.45 km^2 catchment in the arid northern Negev (Naqab) desert in Israel (Historical Palestine). More than 60 events were used for calibration which enabled a successful simulation of daily runoff values at the plot scale, whereas at the catchment scale the different effects of various factors could not be separated. Lavee (1986) simulated the runoff response of arid runoff plots by a complex distributed model with calibration. Since no channel processes were taken into account, model application was restricted to small intensity measured arid hillslopes. Lange (1999) has developed a model not depending on calibration but accounting for the dominant processes of arid zone flood generation. This has been done for the 1400 km^2 Zin catchment in the Negev (Naqab) desert of Israel (Historical Palestine). The ZIN-model is spatially distributed, concentrates on dominant processes of arid and semi-arid zone flood response and can be parameterized including only field-based parameters with rainfall radar as input. The model simulates only the two major processes, namely runoff generation on the terrain and transmission losses into dry channel alluvium. The model has been developed especially for large arid catchments and has been tested successfully in several sites; for 250 km² in the semi-arid Wadi Natuf of Palestine, (Lange et al., 2001), for 680 km² in the semi-arid Wadi Nahal of Israel (Historical Palestine), for 0.5 km^2 in arid Nahal Yael of Negev (Naqab) desert in Israel (Historical Palestine) (Thormählen, 2003), for 1220 km² in the arid Anas catchment of India (Singh, 2004), for 15000 km^2 in the arid Kuiseb catchment of Nambia desert in South Africa (Lange, 2005). Applications of the ZIN-model in the aforementioned case studies have proved that this model is appropriate to predict runoff generation in arid and semi-arid catchments. This situation has motivated the author of this research study to apply this model for a 320 km^2 of an arid to semi-arid Faria catchment in the West Bank, Palestine.

3 Research Project Setting

3.1 General Characteristics of the West Bank

The West Bank, Palestine is located in the Middle East, west of Jordan. It lies within the geographic coordinates 32°00′ N and 35°15′ E, measuring 130 km from north to south and 54 km from east to west (**Fig. 3.1**). It has a surface area of 5,640 km^2. The population of the West Bank is estimated at about 2.3 million, distributed into the eleven governorates. Hebron Governorate has the highest rate of population growth at 13.9% of the total population, while Jericho Governorate has the lowest rate of population growth at 1.1%. Annual population growth in the West Bank is estimated at 3.2%.

The West Bank has a varied topography with ground surface elevations between 1022 m above mean sea level in Tall Asur in Hebron and 410 m below mean sea level near Jericho (adjacent to the Dead Sea) (UNEP, 2003). The West Bank landscape can be divided into five main topographic zones; the semi-costal plain, western slopes, mountain plateau, eastern slopes and Jordan Rift Valley (**Fig. 3.2**). It is divided into four major geomorphologic parts: Nablus Mountains, Jerusalem Mountain, Hebron Mountains and the Jordan Valley. The mountains extend over the length of the central parts of the West Bank from Jenin in the north to Hebron in the south. The drainage and valley systems originate from the mountain range and extend either eastwards or westwards. The summits of these mountains delineate catchment lines and the water divide separating the western and the eastern basins in the West Bank coincide with the summits of these mountains. The Jordan Valley is part of a long and deep depression of the earth's crust, widely known as the Jordan Rift, running along the edge of the country separating it from Jordan. The Valley is characterized by an arid climate with hot summer and warm winters. However, this region would be desert-like without access to water (ARIJ, 2000).

The West Bank is mostly composed of limestone hills, brown lithosols and loessial arid brown soils cover the eastern slopes and grassland, with pockets of cultivation spreading over the steep slopes. Fertile soils are found in the plains. Soil cover is generally thin. Over all, about 12 percent of the land is desert, eroded or saline (UNEP, 2003).

The structural geology of the West Bank is dominated by a series of regional, parallel, southwest-northeast trending folds dissected by faults associated with the Jordan Rift Valley. The fault turns towards the northwest near Jericho. Some faults in West Bank act as conduits and some others represent barriers to groundwater flows.

Fig. 3.1 Regional Location Map of the West Bank (Google Earth)

3.1.1 Climate and Agro-climatic Zones

The West Bank climate may be broadly described as a Mediterranean type, but varies between hot dry in summer to wet cold in winter with short transitional seasons. Because of the wind, humidity, latitude and differences in altitude, there are considerable number of micro-climatic patterns. The area experiences extreme seasonal variations in climate. Large rainfall variations also occur from year to year. Consecutive years of relatively high or low annual rainfall have an enormous effect on the region and, in the case of dry years, present the greatest challenge to managing the region's precious water resources.

The rainy season usually begins in November and ends at the end of March. Rainfall is concentrated over a short period, with more than 60% of the annual rainfall commonly occurring in less than two months. Rain tends to fall in intense storms. This result in tremendous runoff during a few months and the country remains dry for almost the rest of the year. In general, rainfall is characterized by a high variation both temporary and spatially. In Nablus, for example, a minimum of less than 315 mm/season (1951/52) and a maximum of more than 1387 mm/season (1991/92) has been recorded, whereas the long term annual average is 642 mm. Rainfall decreases from north to south and from high to low altitude. The yearly rainfall is as low as 100 mm in the Jordan valley, located in the rain shadow of the mountain ridge, to as high as 700 mm in the semi coastal region. The rainfall distribution in the West Bank is shown in **Fig. 3.3**.

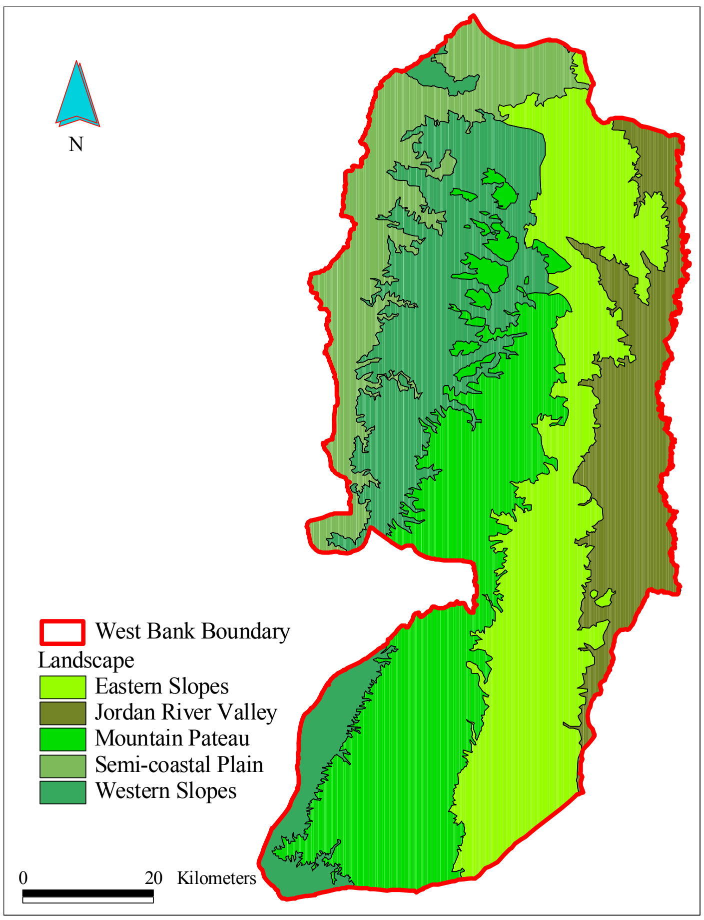

Fig. 3.2 The West Bank Landscape

The West Bank has been divided into 4 major agro-climatic zones based on rainfall, moisture index and crop growing period. This classification is based on the aridity index defined by UNESCO (1984), which is the ratio of mean annual precipitation (P mm) to Penman mean annual potential evapotranspiration (PET mm), where, hyper-arid (P/PET < 0.05); arid (0.05 ≤ P/ PET < 0.20); semi-arid (0.20 ≤ P/ PET < 0.50) and sub-humid (0.50 ≤ P/ PET < 0.65). Except for the Jordan Valley, the climate in the West Bank should more correctly be called semi-arid and even sub-humid. In the Jordan Valley climate is arid all year long and can be classified as desert climate. The West Bank agro-climatic zones distribution are illustrated in **Fig. 3.4**.

Maximum mean daily temperature in Jerusalem is 30°C in August and minimum mean daily temperature is 6°C in January. For the Dead Sea the corresponding figures are 39°C and 12°C. (EXACT, 1998). The annual average relative humidity is about 52 percent at Jericho. Evaporation is high in summer when there is always a water deficit. Winds prevail from the northwest but come from the southwest in winter. Land and sea breezes occur, and in late spring the hot dry Khamsin blows from the desert in the south.

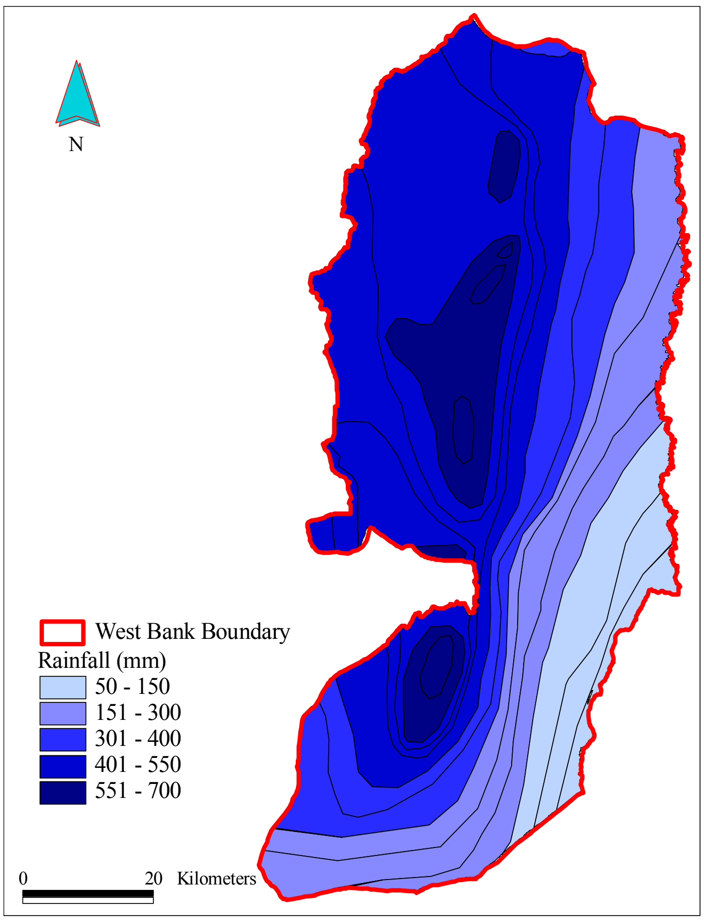

Fig. 3.3 The Rainfall Distribution in the West Bank

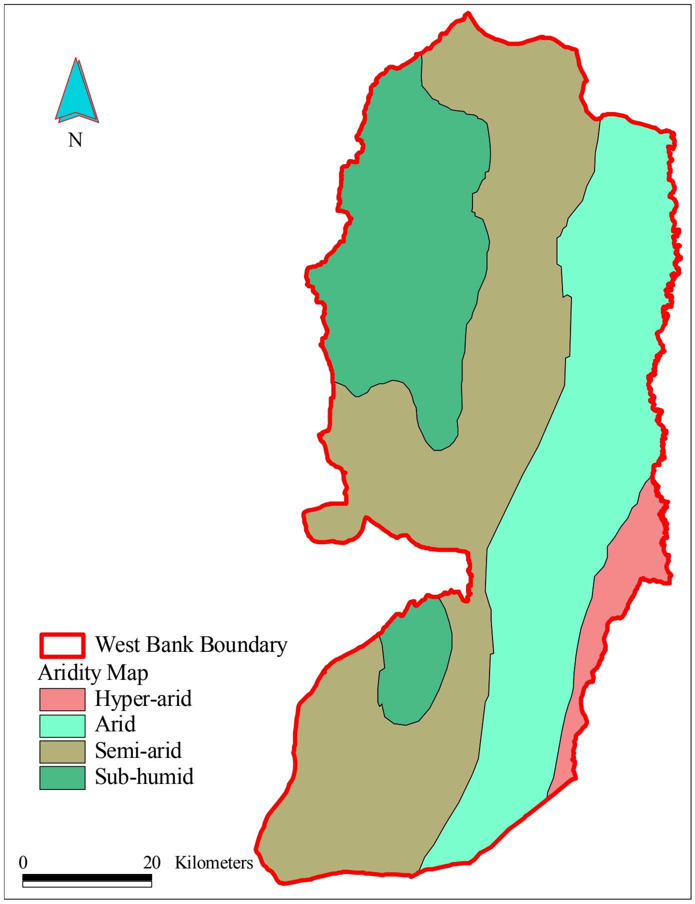

Fig. 3.4 Aridity Map of the West Bank

3.1.2 Water Resources Distribution and Drainage Basins

Contrary to its excellent groundwater potential, the West Bank is void of surface water. Surface runoff is relatively low and there are no permanent lakes. Unless Palestinians gain access to their only river, the Jordan River which is used by Jordanians and Israelis, they exclusively depend on groundwater wells. Springs and harvested rainwater are another two complementary water resources for Palestinians.

The West Bank lies over two main aquifers, the Mountain aquifer and the Coastal aquifer, which are shared with Israel. The Mountain aquifer system is divided into the Western aquifer basin (WAB), the Northeastern aquifer basin (NEAB), and the Eastern aquifer basin (EAB). The EAB and part of the NEAB flow east towards the Jordan River. The WAB, part of the NEAB and the Coastal aquifer all flow westerly towards the Mediterranean Sea (UNEP, 2003). Most of the aquifer rock formations are comprised of carbonate rocks mainly limestone, dolomite, chalk, marl and clay. The groundwater basins are recharged directly from rainfall on the outcropping geologic formations in the West Bank Mountains. Ninety percent of the recharge of the NEAB and the WAB takes place within the West Bank, where rainfall recharges about 145 MCM/year and 366 MCM/year on average for these two basins respectively. The EAB is even an autochthonous Palestinian basin, as it totally lies within the

West Bank territory, and this basin receives about 172 MCM/year from rainfall (EXACT, 1998). **Fig. 3.5** gives a picture of the groundwater aquifer basins in the West Bank.

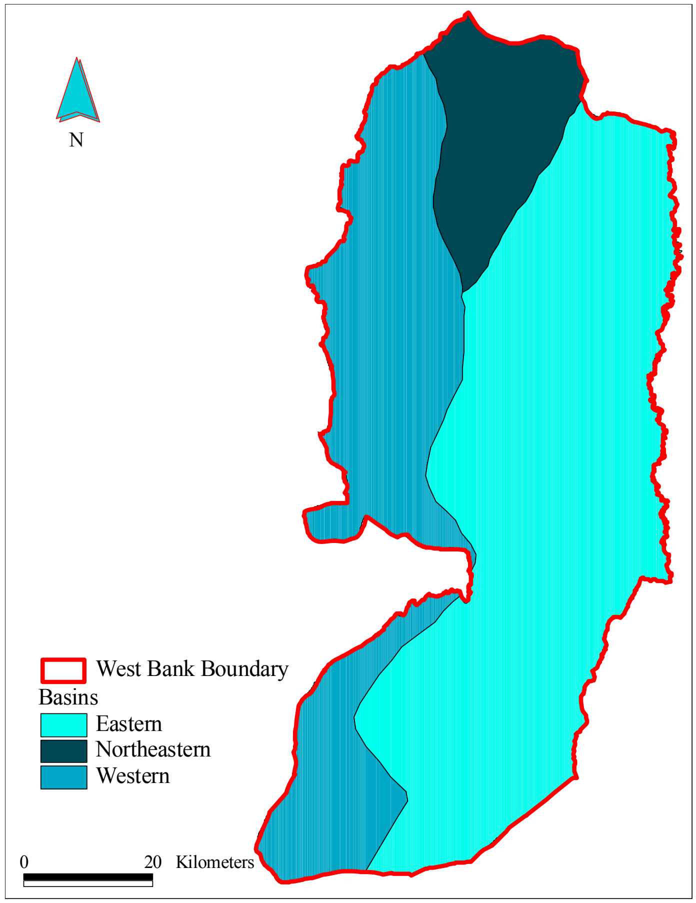

Fig. 3.5 The West Bank Groundwater Aquifer Basins

Surface flood runoff is mostly intermittent. Many studies showed that surface runoff in the eastern slopes of the West Bank probably occurs when rainfall exceeds 50 mm in one day or 70 mm in two consecutive days (e.g. Al-Nubani, 2000). In the West Bank catchments, surface runoff constituted nearly 2.2% of the total equivalent rainfall (Rofe and Raffety, 1965). There are thirty three main catchments in the West Bank (**Fig. 3.6**). A rough estimate of runoff using the rational method formula indicates that about 168.9 MCM per year were generated from these catchments, of which 122.8 MCM flows toward the Mediterranean Sea, 21.8 MCM toward the Dead Sea, and 24.3 MCM discharge into the Jordan River (PWA, 2003). This figure is right only in its approximate overall dimension but is far from being accurate, or even based on solid data, when it comes to specifics. This due to the fact that the IEOF is the dominant runoff generation mechanism in arid and semi-arid regions, so using simple empirical formulas like the rational method to estimate the amount of the runoff generation in the West Bank as arid to semi-arid region is not correct. This motivated the author of this research study to estimate the runoff generation in the Faria catchment, one of the West Bank catchments that contribute to the Jordan River basin, using an appropriate field-based rainfall-runoff model. Success of doing that will pave the way for the follow up research to have the proper tools to estimate the surface runoff in the West Bank catchments truthfully. This will help the decision-makers to incorporate the surface runoff in developing a comprehensive water management plane to save water for future expansion in the West Bank under the effect of climate changes.

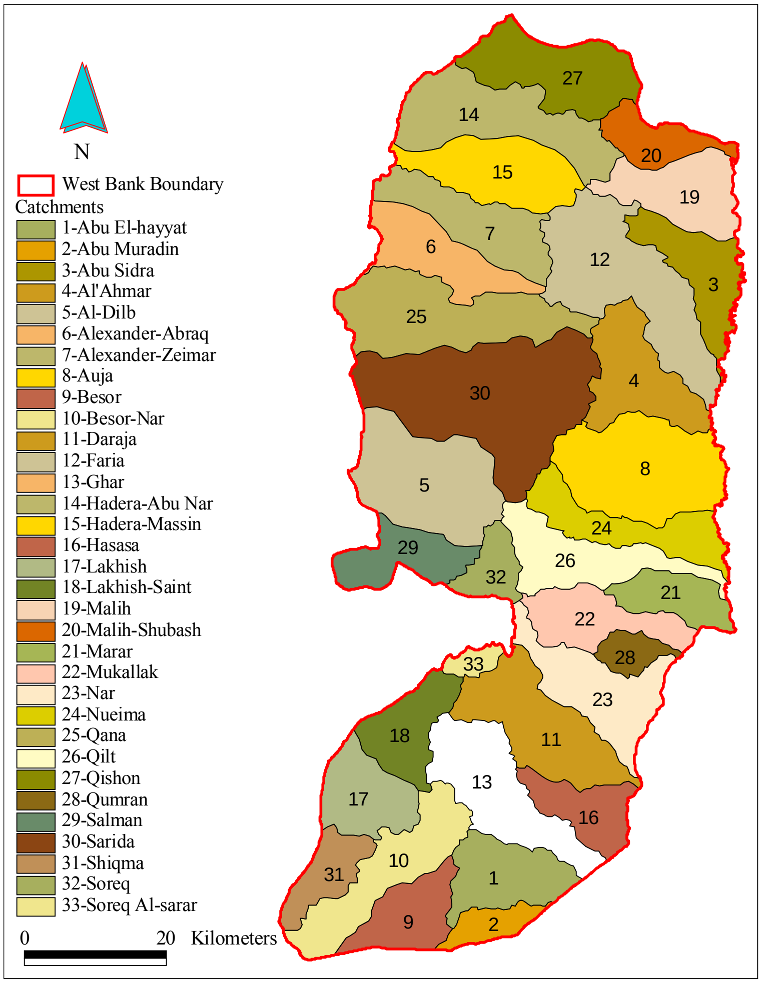

Fig. 3.6 The West Bank Catchments

3.2 Characteristics of Faria Catchment

3.2.1 Geography and Topography

Geographically, the Faria catchment is located in the northeastern part of the West Bank, Palestine with a total area of about 320 km^2 which accounts for about 6% of the total area of the West Bank. The catchment extends from the ridges of Nablus Mountains down the eastern slopes to the Jordan River as shown in **Fig. 3.7**.

Faria catchment overlies three districts of the West Bank. These are: Nablus, Tubas and Jericho district. The Faria catchment lies within the EAB.

Faria catchment is an important agricultural area which is considered as a food basket that provides the West Bank with the main agricultural products. This is because of the climatic variability, the availability of fresh water from the natural springs and wells and the high fertility of the soils. In addition to agriculture, the most common economic activity, there are a few small industrial and commercial activities in the Faria catchment. The upper part of catchment has a few recreational activities and touristic facilities.

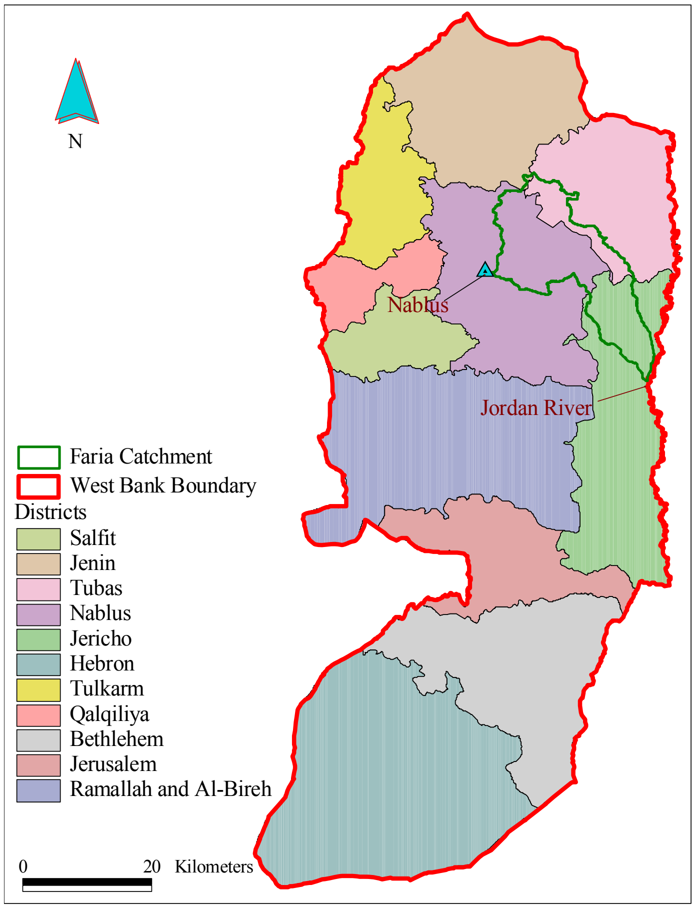

Fig. 3.7 General Location Map of the Faria Catchment

Topography is a unique feature of Faria catchment which starts at an elevation of about 920 meters above mean sea level in the western edge of the catchment in Nablus Mountains and descends drastically to about 385 meters below mean sea level in the east at the confluence with the Jordan River.

Topographic relief changes significantly throughout the catchment. In less than 30 km there is an average decline of 1.3 km in elevation. Such elevation decline rate in a relatively small distance has considerable effects on the prevailing meteorological conditions in the catchment. **Fig. 3.8** depicts the topographic map (DEM) of the Faria catchment.

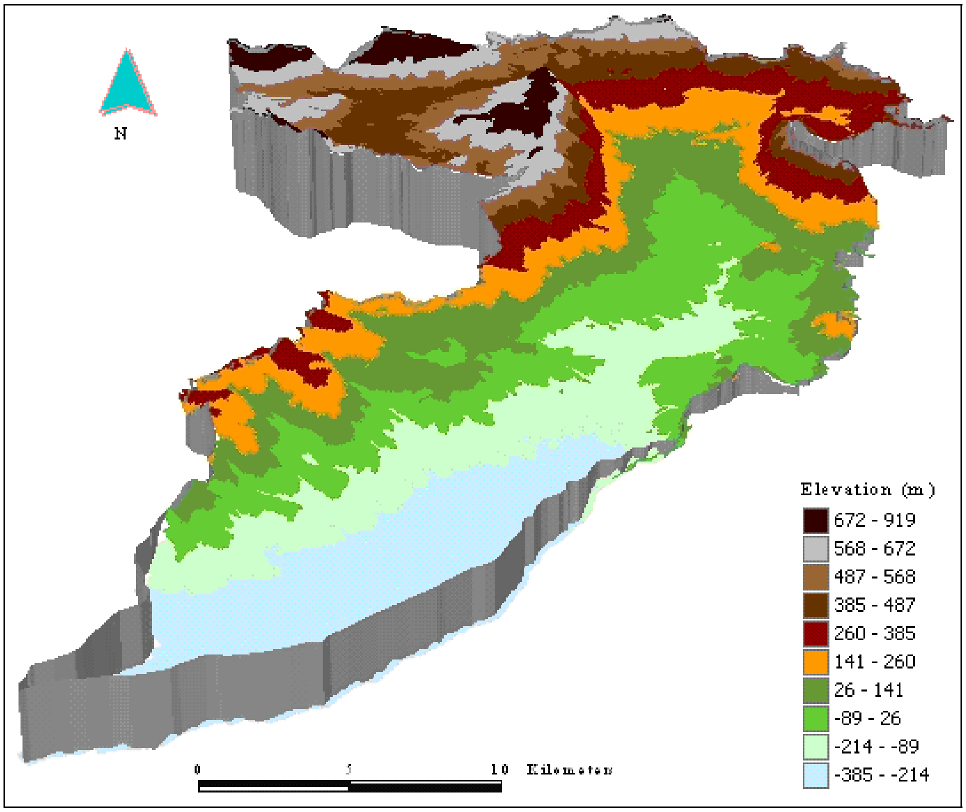

Fig. 3.8 Topographic Map of the Faria Catchment

3.2.2 Climate and Rainfall

The climate in the Faria catchment is dominantly a Mediterranean, semi-arid climate, characterized by mild rainy winters that last about six months and moderately dry and hot summers. Within a few kilometers, the area changes from a Mediterranean climate, ranging from a well marked six-month-long rainy season to an arid climate, where rainfall is limited to a couple of months. The climate is highly variable and influenced by both elevation and the circulation of the air-stream. The upper and western parts of the catchment are affected by moist, west-oriented air streams coming from the Mediterranean Sea. This air stream is responsible for most of the rainfall in the wet season and increases the relative air moisture in the dry season. Three climatic zones are characterized the climate of the Faria catchment (**Fig. 3.9**). Elevation is the main parameter that affects the climate zones. These zones have been described as follows (Birzeit University and Calvin College, 2003; EQA, 2004):

The upper zones: Slopes and mountain uplands that extend all over the western and northwestern parts of the catchment where the ground surface elevation ranges from 920 m above mean sea level to approximately 300 m above mean sea level are considered part of the upper zone. A typical Mediterranean climate prevails over this area. Two well defined wet and dry seasons are six months long each. Rainfall in this zone exceeds 400 mm which makes rainfed agriculture feasible for olives, almonds and field crops. Rainfall exceeds potential evaporation in about four to five months of the year.

The central zone: Eastern slopes that extend from about 300 m above mean sea level to about 50 m below mean sea level. The climate is semi-arid and the rainy season is shorter than the rainy season in the upper zone. Six months of the year are dry and nearly completely devoid of rain. Temperatures are higher in comparison to the upper zone. Rainfall ranges from 200 to 400 mm in this zone which makes rainfed agriculture feasible only in wet years. Rainfall exceeds evaporation during three months of the year on average.

The lower zone: Jordan River Valley extends as a narrow belt with ground surface elevations usually less than 50 meters below mean sea level. The climate in the lower zone is arid. Small amounts of rainfall are concentrated during winter. The summer months are dry with eight months that are completely devoid of rain. Rainfall in this zone is usually less than 200 mm and thus irrigation is essential to achieve agricultural production. Rainfall exceeds evaporation in less than two months of the year in this zone.

Two climatic stations are located within the boundary of the Faria catchment. One of the stations is Nablus meteorological station located in upper climatic zone in Nablus (570 m elevation) and the other is Al-Faria meteorological station located in Al-Jiftlik (-237 m elevation) in the lower climatic zone. Climatic data for these stations were obtained from the Palestinian Meteorological Office (MOT, 1998). The average values for the climatic conditions prevailing in the catchment area are presented in **Tab. A1** and **A2** of the annexes. From these data, it can be inferred that the mean annual temperature changes from 18^{o}C in the western side at the head of the catchment to 24^{o}C in the eastern side in the proximity to the Jordan River. Mean annual relative humidity changes from 61% in the western side of the catchment to 58% in the eastern side. The maximum potential rate of evapotranspiration ranges from 1400 mm/year in Nablus to about 1540 mm/year in the lower part of the catchment. The prevailing winds in the area are the southwest and northwest winds with an annual average wind speed varies from 2.2 m/s in Nablus, at a height of 2 meters from ground surface, to 1.3 m/s in Al-Jiftlik in the lower part of the catchment estimated at the same height from ground surface.

Regionally, the winter rainy season is from October to April in the upper zone, while in the central and lower zones, rainfall events usually occur between November and April. Rainfall events predominantly occur in autumn and winter to account for 90% of the total annual rainfall events. Rainfall measurements within the Faria catchment are highly variable because of the relationship with the topography. In all the three zones, June, July and August are completely devoid of rain.

The Faria catchment is gauged by six rainfall stations that record rainfalls. These stations are: Nablus, Taluza, Tammun, Tubas, Beit Dajan and Al-Faria. The Nablus station is a regular weather station in which most climatic data are measured. Monthly and annual rainfall data of this station is available for more than 55 years (from 1947-2006). Al-Faria station is located in Al-Jiftlik village in the lower part of the catchment and is still under Israeli control. Therefore, data available from this station is limited to only few years. The other four rainfall stations are located in the schools of Taluza, Tubas, Tammun and Beit Dajan. These stations are simple rain gauges which measure daily rainfall. Data from these stations cover also monthly and annual rainfall for 30 to 40 years. No rainfall intensity data are available in the catchment. This is due to lack of continuous measuring instruments for rainfall or other weather data. In August 2004, in the context of EXACT project, four Tipping Bucket Rain-gauges were installed in the schools of Taluza, Tubas, Tammun and Salim. EXACT project is a multilateral project implemented by the PWA and the UNESCO-IHE Institute for Water

Education, Delft, the Netherlands for the purpose of water resources development including water recharge in the Faria catchment. Data are available from these gauges since the rainy season 2004-2005 and up to date (see **Chapter 4**). Selected rainstorm events were chosen from these data and used as input to the coupled TRAIN-ZIN model as discussed in **Chapter 7**.

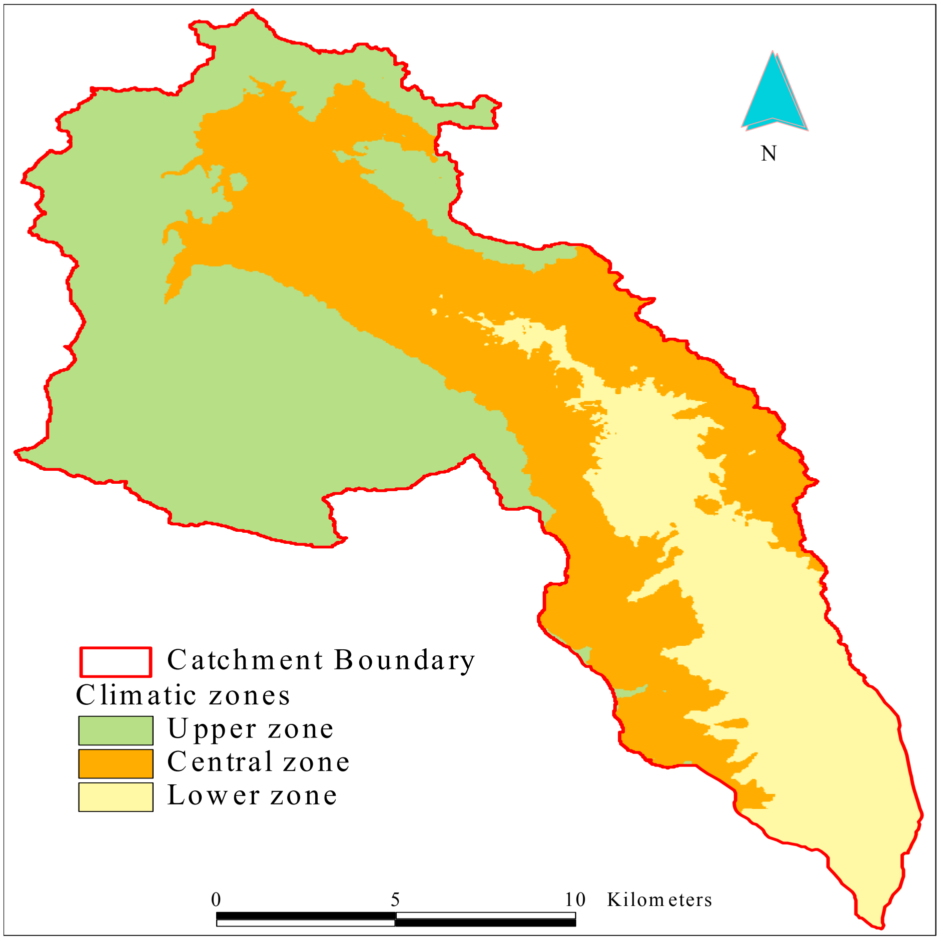

Fig. 3.9 The Climatic Zones of the Faria Catchment

Summary data of the six stations, their annual average (AVG), the standard deviation (STD), the maximum (MAX), the minimum (MIN) rainfalls recorded by these stations and range of data are as tabulated in **Tab. 3.1**.

The magnitude of rainfall in the Faria catchment varies with space and time. The rainfall distribution within the catchment ranges from 640 mm at the headwater to 150 mm at the outlet to the Jordan River (**Fig. 3.10**). In general, rainfall averages decrease from north to south and west to east. The annual rainfall variation for different year periods for various rainfall stations in the Faria catchment are given in **Fig. 3.11**.

Tab. 3.1 Summary of the Available Rainfall Stations within the Faria Catchment

Rainfall Station	Coordinates			AVG (mm)	STD	MAX (mm)	MIN (mm)	Type of Data		
	Y (km)	X (km)	Z (m)					Annual	Monthly	Daily
								Period		
Nablus	178	178	570	642.6	203.3	1387.6	315.5	1947-2006	1975-2006	1975-2006
Taluza	178	186	500	630.5	196.0	1303.1	292.2	1963-2004	1963-2004	1967-2004
Tubas	185	192	375	415.2	143.9	899.5	201.5	1967-2004	1979-2004	1979-2004
Beit Dajan	185	178	520	379.1	134.8	777.0	141.0	1952-2004	1963-2004	1967-2004
Tammun	187	188	340	322.3	106.4	616.1	124.2	1966-2004	1958-2004	1967-2004
Al- Faria	196	172	-237	198.6	83.0	424.0	30.0	1952-1989	1967-1989	1967-1989

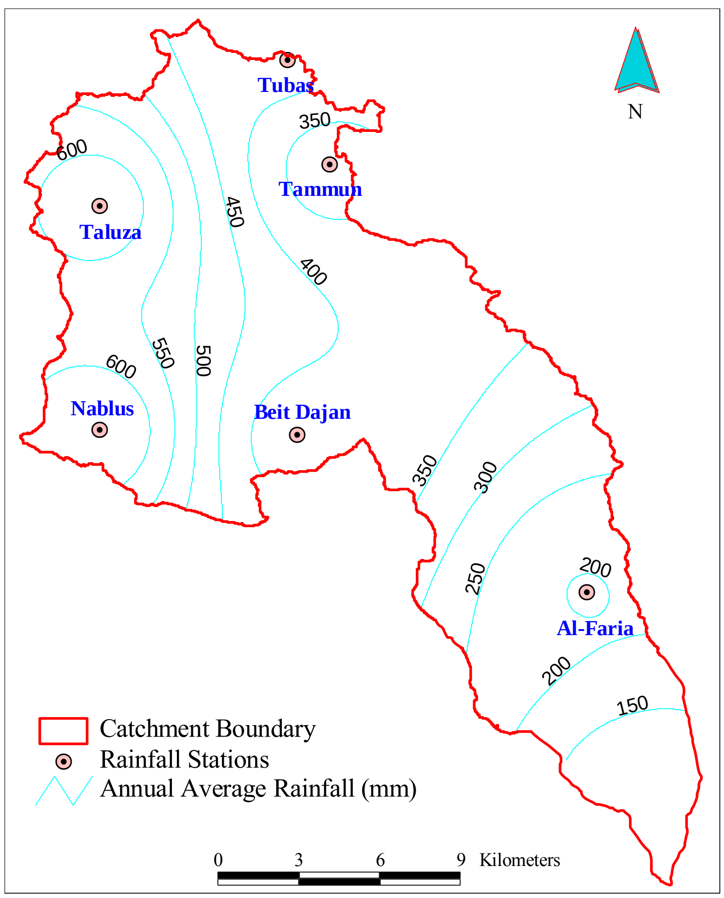

Fig. 3.10 Rainfall Stations and Rainfall Distribution within the Faria Catchment

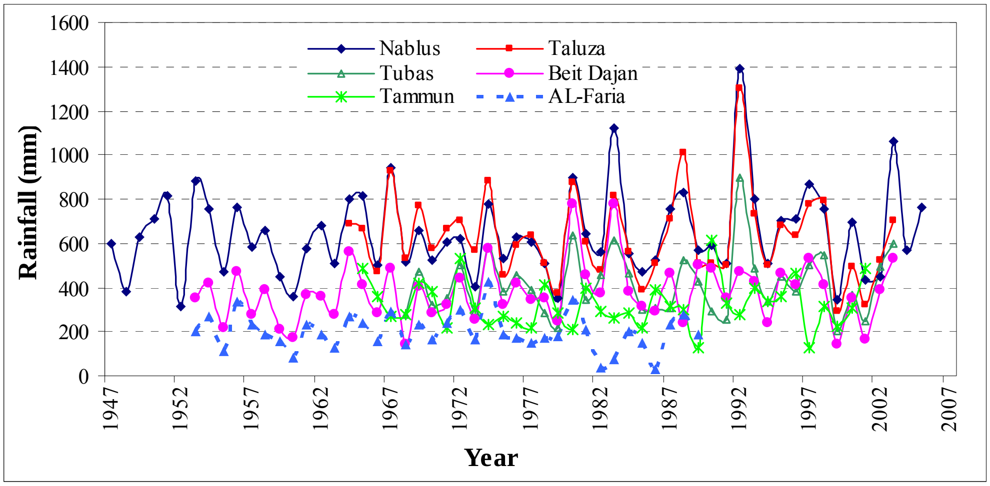

Fig. 3.11 Yearly Rainfall Variability for the 6 Stations in the Faria Catchment

The recurrence interval analysis of annual rainfall data for Nablus station during 1947-2006 for 60 years period has been carried out as shown in **Fig. 3.12**. It is expected that Nablus may receive at more 606 mm and 790 mm of annual rainfall with a return period of 2 and 5 years respectively. While the return period for 1100 mm is about 25 years.

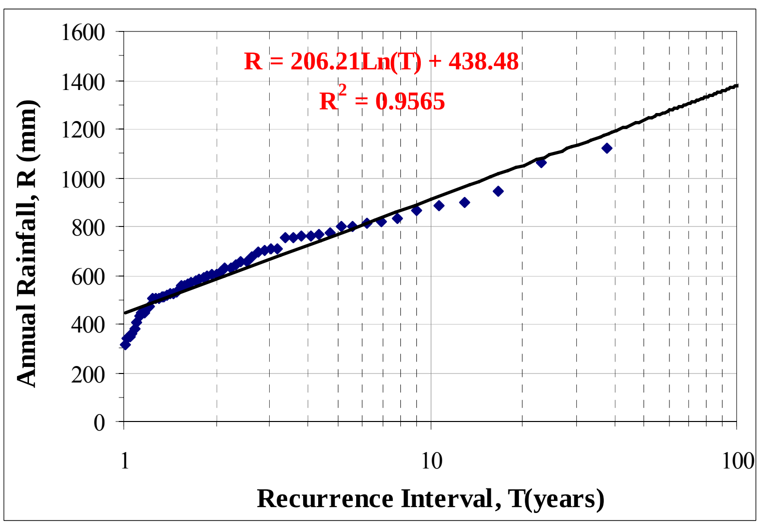

Fig. 3.12 Recurrence Intervals of Annual Rainfall of Nablus Station

3.2.3 Land use

The catchment area which has an area of about 320 km^2 includes Al-Faria Valley which is one of the major agricultural areas in the West Bank. The main economic activity in the area is agriculture. Using satellite images obtained from Google Earth, field work experiences and ground truthing, a new land use map of the Faria catchment has been developed as shown in **Fig. 3.13**. The developed land use map is classified into eight classes; bare rocks (2.8%), built-up areas (4.7%), natural forests (0.9%), olive plantations (6.4%), agricultural areas (22.1%), natural grassed hill slopes (28.3%), scattered olive plantations (8.2%) and sparsely vegetated hill slopes (26.6%).

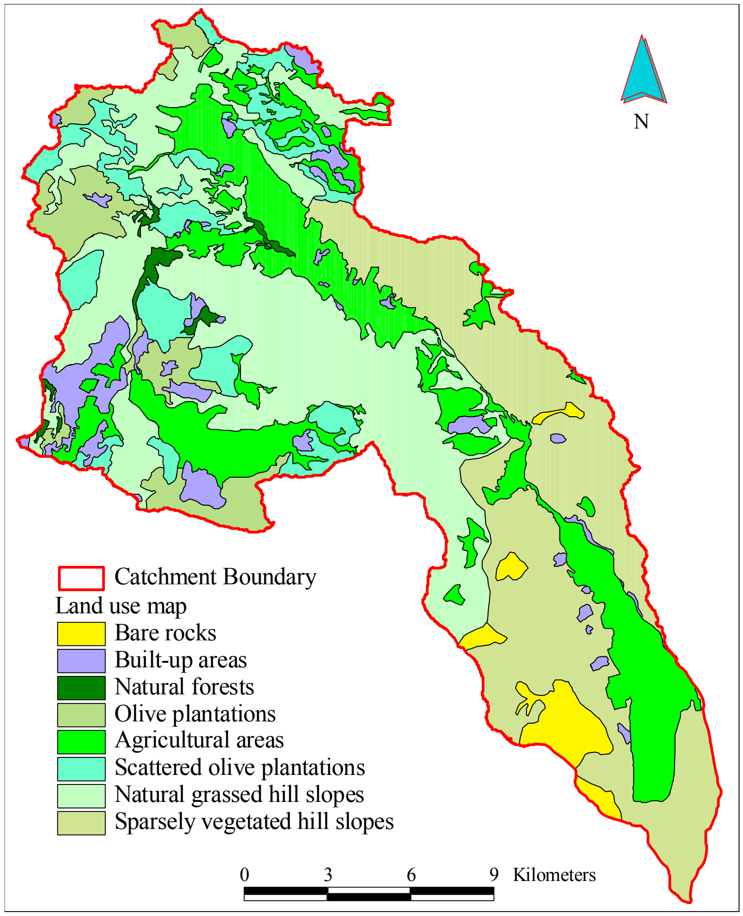

Fig. 3.13 The Developed Land Use Map of the Faria Catchment

3.2.4 Soil and Geology

Six soil types found in the Faria catchment. These are described as follows (EQA, 2004):

1. **Regosols:** The total area of this type of soil is 29.6 km^2. This soil type is found in the east steep eroded areas of the catchment (mostly in the lower parts of the catchment in Al-Jiftlik area). The parent materials for this soil type include sand, clay, loess and lisan marl. This soil type has a weak structure and crust formation on the surface that can be observed after the initiation of tiny rainfall events. The formation of crusts on the surface results in sealing it and preventing the entrance of water into the soil.

2. **Grumusols:** The total area of this type of soil is 46.5 km^2. Parent materials for these soils are alluvial and/or aeolian deposits in the upper areas of the catchment around Al-Faria stream. Heavy clay soil texture is dominant in this soil type with high shrink-swell potential.
3. **Loessial Seozems:** The total area of this type of soil is 19.7 km^2. Parent materials from which this soil type is created are mainly loessial sediments and highly calcareous sediments. This soil type has a sandy loam texture and the soil is calcareous on the surface and saline at the deeper layers due to restricted leaching. Organic matter and clay particles are absent from this soil type, therefore it has a weak structure. This type is found in the lower parts of the catchment.
4. **Brown Rendzianas and Pale Rendzinas:** The total area of this type of soil is 77.6 km^2. This soil type is concentrated in the mountainous areas mainly in the central parts of the catchment. This type of soil has numerous rock outcrops ranging from 20-50%. Soil depths vary from 0.5 meter in the mountains to 2 meters on the hilltops. Parent materials are mostly hard and soft chalk.
5. **Brown Litholsols and Loessial Arid Brown Soils:** The total area of this type of soil is 16.0 km^2. This soil type is concentrated on the hilltops and foot slopes of the lower parts of the catchment. The coverage of rock outcrops could reach 60% of the surface area in these soils. The texture of these soils is mainly loamy. The formation of hard crust on the surface due to the weak structure and the lack of adequate organic matter are the main restrictions for these soils.
6. **Terra Rossas, Brown Rendzianas and Pale Rendzinas:** The total area of this type of soil is 131.1 km^2. This type of soil is common in the highland parts of the catchment. The parent materials for this type of soil originated from mainly dolomite and hard limestone. Soil depth varies from 0.5 to 2 meters depending on the slope of the soil. The texture of these soils is clay to clay loam.

From the above it can be concluded that two basic soils cover most of the Faria catchment. These two types are terra rossas and brown rendzinas/pale rendzinas, taking up more than 65% of the total area. In addition, grumusols cover most of the northern part of the catchment, where as regosols, brown lithosols and loessial arid brown soils are concentrated mainly in the southern-most region of the catchment. A soil map of the Faria catchment is shown in **Fig. 3.14** (MOPIC, 1998).

Geologically, the Faria catchment is part of the larger regional Dead Sea Rift Zone which has formed a number of horsts and grabens which confine the drainage of Faria catchment surface water system. Faria catchment is a structurally complex system with the Faria Anticline that trends northeast to southwest acting as the primary controlling feature. Additionally, a series of smaller faults and joints perpendicular to this anticline have a significant effect on the surface water drainage area. A number of major faults and joints exist parallel to the Jordan Rift Valley as a result of previous tectonic activity. The dominant trends of the faults are east-west with several secondary fractures throughout the region. The tectonic activity was associated with the splitting of the Arabian and Great African plates known as the Red Sea rift zone. The Dead Sea and Jordan Valley is the result of a left lateral fault caused by secondary tectonic movement in the rift zone.

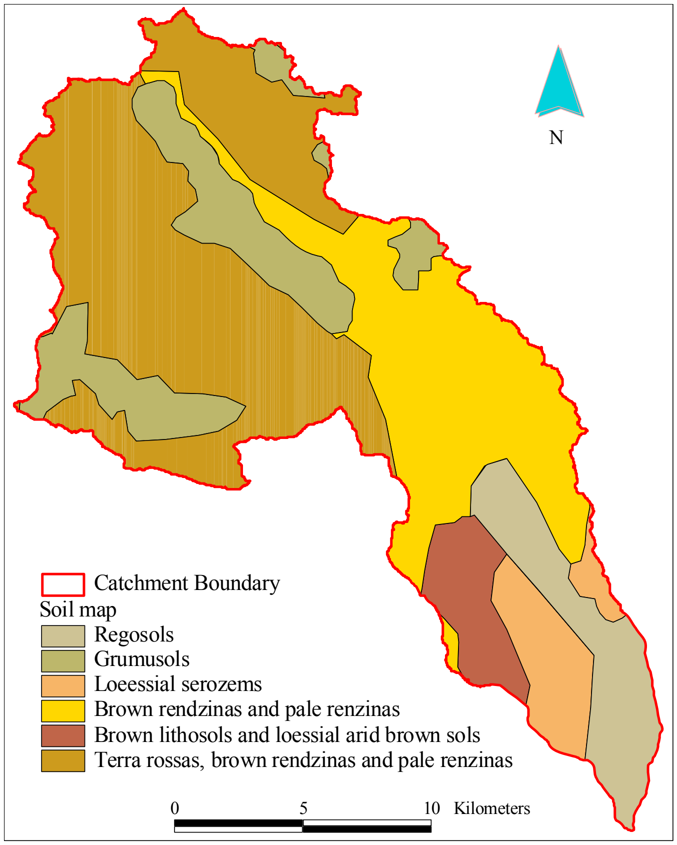

Fig. 3.14 Soil Map of the Faria Catchment

The dominant controlling geologic structure is the Faria Anticline-a graben structure in which the Faria catchment is located. Although the region is presently considered tectonically stable, the quantity of faults and folds is extremely large.

Many sedimentary formations can be found in Faria catchment. The most common formation in the northern part of the catchment is of Albian-Cenomanian age and consists of chert, chalk, dolomite, limestone, and marl. Alluvium of Quaternary age is found as the surface exposure around the village of Tubas. In the central part of the study area, the most common formations are of Cenomonian age and consist of limestone, dolomite, marl, chalk and chert. The southern part of the study area has a dominant exposure of limestone, marl and dolomite of Turonian age (Birzeit University and Calvin College, 2003).

The primary lithology in the region is characterized as various forms of limestone, chert, nummulitic limestone, dolomite, massive limestone and reef limestone. Some evaporates; particularly gypsum and marl are other common lithologies of the catchment. Lastly, it is noted that a series of volcanic layers were deposited during four major periods of folding and faulting in the Early Cretaceous.

The rocks vary in thickness; some of them are more than two meters and some of them are intermediate thickness of about 40-100 cm. The rock formations were deposited at the second time Mesozoic and mostly refer to the geological Era of Mesozoic. The rocks have a high intensity of fissures, because of the geological history that the area has faced. The faults and fissures reflect the geological conditions of the area which passed and affected the hydrology by a huge infiltration quantity and the appearance of many springs as Badan, Faria, and Miska (Ghanem, 1999). **Fig. 3.15** illustrates the geology map which shows the geologic formations prevailing in the Faria catchment (MOPIC, 1998).

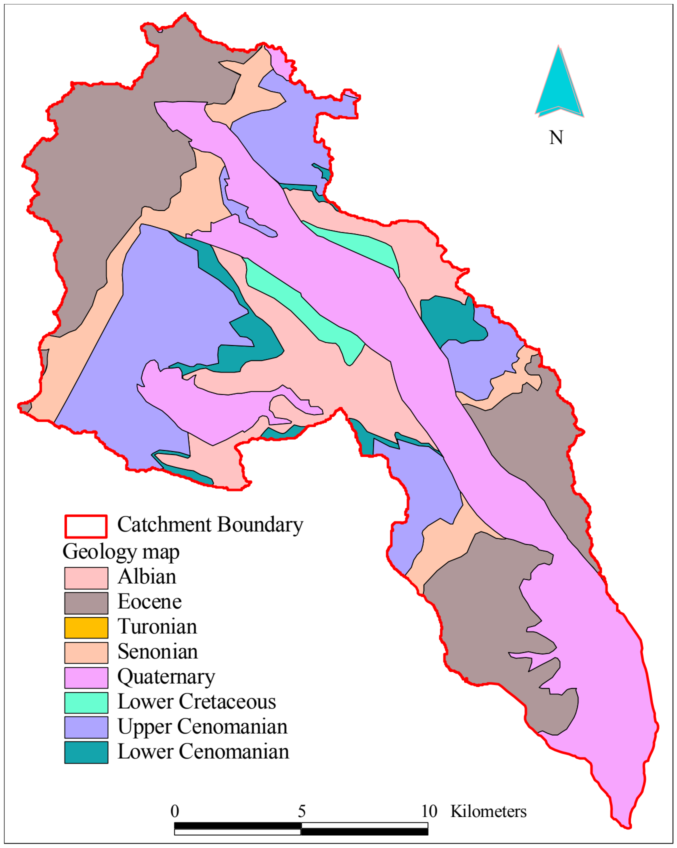

Fig. 3.15 Geology Map of the Faria Catchment

3.2.5 Water Resources

In the Faria catchment, water resources are either surface or groundwater. Most surface runoff in the catchment is usually lost in winter as there are no storage structures in the catchment to store that excess water. The groundwater aquifer system of the Faria catchment comprises several rock formations from the Triassic (Lower Cretaceous) to recent age. These formations are composed mainly of limestone, dolomite and marl. Groundwater aquifers are usually utilized through springs and wells. Most of the springs are located in the upper and middle parts of the catchment.

3.2.5.1 Groundwater Wells

There are 70 wells in the Faria catchment; of which 61 are agricultural, 4 are domestic and 5 are Israeli controlled wells. Based on the available data (**Tab. 3.2**), the total utilization of the

Palestinian wells ranges from 4.4 to 11.5 MCM/year. Water from irrigation wells is used in conjunction with spring discharge in most of the catchment. During wet years when the spring discharge is high, abstraction from wells reduces while pumping increases in dry years. Data on the pumping rates from the Israeli controlled wells are available for four wells for only four years from 1997-2000. The average total abstraction from these four wells was found to be about 8 MCM/year. Average well abstraction from Israeli controlled wells is about 2 MCM/year. Thus, considering the fifth Israeli controlled well without data available, the total abstraction from the 5 Israeli controlled wells in the Faria catchment is estimated at 10 MCM/year, which is more than the 61 Palestinian agricultural wells combined. **Tab. 3.2** presents the total annual abstraction from wells in the Faria catchment from 1977-2003.

Tab. 3.2 Annual Abstraction from Wells in Faria Catchment (MCM)

Year	Agricultural	Domestic	Total	Israeli
1977	5.4	*	5.4	*
1978	4.8	*	4.8	*
1979	5.0	*	5.0	*
1980	3.9	*	3.9	*
1981	4.4	*	4.4	*
1982	4.5	*	4.5	*
1983	4.3	*	4.3	*
1984	4.7	*	4.7	*
1985	5.7	*	5.7	*
1986	5.7	2.2	7.9	*
1987	7.0	2.3	9.2	*
1988	6.8	2.9	9.7	*
1989	6.6	3.3	9.9	*
1990	6.7	3.3	10.0	*
1991	6.3	3.0	9.3	*
1992	4.1	*	4.1	*
1993	5.0	*	5.0	*
1994	5.9	3.0	8.9	*
1995	6.4	3.1	9.5	*
1996	6.6	2.6	9.2	*
1997	5.8	2.8	8.6	6.7
1998	7.6	2.5	10.2	8.3
1999	8.2	3.3	11.5	8.4
2000	7.4	3.9	11.3	8.2
2001	6.1	2.5	8.6	*
2002	6.6	2.7	9.3	*
2003	5.1	2.8	7.9	*

* Missing data (source: PWA)

3.2.5.2 Springs

Springs are the only natural drainage outlets for groundwater in Faria catchment. Most of the springs are located in the upper and middle parts of the catchment. Within the Faria catchment 11 fresh water springs exist forming three groups: Faria, Badan, and Miska in addition to another two springs that are completely utilized by the city of Nablus. The basic data available on these springs include group name, spring name, coordinates, average annual discharge, minimum annual discharge and maximum annual discharge. **Tab. 3.3** presents a summary of these basic data. Discharge data of the springs show high spring discharge variability. Annual discharge from these springs varies from 3.8 to 38.3 MCM/year with an average amount of 14.4 MCM/year. The location of the springs and wells within the Faria catchment are shown in **Fig. 3.16**.

Tab. 3.3 Spring Groups and Spring Information within the Faria Catchment

Group	Spring Name	Coordinates			Ave. Annual Discharge MCM	Min. Annual Discharge MCM	Max. Annual Discharge MCM
		X (km)	Y (km)	Elevation (m)			
Faria	Faria	182.40	188.40	160	5.23	1.71	10.53
	Duleb	182.00	187.95	155	1.27	0.06	8.60
Badan	Asubian	180.52	184.56	130	0.19	0.14	0.23
	Beida & Hammad	180.12	185.32	215	0.81	0.10	1.75
	Sidreh	179.95	185.58	240	1.34	0.00	8.12
	Tabban	180.42	184.82	160	1.38	0.98	1.63
	Qudeira	180.13	185.28	215	1.33	0.00	2.33
	Jiser	180.37	185.10	170	0.14	0.03	0.23
Miska	Miska	187.03	182.90	-38	1.32	0.02	2.21
	Shibli	189.90	181.28	-80	0.95	0.71	1.15
	Abu Saleh	186.26	183.57	-19	0.19	0.00	0.50
Nablus	Balata	176.20	179.77	510	0.17	0.05	0.55
	Dafna	176.20	179.90	560	0.13	0.02	0.49
Total					14.44	3.81	38.31

(Source: PWA)

3.2.5.3 Surface Water

No detailed runoff data were available for Faria catchment. The only hydraulic structure which was constructed in the early 1970's for measuring surface runoff in the Faria catchment is located next to Ein Shibli in the lower central part of the catchment. This hydraulic structure is a wide crested weir which is used as a diversion structure to Al-Faria Irrigation Project. The structure has an upstream stage gauge which could be monitored to estimate runoff flows. However, the structure does not have an automatic recorder to register water stage continuously. Therefore, only a few sporadic measurements are available. These measurements are not sufficient to estimate the volume of annual runoff through the structure. In August 2003, An-Najah National University in coordination with GLOWA-JR project established two Parshall Flumes at the upper part the catchment to measure runoff rates from both Al-Badan and Al-Faria streams, which meet at Al-Malaqi Bridge, 10 km east of Nablus city. Detailed discussion of runoff measurements are presented in **Chapter 4**.

Surface runoff in the Faria catchment is considered high compared to other catchments in the West Bank. Within the catchment the runoff decreases from west to east with decreasing rainfall. The city of Nablus discharges untreated industrial and domestic wastewater effluents to Al-Badan stream while Al-Faria Refugee camp discharges untreated domestic wastewater to Al-Faria stream. Therefore, the streamflow of the Faria catchment is a mix of:

1. Runoff generated from winter storms. This includes urban runoff from the eastern side of the city of Nablus and other built up areas in the catchment.
2. Untreated wastewater of the eastern part of Nablus and of Al-Faria Refugee camp.
3. Fresh water from springs which provides the baseflow for the catchment main stream preventing it from drying up during hot summers.

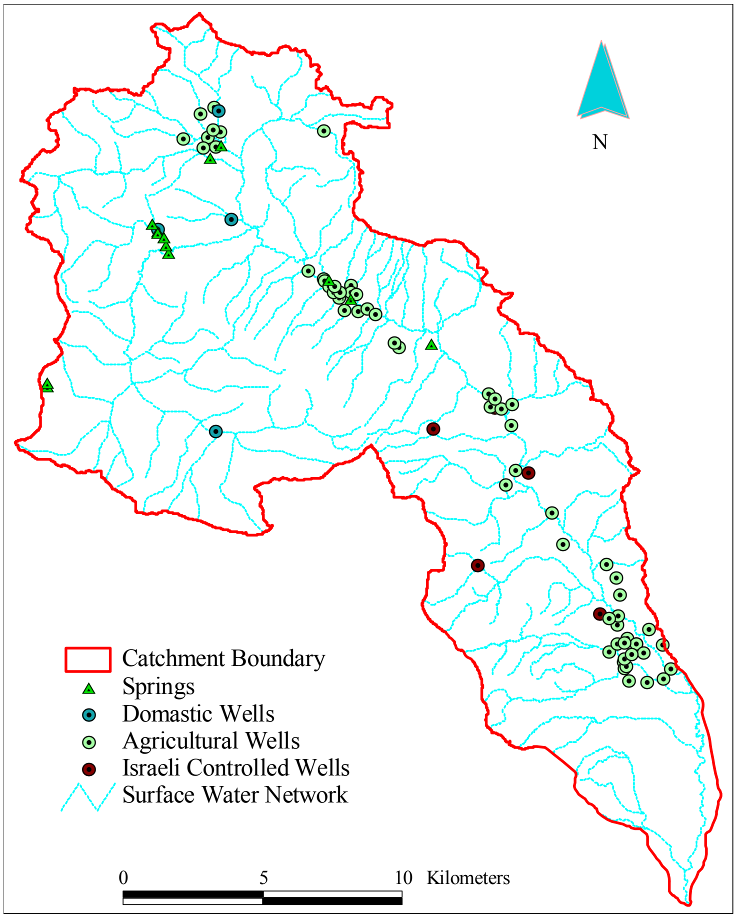

Fig. 3.16 Location Map for Springs and Wells in Faria Catchment

3.2.6 Water Demands

In the Faria catchment as well as the rest of the West Bank, data on total water demand are not available. Data available regarding demands is mostly consumption data.

Based on the existing population in the area and assuming a consumption rate of 70 litter/capita/day with 30% losses and unaccounted for water, the annual domestic water demands are estimated at about 5.7 MCM for the year 2004. By the year 2015, it is expected that most villages and communities in the catchment will have pipe networks and the target will be to satisfy the domestic demands of about 120 litter/capita/day which is less than 150 litter/capita/day, the recommended consumption by WHO. Based on this assumption and assuming a 20% water losses in the systems, the annual domestic demands were estimated at about 8.3 MCM (EQA, 2004).

Data for actual agricultural consumption and agricultural demands are not available for the Faria catchment. Therefore, EQA (2004) analyzed the climatic data to determine crop water requirements in the catchment utilizing the FAO irrigation model known as CROPWAT. Using this model, the annual irrigation water demands in the Faria catchment was estimated at about 15.3 MCM.

4 Data Collection and Analysis

4.1 General

Hydrological data are the foundation of hydrological science and engineering that lead to successful water resources planning and policy making. Ultimately, the success and the type of a hydrological model to be built depend critically on the availability of the relevant data. In general, distributed models require more data than lumped parameters models. In most cases, required data either do not exist or are not available in full. That is one reason why regionalization and synthetic techniques are useful. Even if the needed data are available, problems remain with regard to completeness, inaccuracy and in homogeneity of data (Singh et al., 2002).

Despite the critical importance of water in arid and semi-arid areas, hydrological data have historically been severely limited. It has been widely stated that the major limitation of the development of arid zone hydrology is the lack of high quality observations (McMahon, 1979; Nemec and Rodier, 1979 and Pilgrim et al., 1988). There are many reasons for this. Populations are usually sparse and economic resources limited; in addition the climate is harsh and hydrological events infrequent, but damaging. However, in the general absence of reliable long-term data and experimental research, there has been a tendency to rely on humid zone experience and modeling tools, and data from other regions. At best, such results will be highly inaccurate. At worst, there is a real danger of adopting inappropriate management solutions which ignore the specific features of arid catchment rainfall response (Wheater, 2002 and references quoted therein).

In the West Bank hydrological data is very limited and not in the public domain. The lack of hydrological data is the barrier to the development of robust hydrological models that are essential to assess and to manage the water resources in the West Bank. In this study the available relevant data were collected through personal communication with governmental and non governmental organization agencies and authorities. The data needed to carry out this research study were listed and compared to the list of data present for the study area. Some gaps occurred, mainly in spatial distribution of the data required for running the coupled TRAIN-ZIN model. These gaps were filled by estimated values and extrapolation of data. Field measurements and field surveys were made to investigate and to estimate parameters.

During a field campaign of several days, double-ring infeltrometers using falling head test was carried out in the different terrain types that formed the Faria catchment to measure infiltration rates. Field measurements were carried out directly in the field for different selected channels in the catchment to investigate the channel geometry including cross section, channel depth and depth of the alluvium.

Ground truthing through several field survey activities were carried out to inspect the land cover and to develop the land use map of the Faria catchment. The delineation of streams and sub-catchments were approved directly in the field surveys. Through field survey, the practicability of different water resources management was checked. Additionally, local people were interviewed to assess the Faria catchment water related problems. GPS, digital camera and field book were used to support this work. Field measurements and surveys were analyzed and incorporated into a GIS-database.

4.2 General Data

1. GIS Data

- Geographical location
- Topographic map
- Digital elevation model (DEM)
- Soil map
- Geological map
- Location map of springs and wells
- Location map of rainfall stations

2. Hydrological Data

- Wells data
- Springs data
- Rainfall data
- Runoff data
- Climatic data

3. Reports and Thesis

- Several reports were reported by different institutions about the situation of the Faria catchment.
- Few M.Sc. theses were carried out and deal with water and environmental issues in the Faria catchment.

4. Images

- Satellite images with fine resolution that cover the entire study area were obtained from Google Map.

4.3 Rainfall Data

4.3.1 Tipping Bucket Rain-gauges

Rainfall data is one of the most important inputs required in rainfall-runoff modeling and forecasting. In a rainfall-runoff model, accurate knowledge of rainfall is a prerequisite for accurately estimating of the runoff generation (Syed et al., 2003 and Zehe et al., 2005).

For the majority of the catchments, point-measuring rain-gauges are still the most common recording systems. Rain-gauges are fundamental tools that provide an estimate of rainfall at a point (Bardossy and Das, 2006).

Rainfall-runoff modeling still depends heavily on the records from point rain-gauges , both recording rain-gauges giving estimates of rainfall intensities at time steps of one hour or better and daily rain-gauges (Beven, 2001).

The measurement of rain intensity is traditionally performed by means of Tipping Bucket Rain-gauges (TBRs) (Fankhauser, 1997; La Barbera et al., 2002 and Molini et al., 2005). TBRs are widely used in hydrology because of their good time resolution at high rainfall intensities (Fankhauser, 1997). For runoff simulation, most of the TBRs used in rainfall measurements networks have a rainfall depth per tip of 0.2 mm (Fankhauser, 1998).

Four TBRs of 0.2 mm of rainfall depth per tip were installed at four different locations within the Faria catchment to get a representative picture of the areal distribution of rainfall intensities. The four TBRs were installed in the schools of Taluza, Tubas, Tammun and Salim. Data are available from these TBRs since the rainy season 2004-2005 and up to date for the period from the first of October till the end of April. Unfortunately, for the rainy season 2004-2005, data are available for three TBRs only, since Taluza TBR was broken and didn't produce reliable data. In the rainy season 2006-2007, Salim station was defective until the end of November, due to damage of the Bucket. Therefore, the missing data for Salim station through the end of November were filled by taking the average values from the surrounding stations. The cumulative rainfall data for these TBRs for the three rainy seasons 2004-2007 are presented in **Fig. 4.1**. It is noticed that for the three seasons, little amounts of rainfall fell in October. In contrast to the first and last rainy seasons, a considerable amount of rainfall was occurred in April of the season 2005/06. Hence for the purpose of continuous modeling of the entire rainy season, the rainfall data for the period from the first of October till the end of April was used.

The time resolution for these TBRs is irregular. The time for each 0.2 mm depth of rainfall is recorded. For modeling purposes, MS EXCEL was used to re-arrange the data, so that for each 5 minutes time step, the depth of rainfall was produced.

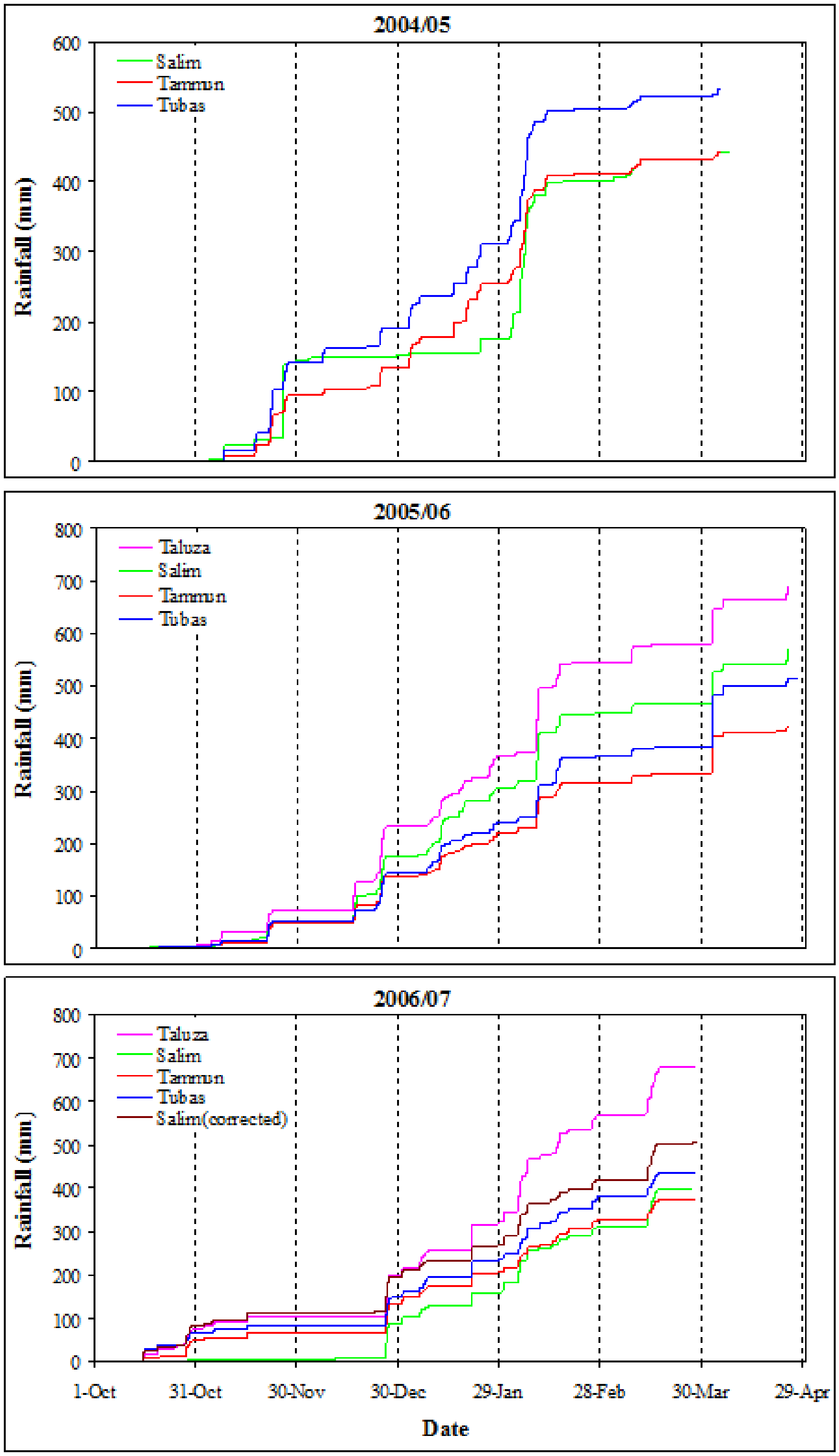

Fig. 4.1 The Cumulative Rainfall Data for the TBRs in the Faria Catchment for the Three Rainy Seasons 2004-2007

4.3.2 Density of Rain Gauges

It is true that one of the most important limits of hydrological prediction is the low resolution of input of hydrological models (Vaes et al., 2001). This input is given by rain gauge measurements so that the accuracy of the output depends essentially on the rain gauge network density configuration and on the instrument accuracy (Maheepala et al., 2001).

In the Faria catchment, the existing rainfall stations are not adequate to characterize the spatial variation of rainfall especially in the central and lower parts of the catchment.

Depending on the basis of an assigned percentage of error in estimating the mean areal rainfall, the following statistical analysis helps to obtain the optimal number of rain-gauges for a catchment (Patra, 2001).

$$N = \left\{ \frac{C_v}{E_p} \right\}^2 \tag{4.1}$$

Where N is the optimal number of rain-gauges, E_p the allowable percentage of error in the estimation of mean aerial rainfall, C_v is the coefficient of variation of the rainfall from the existing stations in percentage. Coefficient of variation can be calculated applying the following steps on the data of the existing n stations.

Calculate the arithmetic mean of rainfall from the equation

$$P_{av} = \left(1/n \right) \sum P_i \tag{4.2}$$

Calculate the standard deviation as

$$\sigma_{n-1} = \left\{ \frac{1}{(n-1)} \sum \left(P_i - P_{av} \right)^2 \right\}^{\frac{1}{2}} \tag{4.3}$$

Compute the coefficient of variation as

$$C_v = \frac{\sigma_{n-1} \times 100}{P_{av}} \tag{4.4}$$

If the allowable percent of error in estimating the mean rainfall is increased, then the catchment will require fewer numbers of gauges and vice-versa. The allowable percentage of error E_p is normally taken as 10%. While computing the value of C_v and if its value is less than 10%, it can be assumed that the existing stations are sufficient for the catchment. The additional station required for the catchment can be found as (N-n). Annual rainfall values are normally used in the above analysis. Additional stations are to be established at the appropriate locations giving an even distribution over the catchment (Patra, 2001).

Based on the information from the six stations in the Faria catchment, the above statistical parameters have been calculated; P_{av} = 431.4, σ_{n-1} = 175.1 and C_v = 40.6. Based on an 11% permissible error (E_p) and rainfall data of available stations, the minimum required number of stations (N) is 14. The existing stations (n) = 6. Thus, additional stations required = (N-n) = 8.

Salim TBR is a new station installed in the catchment. To have a clear picture of the spatial distribution of rainfall in the Faria catchment and to attain the minimum required number of rainfall stations (14), 7 dummy stations were selected randomly in the catchment.

Like all empirical formulas, the previous method has some limitations. From this method, the same number of optimal rain-gauges for two catchments with substantially different sizes (scale independent) can be obtained. Moreover, this method does not depend on the geographic location nor on topographic elevation (spatially free). However, this method was applied cleverly on the Faria catchment where the required dummy stations are distributed in a way to cover the entire catchment (**Fig. 4.2**).

4.3.3 Spatial Estimation of Rainfall

Rainfall is often significantly variable in space and time within a catchment. Rainfall data with high-resolution in space and time are required for distributed hydrological modeling of floods (e.g. TRAIN-ZIN model), (Haberlandt, 2007). A key factor for accurate flood estimates, in many hydrological applications, is to know accurate rainfall input. Due to the evolution of the meteorological phenomena over the selected area, several rain gauges should be installed in different places in order to determine the spatial rainfall distribution (Paoletti, 1993).

In the Faria catchment, rainfall is not uniform and often varies spatially with catchment topography, for example areas in higher elevations generally receive more rainfall than areas in lower elevations within the catchment. To quantify the effect of topography, Shadeed (2005) developed a spatial-oriented formula using multiple linear regression analysis on observed mean annual rainfall data and predictor variables of X, Y (local Palestinian coordinates) and elevations for the six rain-gauges within the Faria catchment (see **Section 3.2.2**) as follows:

$$R = 8285 - 39.41X - 2.46Y - 0.34Z \tag{4.5}$$

Where, R is the annual average rainfall in mm, X is the x-coordinate in km, Y is the y-coordinate in km and Z is the elevation in m.

The above formula was developed using five stations and validated on the sixth one with correlation coefficient ($r^2 = 0.99$).

Unfortunately, the four TBRs were installed in the upper part of the Faria catchment, whereas the central and lower parts of the catchment are not gauged. To overcome this problem, equation (**4.5**) is applied to estimate the mean annual rainfall in the central and lower parts (suggested rainfall stations) of the catchment and the results are presented in **Fig. 4.2**.

From the four TBRs data, the five minute time step rainfall data were estimated for the other ten stations using a filling missing data formula as follows:

$$P_x^y = \left(\frac{P_{avx}}{n}\right)\sum_{i=1}^{n}\left(\frac{P_i^y}{P_{avi}}\right) \tag{4.6}$$

Where:-

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

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

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

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

By doing that, the seasonal five minutes time step rainfall time series data were made available for the fourteen stations in the Faria catchment.

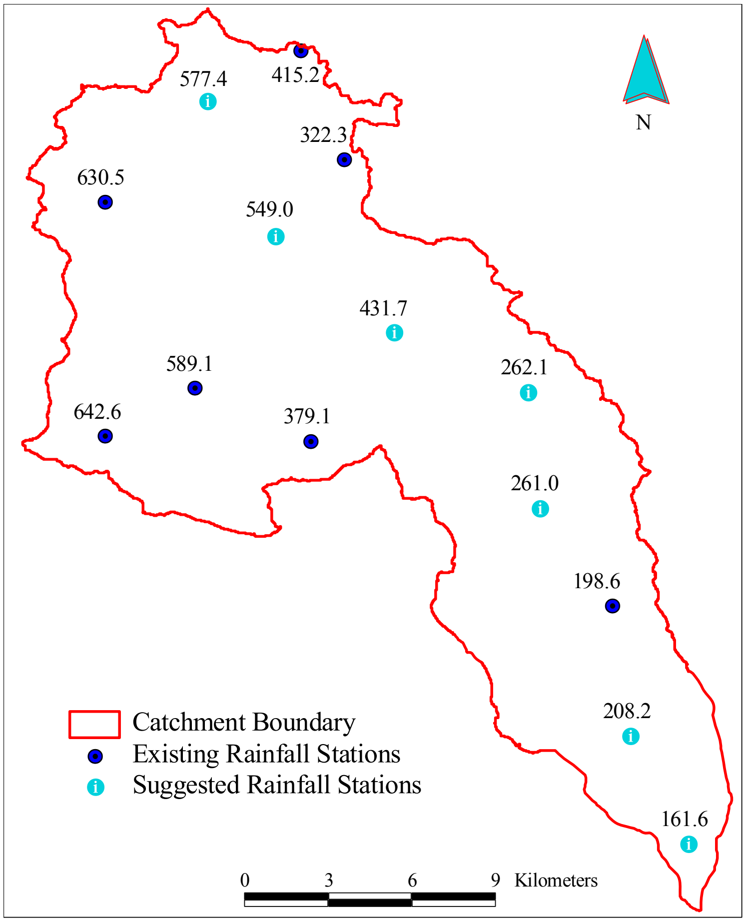

Fig. 4.2 Existing and Suggested Rainfall Stations with Long Term Annual Average in mm

The above formula was validated by using the recorded daily data of Taluza station. The daily rainfall data of Taluza station was produced using equation (**4.6**) and plotted against the recorded values as illustrated in **Fig. 4.3**. The determination coefficient (r^2) is 0.87. This means that using such formulas in the Faria catchment, which does not have enough number of rain gauge stations, provides reliable results.

To estimate the rainfall fields over the entire catchment, rain gauge pointwise measurements need to be interpolated. Several interpolation methods exist (i.e. kriging, Thiessen polygons, and inverse distance weight method). These methods allow the user to convert point measurements to a surface that describes the spatial pattern over an area.

In this study, the well-known Inverse Distance Weight (IDW) method was used. IDW is the most common method used for interpolation onto a regular grid from random spaced points. Rainfall records obtained from the existing TBRs and estimated for the suggested stations were used to generate the rainfall isohyets (grids) for the Faria catchment using the IDW method. AML code was written and supplied by ArcInfo to generate the five minute time step rainfall grids. For the TRAIN model daily rain sum grids were generated using ArcInfo also. Summing up the daily rainfall grids produced the seasonal sum.

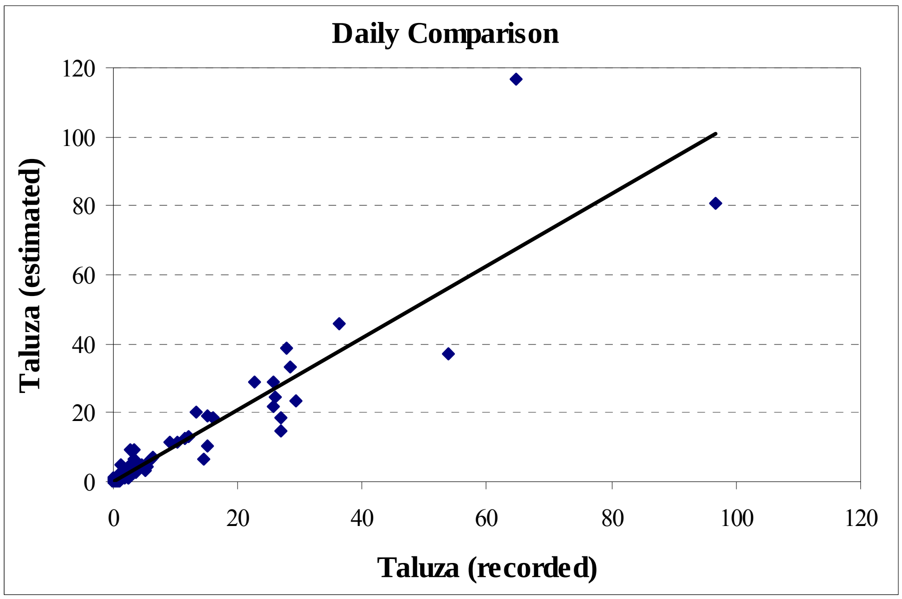

Fig. 4.3 Estimated and Recorded Daily Rainfall Data of Taluza Station

Fig. A1-A3 of the annexes present the seasonal sum for the three rainy seasons 2004/05, 2005/06 and 2006/07 respectively. To assess the seasonal sum of these three rainy seasons, the long term average rainfall grid for the Faria catchment was also generated using the IDW method (**Fig. A4** of the annexes). Grid descriptive statistics were estimated by Arc View for the four grids and the results were tabulated in **Tab. 4.1**.

Tab. 4.1 Descriptive Statistics for the Three Modeled Seasons and the Long Term Average in (mm)

Parameter	Long Term Average	2004/05	2005/06	2006/07
Minimum Value	162	184	187	160
Maximum Value	665	731	742	677
Mean Value	412	423	430	404
Standard Deviation	138	147	151	133
Range	504	547	556	517

From the table, it can be noticed that the areal average of the long term annual rainfall average of the Faria catchment is 412 mm. It can be noticed also that the statistical parameters of the two years 2004/05 and 2005/06 are very close and areal average for the two years was greater than the long term average. This means that these two years are wet compared to the last year 2006/07 (dry) where the areal mean is 404 mm.

4.4 Streamflow Data

In this study, streamflow includes for both direct runoff and baseflow. Direct runoff is the rainfall that does not infiltrate into the ground or return to the atmosphere by transpiration or evaporation. Baseflow is the amount of water in a stream from groundwater contributions. In the case of the Faria catchment, the baseflow comes from fresh water springs. Measurements of streamflow are important as they give an indication of the sensitivity of a catchment to changes in land use and climate. Continuous measurements of streamflow are needed at numerous locations in the catchment to build a long term database. This will facilitate the proper assessment and management of surface water resources in the catchment.

The availability of streamflow data is important for the model calibration process. Streamflow data are, however, generally available at only a small number of sites in any catchment (Beven, 2001).

4.4.1 Parshall Flumes

There are many different ways of measuring streamflow (e.g. Herschy, 1995). The common method of measuring flow through an open channel is to measure the depth of water as it passes over an obstruction (a flume) in the channel. The flume invented by Ralph L. Parshall in 1922 is now known by his name and used in many hydrological applications for measuring water depth in open channels.

Two Parshall flumes were constructed at the upper part of the Faria catchment to measure runoff rates from both Al-Badan and Al-Faria sub-catchments. The areas of the sub-catchments are 83 km^2 and 56 km^2, respectively (**Fig. 4.4**). The water level data inside the flumes are recorded automatically by data loggers, which are installed alongside the critical sections of the flumes. Continuous records of 10 minutes time steps are available for about 5 months from November to March for the three seasons 2004-2007.

The recorded water level was converted into flow rates using an empirical formula that was developed by Parshall (1953).

$$Q = KH^n \tag{4.7}$$

Where

Q: flow (m^3/s);
H: depth of water level (m);
K: constant depends on the size of flume; and
n: empirical constant.

Both Parshall flumes are different in size. The flume at Al-Faria sub-catchment has a throat width of 3.65 m and K equals 8.859 designed for a maximum discharge of 15 m^3/s, whereas for Al-Badan, it is designed for 25 m^3/s discharge with a throat width of 4.57 m and K equal to 10.96. The value of n for both flumes is 1.6. Values of the two constants K and n were assigned by Parshall for standard flumes of which the constructed flumes were designed and constructed accordingly.

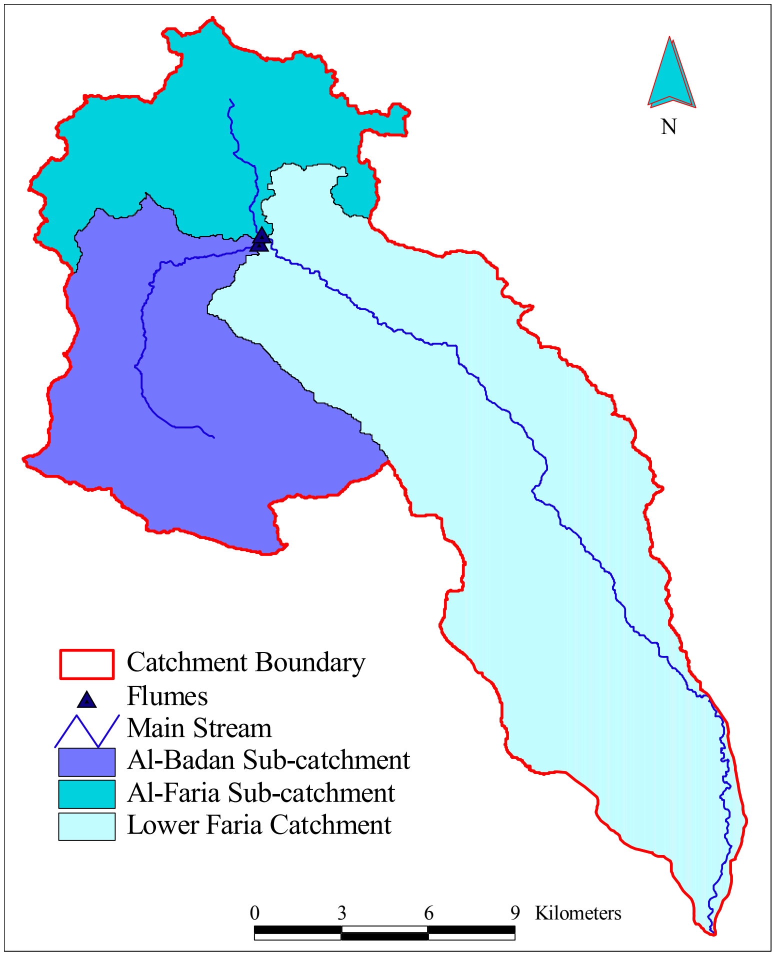

Fig. 4.4 The Upper and Lower Faria Sub-catchments

4.4.2 Analysis of Raw Data

No hydrological device is free from measurement errors. In this study manual readings were taken on hourly basis during a flood and on daily basis otherwise. The diver readings were compared with the corresponding manual readings and some differences were found. This was because the sediment could enter the pipe where the divers were installed and disrupt the readings. To overcome this problem the diver readings were corrected according to manual readings.

For the Al-Badan flume, during the first measuring season 2004/05 particularly on the 6th of February, a considerable event (event 1) occurred and washed out the earth dam built along one wing of the flume to catch the flood towards the flume. Therefore, the data available for the 6 February is not reliable. A regression analysis with the Al-Faria runoff data was carried out to simulate the lost and highest peak discharge of that flume (**Fig. 4.5**). The data set that was used for the regression analysis was from 6 February at 4:00 AM until 6 February at 20:00 PM. The coefficient of determination (r^2) value was found to be 0.93.

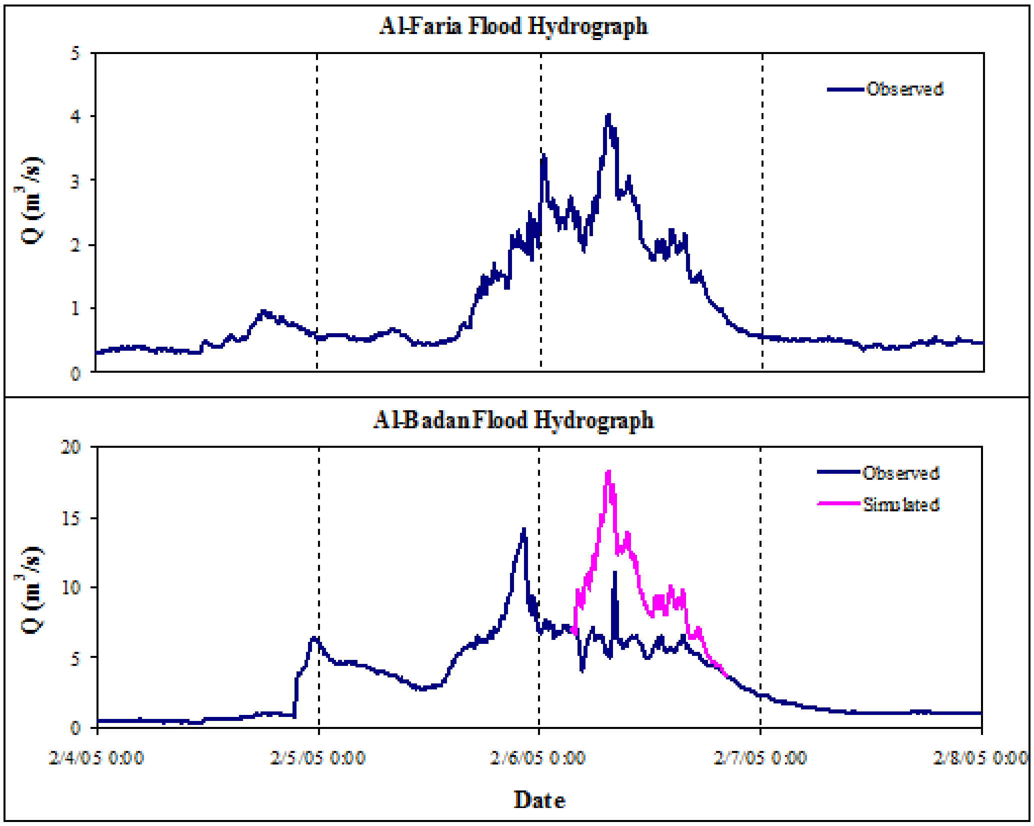

Fig. 4.5 Al-Faria and Al-Badan Flood Hydrographs for Event 1

On the second measuring season 2005/06, and to overcome the problems from the first season, the earth dam that washed out was replaced by a reinforced concrete one. In spite of that, a big flood event (event 2) occurred on the 9th of February and unfortunately a part of the flood passed by the flume and was not measured (**Fig. 4.6**).

Fig. 4.6 Al-Badan Flood on the 9th of February 2006

However rough estimates of the lost water could be done by field observations and the measured water levels were corrected according to the field estimates. It was estimated that more than 80% of the flood was measured. Thus the data set from 9 February at 16:30 PM until 9 February at 18:00 PM, when the peak flood reached the Flume, was increased by 20% (**Fig. 4.7**).

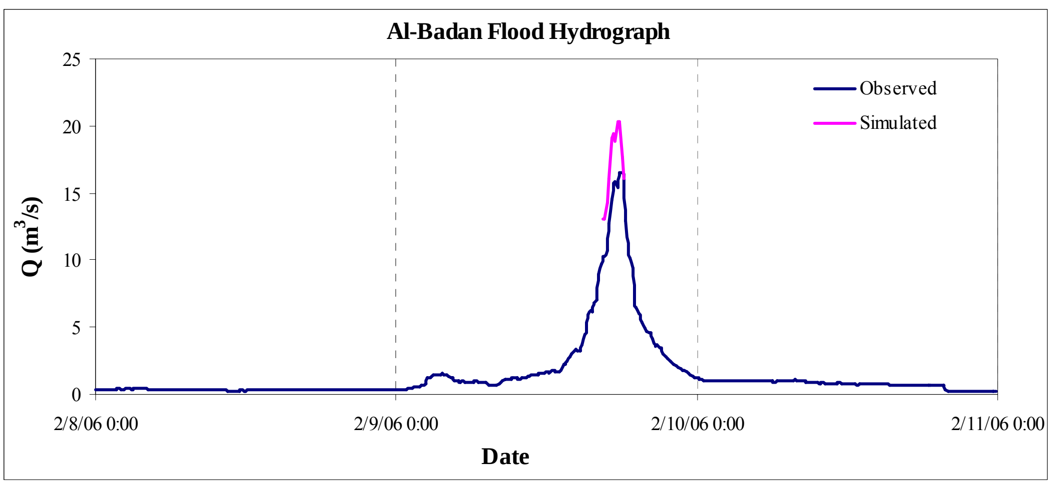

Fig. 4.7 Al-Badan Flood Hydrograph for Event 2

The corrected runoff for both Al-Badan and Al-Faria Flumes for the three seasons 2004-2007 are presented in **Fig. 4.8** and **Fig. 4.9** respectively.

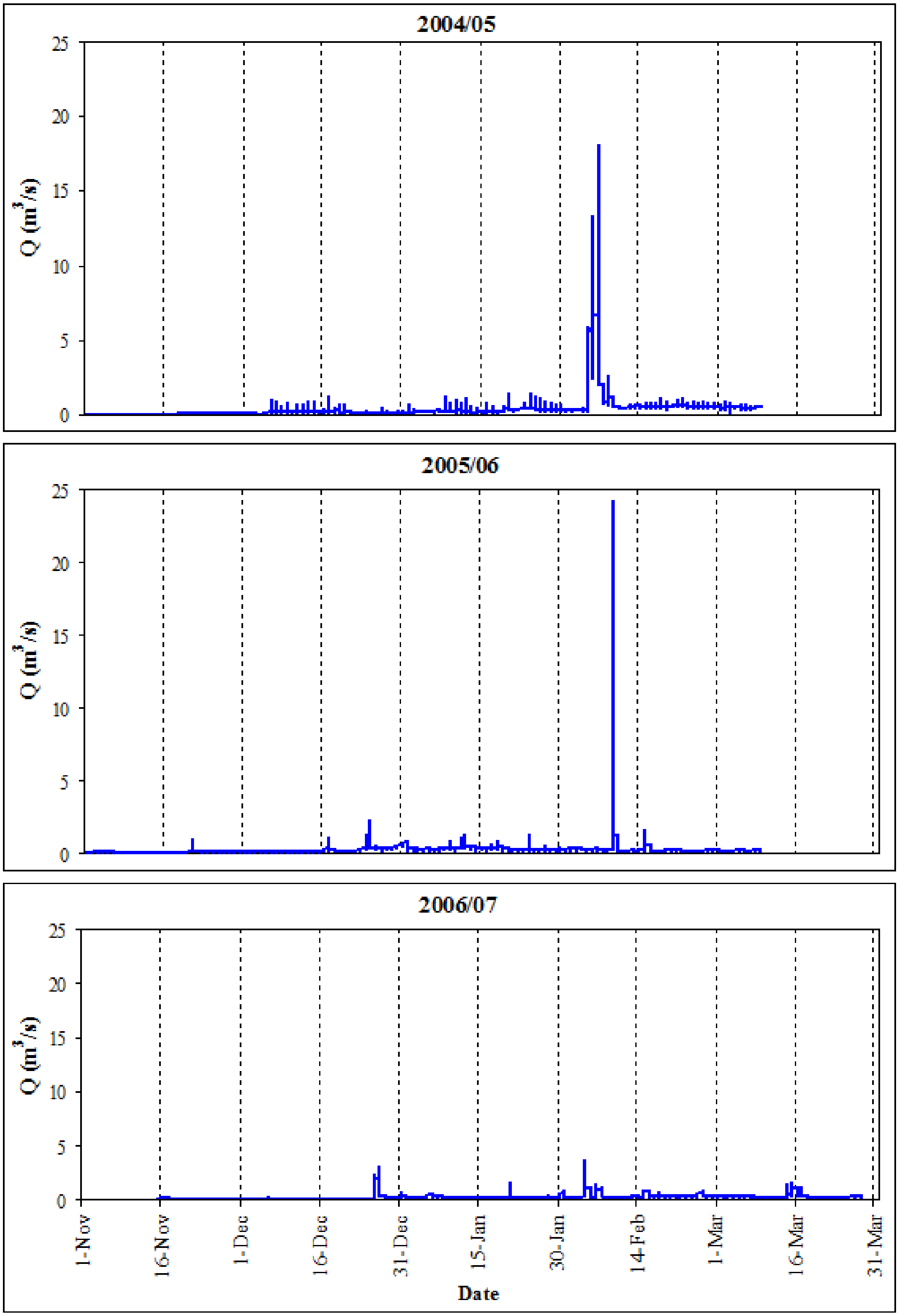

Fig. 4.8 Runoff of Al-Badan Flume for the Three Seasons 2004-2007

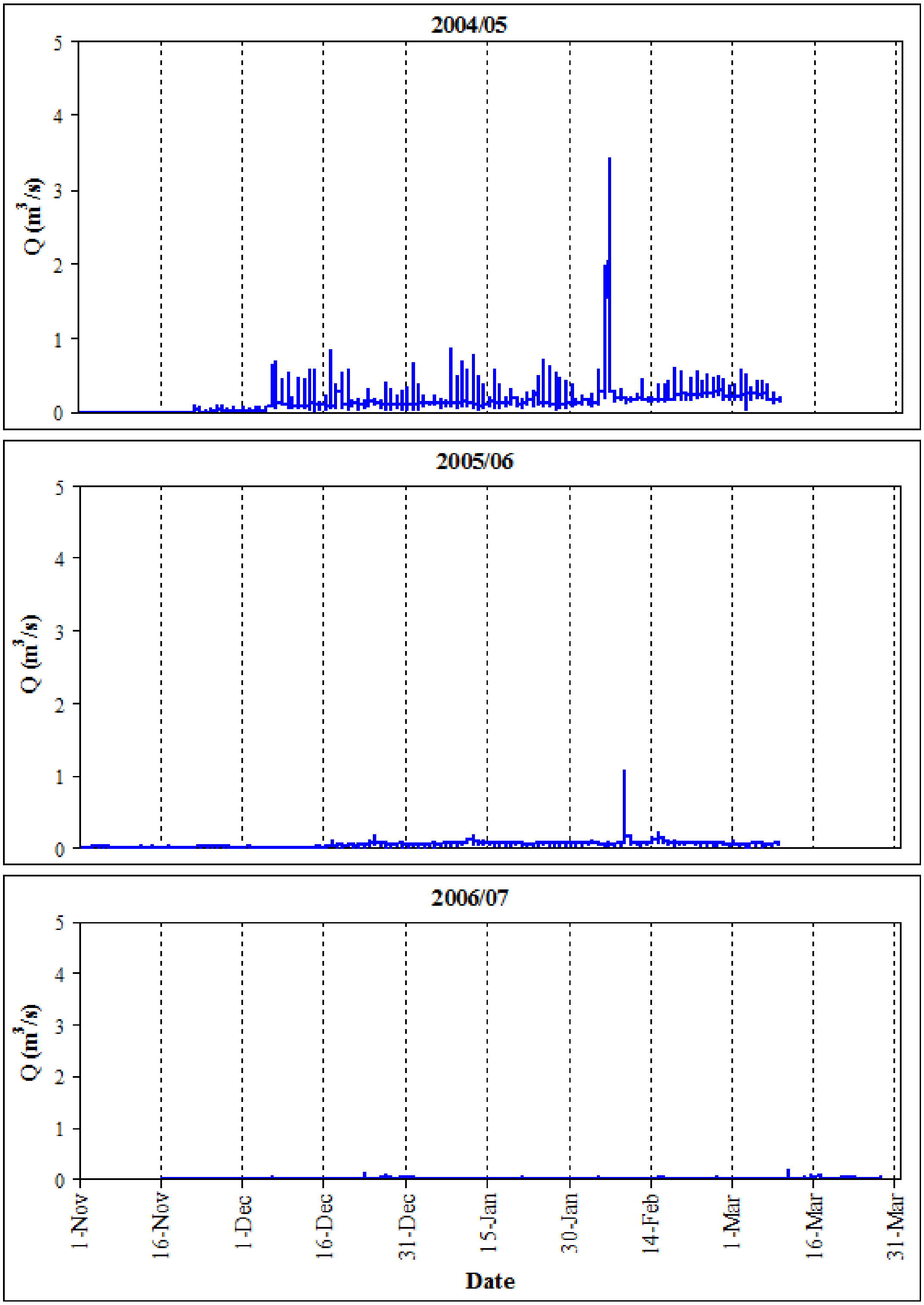

Fig. 4.9 Runoff of Al-Faria Flume for the Three Seasons 2004-2007

From the figures, it can be inferred that the flow in the flumes varies from time to time, particularly during and in response to rainstorm events. As rain falls and moves through the catchment, water levels in the Flumes rise and may continue to do so after the rainfall has terminated. There are not many events which caused high floods within this recorded period. For each year, one major runoff event, low-frequency and high-amplitude, is observed as part of the obvious continuous, high-frequency and low-amplitude baseflow.

For both sub-catchments, the most significant flood occurred in the rainy season of 2004/05 from 4 to 6 February. For the rainy season 2005/06, the most significant flood occurred from 8 to 9 February. These are the only two events that are taken into consideration in calibration processes of the TRAIN-ZIN model. Another significant rainfall event occurred on the 2nd of April 2006 in which more than 60 mm of rain fell in one day. Unfortunately, the runoff for this event was not measured since for that season the data loggers had already stopped by 16 March 2006. However continuous simulation of the entire rainy season showed that a considerable flood occurred as a result of this rainstorm event (see **Chapter 7**). For the rainy season 2006/07, two small events occurred in the period from 26 to 27 of December and between 3 and 6 of February. These two events were used for model validation.

4.4.3 Baseflow Separation

Baseflow is typically measured during times when there is no runoff from excess rainfall. Baseflow may vary considerably along the stream due to groundwater levels and geological influences, such as underlying soils and bedrock conditions. Measurements of baseflow are important as they indicate the sensitivity of the stream to land use changes, water extraction, or extended periods of dry weather. In the Faria catchment, the baseflow has been measured continuously since the construction of both Al-Badan and Al-Faria flumes.

Since this research study aims to model the runoff generation in the Faria catchment, the measured total runoff was separated into two components, the baseflow and the direct runoff components.

Despite the fact that theoretical separation of baseflow and direct runoff components of a stream hydrograph is conceptually simple, objective baseflow separation proves to be extremely difficult in practice (Stanger, 1994).

Several techniques have been developed for numerical separation of flow hydrograph into baseflow and surface runoff. The Lyne and Hollick Filter method (Nathan and McMahon, 1990) is a widely used method of baseflow separation applied to daily data and was used in this study. The equation used is as follows:

$$q_i = \alpha q_{i-1} + 0.5(1+\alpha)(Q_i - Q_{i-1}) \text{, for } q_i \geq 0 \tag{4.8}$$

$$QB_i = Q_i - q_i \tag{4.9}$$

Where:

Q_i = total flow time series

q_i = high flow time series component (surface runoff)

QB_i = low flow time series component (baseflow)

i = time step index

α = separation parameter ($0<\alpha<1$), for daily data a value of 0.925 is recommended for the separation parameter (α) (Savadamuthu, 2004).

The baseflow component (QB_i) for each time step is constrained to be never less than zero or greater than the total flow (Q_i). EXCEL spreadsheet was developed to solve the above equation for the available time series data. A conditional statement has been used; wherever the computed value of q_i is less than zero, QB_i is set to Q_i .

The developed EXCEL spreadsheet was used to aggregate daily data from the recorded 10 minute time series data and was used to separate the baseflow component using the recommend value of α =0.925.

In making use of the Lyne and Hollick separation method for any step time series discharge data, Smakhtin (2001) and Denis et al. (2003) suggested using equation (**4.8**) and calibrating α until the same baseflow volume is achieved as a separation based on daily data. In the developed EXCEL spreadsheet, the Goal Seek tool was employed to calibrate the value of the separation parameter α for the available 10 minute time series data for the three years 2004-2007 for both Al-Badan and Al-Faria sub-catchments. Having done the calibration of the separation parameter α , a value of 0.999 was obtained. The results are plotted in **Fig. A6-A8** of the annexes.

4.5 Rainfall and Runoff Data Assessment

Analysis of rainfall and runoff records is essential to investigate the relation between them. For both Al-Badan and Al-Faria sub-catchments, daily rainfall values were used in the following analysis as follows:

1. Daily rainfall was created by summing up the 5 minute time step grids that were generated using the IDW method (**Section 4.1.3**);
2. Using ArcInfo workstation, the daily rainfall grids were clipped for both Al-Badan and Al-Faria sub-catchments and then the areal average rainfall depth was read out from each daily grid; and
3. Direct runoff in m^3/s was obtained after the baseflow was separated.

The abovementioned steps were followed for the three rainy seasons 2004-2007 and the results are as shown in **Fig. 4.10** through **Fig. 4.12**. As for both sub-catchments, the most significant flood occurred in the rainy season of 2004/05 from 4 to 6 of February. For the rainy season 2005/06, the most significant flood occurred from 8 to 9 of February whereas for the last season, 2006/07, no significant flood events occurred.

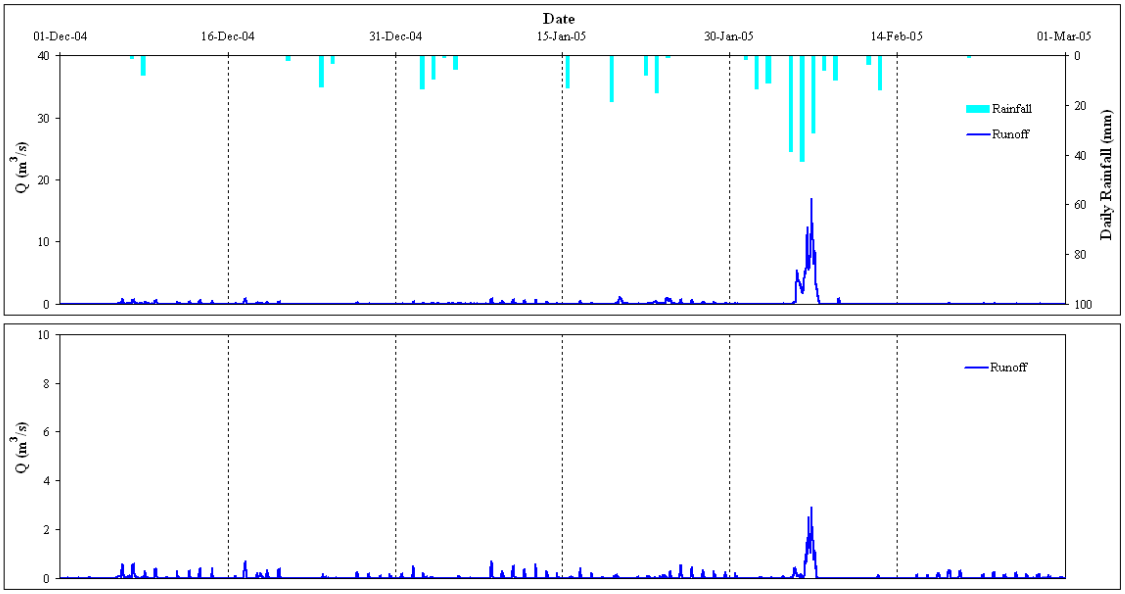

Fig. 4.10 Rainfall and the Corresponding Runoff for the Season 2004/05; upper part: Al-Badan Sub-catchment and lower part: Al-Faria Sub-catchment

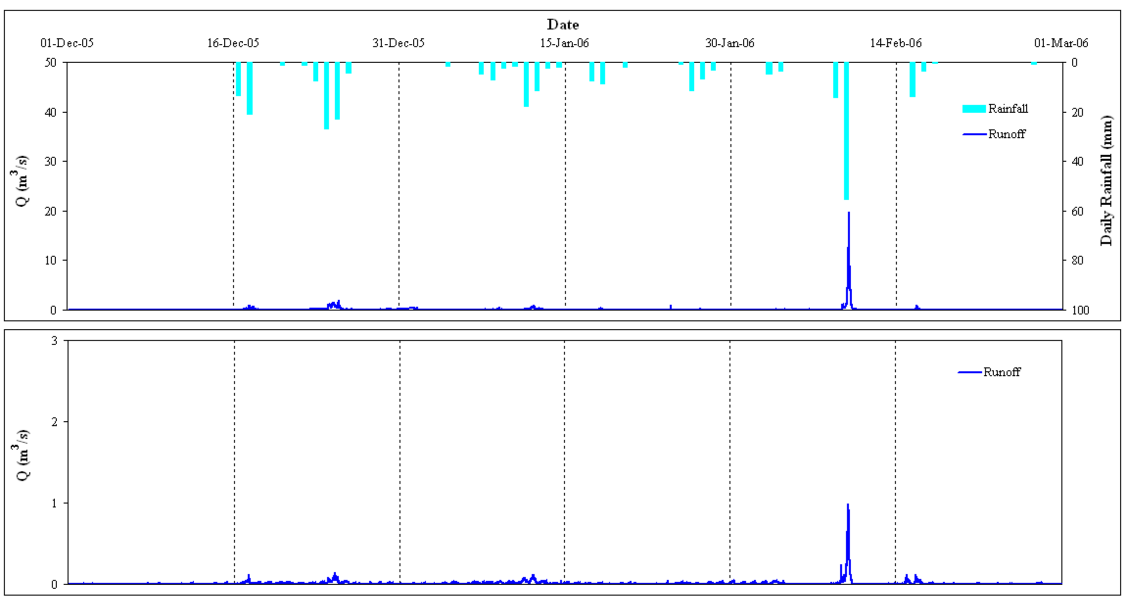

Fig. 4.11 Rainfall and the Corresponding Runoff for the Season 2005/06; upper part: Al-Badan Sub-catchment and lower part: Al-Faria Sub-catchment

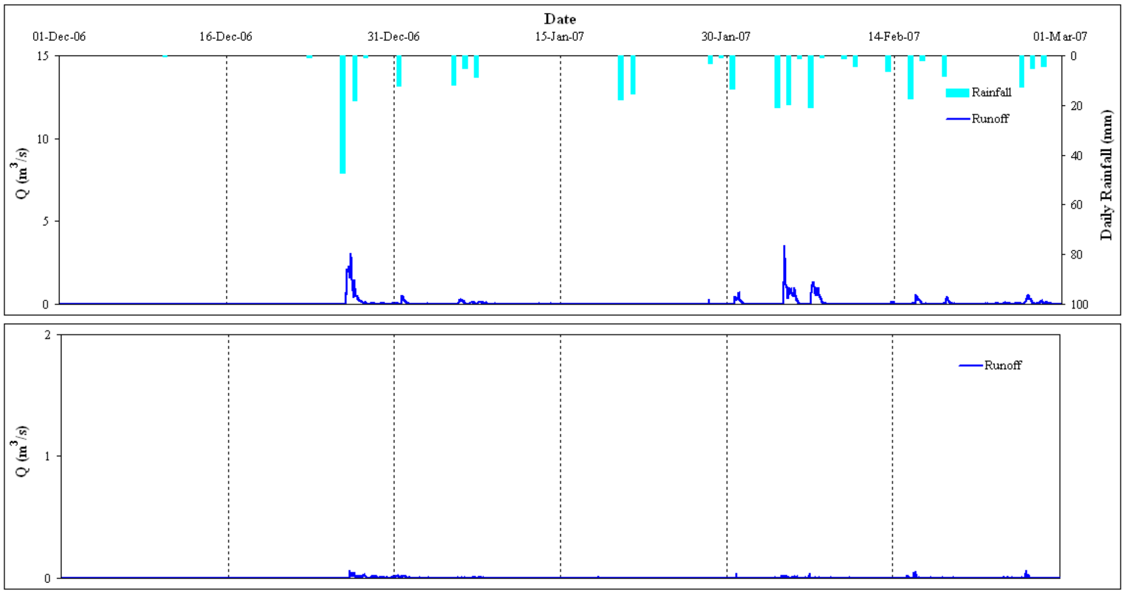

Fig. 4.12 Rainfall and the Corresponding Runoff for the Season 2006/07; upper part: Al-Badan Sub-catchment and lower part: Al-Faria Sub-catchment

From the figures it can be inferred that for the three rainy seasons, the amount of runoff generated in Al-Badan sub-catchment is greater than that of Al-Faria sub-catchment. This can be attributed to the following reasons:

1. The surface area of Al-Badan sub-catchment (83 km^2) is greater than that of Al-Faria sub-catchment (56 km^2);
2. Slopes of Al-Badan sub-catchment are steeper than Al-Faria slopes; this makes the potential of runoff generation in Al-Badan sub-catchment greater than of Al-Faria;
3. Terrain types of Al-Faria sub-catchment have more infiltration rate than Al-Badan. The dominant terrains of Al-Badan sub-catchment are type B and D with low final infiltration rates, whereas type E and H of relatively high infiltration rates are the dominant terrains of Al-Faria sub-catchment (see **Chapter 6**), and
4. In Al-Badan sub-catchment, the highest amounts and intensities of rainfall usually fall over Nablus area which is an urban area (type B) that produced a considerable amount of runoff, whereas in Al-Faria sub-catchment, Taluza area which is mostly covered with olive plantation (type G) received the highest amounts of rainfall and produced negligible amount of runoff.

It is well documented in literature that surface runoff in the eastern slopes of the West Bank, where the Faria catchment is located, is habitually intermittent and most likely occurs when the rainfall exceeds 50 mm in one day or 70 mm in two consecutive days (e.g. Al-Nubani, 2000). To check this assumption, an inventory of daily rainfall depths for the three seasons 2004-2007 was carried out. As a result, it was found that two rainfall events matched with the aforementioned assumption. These events are; 8-9.02.06 (event 2) and 26-27.12.06 (event 3). In the season 2004/05 a big event occurred in three consecutive days and brought more than 100 mm of rainfall. This happened in the period of 4-6.02.05 (event 1). In addition to that it was found that in the season 2006/07 more than 70 mm of rainfall fell in four consecutive days (event 4). For event 1 (3 days>100 mm) and event 2 (2 days>70 mm) and from the previous figures it can be inferred that these two events were followed by a significant floods measured at Al-Badan Flume, whereas only small floods were measured at Al-Faria flume.

Event 3 (2 days>70 mm) and event 4 (4 days>70 mm) were followed by small floods recorded at Al-Badan Flume and negligible floods recorded at Al-Faria Flume. Characteristics of these four events were studied in order to have a solid conclusion regarding the relationship between rainfall and runoff in the Faria catchment. Date of occurrence, amount of rainfall, maximum and average rainfall intensities and initial conditions (e.g. number of days since last event) were studied and tabulated in **Tab. 4.2**.

Tab. 4.2 Characteristics of the Four Rainfall Events

Parameter		Event 1	Event 2	Event 3	Event 4
Date of occurrence		4-6.02.05	8-9.02.06	26-27.12.06	3-6.2.07
Amount of Rainfall (mm) (Averaged over Al-Badan sub-catchment)		136	91	82	81
Number of Days		3	2	2	4
Number of rainy hours		55	22	28	48
Average Rainfall Intensity (mm/hr)		2.5	4.2	2.8	1.5
Number of days since last event		2	5	40	3
Runoff Volume (m^3)	**Al-Badan**	976,161	316,142	119,355	161,728
	Al-Faria	125,661	20,956	1,679	1,541

From **Tab. 4.2**, it is clear that events 1, 2 and 4 occurred on February, whereas event 3 was occurred in December. Event 1 lasted for 55 hours during three consecutive days and brought 136 mm of rainfall averaged over Al-Badan sub-catchment. Event 2 lasted for 22 hours during two consecutive days and brought about 91 mm of rainfall. These two events occurred almost at the same time in two consecutive years producing a significant amount of runoff. The initial conditions of event 1 (after less than 2 days of no rainfall, high initial soil moisture content) made it possible for this event to produce a considerable amount of runoff. Despite the 5 dry days preceding event 2 and low initial soil moisture content, this event produced a significant amount of runoff. This is due to the high rainfall intensity, 4.2 mm/hr, compared to event 1 which had an average intensity of only 2.5 mm/hr. Although event 4 occurred on February and came after 3 days of no rainfall at intermediate initial soil moisture content, this event was followed by a small flood. This is due to the low rainfall intensity (1.5 mm/hr) that characterized this rainfall event, in which 81 mm of rain was distributed over 4 consecutive days.

For event 3 that occurred in December, although the rainfall amount is very close to event 2, which produced a significant amount of runoff, this event produced a small amount of runoff. This can be attributed to the initial conditions of this rainstorm event. After 40 days of no rainfall, this event occurred. Thus the soil was very dry (zero antecedent soil moisture content) and the initial losses could be very high at that time of the year. In addition the average rainfall intensity, 2.8 mm/hr, was less than that of event 2. Consequently, these reasons together made it unlikely for this event to produce a considerable amount of runoff.

From the aforementioned discussion it can be concluded that the well-known assumption regarding the rainfall threshold for runoff generation in the region is not absolutely true. This should be compared with the other factors that control the runoff generation (e.g. infiltration rate, initial soil moisture conditions initial losses and rainfall intensity and duration).

Given the different initial soil moisture conditions, which can heavily modify runoff generation in a catchment, it is necessary to clarify that it is not possible to determine a unique rainfall threshold for a given catchment. It is well-known that the water content in the soil strongly affects the catchment hydrologic response to a given rainstorm, with the consequence that a storm event considered irrelevant in a dry season can be extremely dangerous in a wet season when the extent of saturated areas may be large. This is the case of event 3 which is considered irrelevant in December 2006 when the soil was totally dry. In contrast, event 1 which companied wet initial soil moisture conditions in February 2005 was considered a relevant event. This implies the necessity of determining several rainfall thresholds for different soil moisture conditions. In addition it was found that more than 100 mm of rainfall fell in three consecutive days and more than 70 mm fell in four consecutive days generated runoff when the initial conditions were accordingly.

5 Hydrological Modeling

5.1 ZIN-Model

The ZIN is a spatially distributed and physically-based rainfall-runoff model that was developed by Lange (1999) particularly to simulate high magnitude events in dry environments. Similar to all hydrological models, the ZIN model is a simplified representation of natural systems and is used as a mathematical tool to simulate and interpret hydrological processes. The ZIN is a distributed model in the sense that the catchment can be subdivided into smaller geographical segments in order to account for the variability of hydrological behavior. As all parameters should be determined in the field and not a single parameter is fitted by calibration with measured streamflow data, the model may be termed "field-based" (Lange, 1999). In addition it is a process-based model since all water fluxes represented in the model are assigned from field-based hydrological processes.

The ZIN model uses spatially distributed sub-catchments determined by geomorphological analysis with the help of air-photography, topographic maps or digital elevation model and several field campaigns. The ZIN model is subdivided into three different sub-systems or routines:

1. Runoff generation based on terrain types;
2. Runoff concentration based on mean response function of tributary sub-catchments; and
3. Channel routing and transmission losses based on channel segments.

Settings up the GIS database with the field measurements facilitate the effective determination of the model parameters for each spatial sub-catchment. The aggregation of spatially homogenous areas into model sub-units is carried out independently for each sub-system. Thus, the model is very flexible and allows maximum accuracy with minimum spatial resolution. **Fig. 5.1** shows a schematic representation of the ZIN model including the different types of spatial subdivision in the sub-systems.

Rainfall is event-based, since rain amount and intensity differ considerably from event to event. The model uses a catchment wide pattern of rainfall intensities as input. Interpolation of rainfall data from a network of recording rain-gauges is used herein to prepare the rainfall input data. As output, the model mainly yields a hydrograph of discharge at any user defined point along the watercourse.

Leistert (2005) modified the original ZIN model by integrating the Green-Ampt infiltration model to improve the simulation of the transmission losses (see **Section 5.2.2**).

Gunkel (2006) in the context of her PhD dissertation made other modifications on the original ZIN model; in addition she coupled the TRAIN and ZIN models (see **Section 5.3**).

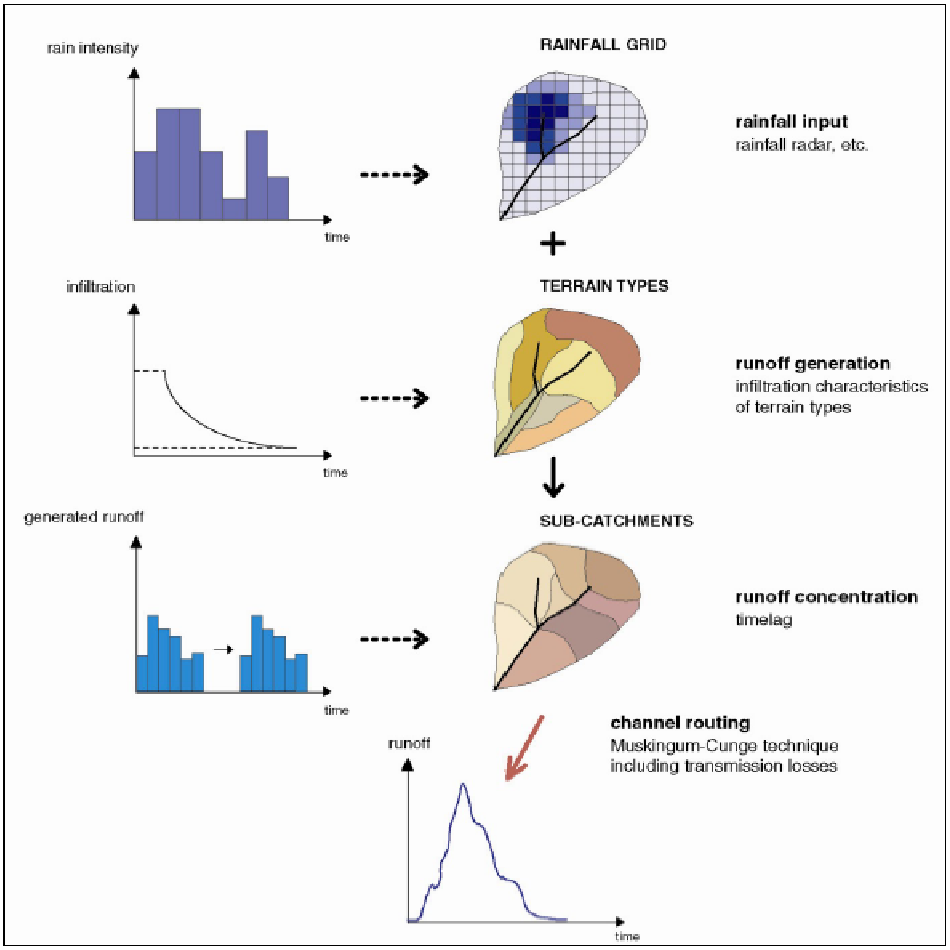

Fig. 5.1 Schematic Flow Chart of the Non-Calibrated Rainfall-Runoff Model
(Thormählen, 2003, after Lange, 1999)

5.2 Runoff Generation

The runoff generation process determines the fraction of the rainfall that is transformed into direct runoff. As described in **Section 2.1.4**, the IEOF is generally assumed to be the dominant mechanism of runoff generation in most arid regions. IEOF is defined as the flow of water from a catchment that occurs when the rainfall intensities exceed the infiltration rate of the terrain. In ZIN, IEOF is parameterized by a concept of initial losses and a temporally variable infiltration rate. During a rainstorm event on vegetated surfaces, some portion of the rainfall will be intercepted on the vegetation. This portion of the rainfall does not contribute to infiltration or runoff. Therefore, an initial loss is subtracted from the rainfall before infiltration or runoff is performed.

In the ZIN model, a total depth of initial loss is specified for each terrain type, based on the vegetation or other surface condition. This amount is taken from the earliest rainfall pulses until the initial loss depth is filled. In other words, this represents the declination of the initial infiltration rate to a constant rate (final infiltration rate). The infiltrated amount is filling a volume of soil storage which is emptied by evapotranspiration or deep percolation. Lower rainfall intensities are added to the soil storage, and may eventually generate the SEOF.

In the Faria catchment, which is characterized as an arid to semi-arid region, SEOF may take place when the soil reaches saturation. This results from the preceding low intensity rainfall events (Castillo et al., 2003).

In the original ZIN version deep percolation was quantified with a constant value. Schütz (2006) integrated the Van-Genuchten method (1980) to the original ZIN version to simulate water losses through deep percolation with a dynamic function. The unsaturated hydraulic conductivity is determined as a function of the actual soil moisture as follows:

$$\frac{K(\theta)}{K_S} = \left(\frac{\theta - \theta_r}{\phi - \theta_r}\right)^{1/2} \left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\phi - \theta_r}\right)^{1/m}\right]^m\right\}^2 \tag{5.1}$$

$$m = \frac{\lambda}{\lambda + 1} \tag{5.2}$$

Where:

$K(\theta)$ is the an unsaturated hydraulic conductivity [cm/h]

K_S is the saturated hydraulic conductivity [cm/h]

θ is the soil water content (volume fraction)

θ_r is the residual water content (volume fraction)

ϕ is the porosity (volume fraction)

λ is the Brook-Corey pore-size distribution index

The Brook-Corey pore-size distribution index (λ) and the residual water content (θ_r) are determined with empirical functions of the pore size distribution. In Rawls et al. (1992) these parameters are listed for the most common soil texture classes.

5.2.1 Runoff Concentration

A channel network had been prepared as required for the ZIN model. The channel network is divided into segments. The adjoining small sub-catchments, predetermined by topography are defined as model elements for runoff concentration. Runoff concentration describes the transformation of runoff generated (IEOF and/or SEOF) at each model element to lateral inflow into the adjacent channel through a mean response function. The amount of runoff as calculated by the runoff generation routine is summed up for each sub-catchment and for each time step, respectively.

In large catchments, the runoff concentration often follows conceptualizations close to the Unit Hydrograph concept (Sherman, 1932). In this style, the original ZIN model uses a mean response function of model elements, consisting of a hydrologic time lag and a standardized shape.

Hence, the mean response function is replaced by a simple constant time delay as runoff concentration mechanism. After this concept, the shape of the runoff hydrograph does not change during runoff concentration but lateral inflow to the channel is only delayed.

5.2.2 Channel Flow and Transmission Losses

The spatial sub-catchments for this part of the model are predefined by the channel segments used for runoff concentration. The resulting channel network is subdivided into channel segments which begin and end with a node. Each segment represents a cross-sectional homogeneous section of the channel network. Channel flow is routed from one node to another, accounting for lateral inflow and transmission losses.

As defined by Fread (1981, 1985, 1992); Linsley et al. (1982) and Chow et al. (1988) flood routing is a mathematical method for predicting the changing magnitude and celerity of a flood wave as it propagates down rivers or through reservoirs. The result is a flow hydrograph at the respective stream section or at the catchment outlet.

Flood routing procedures may be classified as either hydrological or hydraulic (Choudhury et al., 2002; Tewolde and Smithers, 2006). Hydrological methods use the principle of continuity and a relationship between discharge and the temporary storage of excess volumes of water during the flood period (Shaw, 1994). Hydraulic methods of routing involve the numerical solutions of either the convective diffusion equations or the one dimensional Saint-Venant equations of gradually varied unsteady flow in open channels (France, 1985). Based on the Saint-Venant equations, the ZIN model uses a distributed, hydraulic, routing procedure which describes the flow process accounting for channel properties such as cross sectional geometry, slope, flow length and channel roughness. The basic channel routing model used in the ZIN model has been based on the Muskingum-Cunge method. This method which capable of predicting hydrograph attenuation has been developed by Cunge (1969), modifying the hydrologic Muskingum procedures and has been effectively used as a distributed flow routing procedure (Chow, 1988; Fread, 1992). Cunge demonstrated that this solution corresponds to the approximation of the diffusive wave of the full Saint-Venant equations. The Muskingum-Cunge method calculates the advancing flood wave from channel node to channel node at different time steps. By means of finite difference approximation, one can obtain (Lange, 1999 after Chow, 1988):

$$Q_{i+1}^{j} = C_1 Q_i^j + C_2 Q_i^{j-1} + C_3 Q_{i+1}^{j-1} \tag{5.3}$$

$$C_1 = \frac{(\Delta t - 2KX)}{2K(1-X) + \Delta t} \tag{5.4}$$

$$C_2 = \frac{(\Delta t + 2KX)}{2K(1-X) + \Delta t} \tag{5.5}$$

$$C_3 = \frac{(2K(1-X) - \Delta t)}{2K(1-X) + \Delta t} \tag{5.6}$$

$$K = \frac{\Delta X}{V_k} \tag{5.7}$$

$$X = \frac{1}{2}\left[1 - \left(\frac{Q_{ref}}{BV_k S_o \Delta X}\right)\right] \tag{5.8}$$

Where Δt is the computational time step [s], Q_{i+1}^{j} is the unknown discharge at the next node at the present time step [m^3/s], Q_i^j is the discharge at the present node at the present time [m^3/s], Q_{i+1}^{j-1} is the discharge at the next channel node at the last time step [m^3/s], Q_i^{j-1} is the discharge at the present channel node at the last time step [m^3/s], $C_{1,2,3}$ are auxiliary variables ($C_1 + C_2 + C_3 = 1$), K is storage constant [s], X is a weighting factor expressing the relative importance inflow and outflow have on the storage, Q_{ref} is the reference discharge [m^3/s], B is width of water surface, V_k is the kinematic wave celerity [m/s], S_o is the energy slope and ΔX is the distance step (channel reach length) [m].

For a wide channel where the hydraulic radius approaches the flow depth, the following approximation is valid:

$$V_k \approx \frac{5}{3}V \tag{5.9}$$

Where V is the flow velocity [m/s], which may be calculated by solving a steady, uniform flow formula such as the Manning equation:

$$V = \frac{R_h^{2/3} S_o^{1/2}}{n} \tag{5.10}$$

Where R_h is the hydraulic radius [m] and n is the Manning roughness coefficient [dimensionless] which may be estimated using the method outlined by Chow (1959). For the determination of the reference discharge Q_{ref}, different modes of the Muskingum-Cunge method exist. These methods depend on the value chosen for Q_{ref}. Linear modes use a constant value for Q_{ref} making the routing parameters X and K for all time steps. It is not capable of predicting wave steepening. Non linear modes recalculate the routing parameters at each time step by extrapolation available Q-values from previously computed time and distance steps. The solution procedure is iterative and converges when computed and estimated values of Q agree within a suitably small tolerance. This procedure is capable of describing a steepening of a flood front, accounting for the fact that different discharges travel at different velocities. The present ZIN model, applies the non-linear MVPMC3-method (Ponce and Chaganti, 1994), using the maximum available information for Q_{ref}:

$$Q_{ref} = \frac{Q_i^j + Q_i^{j-1} + Q_{i+1}^{j-1}}{3} \tag{5.11}$$

Channel geometry is represented by a compound section consisting of inner channels, bars and banks, each with a certain proportion of the total width. The flood always covers the inner channel, a small percentage of the channel width, whereas the covering of the bars and banks by the flood depends on the water depth.

In the ZIN model, a constant infiltration rate was selected to parameterize the channel transmission losses. For each channel type two different but constant infiltration rates are assumed, one for the inner channel and one for the bars and banks. The inner channel infiltration occurs on the entire inner channel area of each segment, whereas the infiltration into the bars and banks depends on the flooded area. The flooded area for each time step is calculated as the product of constant segment length and variable segment width.

Leistert (2005) replaced the linear approximation used by the original ZIN model to calculate the flooded area by two composite power functions. He considered that the expansion of the flooded area has to be approximated with a slow growing function. On one hand, a slowly growing function hardly ever reflects the real cross sectional geometry. On other hand, the floodplains are often huge and smooth, so that a small rise of the water level can result in flooding of large areas. So in addition to a slowly growing function, the floodplains have to be simulated with a fast growing function. Therefore, he divided the entire channel width into three sections as shown in **Fig. 5.2**.

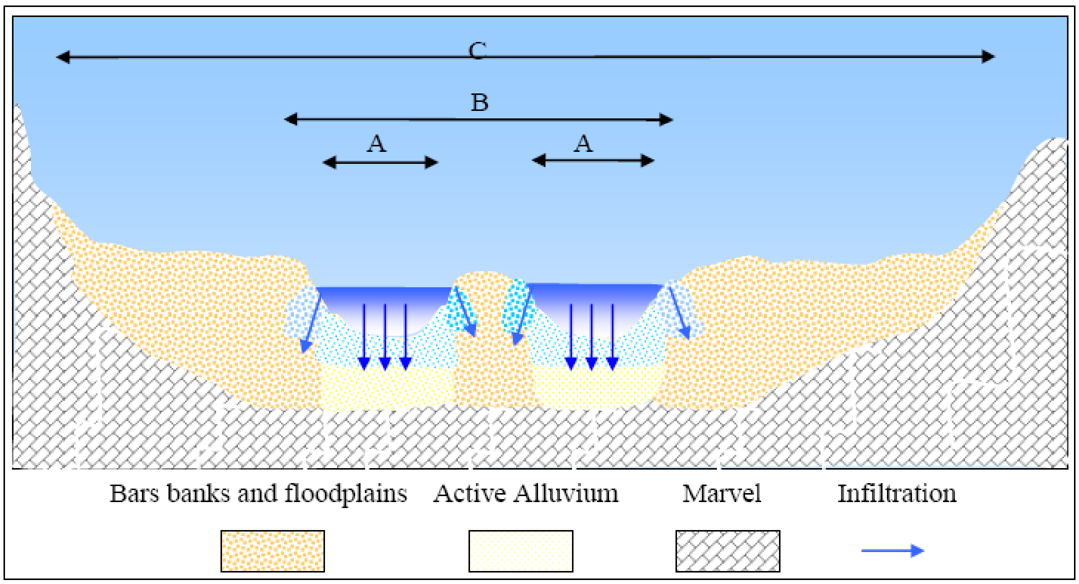

Fig. 5.2 Schematic Profile of Cross Sectional Channel Geometry; A - Approximation of Inner Channel Area, B - Approximation of Banks And Bars And C - Approximation of Floodplains Area (Leistert, 2005)

The inner channel section (A) which is assumed to be flooded immediately and completely is simulated as:

$$bv_A = b_c \times v \tag{5.12}$$

In section B, which represents the bars and the banks with a steep incline, the growth of the flooded area is simulated as:

$$bv_B = b_c \times v \times (1 + H^x) \tag{5.13}$$

Where bv_B is a variable channel for section B, H is the water depth, b_c is the maximum channel width and x is a constant accounts for the inclination of bars and banks function.

The third section (C) represents the floodplains and is simulated as:

$$bv_C = \sqrt[d]{\left(\frac{H - f_a}{f_b}\right)} \tag{5.14}$$

$$f_a = H_f - (f_b . b_c^{\ d}) \tag{5.15}$$

$$f_b = \frac{H_f - \sqrt[x]{y}}{b_c^{\ d} .(1 - ((1 + y).v)^d)} \tag{5.16}$$

Where bv_C is a variable channel for section C, d is a constant that accounts for the inclination of the floodplain function, f_a and f_b are functions to fulfill the criterion of continuity, H_f is the water depth where maximum segment width is over-flooded and y is the relative fraction of bars and banks of total inner channel width.

For each time step (Δt), the transmission losses (T_L) are computed by multiplying the flooded area (A) times the infiltration rate as follows:

$$T_L = \Delta t.A.(k_b - k_f).\exp\left(\frac{-t}{k_b + bv}\right) \tag{5.17}$$

Where k_b is the hydraulic conductivity for underlying strata, k_f is the initial infiltration rate (bars, banks and floodplains) and bv is the flooded width.

The computation of the transmission losses into over-bank areas basically follows the same method as the one into bars and banks. In contrast to bars and banks, over-bank areas are not partly flooded right from the start of the event. When the water depth surpasses a certain height, this area is activated with regard to transmission losses and the storage can be filled. Consequently, this area is deactivated when the water depth falls below this height. Considering this, the computation of the transmission losses remains like equation (**5.17**) with the difference that time starts running (and so the decline of the infiltration rate) when the water depth exceeds a certain height. As a result, infiltration occurs only when the over-bank areas are flooded (Leistert, 2005).

The following channel parameters such as channel length [m], percentage covered by inner channel, channel width [m], bankful stage [m], Manning n, infiltration rates [mm/hr] for inner channels and bars and the depth of active alluvium [m] are selected. For the Faria catchment and to limit the amount of needed input data, the channel segments are grouped into five different types classified in the field according to their morphological features. Model parameters are assigned uniformly for these different types.

5.3 TRAIN Model

TRAIN is a physically-based, spatially distributed model that has been designed to simulate the spatial pattern of actual evapotranspiration (Menzel, 1999). The model includes information from comprehensive field studies of the water and energy balance. It has been designed to simulate the spatial pattern of the individual water budget components at different spatial and temporal resolutions. Special focus is on processes at the soil-vegetation-atmosphere interface, with evapotranspiration as one of the principal mechanisms. The direction of these processes modeled by TRAIN is mainly vertical (**Fig. 5.3**).

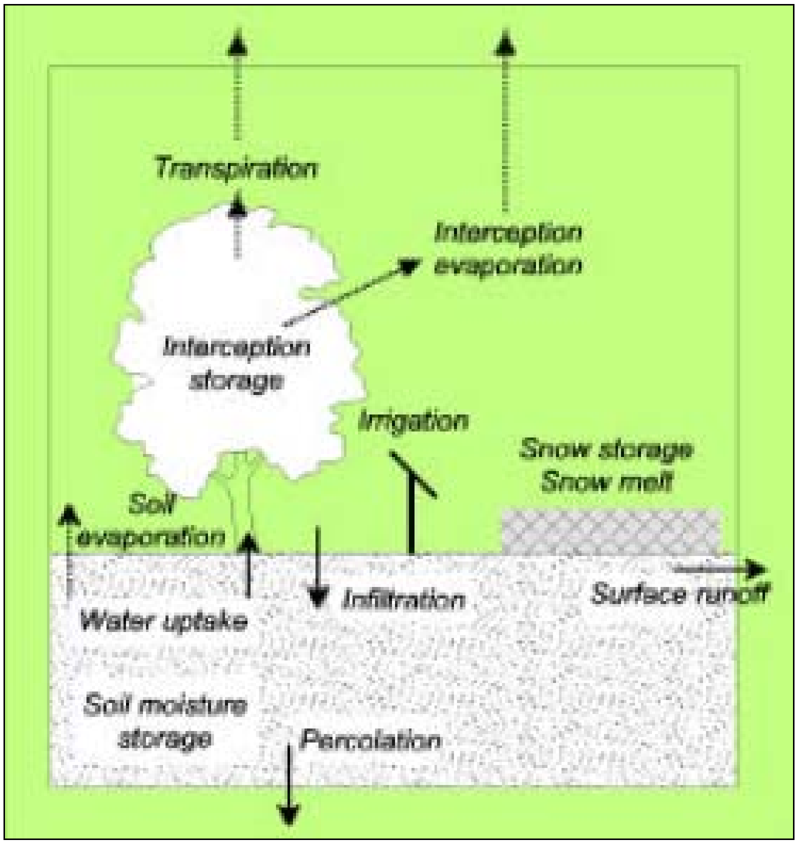

Fig. 5.3 Processes Simulated with the TRAIN Model (Menzel, 1999)

Soil moisture storage, deep percolation and evapotranspiration are components with longer term temporal fluctuations and do not vary within short time steps. The temporal resolution of one day is sufficient for good results. Spatially, the area is divided into raster cells.

In the original ZIN model, a constant value of evaporation (mm) was assumed. For continuous modeling of rainfall over the entire rainy season, TRAIN calculates the evapotranspiration with the Penman-Monteith equation using meteorological inputs of temperature, rainfall, relative humidity, wind speed and sunshine duration.

A soil grid and a land use grid assign every cell a corresponding value. There are 8 land cover categories and 8 soil types in the TRAIN database to choose from. A digital elevation model is needed to calculate exposition and shade correction.

TRAIN was developed for the estimation of evapotranspiration of the Swiss Alps, but has already been applied and validated successfully at selected sites (including both agricultural and natural vegetation) in the Jordan region, where continuous climate data series and information on soils, land cover and individual water balance components were available. This work served to further develop the model for an improved consideration of hydrological processes of arid and semi-arid environments and helped to evaluate the interactions between water fluxes, vegetation and land use under the given climatic and physiographic conditions.

5.4 Coupled TRAIN-ZIN Model

ZIN simulates short term runoff generation processes whereas TRAIN simulates longer term fluxes between soils, vegetation and atmosphere. Coupling TRAIN and ZIN leads to an improved real-time modeling of processes with a different temporal and spatial scale. The coupling layer of both models is the soil storage with a flexible time step of modeling is adapted to periods of rain and no-rain. During times of rain, ZIN model is active describing the filling of the soil storage and runoff generation by IEOF and/or SEOF in time steps of minutes. Runoff concentration and routing can be conducted in even smaller time steps. During times of no-rain (dry) the soil module of TRAIN is active and calculates the emptying of the soil storage by evapotranspiration and percolation. These calculations are important for modeling the next event, as they describe initial filling of the soil storage. With time steps of one day, TRAIN provides the missing long term simulation of soil moisture to ZIN. This modifies the ZIN model to a combined model that can be run in a continuous mode instead of single event oriented.

Fig. 5.4 illustrates the structure of a model coupling that done by Gunkel (2006) in the context of her PhD dissertation. Although the models are not directly linked through an iterative solution, a tight coupling was achieved. The models are not run parallel, but successively. TRAIN passes the values of one day of simulation to ZIN, which, in the case of rainfall, then starts its calculation for the same day in shorter time steps. Daily values of evaporation are converted into values for the ZIN time steps considering the hourly radiation and rainfall. ZIN uses the passed-on soil moisture content as initial moisture for its calculations. In this way, feedback and exchange between the models are done in real-time.

Both models were written in different programming languages. Therefore, a solution which allows the different codes to run parallel had to be found. The TRAIN code is written in FORTRAN77 and ZIN is available in C++. With the help of special software the TRAIN code can be run in a C++ environment. The connection was made without major modifications in the cores of each model (Gunkel, 2006).

The coupled TRAIN-ZIN model was used for the first time by Schütz (2006). The coupled model was successfully applied to a micro-scale (1.1 km²) catchment in the foothills of the Judean Mountains of Israel (Historical Palestine). The model produced acceptable simulations and functionality was proven. Although the model was applied for a data rich catchment, the deviation between the simulated and observed hydrographs showed the difficulty of reproducing runoff events with hydrological models without calibration.

After the successful application of the coupled TRAIN-ZIN model to a micro-scale catchment with sufficient data for a non-calibrated simulation, Fischer (2007) applied the coupled model for the meso-scale Harod catchment (170 km²) located in the north boarders of the West Bank, Palestine between Lake Tiberias and the Dead Sea in the LJRB. The model proved its functionality for meso-scale catchments with parameters determined through calibration.

Coupling TRAIN and ZIN, continuous and accurate simulations of hydrological responses across entire rainy seasons can be depicted for the Faria catchment as a focus region that helps to regionalize the model to the entire LJRB.

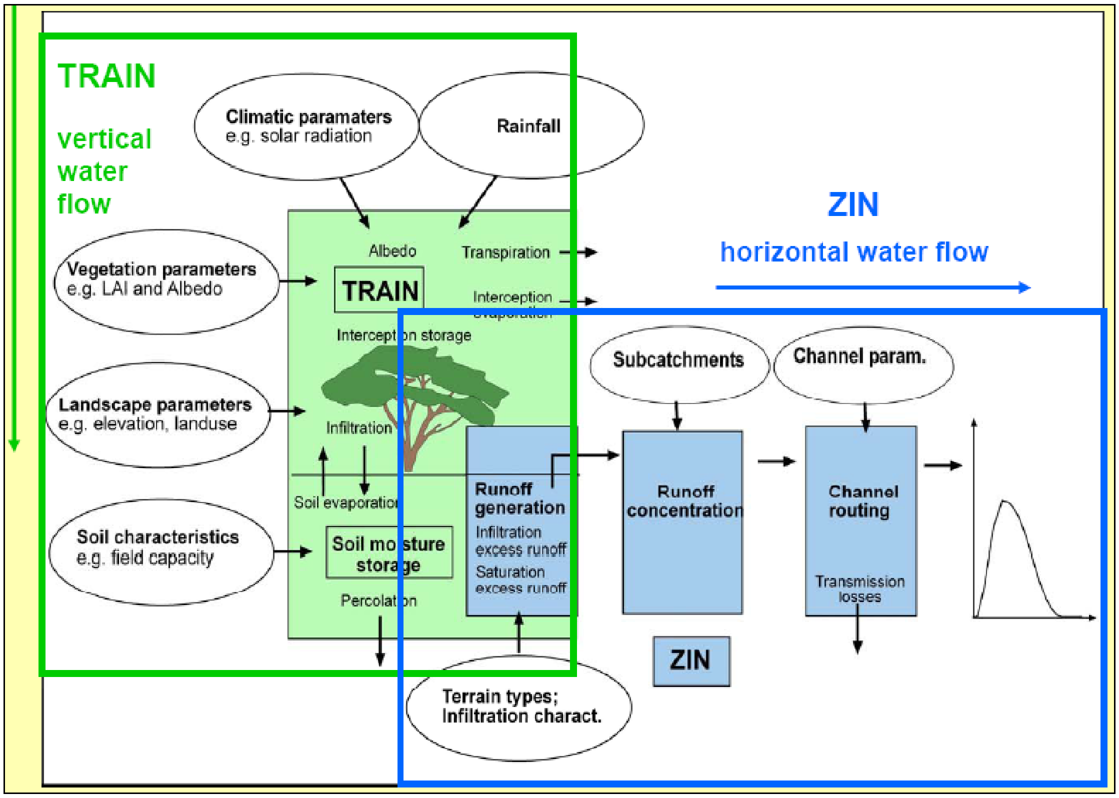

Fig. 5.4 The TRAIN-ZIN Coupling Scheme (Gunkel, 2006)

6 Parameterization

6.1 ZIN Parameters

6.1.1 Runoff Generation

From the screening of the research literature (see **Section 2.1.4**), it is clear that the IEOF is generally assumed to be the dominant mechanism of runoff generation in most arid and semi-arid regions. In some cases the SEOF takes place. In the ZIN model, both the IEOF and the SEOF are parameterized independently for each terrain type. The terrain types represent the sub-units for the model's runoff generation routine according to hydrologically relevant surface characteristics. In the Faria catchment, the spatial sub-units for runoff generation are mapped with the help of aerial photographs that cover the entire catchment (**Fig. 6.1**). By means of field work experiences and ground truthing, the different terrain types were checked directly in the field. As a result a detailed runoff generation map representing the spatial distribution of the different terrain types of the Faria catchment is obtained.

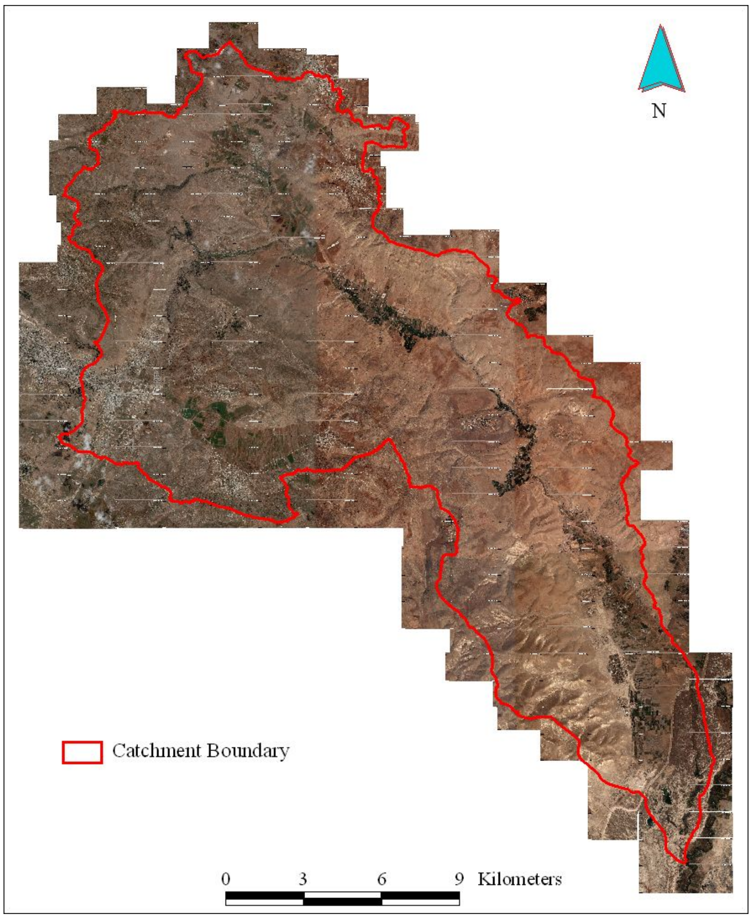

Fig. 6.1 Aerial Photographs Coverage of the Faria Catchment (Google Earth)

The map was produced from the combination of both land use (see **Fig. 3.13**) and soil (see **Fig. 3.14**) maps of the Faria catchment. Eight different terrains were mapped and named from **A** (high potential for runoff generation) to **H** (low potential for runoff generation). **Tab. 6.1** summarizes the characteristics of these terrain types. **Fig. 6.2** illustrates the runoff generation map of the Faria catchment. Based on this map, the model parameters for various terrain types are estimated. All different terrain types are shown in the annexes **(Pic. A1-A8)**.

Tab. 6.1 Characteristics of Different Terrain Types in the Faria Catchment

Terrain Type	% of Area	Description
A	2.84	Bare rocks that are located in lower part of the catchment
B	4.71	Built-up areas, the eastern part of Nablus city forms the largest part of this terrain
C	26.58	Sparsely vegetated hillslopes located in central and lower parts with small amounts of rainfall a companied by sparse vegetation cover. The potential for runoff generation is considerable
D	23.07	Grassland located mainly in upper part in Al-Badan sub-catchment hills
E	5.91	Grassland located in Al-Faria sub-catchment with a noticeable fragmented stone cover that is storing the rainfall and as a result little runoff is generated
F	7.80	Scattered and un-managed olive areas with little amount of runoff generation
G	6.37	Managed (tillage) olive plantations with terraces that prevent runoff generation
H	22.72	Agricultural areas, flat with deep soil and no runoff generation

For the above mentioned terrain types, several parameters were estimated. These parameters are: final infiltration rate (F_R), initial loss (I_L), soil depth (D), effective porosity (ϕ), permanent wilting point (PWP), saturated hydraulic conductivity (K_S), field capacity (FC) and lambda (λ). The final infiltration rate, the most sensitive parameter, for each terrain type was studied directly in the field. The spatial disaggregation for runoff generation is based on the results of double-ring infiltrometer experiments that were accomplished inside the Faria catchment. The double-ring-infiltrometer test is a well-recognized and documented technique for directly measuring soil infiltration rates (ASTM, 2003; Bouwer, 1986). A double-ring-infiltrometer (15 cm and 30 cm rings) using falling heads was used to investigate the infiltration rates in the Faria catchment. The experiment was established in several locations of the different terrain types and the time functions of infiltration in a five minute time step were obtained as shown in **Fig. 6.2**. Infiltration tests results provide the necessary information on infiltration properties on different surfaces. The spatial sub-units for runoff generation are represented by terrain types with the same temporal behavior of infiltration. For terrain types **A** (rock cover) and **B** (built-up areas) the final infiltration rate values were obtained from the literature and then calibrated. Measuring the infiltration rate in built-up areas is questionable. Built-up areas, on the one hand, consist of paved surface and house roofs that generate a high amount of runoff. On the other hand, they contain parks, green strips or gardens that allow high amount of rainfall to infiltrate. In this study, a lumped value was assumed and then calibrated.

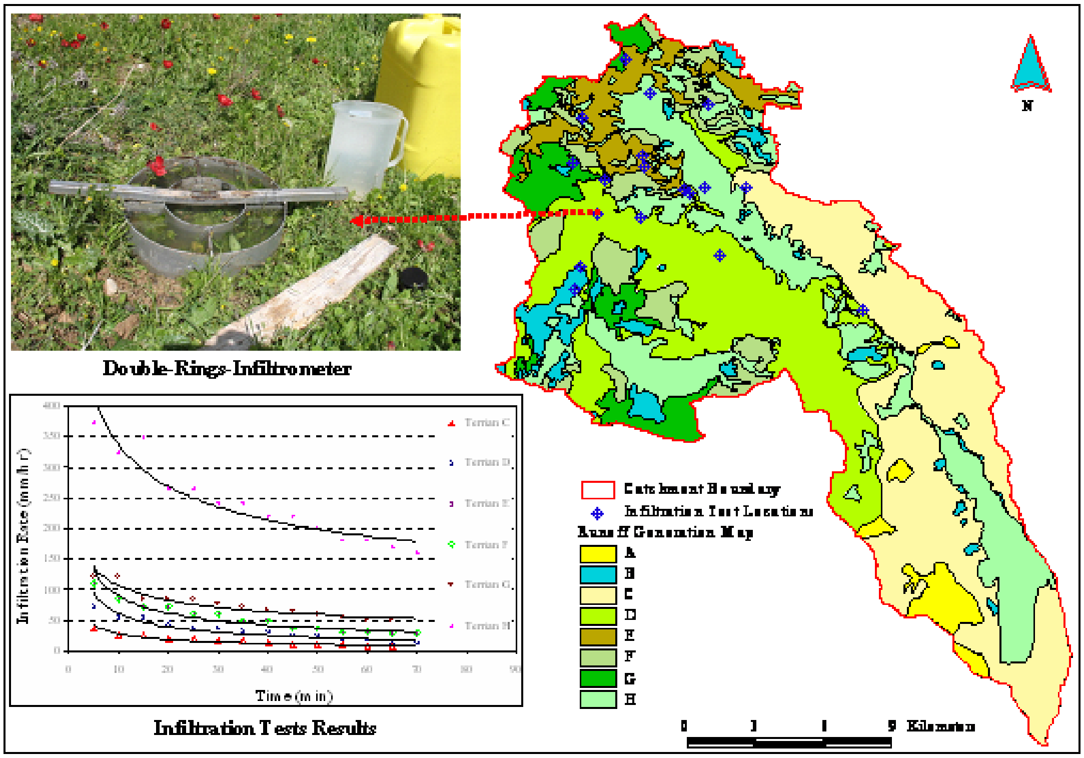

Fig. 6.2 Runoff Generation Map with the Measured Infiltration Rates at Different Locutions inside the Faria Catchment

When analyzing the measured data (see **Section 4.5**) it was noticed that a certain amount of rainfall is always required before any runoff occurs. This amount, usually referred to as threshold rainfall, represents the initial losses due to interception and depression storage as well as to meet the initially high infiltration losses. The threshold rainfall depends on the physical characteristics of the area and varies from catchment to catchment. In areas with only sparse vegetation and where the land is very regularly shaped, the threshold rainfall may be only in the range of 3 mm while in other catchments this value can easily exceed 12 mm, particularly where the prevailing soils have a high infiltration capacity. The fact that the threshold rainfall has first to be surpassed explains why not every rainstorm produces runoff (Critchley and Siegert, 1991). In this study, based on the vegetation conditions, initial loss was assumed and calibrated for each terrain type.

All infiltration curves and the values for initial loss were attributed to the eight terrain types yielding a catchment wide GIS-layer of infiltration characteristics. The infiltration characteristics in combination with the temporal behavior of rainfall intensities govern the model's runoff generation. The temporal sequence of rainfall input in a five minute time step was applied onto the layer of infiltration properties. The catchment wide runoff generation was calculated for each five minute time step on a cell-by-cell basis, using a 50x50m grid.

After enough rain had fallen to meet the initial loss, runoff generation started, when rainfall intensities exceeded infiltration capacity.

According to the different soil texture, the effective porosity and lambda were estimated from Maidment (1992). The capacity of the soil storage was determined with the effective porosity and soil depth. The soil depth was taken out from the study of MOPIC (1998) for each terrain type. Other parameters needed to be determined for the calculation of the unsaturated hydraulic conductivity with the Van-Genuchten equation (**5.1**). Based on the soil texture, K_S, PWP and FC were calculated by the SPAW hydraulic properties calculator (Saxton and Rewards, 1986). The equations of this tool are derived from statistical analysis of over 2000 soil samples from the USDA/NRCS national soil characterization data base. All terrain properties are tabulated in **Tab. 6.2**.

Tab. 6.2 Terrain Types Parameters

Terrain	**F_R (mm/h)**	**I_L (mm)**	**D (m)**	ϕ	**PWP**	K_S (cm/h)	λ	**FC**
A	1	3	0.1	0.340	0.010	0.100	0.100	0.020
B	4	6	0.5	0.360	0.124	0.102	0.107	0.180
C	7	4	0.6	0.396	0.204	0.325	0.276	0.269
D	14	5	0.8	0.388	0.237	0.382	0.231	0.325
E	28	9	1.0	0.386	0.267	0.542	0.176	0.360
F	34	8	1.1	0.400	0.295	0.604	0.168	0.397
G	50	10	1.2	0.410	0.290	0.876	0.173	0.410
H	100	12	1.6	0.420	0.276	1.220	0.186	0.450

6.1.2 Runoff Concentration

For the determination of sub-catchments, the channel network is divided into segments which are adjoined by small sub-catchments (model elements) delineated according to catchment topography. For this purpose, a detailed topographic map supported by a Digital Elevation Model (DEM), (20×20 m) and aerial photographs were made available and used. DEM is a valuable tool for the topographic parameterization of hydrological models. DEM is easily used within the GIS ArcView system to extract the hydrological data by analyzing different topographical attributes (elevation, slope, aspect, relief, curvatures) for modeling purposes. The HEC-GeoHMS 1.1 extension (Doan, 2000) with available DEM extends ArcView and Spatial Analyst capabilities were used to preprocess the channel network as required for the ZIN model. As a result, the channel network adjoined by small sub-catchments was obtained and mapped. These were checked directly on the aerial photographs and modifications were made.

For model purposes, first order channels had been extended up to the catchment divide. Channel nodes were placed along the water course, firstly accounting for confluences. Secondly, the condition that generally applies is that the distance traveled by the wave or hydrograph in one time step Δt must never exceed the distance between computational nodes. If the length of a segment Δx is too short, then computational instability errors may occur, resulting in large non-physical oscillations. Courant and Friedrichs (1948) in Chow et al.

(1988) used approximate stability criteria for explicit numerical solution schemes of the kinematic wave of the full Saint-Venant equations for open channel flow. The approximation, which is known as Courant Condition, can be expressed in terms:

$$\Delta t \leq \frac{\Delta x}{V_k} \tag{6.1}$$

Where Δt is the computational time step, Δx is the distance step (channel segment length) and V_k is the kinematic wave celerity.

In the case of Faria catchment, a constant one minute time step is used for model routing application. For flow velocity the maximum velocity of flood waves is assumed to be 5 m/s, measured in a comparable environment (Schick, 1988). Substituting in equations (**5.9**) and (**6.1**), a minimum channel segment length of 500 m for Δx resulted. Having this length in mind, channel nodes were placed. The average length of the resulting 544 channel segments inside the Faria catchment was 847 m, with maximum length of 1940 m. The average area of the contributing sub-catchments on both sides of the channel segments (1088 polygons) is about 0.295 km^2. **Fig. 6.3** shows the subdivided channel network with adjacent polygons that represent spatial sub-units for runoff concentration.

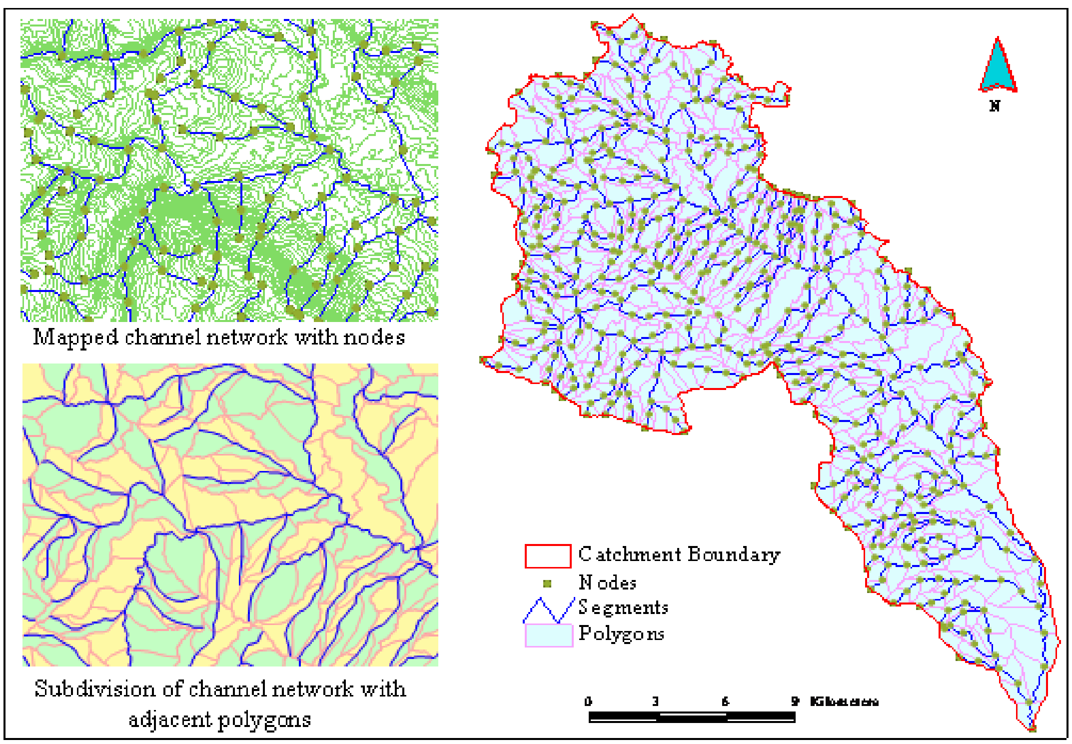

Fig. 6.3 Spatial Subdivision for Runoff Generation in the Faria Catchment

6.1.2.1 Hydrological Lag Time

In the Faria catchment, a lack of information on the mean response function or runoff hydrograph for sub-catchments exists. As shown above, the Faria catchment was divided into

1088 sub-catchments with an average area of about 0.295 km^2. For runoff concentration, a uniform response function was assumed and a constant value for the time lag was used and calibrated for both events 1 and 2. The model was run several times in order to get the best value that represents the situation in the Faria catchment. In **Fig. 6.4** and **Fig. 6.5**, the simulated runoff with different values of the hydrological time lag for both Al-Badan and Al-Faria sub-catchments are presented. As a result it was found that 70 minutes is the best value for the hydrological lag time in the Faria catchment.

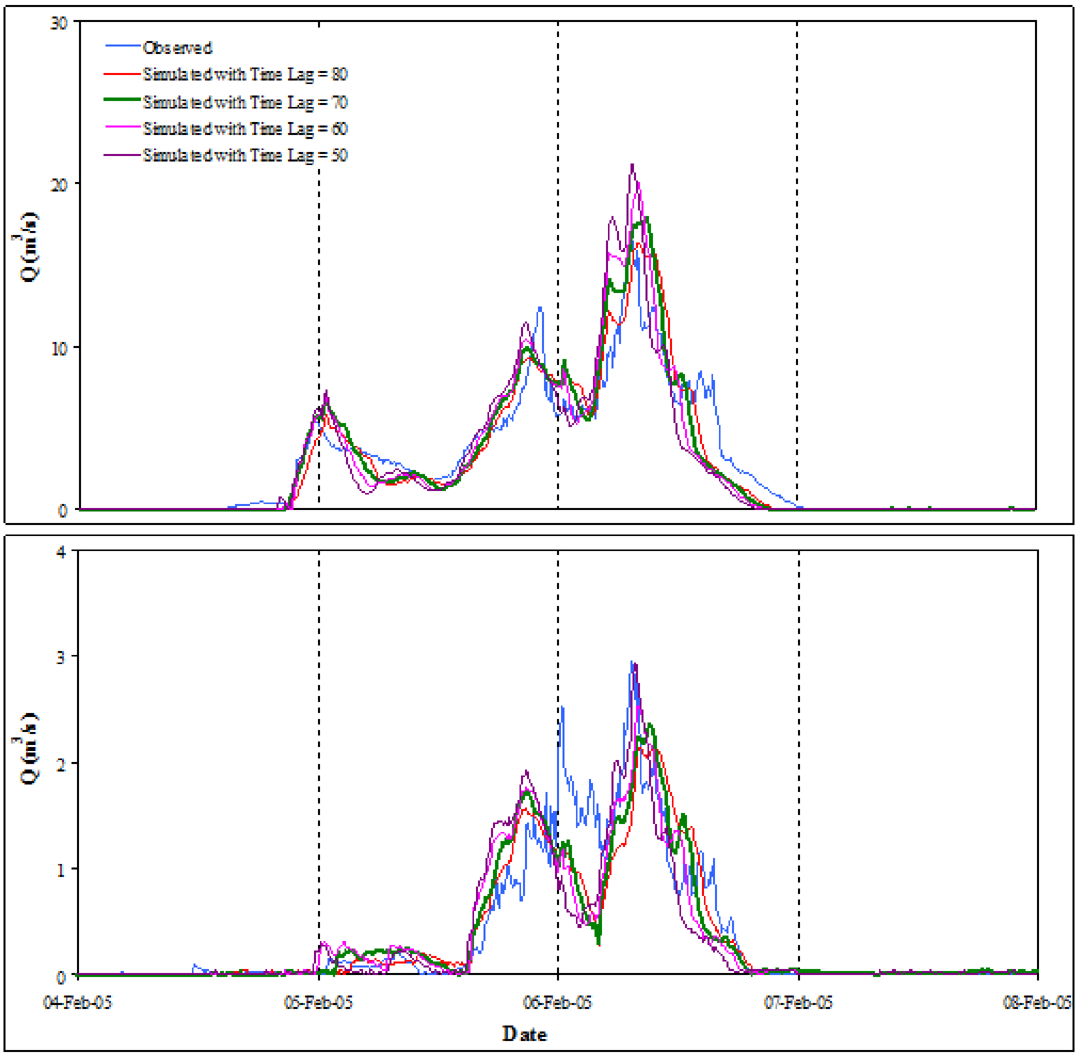

Fig. 6.4 Calibration of the Hydrological Time Lag for Event 1; upper part: Al-Badan Sub-catchment and lower part: Al-Faria Sub-catchment

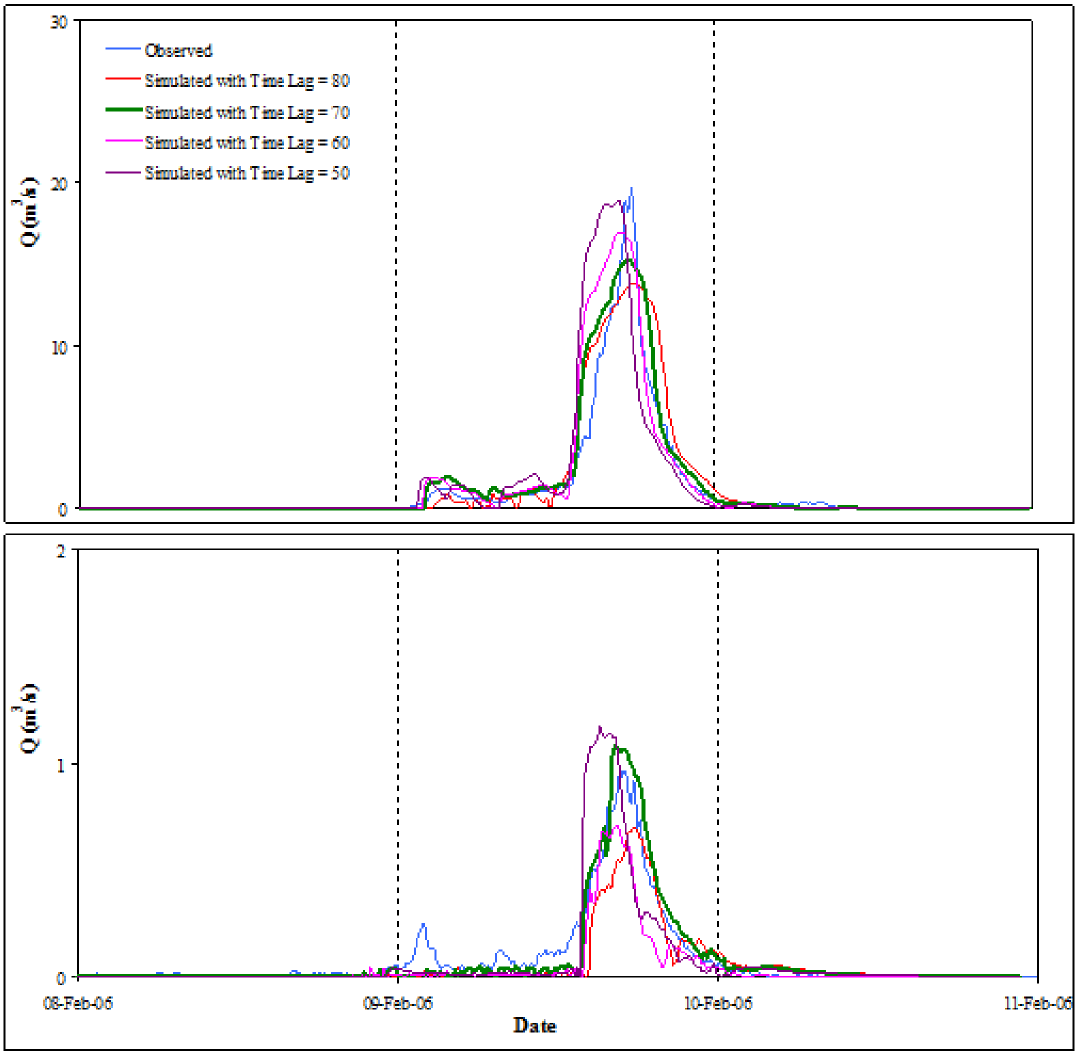

Fig. 6.5 **Calibration of the Hydrological Time Lag for Event 2; upper part: Al-Badan Sub-catchment and lower part: Al-Faria Sub-catchment**

6.1.3 Channel Flow and Transmission Losses Parameters

For the computation of the channel flow and transmission losses using the routing routine, 12 model parameters for each channel segment had to be determined resulting in 6528 different parameter values. However, to reduce the large number of these parameters, Lange (1999) applied a classification scheme for channel types. This was done according to similarities between single channel reaches. In the Faria catchment, the channel segments are grouped into 5 different channel types according to their morphological feature similarities as described in **Tab. 6.3**. It was based upon a thorough field survey and on aerial photographs. Examples of the different channel types are given in the annexes (**Pic. A9-A13**).

Tab. 6.3 Channel Types Description

Channel Type	Description
1	Steep headwater (first order channels) reaches
2	Channels that pass through agricultural areas, where the channel bed is covered by alluvial cover with 6% mean channel slope.
3	Clearly definable main channel with pronounced entrenchment with coarse channel bed alluvium and vegetation is limited to banks and high bars
4	Perennial flat channels (springs flow) filled with a dense vegetation cover
5	Perennial braided channel systems with large cross sectional widths with coarse channel bed alluvium and a dense vegetation cover

For the determination of channel parameters, information from a topographic map and aerial photographs, as well as information from field campaigns were available. All this information was arranged inside the GIS environment to facilitate further analysis.

From the topographic map (DEM), information on channel length and slope was extracted for each channel segment independently. Slopes were determined by dividing the difference in height of the nodes (they were read out of the DEM) with the segment length. As described in Lange (1999), a representative channel width was derived from aerial photograph analysis. Channel width is calculated for each segment, dividing the segment's inundated area at bankfull stage by the respective channel length. The inundated area at the bankfull stage that can be flooded (inner channel plus over-bank area) was determined by digitizing the active channel bed alluvium from the aerial photographs for each channel segment (**Fig. 6.6**).

For the small channel segments (head water channels) with widths of less than two meters no exact measurement was possible because it is too hard to digitize their active bed alluvium. To overcome this difficulty, an empirical formula that developed by Lee and Yen (1997) was used for channel width estimation as follows:

$$B_i = \frac{B_\Omega \sum_{i=1}^{1} L_{c_i}}{\sum_{i=1}^{\Omega} L_{c_i}} \qquad (6.2)$$

Where B_Ω denote the channel width at the catchment outlet and L_{c_i} is the ith channel length. To use the above formula the outlet width of the Faria catchment was measured from the aerial photographs. The estimated values were verified at several locations on the aerial photographs with good results; and a field check of more than 50 selected channels was carried out with a reasonable matching. For the remaining model parameters the used channel classification scheme reduced the number of independently determined parameter values from 544 for each channel segment to five for each channel type.

Fig. 6.6 Determination of a Spatially Averaged Channel Width

For each channel type, the percentage covered by inner channels (I_P) (the area of the inner channel divided by the total area that can be flooded), the depth of active alluvium (D_A) and the depth to the bankfull stage (H_F) were estimated through field surveys. Bankfull stage is a decisive parameter for the interpolation of cross sectional width. Several cross sections for each channel types were measured and analyzed. Then mean values for these parameters according to the different types were calculated. Other parameters including the hydraulic conductivity (inner channel) (k_i), the infiltration constant (bars, banks and floodplains) (k_b), the final infiltration rate (hydraulic conductivity of the underlying strata) (k_f), the effective suction head (He), the critical flow velocity/shear stress (Vk), the infiltration reduction factor (L) and the antecedent moisture index (AMI) were assigned from previous research (e.g. Leistert, 2005).

The most important factors influencing the determination of Manning roughness coefficient (n) are the surface roughness of the bed material, vegetation cover and flow obstructions. In this study, a Manning value for each channel type in the Faria catchment is estimated using the listed values outlined by Chow (1959). Photographs of channel cross-sections found therein help to select representative values. Channel roughness coefficients were kept constant in time and not varied according to water level. **Tab. 6.4** depicts the channel properties for the 5 channel types.

Tab. 6.4 Channel Types Parameters

Parameter	Type1	Type2	Type3	Type4	Type5
D_A (m)	0.2	0.9	1.0	1.2	1.4
n	0.05	0.03	0.035	0.04	0.045
I_P	0.7	0.7	0.5	0.4	0.35
H_F (m)	0.3	0.7	0.8	0.9	1.0
ϕ	0.38	0.4	0.4	0.43	0.45
k_i (mm/h)	130	80	70	60	50
k_b (mm/h)	150	100	80	70	60
k_f (mm/h)	10	6	5	4	4
He	0.1	0.1	0.1	0.15	0.15
Vk	0.035	0.03	0.025	0.02	0.015
L	0.1	0.1	0.1	0.1	0.1
AMI	0.65	0.85	0.8	0.85	0.9

6.2 TRAIN Parameters

Climate data, land use, soil and elevation are the required parameters for the TRAIN model. The daily values of temperature, relative humidity, wind speed, and sunshine duration mark the meteorological input. The relative sunshine duration is additionally connected to hourly radiation data to insert a quantitative energy value into the model. In the Faria catchment, meteorological data were taken from the Nablus Meteorological Station (NMS) which is the only weather station still working in the catchment. **Tab. 6.5** depicts part of the climatic data from NMS that used in the TRAIN model.

Tab. 6.5 Climatic Data from the NMS

Year	Month	Day	T [°C]	RH [%]	U [m/s]	SSD
2005	1	1	15.3	0.39	0.8	0.2
...	...	...	...	...	...	...
2005	3	1	16.4	0.36	1.4	0.4
...	...	...	...	...	...	...

The land use, soil and elevation are stored in a grid. The catchment was divided into 322,056 cells of 50x50m² in 504 columns and 639 rows. The land use grid was created out of the developed land use map. Each cell was assigned to one of the 8 land cover classes of the TRAIN database. The soil grid with the 8 possible soil classes out of the database was generated from the soil map. These inputted data for the TRAIN model facilitate the simulation of the spatial pattern of actual evapotranspiration in the Faria catchment.

7 Application of the Coupled TRAIN-ZIN Model

7.1 General Aspects

7.1.1 Model Calibration and Validation

Calibration is a process of adjusting simulated values, using deviations from observed values for a particular area to derive correction parameters that can be applied to generate simulated values that are consistent with the observed values (Muthukrishnan et al., 2006).

Calibration is a necessary process for rainfall-runoff models. It is understood that every rainfall-runoff model should be tested against observed data, from the catchment under study, to understand the level of reliability of the model (Linsley, 1982; Melching, 1995).

For physically-based distributed models such as the coupled TRAIN-ZIN model used in this study, a large amount of data is required. This data often is not available and so becomes subject to calibration. A common problem in rainfall-runoff models is that equally good model simulations might be obtained with different sets of parameters. This phenomenon is termed by Beven (1993, 2001) as equifinality. For that reason, a parameter set should always be checked on its physical justification and compared with measured or reported values. In this study, direct measurements conducted in the field were used as starting values for the calibration process.

Two methods were used for calibration: the traditional method which is based on a trial-and-error process and the automatic method based on techniques such as multiple objective methods, linear and non linear regression models (Cooper et al., 1997; Yu and Yang, 2000; Elshorbagy et al., 2000; Ndiritu and Daniell, 2001; Madsen et al., 2002 and Muthukrishnan et al., 2006).

In this study, the traditional method of calibration was used due to the large number of raster cells and different parameters that make model runs computationally expensive. Through a trial-and-error process, input parameters were adjusted one at a time and the model performance during calibration was evaluated by visual comparison of the observed and simulated hydrographs. In addition, the different statistical goodness-of-fit measures listed in the following section were also used to assess the performance of the model results after each model run. This method was carried out sequentially by adjusting the model input parameters until the simulated values approximate the observed values.

Since the Faria catchment was not gauged at its outlet, the upper Faria catchment which was gauged by two Parshall Flumes, one on the Al-Badan sub-catchment outlet and the other on Al-Faria sub-catchment outlet was used for model calibration. Subsequently, the model was extended to the entire catchment. Senarath et al. (2000) tested their calibrated model against observed runoff at several stations within a catchment. They also noted that as the size of a sub-catchment increases, the quality of the runoff simulations for this sub-catchment predictably approaches the quality of the simulations for the entire catchment. Therefore, calibration of the TRAIN-ZIN model on the upper Faria catchment which covers more than 43% of the entire catchment was assumed to be enough to have a set of parameters that are valid for the entire Faria catchment.

The parameter values for the three basic components in the coupled TRAIN-ZIN model, namely the runoff generation component, channel flow and transmission losses components and evapotranspiration component (climatic data for TRAIN part), were measured directly in the field (infiltration rate and channel geometry) estimated from the literature (e.g. hydraulic conductivity, porosity, channel roughness, field capacity and others) and recorded (climatic parameters).

In this study, only four events were available for model calibration and validation. The runoff simulation of event 1 with more SEOF and event 2 with mainly IEOF were calibrated using the TRAIN-ZIN model. The runoff simulation of event 3 and event 4 were used for model testing. Procedures of model testing are usually called validation. Validation is defined as the estimation of the confidence in the ability of a model to perform with a certain quality for its intended purpose (Seibert, 1999). In this study the purpose of model validation is to assess the ability of the calibrated TRAIN-ZIN model to reproduce the rainfall response in the Faria catchment in terms of direct runoff for rainfall events that are not used in calibration. Actually, validation is not restricted to an application in a special catchment but also includes a general assessment of the capabilities and limitations of a model. Therefore, it is important to distinguish between situations where parameter values are changed to minimize the deviations between simulations and observations (calibration) and situations where such an optimization is not performed (validation).

A common set of parameters was tested and tuned for both calibration events (event 1 and event 2). After alternating calibration of the first and the second rainfall events, it was found that tuning of the initial saturation is the most important parameter to attain a good match between the simulated and observed hydrographs. The process of SEOF was much more important for event 1 which took place after several rainy days. Assuming that the soil was close to saturation, therefore calibration focuses on the initial moisture conditions. For event 2 which came after several dry days and due to the short duration (22 hour) compared to event 1 (55 hour), no SEOF is expected. Calibration therefore could focus on the parameters which influence the generation of IEOF (e.g. initial losses).

In the whole calibration process the parameter values for the runoff generation component (infiltration rate for terrain type B (built-up areas), initial loss, soil depth and saturated conductivity) were changed. Porosity, field capacity and permanent wilting point were kept untouched. For runoff concentration, the time delay was adjusted during the first model runs. Parameter values for channel flow and transmission losses components, namely the hydraulic conductivity, infiltration capacity and the antecedent moisture index were also changed whereas the others kept unchanged. All parameters of the TRAIN model did not undergo any calibration. **Tab. 6.2** and **Tab. 6.4** presented in the previous Chapter summarized the final set of parameter values attained after the simultaneously calibration process for both event 1 and event 2. For the verification of the model, event 3 and event 4 (which were not used during calibration process) were simulated with the obtained parameter set from the calibration of the other two events. After a short description of event characteristics, calibration and validation results are presented for each event in the following sections. The presented simulated hydrographs were all obtained with the final parameter set (**Tab. 6.2** and **Tab. 6.4**).
After the modeling of the four single rainfall events the calibrated TRAIN-ZIN model was applied in continuous mode for the entire rainy seasons 2004/05, 2005/06 and 2006/07.

7.1.2 Model Performance

During calibration, model performance was evaluated by visual comparison of the observed and simulated hydrographs. In addition, to assess model performance (the ability of the model to reproduce the observations with acceptable accuracy) the simulation results were compared with the observed data using different statistical goodness-of-fit measures such as the Nash-Sutcliffe coefficient, the volume error and the peak error.

The Nash-Sutcliffe coefficient (EFC) developed by Nash and Sutcliffe (1970) is a dimensionless transformation of the sum of squared errors and has become one of the most widely used goodness-of-fit measures used to evaluate rainfall-runoff model performance:

$$EFC = 1 - \left(\frac{\sum_{i=1}^{n} \left(Q_{O_i} - Q_{S_i} \right)^2}{\sum_{i=1}^{n} \left(Q_{O_i} - \overline{Q_O} \right)^2} \right) \tag{7.1}$$

In which Q_{O_i} is the observed runoff, Q_{S_i} is the simulated runoff, $\overline{Q_O}$ is the mean observed runoff, i is the time step and n is the number of time steps. Possible values of EFC range from $-\infty$ to 1. EFC= 1 when all the simulations equal their corresponding observations; EFC= 0 when model simulations estimate the mean observed streamflow. Bad simulations exhibit negative EFC.

The volume error (VE) and the peak error (PE) were computed to judge the performance of the model with regard to its ability to maintain the water balance and its estimation capacity of peak flow. As the values of VE and PE become close to zero (negative or positive), good model performance is attained.

The VE specifies the deviation between observed and simulated runoff and assesses the model performance with an emphasis on total runoff volume and is defined as:

$$VE = \left(\frac{\sum_{i=1}^{n} \left(Q_{S_i} - Q_{O_i} \right)}{\sum_{i=1}^{n} \left(Q_{O_i} \right)} \right) \tag{7.2}$$

The PE is defined based on the relative difference between the maximum observed ($Q_{O(\max)}$) and the maximum simulated ($Q_{S(\max)}$) runoff:

$$PE = \left(\frac{Q_{S(\max)} - Q_{O(\max)}}{Q_{O(\max)}} \right) \tag{7.3}$$

7.2 Event Modeling

7.2.1 Event 1, 4 – 6 February 2005

7.2.1.1 Event Characteristics

During the rainy season of 2004/05, only one considerable event was recorded. After less than two days of no rainfall, a big rainstorm event occurred. In three consecutive days, an areal averaged rainfall of 113 mm was recorded; 39 mm of rain fell during the first day, 43 mm and 31 mm on the following two days respectively. The spatial distribution of this rainstorm event is presented in **Fig. 7.1**. At about midnight of the first day, a small peak of runoff of 5 m³/s was recorded at Al-Badan flume. This peak occurred after the initial losses were reached, in a matter of hours, due to the high rainfall intensities preceding this peak. After that, low intensities of rainfall were recorded producing a peak runoff of 13 m³/s 22 hours later. Then, and after nine hours, in the morning of the third day a peak runoff of about 17 m³/s was observed. After two days of no rainfall, it can be assumed that soil moisture content is low and due to the relative high initial losses, saturation was not reached. The generated runoff should mainly be from the IEOF type. Whereas the second and the third peak came after 22 and 31 hours of the first peak respectively, saturation of the soil storage could be expected due to the high amount and low intensity of rainfall that fell prior these peaks. The generated runoff should be mostly from the SEOF type.

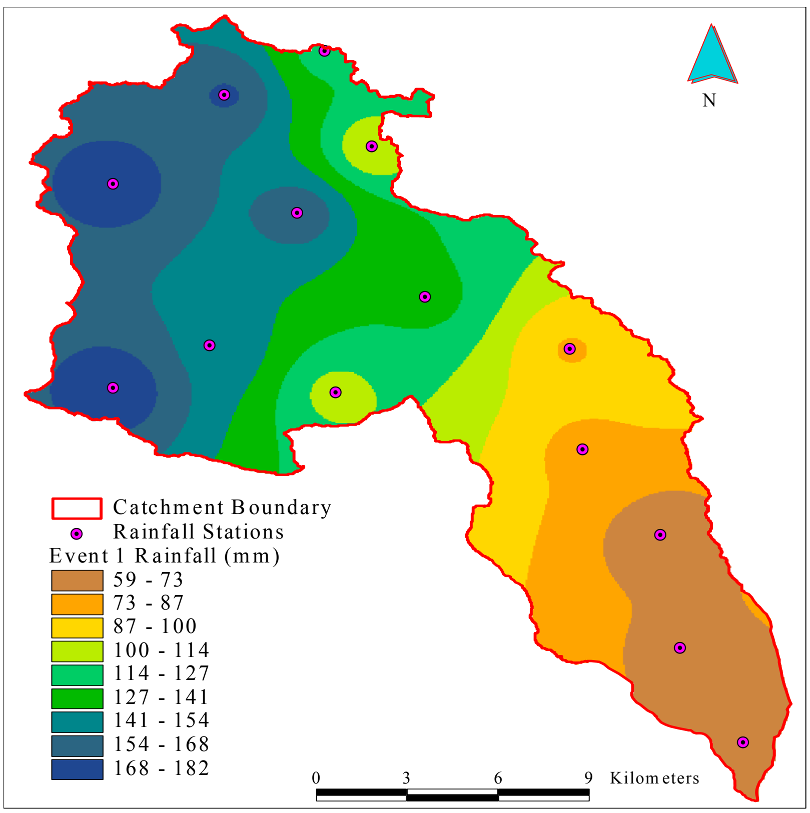

Fig. 7.1 Rainfall Grid of Event 1 (4-6/02/05) Generated By the IDW Method

It is worth mentioning here that this rainstorm event produced low peaks of runoff observed at Al-Faria flume comparing to the observed peaks at Al-Badan flume only: 0.5, 2.9 and 3.5 m^3/s of runoff.

The total volume of the flood recorded at Al-Badan flume was 976,161 m^3 and the runoff coefficient of the whole event was 0.10, while at Al-Faria flume; the recorded volume and runoff coefficient were 125,661 m^3 and 0.02 respectively.

7.2.1.2 Model Results and Discussion

Observed and simulated hydrographs are shown in **Fig. 7.2**. The simulated hydrograph was produced with the common set of final parameters obtained after the calibration of the two events (1 and 2). **Fig. 7.2** shows that the three peaks as well as the rising and falling limb of the hydrograph were reproduced successfully for both Al-Badan and Al-Faria sub-catchments. It is noticed also that the first and the second peaks are generated mostly from the IEOF while the third one is mostly SEOF. For the entire event, 62% of runoff was generated as SEOF. Initial moisture was, as expected, a very sensitive parameter for the start of SEOF. For this event, initial moisture of 0.70 is the best value obtained after several runs during calibration.

The Nash-Sutcliffe coefficient (EFC), the volume error (VE) and the peak error (PE) for both Sub-catchments are calculated as presented in **Tab. 7.1**.

Tab. 7.1 Performance Coefficients of Event 1

Parameter	EFC	VE	PE
Al-Badan	0.84	0.01	0.06
Al-Faria	0.78	-0.04	-0.20

Tab. 7.2 shows that for Al-Faria sub-catchment the model underestimated both runoff volume and peak. Relatively speaking, the PE for Al-Faria sub-catchment (-0.20) is not so different from the one of Al-Badan sub-catchment (0.06) since the peak runoff of Al-Faria is small (~3 m^3/s) compared to that of Al-Badan (~17 m^3/s).

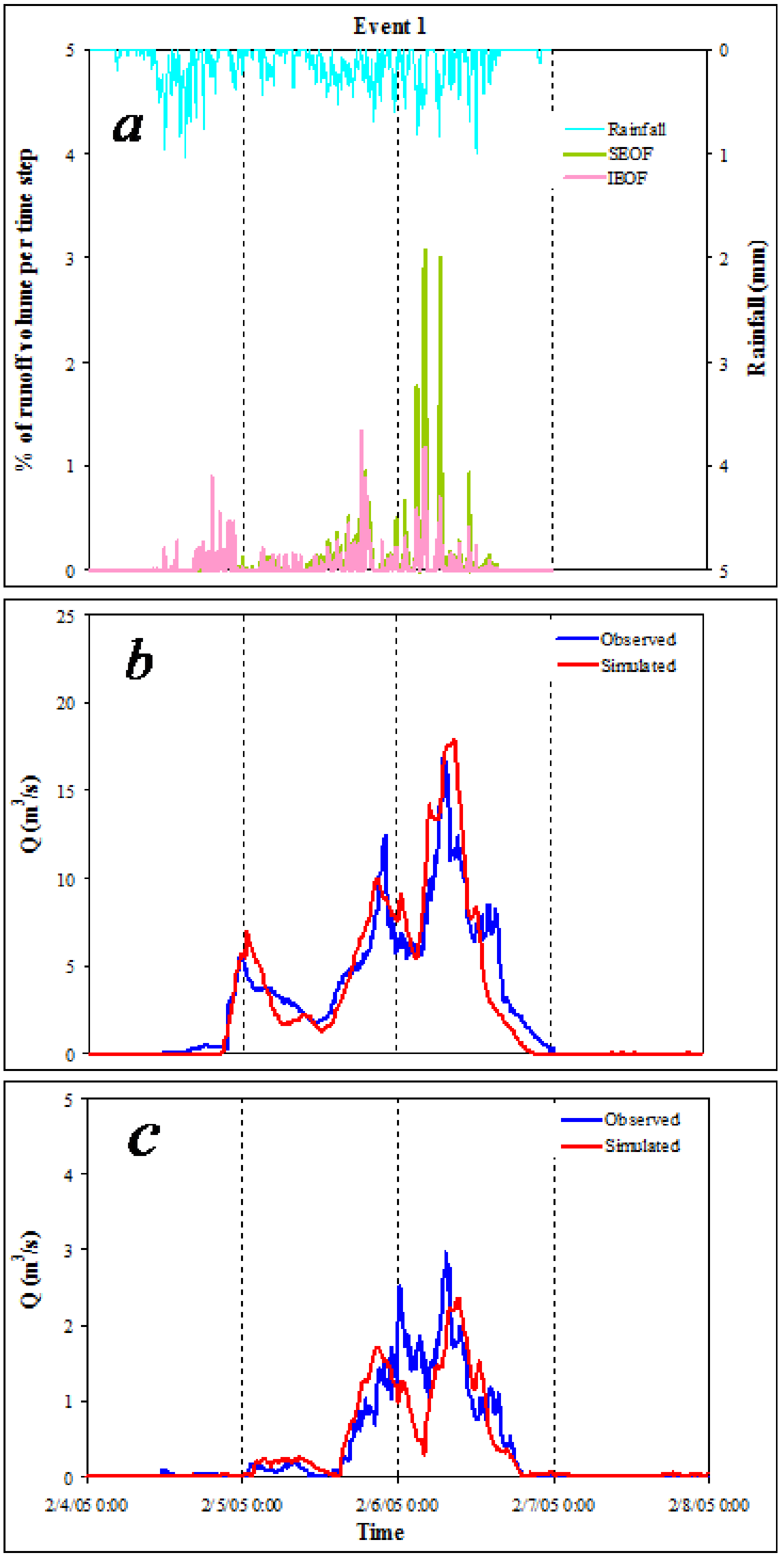

Fig. 7.2 **Simulation of the Event 1: (a) Rainfall, SEOF and IEOF; (b) Al-Badan Sub-catchment and (c) Al-Faria Sub-catchment**

7.2.2 Event 2, 8 – 9 February 2006

7.2.2.1 Event Characteristics

The second simulated rainstorm event occurred during the rainy season of 2006. In two days the event brought, on average, about 70 mm of rainfall; 15 mm fell in the first day and 55 mm fell during the second day (**Fig. 7.3**). This event came after a dry period of 5 days. As a result one peak runoff of about 20 m^3/s and 1 m^3/s was recorded at Al-Badan and Al-Faria flumes respectively. Compared to the first event, about half of the total rainfall produced one large peak runoff which is larger than the peaks recorded at Al-Badan flume and less than the observed peaks at Al-Faria flume. In this event saturation was not reached after five dry days where the soil moisture content is very low. The generated runoff should mainly be from the IEOF type.

The total volume of the flood recorded at Al-Badan flume was 316,142 m^3 and the runoff coefficient of the whole event is 0.05, while at Al-Faria Flume, the recorded volume and runoff coefficient are 20,956 m^3 and 0.005 respectively.

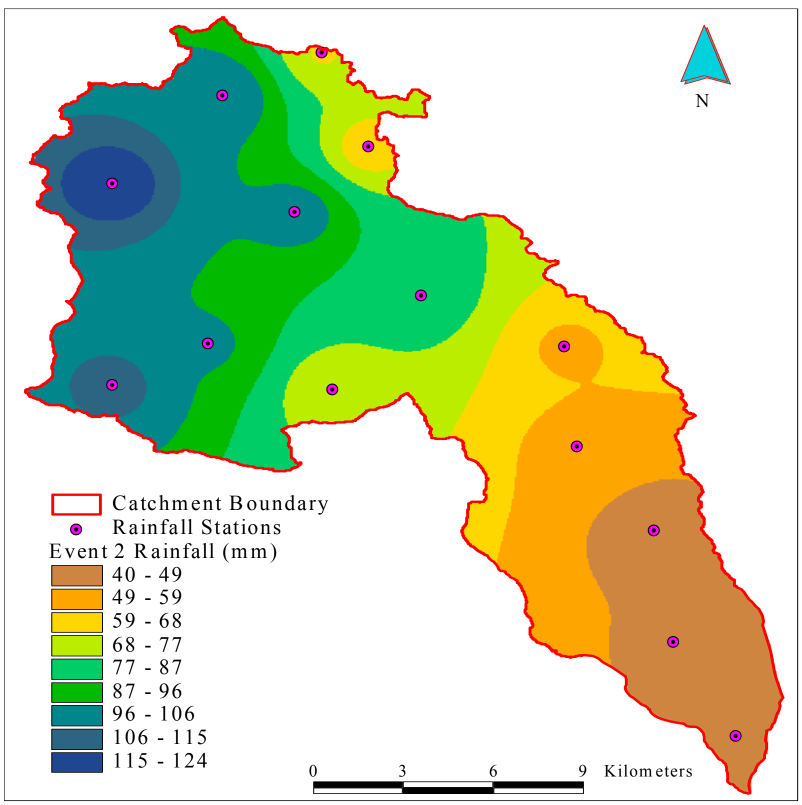

Fig. 7.3 Rainfall Grid of Event 2 (8-9/02/06) Generated by the IDW Method

7.2.2.2 Model Results and Discussion

In **Fig. 7.4** the observed and the simulated hydrographs are plotted. As for event 1, the simulated hydrograph was produced with the determined final parameter set after the calibration of two events. Visual inspection of the figure shows the good agreement between observed and simulated hydrographs for both Al-Badan and Al-Faria sub-catchments. Both peak and time to peak were modeled correctly. From the figure it is clear that this event was generated mostly from the IEOF (98%). For this event the performance coefficients are as shown in **Tab. 7.2**.

Tab. 7.3 Performance Coefficients of Event 2

Parameter	**EFC**	**VE**	**PE**
Al-Badan	0.91	0.13	-0.22
Al-Faria	0.90	0.003	0.09

It is clear that EFC is good for both sub-catchments. For Al-Badan sub-catchment, the model overestimated the runoff volume and underestimated the runoff peak.

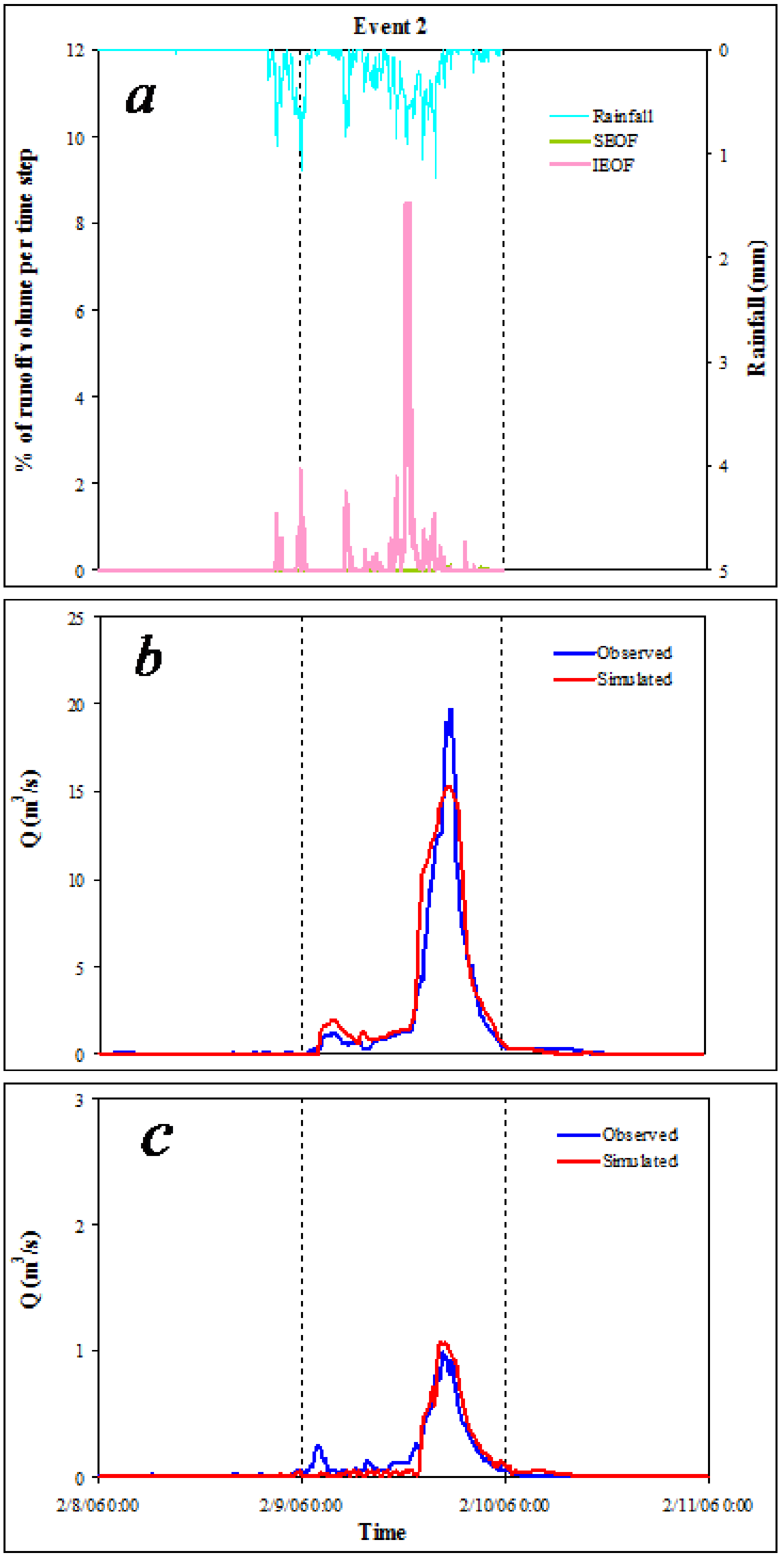

Fig. 7.4 **Simulation of the Event 2: (a) Rainfall, SEOF and IEOF; (b) Al-Badan Sub-catchment and (c) Al-Faria Sub-catchment**

7.2.3 Event 3, 26 – 27 December 2006

7.2.3.1 Event Characteristics

The third simulated rainstorm event with a total average rainfall of 65 mm was occurred in two consecutive days in December 2006. On the first day 47 mm of rainfall fell followed by 18 mm of rainfall in the second day (**Fig. 7.5**). Compared to event 2 which produced a significant amount of runoff, although the rainfall amount was similar, the generated runoff from this event was very small. This can be attributed to the initial conditions of this rainfall event. After 40 days of no rainfall, the initial soil moisture was undoubtedly zero. IEOF is the expected runoff generation type. At Al-Badan Flume, peak flow was about 3 m^3/s and runoff volume accumulated to 119,355 m^3. Whereas, at Al-Faria flume, a negligible amount of runoff was accumulated (1,679 m^3) and the peak flow was 0.06 m^3/s. The runoff coefficient was 0.02 and 0.0006 for Al-Badan and Al-Faria sub-catchments respectively.

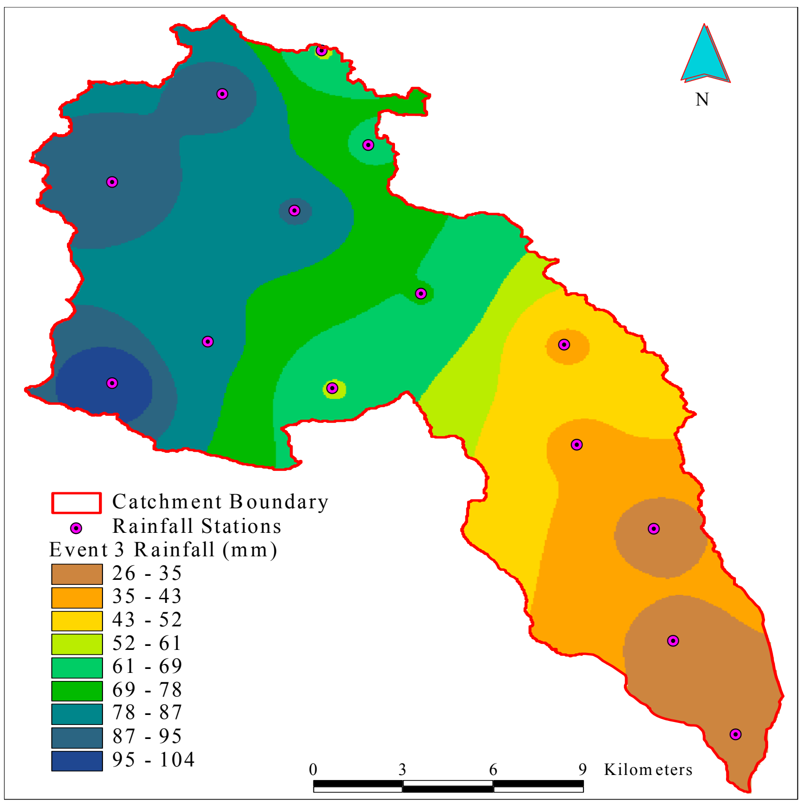

Fig. 7.5 Rainfall Grid of Event 3 (26-27/12/06) Generated By the IDW Method

7.2.3.2 Model Results and Discussion

This is the first event used for model validation. The same set of parameter values obtained after the calibration procedure were used to simulate this event. Observed and simulated hydrographs are presented in **Fig. 7.6**. The figure shows that the coupled TRAIN-ZIN model was able to simulate this event after calibration of the model by using events 1 and 2. **Fig. 7.6** clearly shows that in this event, which occurred after a long dry period, IEOF is responsible for the main peak flow. It makes up over 90% of the peak runoff.

Besides the visual inspection that proves good model performance, the performance coefficients were estimated as presented in **Tab. 7.3**.

Tab. 7.4 Performance Coefficients of Event 3

Parameter	**EFC**	**VE**	**PE**
Al-Badan	0.84	-0.22	0.10
Al-Faria	0.15	-0.37	-0.42

It can be inferred from the table that EFC of 0.84 was reached for Al-Badan sub-catchment. For Al-Faria sub-catchment, the model was underestimated the runoff volume and the runoff peak as well. This can be explained by the very low flood generated out from this sub-catchment. The measured runoff volume and runoff peak (1,670 m^3 and 0.06 m^3/s) are not so far from the simulated values (1,050 m^3 and 0.04 m^3/s).

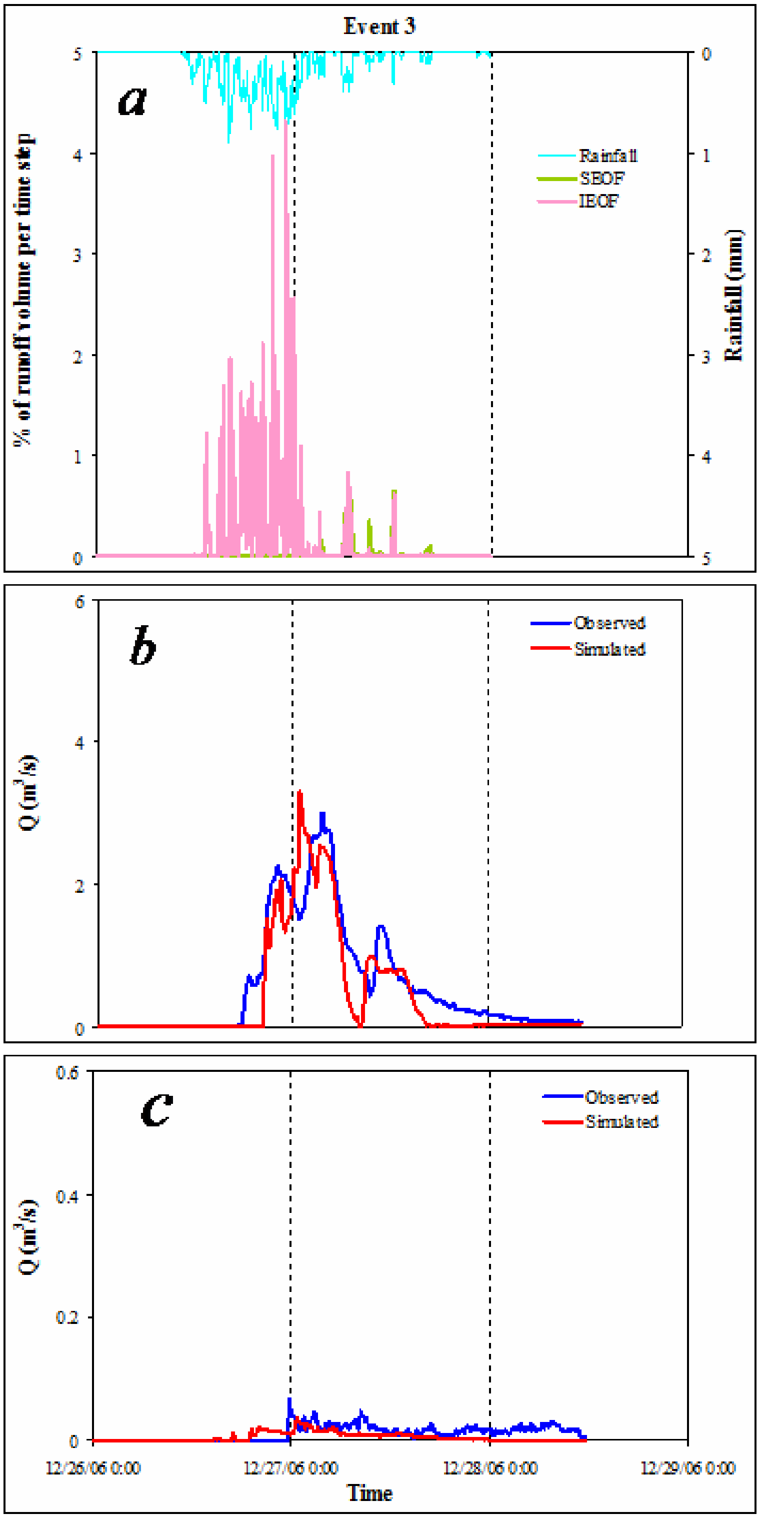

Fig. 7. 6 Simulation of the Event 3: (a) Rainfall, SEOF and IEOF; (b) Al-Badan Sub-catchment and (c) Al-Faria Sub-catchment

7.2.4 Event 4, 3 – 6 February 2007

7.2.4.1 Event Characteristics

The fourth simulated event with a total rainfall of 62 mm, **Fig. 7.7**, occurred in four consecutive days in February. Although this event came after 3 days of no rainfall, compared to event 1 which produced a significant amount of runoff, the generated runoff from this event was very small. This can be attributed to the both rainfall amount and intensity of this rainfall event. After 3 days of no rainfall, intermediate initial soil moisture is expected. For this event both SEOF and IEOF are the expected runoff generation types. Peak runoff and runoff volume measured at Al-Badan flume were 3.5 m^3/s and 161,728 m^3 respectively, whereas, at Al-Faria flume, not much runoff accumulated (1,541 m^3) and the peak flow was 0.04 m^3/s. The runoff coefficient was 0.03 and 0.0005 for Al-Badan and Al-Faria sub-catchments respectively.

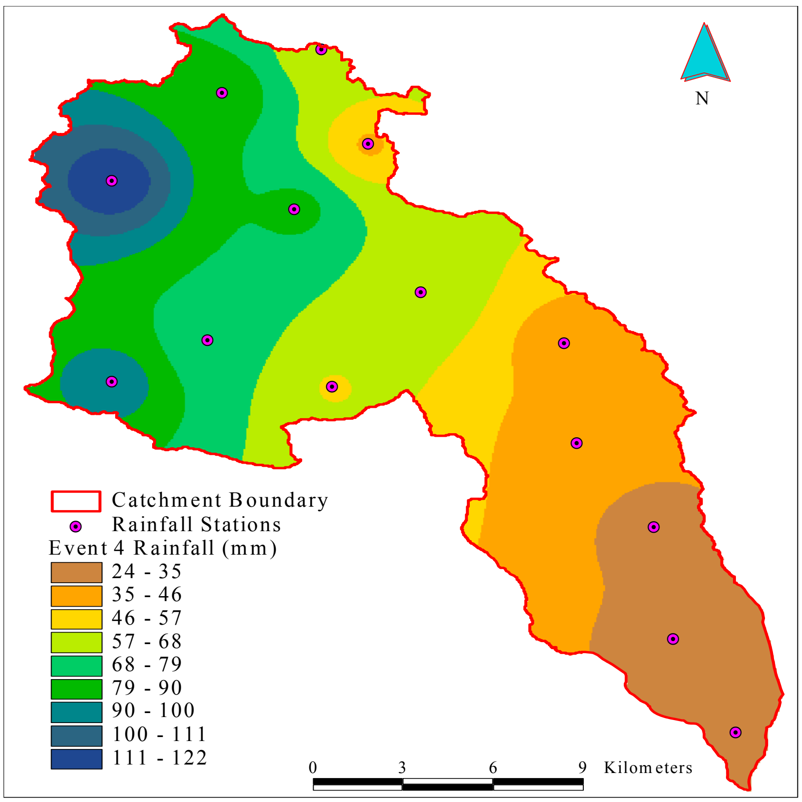

Fig. 7.7 Rainfall Grid of Event 4 (3-6/02/07) Generated By the IDW Method

7.2.4.2 Model Results and Discussion

Similar to event 3, this event was used for model validation. In **Fig. 7.8** the observed and the simulated hydrographs are plotted. This result is obtained using the calibrated set of parameter values. Since this event came after less than three dry days, intermediate initial moisture condition was assumed. Consequently, good results are obtained with the initial moisture of 0.6. IEOF was taking place at the beginning then saturation was reached. 60% of generated runoff is from the IEOF and 40% from the SEOF. **Tab. 7.4** presents the performance coefficients for this event.

Tab. 7.5 Performance Coefficients of Event 4

Parameter	**EFC**	**VE**	**PE**
Al-Badan	0.74	-0.07	-0.34
Al-Faria	-2.77	0.51	6.34

Tab. 7.6 shows that the coupled TRAIN-ZIN model was successful at simulating the runoff for Al-Badan sub-catchment, whereas for Al-Faria sub-catchment the model overestimated the flood hydrograph. This is not a significant drawback, since the flow recorded was very low.

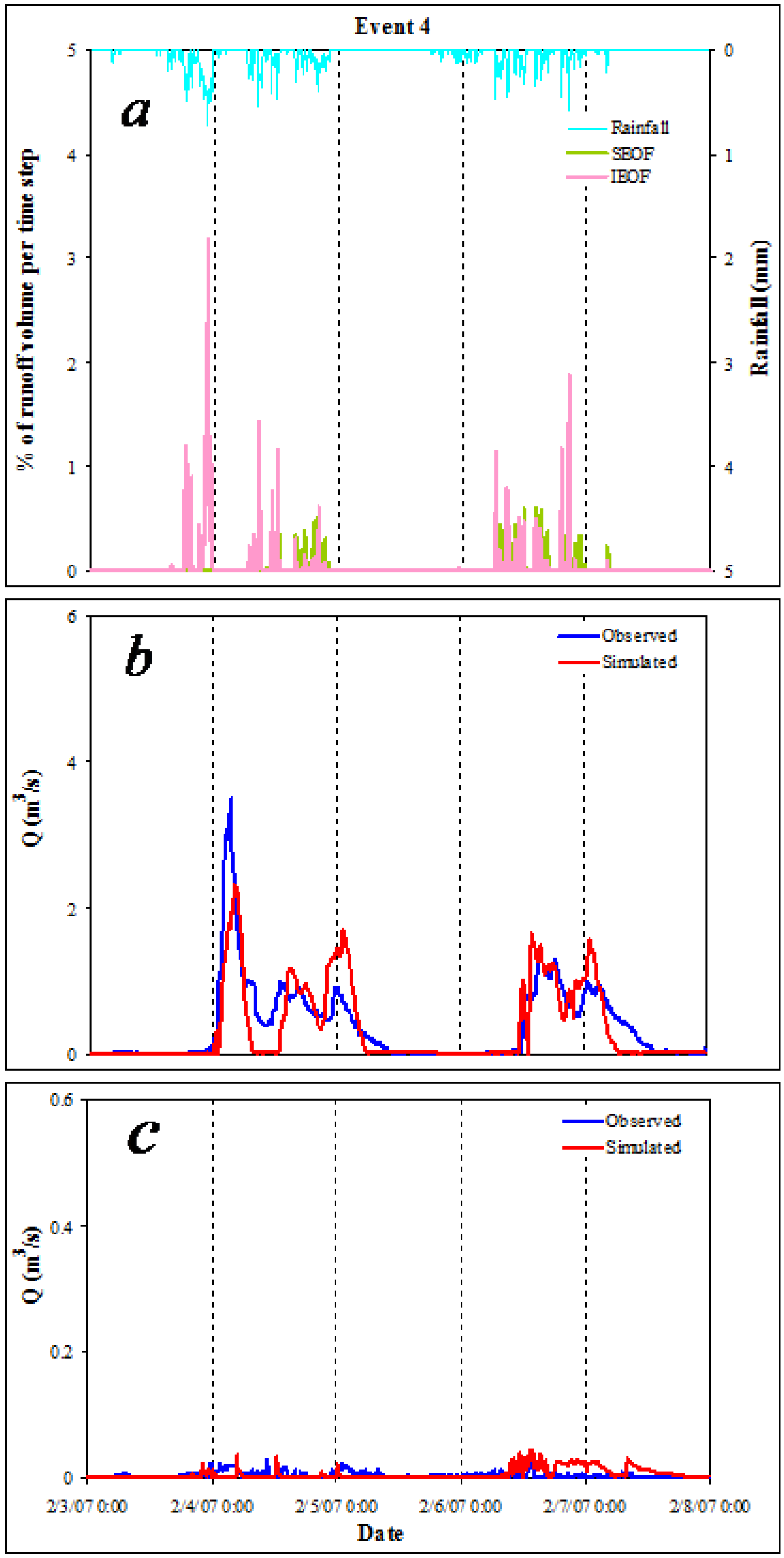

Fig. 7.8 **Simulation of the Event 4: (a) Rainfall, SEOF and IEOF; (b) Al-Badan Sub-catchment and (c) Al-Faria Sub-catchment**

7.3 Continuous Modeling

7.3.1 Parameters

The common set parameter values used for continuous simulation was taken from the prior calibration and validation of single rainfall events. For the events simulation, mainly when the SEOF is the dominant runoff generation type, the initial soil moisture parameter needs to be determined. For continuous simulation the parameter initial soil moisture was set to zero assuming that the soil was totally dry at the beginning of rainy season. The coupled TRAIN-ZIN model calculates the actual soil moisture for the rainy days and for periods in between rainfall events. Evapotranspiration and deep percolation are the two processes that controlled the emptying of the soil storage. During calibration of the model, as mentioned before, parameters controlling the evapotranspiration process were not adjusted. For the rainy days, emptying of the soil storage is mainly controlled by deep percolation since evapotranspiration is minimal, whereas for longer dry periods evapotranspiration becomes more significant. Continuous simulation of the entire rainy season evaluates the continuous behavior of the vertical fluxes. In addition, continuous simulation can provide additional verification of the event simulation.

After the successful calibration and validation of the coupled TRAIN-ZIN model using event simulation on the upper Faria catchment, continuous simulation was applied for the upper catchment (Al-Badan and Al-Faria sub-catchments) as well as for the entire Faria catchment.

In the following sections, continuous simulation of the entire rainy seasons 2004/05, 2005/06 and 2006/07 from the first of October to the end of April is carried out.

Statistical performance coefficients (EFC, VE and PE), in addition to the visual inspection were used to investigate the quality of the simulation results.

7.3.2 Runoff Simulation

As already mentioned, in the rainy season 2004/05, one considerable rainfall event occurred on the period from 4 to 6 February (event 1) which was modeled during the calibration process. Small runoff pulses occurred through the entire season. Observed and simulated runoff hydrographs for this season are shown in **Fig. 7.9**.

From the figure it is clear that both peak and time to peak were simulated correctly. Event 1 is mainly made up from SEOF, so soil water content becomes more important for runoff generation. However for this event the calibrated initial soil moisture content and its continuous estimation did not have much influence on the model output. The hydrographs obtained from event simulation and from continuous simulation are plotted together in **Fig. 7.10** with the observed hydrograph.

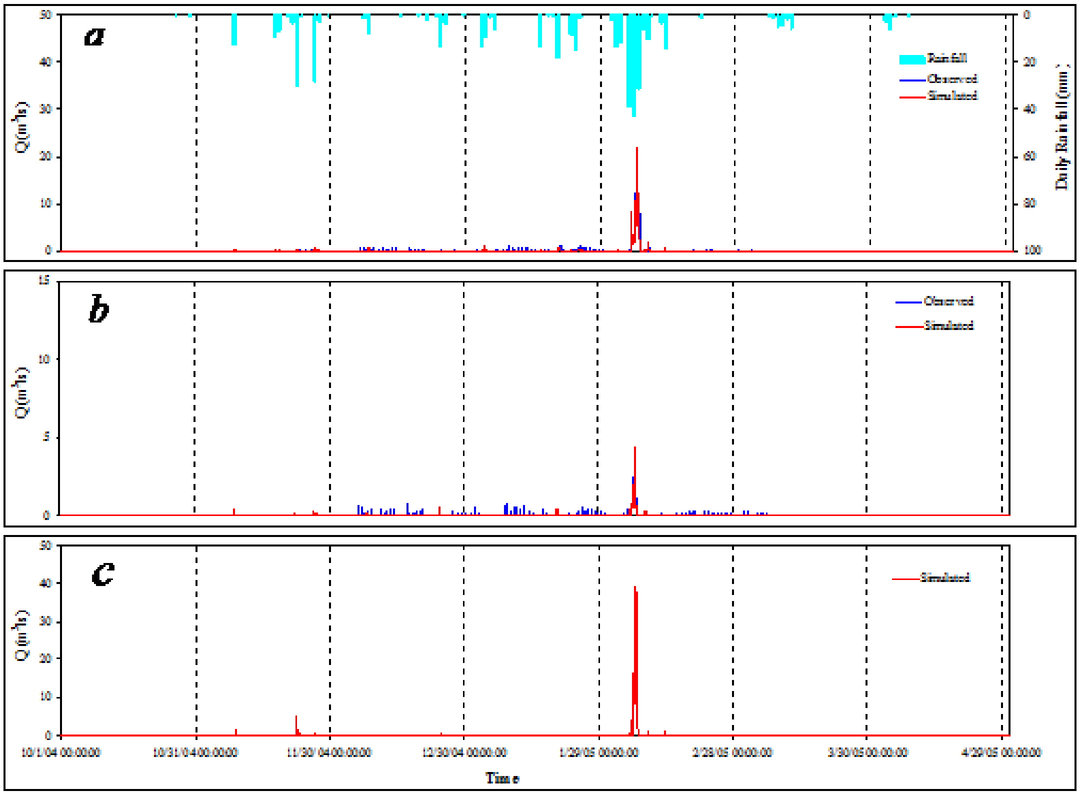

Fig. 7.9 **Continuous Simulation of the Rainy Season 2004/05: (a) Daily Rainfall, Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment**

As seen in **Fig. 7.9** (**c**), the entire Faria catchment produced much runoff from rainfall event 1. This indicates that in case of SEOF the entire catchment may contribute to runoff generation even if the rainfall intensities are small like in the central and lower parts of the Faria catchment.

Generally, **Fig. 7.10** shows that both event and continuous simulations matched well for both Al-Badan and Al-Faria sub-catchments. During the continuous simulation peaks overestimations were observed. This could be because in event simulation the soil storage is less than that of continuous simulation. Also, in event simulation, soil storage is emptied fast through deep percolation. This is clear from the water balance output; deep percolation for event simulation is 8.06×10^6 m^3 while for continuous simulation it is 7.39×10^6 m^3.

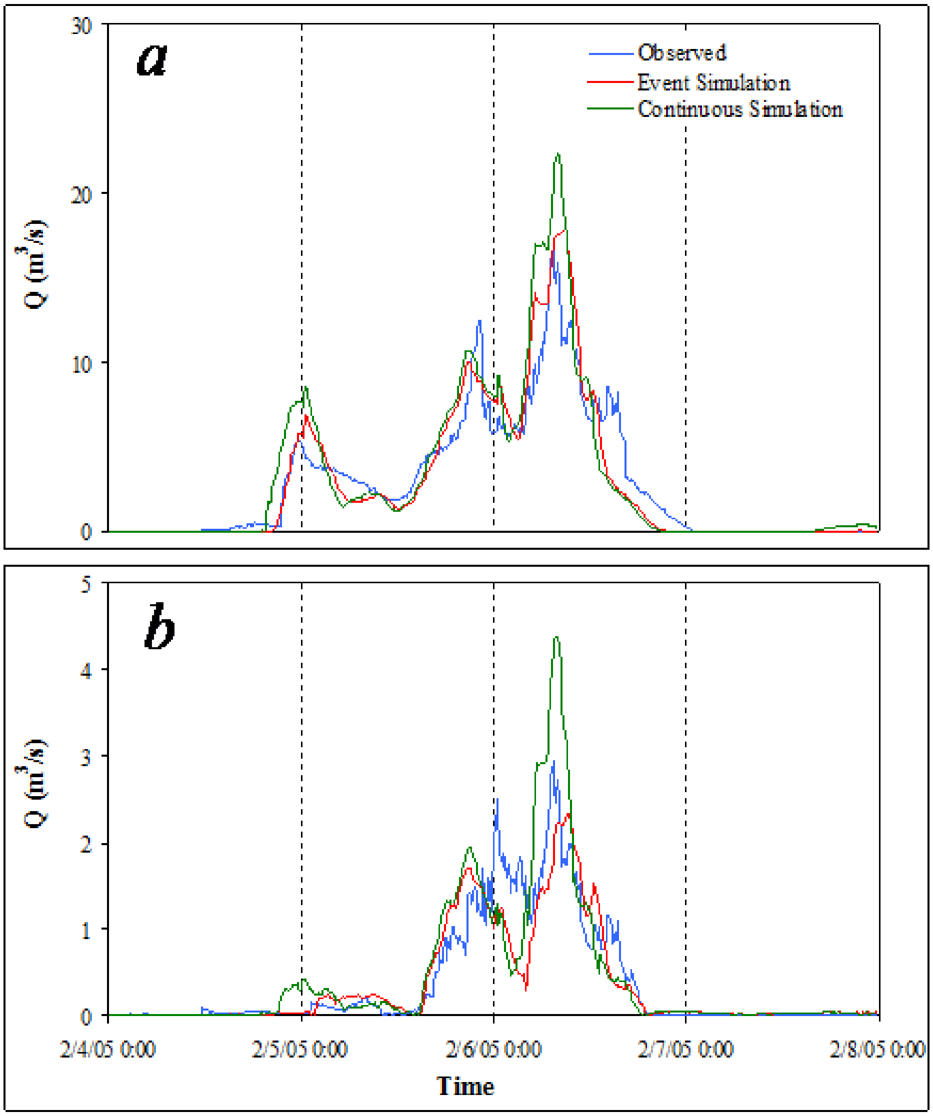

Fig. 7.10 Comparison of Event and Continuous Simulation of Event 1: (a) Al-Badan Sub-catchment and (b) Al-Faria Sub-catchment

The second rainy season 2005/06 was modeled continuously as presented in **Fig. 7.11**. From the rainfall distribution it is expected that IEOF is the dominant runoff generation type for this season. Compared to the season 2004/05, where low rainfall intensities over a long period measured, this season had high rainfall intensities over a short period. Event 2, which was also used for model calibration, is modeled correctly during the continuous simulation (**Fig. 7.12**). As already mentioned, a second and significant event occurred on the 2nd of April 2006. More than 60 mm of rainfall fell in one day and produced a noticeable flood. The generated flood of this event was not measured. However the model simulation proved that a significant amount of runoff was produced as a result of IEOF (99%).

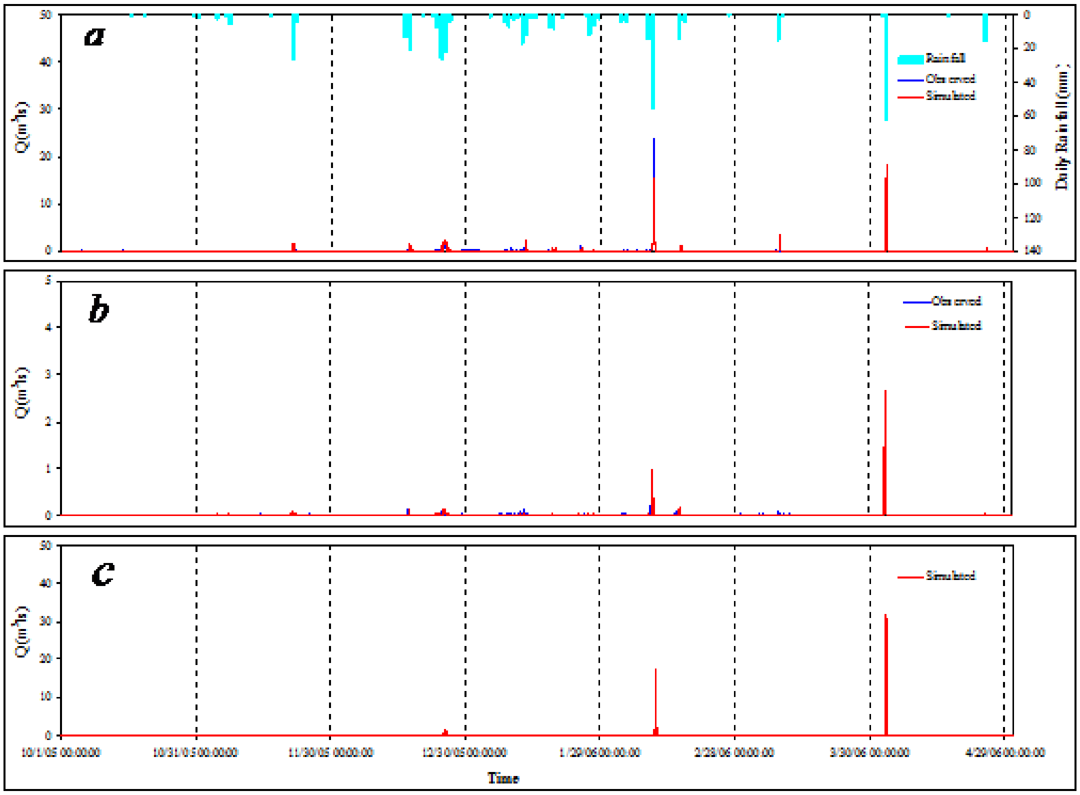

Fig. 7.11 Continuous Simulation of the Rainy Season 2005/06: (a) Daily Rainfall, Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment

Fig. 7.12 clearly shows that both event and continuous simulations were produced almost the same results. Event 2 is mainly made up of IEOF. This means that the initial soil moisture and its continuous calculation had very little influence on model output. As a result almost the same hydrographs were obtained.

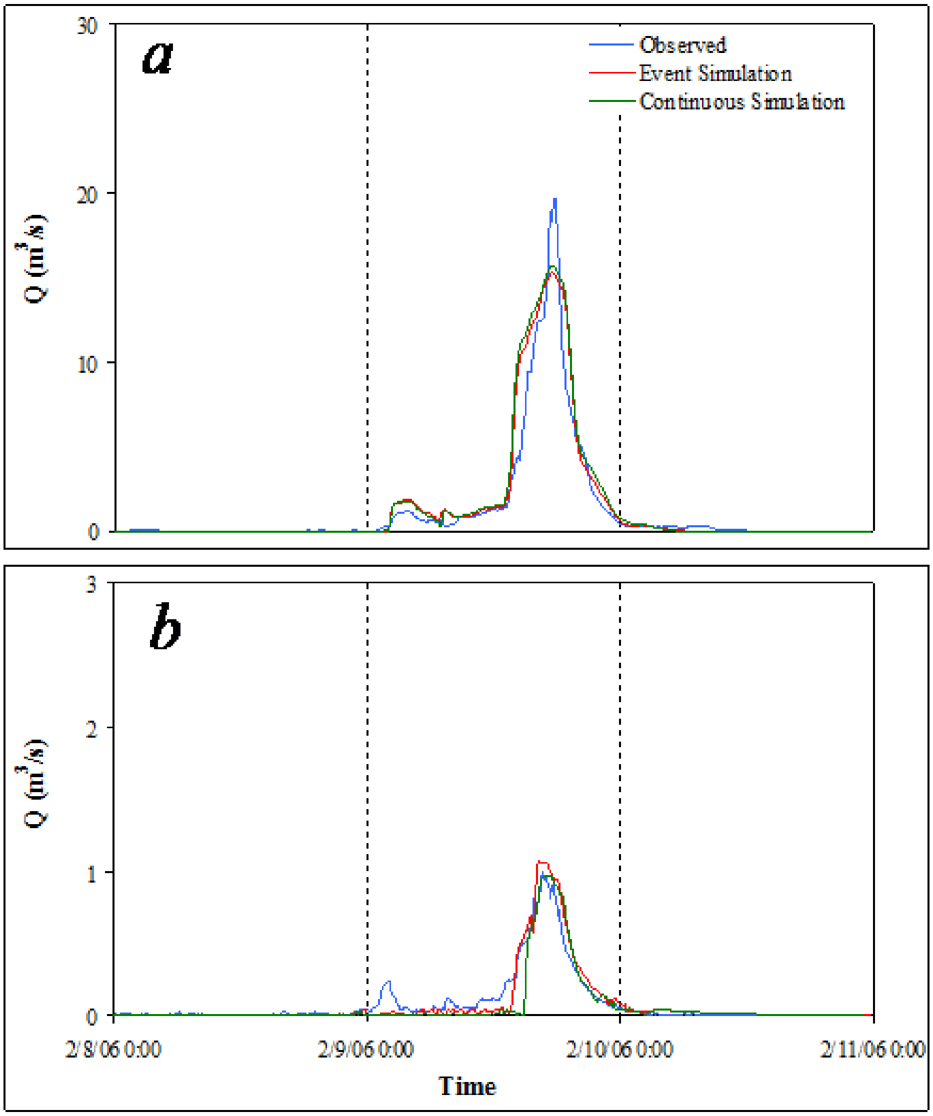

Fig. 7.12 Comparison of Event and Continuous Simulation of Event 2: (a) Al-Badan Sub-catchment and (b) Al-Faria Sub-catchment

In contrast to 2004/05 season, the continuous simulation of the rainy season 2005/06 generated almost the same runoff at the catchment outlet compared to runoff simulated at the upper part of the catchment. This is because, as already mentioned, the generated runoff consists mainly out of IEOF. In this case the central and lower parts of the Faria catchment, where there is less rainfall, contribute almost nothing to the generated runoff. In addition, significant transmission losses that took place while the water routed from the upper part to the catchment outlet. In **Fig. 7.13** and **Fig. 7.14**, the simulated runoff with and without transmission losses at the catchment outlet for event 1 and event 2 is depicted respectively.

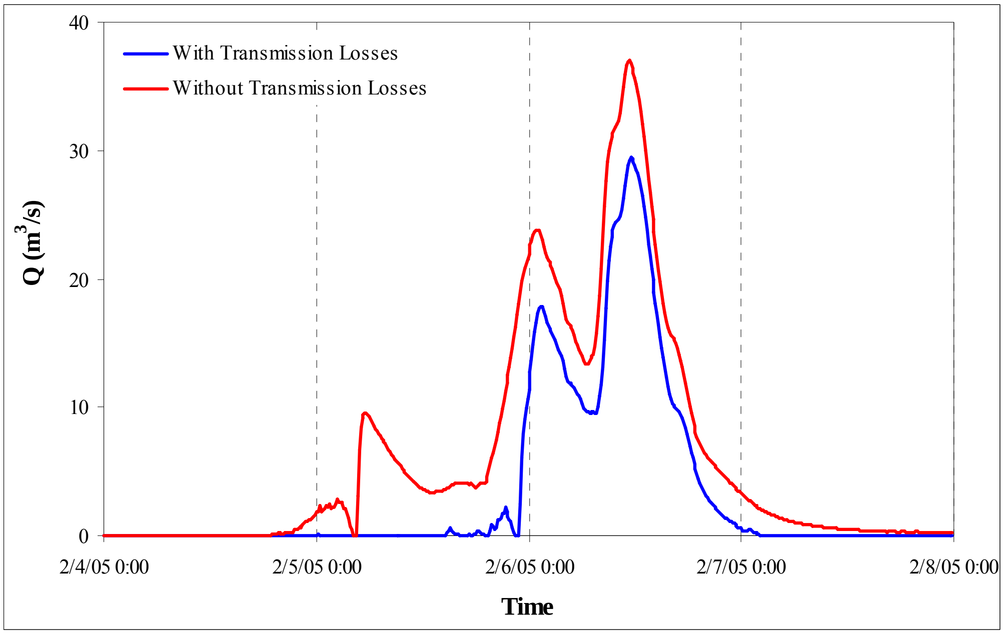

Fig. 7.13 Comparison between Simulated Runoff with and without Transmission Losses at the Catchment Outlet for Event 1

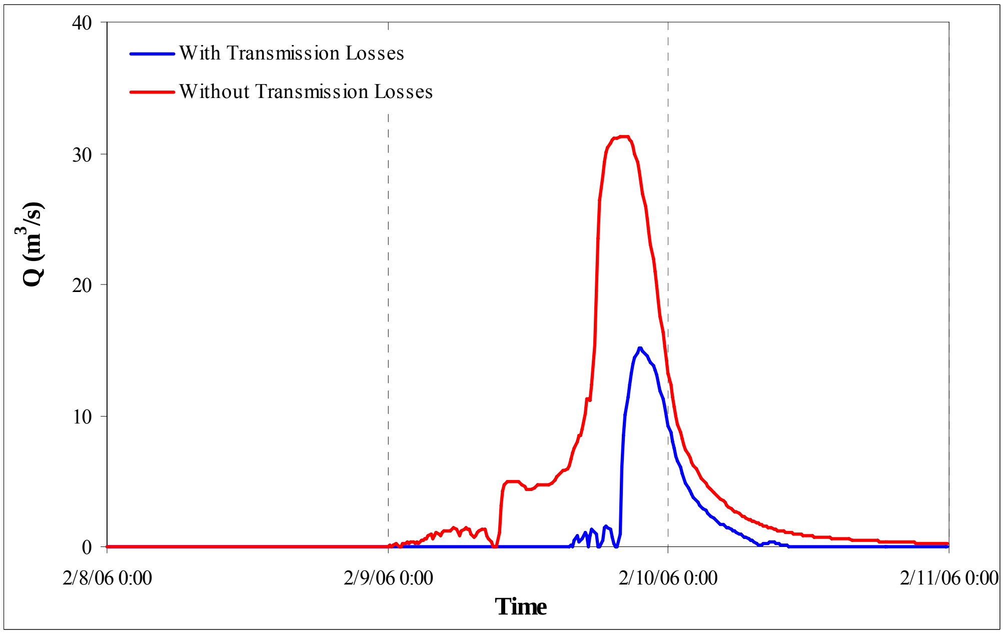

Fig. 7.14 Comparison between Simulated Runoff with and without Transmission Losses at the Catchment Outlet for Event 2

It is obvious that the transmission losses in the Faria catchment are considerable. At the catchment outlet and for event 1 nearly half (54%) of the simulated runoff was reached after the transmission losses took place whereas for event 2, about one third (29%) of simulated runoff reached the catchment outlet. This can be interpreted to mean that the runoff generation mechanism controlled the generated runoff for event 1 and event 2. This results show the importance of the quantification of transmission losses in arid and semi-arid regions to assess the hydrographs accurately at the catchments outlet.

The third rainy season (2006/07), among which two rainfall events were used for model testing, was also simulated continuously. Results are as presented in **Fig. 7.15**.

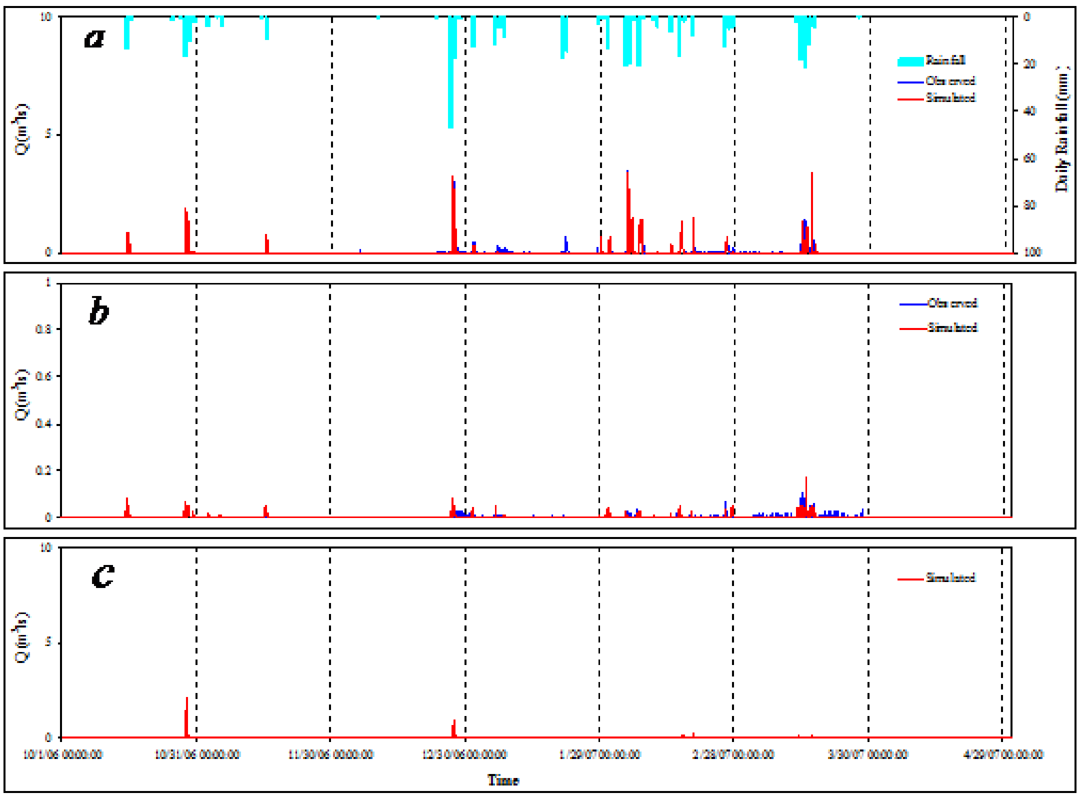

Fig. 7.15 Continuous Simulation of the Rainy Season 2006/07: (a) Daily Rainfall, Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment

For this rainy season, the IEOF is the major runoff generation mechanism like for the rainy season 2005/06. Visual inspection of the figure proves the good match between observed and simulated hydrograph for both sub-catchments. The generated runoff from the entire catchment (**Fig. 7.15** (**c**)) was less than that generated at Al-Badan outlet. As mentioned previously, this is because IEOF is the major runoff generation process.

To investigate the workability of the continuous simulation for this rainy season, both event and continuous simulations are plotted in **Fig. 7.16** and **Fig. 7.17** with observed hydrographs for the two events used for model testing (events 3 and 4).

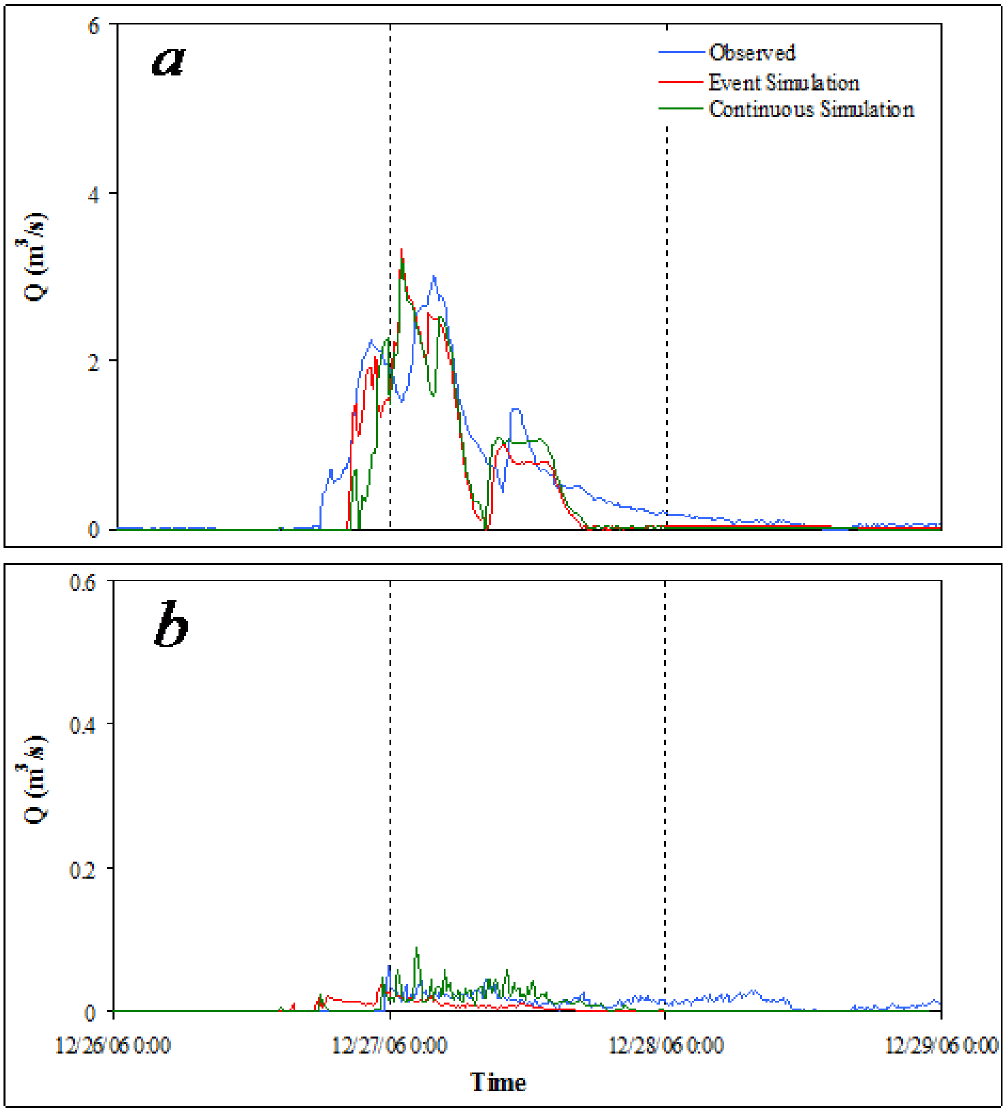

Fig. 7. 16 Comparison of Event and Continuous Simulation of Event 3: (a) Al-Badan Sub-catchment and (b) Al-Faria Sub-catchment

For this event IEOF (90%) is responsible for the main peak flow. Therefore soil storage emptying that took place in the continuous simulation has little influence on the model output. For both sub-catchments the previous figure shows that event based and continuous simulations are very close which assures the workability of the model.

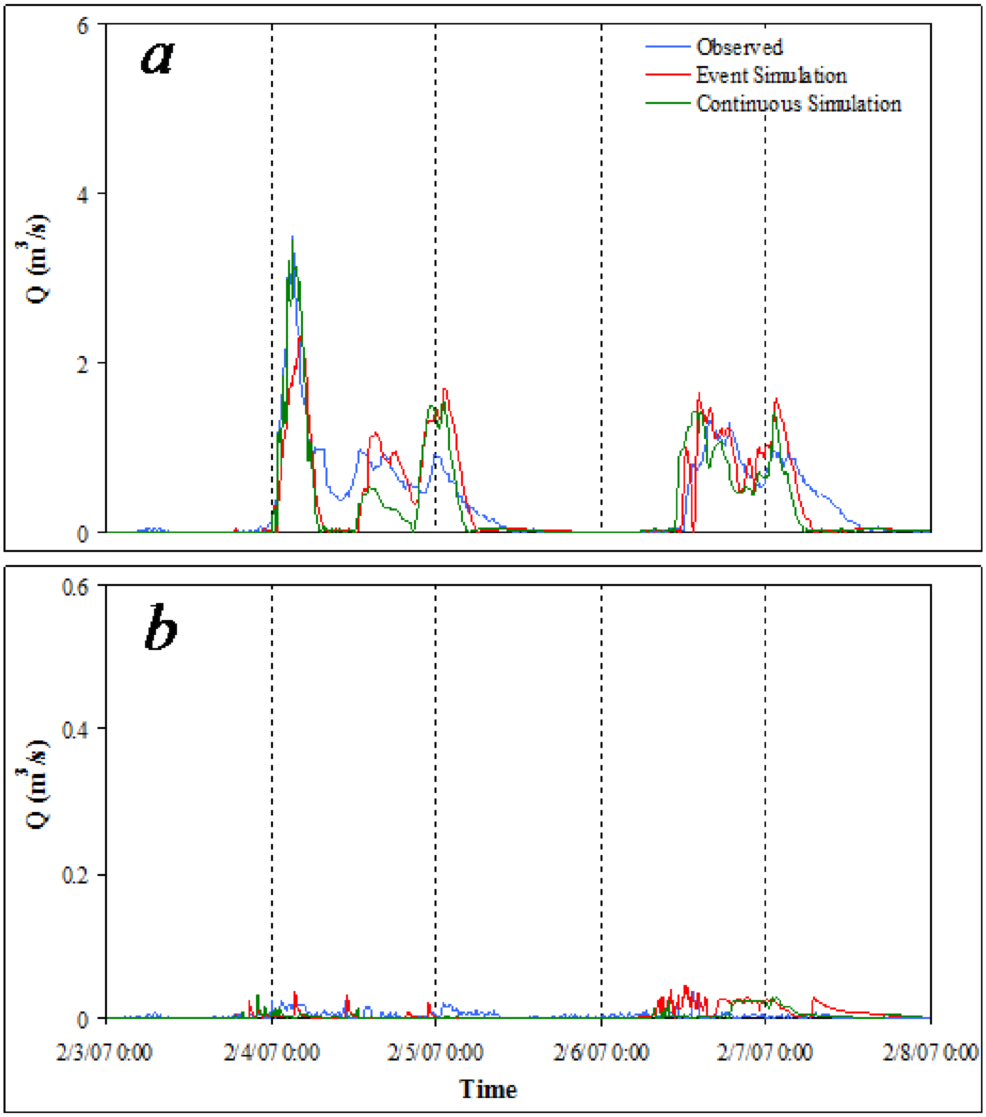

Fig. 7.17 Comparison of Event and Continuous Simulation of Event 4: (a) Al-Badan Sub-catchment and (b) Al-Faria Sub-catchment

This simulated event consists of SEOF (43%) and IEOF (57%). In such a case, soil water content becomes more important for runoff generation. The first peak was positively overestimated (close to the observed value) during the seasonal simulation. This indicates that the SEOF was generated sufficiently. One reason could be that the soil storage is emptied slowly through deep percolation. Another possible reason is that the validation of the event was done with relatively low initial moisture content (0.6). The situation was switched for the second peak. The peak was under estimated possibly due to the fast emptying of the soil storage, whereas the remaining part of the hydrograph is the same for both the event based and continuous simulations.

The knowledge of runoff from individual rainfall events is essential to assess the runoff behavior of a catchment area and to obtain an indication both of runoff peaks which e.g. the hydraulic structure of a water harvesting system must withstand and of the needed capacity for temporary surface storage of runoff. However, to determine the gross runoff coefficient, it is necessary to assess the seasonal runoff coefficient. This is defined as the total runoff observed in a season divided by the total rainfall in the same season. The seasonal runoff coefficient differs from the runoff coefficients derived from individual rainfall events as it takes into account also those rainfall events which did not produce any runoff. The seasonal runoff coefficient is therefore always smaller than the arithmetic mean of runoff coefficients derived from individual runoff producing storms.

For the entire rainy seasons 2004-2007 and for both Al-Badan and Al-Faria sub-catchment the seasonal runoff coefficients were calculated as shown in **Tab. 7.5**.

Tab. 7.7 Rainfall Volumes, Runoff Volumes and the Seasonal Runoff Coefficient for the Three Simulated Seasons 2004-2007 for both Al-Badan and Al-Faria sub-catchment

Year	Rainfall Volume (m^3)		Runoff Volume (m^3)		Runoff Coefficient (%)	
	Al-Badan	**Al-Faria**	**Al-Badan**	**Al-Faria**	**Al-Badan**	**Al-Faria**
2004/05	35,099,844	23,720,488	1,343,913	208,789	3.8	0.88
2005/06	35,604,057	24,061,234	1,157,805	108,660	3.3	0.45
2006/07	33,491,954	22,630,904	569,763	31,500	1.7	0.14

It is obvious that the seasonal runoff coefficient varies temporally from year to year and spatially from Al-Badan to Al-Faria sub-catchments. Although the seasonal rainfall volumes of the three years are very close, the runoff volumes as well as the runoff coefficient are different. This is due to the rainfall characteristics (intensity and duration) that affect the runoff generation processes. Seasonal runoff coefficient of the year 2004/05 is 3.8% for Al-Badan sub-catchment while the corresponding event (event 1) runoff coefficient is 10%.

Alongside the visual inspection that proves good model performance for the three seasons, the performance coefficients for the same periods of the observed and the simulated hydrographs were estimated as presented in **Tab. 7.6**.

Tab. 7.8 Performance Coefficients of the Thee Seasons (2004/05, 2005/06 and 2006/07)

Parameter		EFC	VE	PE
2004/05	**Al-Badan**	0.77	-0.06	0.32
	Al-Faria	0.47	-0.42	0.48
2005/06	**Al-Badan**	0.72	0.03	-0.35
	Al-Faria	0.35	-0.46	-0.02
2006/07	**Al-Badan**	0.44	-0.19	-0.01
	Al-Faria	-0.62	0.01	0.65

It is seen that EFC is in the range from 0.35 to 0.77 excluding the one for Al-Faria sub-catchment for the last season. The low efficiency coefficient can be explained by the low flow generation in the season 2006/07. Statistically it is pessimistic value but relatively speaking it is acceptable one. However, it can be concluded that the results of both event based and continuous simulations are promising and prove the applicability of the coupled TRAIN-ZIN model to the Faria catchment as an arid to semi-arid area.

7.4 Evapotranspiration Simulation

Soil storage is the common layer between the ZIN and TRAIN models. For the period of rain, the ZIN model is active describing the filling of the soil storage and runoff generation by IEOF and/or SEOF, whereas during times of no-rain the soil module of TRAIN is active and calculates the emptying of the soil storage by Evapotranspiration and percolation. Throughout the analysis of the simulation results, it became clear that the model for some cases did not generated enough SEOF due to the fast emptying of the soil storage and for other cases the model generate enough SEOF due to the slow emptying of the soil storage. There is no data available to check the determined parameters that control the evapotranspiration. As already mentioned, parameters for the evapotranspiration process were not adjusted during calibration. In addition, the climatic data of Nablus meteorological station (the only meteorological station in the catchment) which is located in the upper part of the catchment was assumed to represent the entire Faria catchment, whereas a noticeable difference in climatic parameters between the upper and lower parts of the catchment was observed in reality. Hence no regionalization of the meteorological data was done.

From the aforementioned discussion estimated water loss through evapotranspiration cannot be verified. However, the coupled TRAIN-ZIN model was used to simulate the evapotranspiration for the entire Faria catchment. By using the model, it is possible to produce the daily evapotranspiration of every raster cell. **Fig. 7.18** and **Fig. 7.19** illustrate examples of daily spatial distribution of evapotranspiration in the Faria catchment for rainy and dry days.

From both figures it can be concluded that the actual evapotranspiration is accompanied by the rainfall among other factors. For the rainy day (9th of February 2006) actual evapotranspiration is considerable whereas for the dry day (5th of February 2007) actual evapotranspiration (**Fig. 7.19**) is small compared to the rainy day (**Fig. 7.18**).

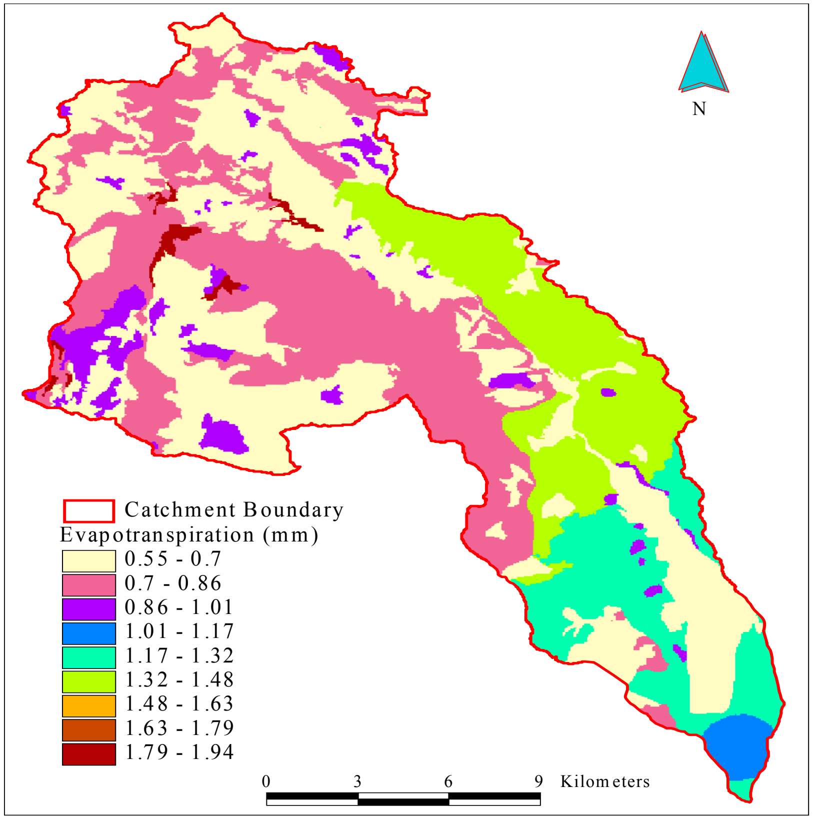

Fig. 7.18 Evapotranspiration of Feb 9th 2006

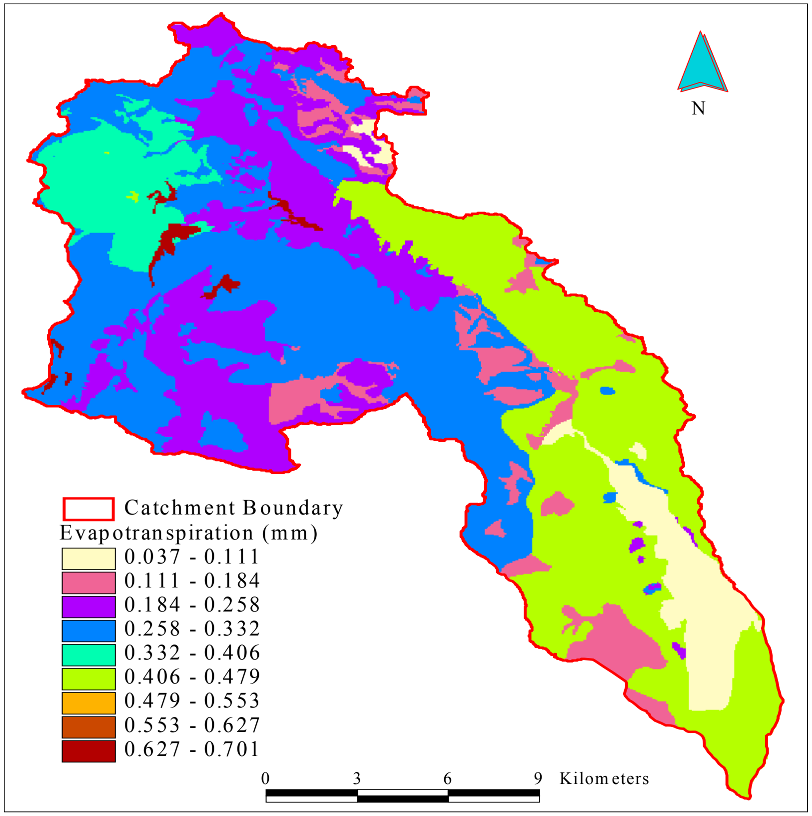

Fig. 7.19 Evapotranspiration of Feb 5th 2007

7.5 Seasonal Water Balance

Although the primary objective of the TRAIN-ZIN model is to predict runoff generation, the water balance values of the entire catchment can also be estimated. Using the model, the water balance was estimated for the three modeled seasons (2004/05, 2005/06 and 2006/07) for the entire Faria catchment. Daily evapotranspiration, percolation and surface runoff were estimated by the model. From that the amount of daily water stored in soil was calculated by subtracting these values from the corresponding daily rainfall values. Consequently, the seasonal water balance was estimated by summing up the daily values for the simulated period from the first of October to end of April. In **Tab. 7.7**, the water balance for the three simulated seasons is tabulated.

Tab. 7.9 Seasonal Water Balance (October-April) for the Continuous Simulation

Parameter	Depths (mm)			Volumes (MCM)		
	2004/05	2005/06	2006/07	2004/05	2005/06	2006/07
Rainfall	423	430	404	135.78	137.74	129.56
Evapotranspiration	101	143	141	32.49	45.87	45.25
Percolation	41	8	7	13.23	2.64	2.18
Runoff	5	4	1	1.55	0.93	0.24
Soil Storage	276	275	255	88.52	88.30	81.89

Although the rainfall volumes for the two seasons 2004/05 and 2005/06 are very close, evapotranspiration differs. This is identifies the effects of rainfall characteristics (intensity and duration) and runoff generation processes that took place during the two seasons. In the first season where SEOF was the dominant runoff generation mechanism, there was a good chance for runoff generation and for fast percolation resulting from soil saturation. In contrast to the first season, IEOF was the major runoff generation mechanisms for the last two seasons. Thus deep percolation was less and evapotranspiration was considerable. On average circa 70% of the rainfall was stored in the soil of which, a certain amount is percolating and the remaining goes back to the atmosphere by means of evaporation and transpiration. The percolated water is replenishing the groundwater aquifers. Ghanem et al. (2005) estimated the groundwater recharge in the Faria catchment by using global and hydrometeorological groundwater balance equations. As a result, they estimated the annual recharge volume to be 60 MCM. In spite of the uncertainties accumulated in this research study in the estimated percolation, it is clear that the previous studies overestimated the groundwater recharge in the Faria catchment. However, there are no real measurements of soil saturation in the catchment. On the other hand, currently there is no observation method that can provide soil moisture measurements at the appropriate spatial and temporal resolution, especially when soil moisture information on deeper layers is required. This makes it difficult to estimate the exact volume of annual rainfall that is replenishing the groundwater aquifers and to validate the simulated results.

7.6 General Conclusion

Subsequent to the successful calibration, validation and application of the coupled TRAIN-ZIN model for the Faria catchment, it can be concluded that the model proved its applicability for an arid and semi-arid catchment with parameters determined directly in the field and through calibration. Rainfall characteristics (mainly the rainfall intensity) and the initial soil moisture content are the main parameter that controlled the runoff generation processes (IEOF and/or SEOF) that took place in the Faria catchment. The determination of parameters controlling the runoff generation (mainly the infiltration rate) directly in the field is of great important for model calibration and application. The dynamic function of filling and emptying the soil storage during rainy and no rainy days makes it possible to run the model accurately for entire rainy seasons. Through the analyses of the model output, a determination of the main runoff contributing areas and the main runoff generation process is possible. The seasonal water balance which can be obtained out of the coupled TRAIN-ZIN model is the main input for sustainable water resources management in the Faria catchment.

8 Sensitivity Analysis and Uncertainty Assessments

8.1 General Aspects

The use of uncertainty analysis is gaining substantial popularity in catchment hydrological modeling. Particularly, the choice of appropriate model structure, identifiability of parameter values and the reduction of model predictive uncertainty are deemed as essential elements of hydrological modeling (Sivapalan, 2007). In fact, all model calibrations and subsequent predictions are subject to uncertainty. This uncertainty comes up since no rainfall-runoff model is a true reflection of the process involved in a certain catchment. Therefore, it is impossible to identify the initial and boundary conditions required by the model with absolute accuracy. In addition, the observational data available for model calibration are not error-free (Beven, 2001).

Uncertainty in rainfall-runoff modeling arises from different causes which interact with each other. However, four main sources of uncertainties can be identified in rainfall-runoff models (e.g Aitken, 1973; Singh, 1988, Milching, 1995 and Michael et al., 2004): (1) natural uncertainties, associated with the random fluctuations built-in the natural hydrological processes (e.g. soil infiltration-ability in consecutive years); (2) parameter uncertainties, associated with the parameters value used in the equations and how accurate these parameters are identified by model calibration or measured data; (3) data uncertainties, associated with rainfall and other forcing data besides the random errors that may take place during measurement and spatial averaging of input data; and (4) model structure uncertainties, associated with the model's mathematical equations that never represent the physical runoff process accurately.

The contribution of the different sources of uncertainty (natural, data, parameter and structure) are not independent and therefore in principle can not be treated separately. This is because the modeling process is complex and there is a lack of knowledge about the catchment and its hydrological responses. Therefore, the four uncertainty (error) components contribute to integrated errors, such as the difference between simulated and observed runoff at the catchment outlet (Ewen et al., 2006). Sometimes, this difference (goodness-of-fit) is misleading; since good model fits (minimum integrated errors) may be possible with completely unrealistic parameter values or process descriptions (e.g. Mein and Brown, 1978 and Grayson et al., 1992).

In this research study the focus is on model parameter uncertainty and on the uncertainty caused by uncertain input (rainfall) data. Parameters of the coupled TRAIN-ZIN model were determined through physical measurements that were carried out directly in the field (e.g. infiltration rate) or from topographic maps (e.g. channels slope), from aerial photographs (e.g. channels geometry) or from information in the literature (e.g. hydraulic conductivity, porosity, Manning n, etc). This means that a high degree of uncertainty accompanied parameter determination.

Data certainty, in many hydrological applications, is a key factor for accurate flood estimates. For example, highly accurate rainfall input is crucial to drive hydrological models perfectly (Lopez et al., 2005). Due to the evolution of the meteorological phenomena over the selected catchment, several rain-gauges should be installed in different places in order to capture the spatial rainfall distribution accurately (Paoletti, 1993). One of the most important limits of hydrological prediction is the low resolution of input of hydrological models (Vaes et al., 2001). This input is given by rain-gauge measurements so the accuracy of the output depends essentially on the rain-gauge network density configuration and on the instrument accuracy (Maheepala et al., 2001). Andreassian et al. (2001) stated that model efficiency of different hydrological models increased with a better description of the catchment rainfall inputs.

In the Faria catchment, the number of the existing rain-gauges is not enough to determine the spatial distribution of the catchment rainfall. This was discussed thoroughly in Chapter 4. Despite the good results obtained out of the method that have been employed to overcome the shortages of rain-gauges in the Faria catchment, a certain amount of data uncertainties can be propagated. To estimate the rainfall distributions over the entire catchment, rain-gauge pointwise measurements need to be interpolated. Therefore, different interpolation methods can lead to significant differences in rainfall distribution estimates (Dirks et al., 1998). This will also increase the uncertainty of rainfall as model input data.

Moreover, the uncertainty of gauged runoff data should also be considered. Gauged streamflow that is used for comparison with the simulated flows may also contain errors. These errors can be increased considerably because of measurements problems, such as, sediment accumulation, cross-section instability and high flow velocities.

From the above, it can be concluded that certain amounts (ranges) of uncertainties are combined with the first three sources of model uncertainties listed above (natural, data and parameter).

Model structure uncertainty is the fourth source of modeling errors that should be considered. Different model structures are expected to perform differently. The uncertainty of variations in acceptable model structure is of the same magnitude as uncertainties arising from the other sources of errors. The question is: how does the magnitude of model structure uncertainty compare to the other sources of uncertainty? The relative performance of different acceptable model structures is evaluated as a demonstration of structural uncertainty and compared to estimates of the uncertainty arising from the other sources (natural, data and parameters). In the TRAIN part, the built-in land cover classes and their evapotranspiration processes are developed for humid regions. Therefore personal judgment along with some field experiences were employed to select the suitable TRAIN land covers that represent the available land covers of the Faria catchment. This caused some model structure uncertainty that affects the model output.

In general, it can be concluded that model performance is strongly dependent on model structure (Michael et al., 2004). Model structure uncertainty can be determined by validating model simulations with field-measured data where distributed data provide best judgments (Lange, 1999).

8.2 Parameters Uncertainty Ranges and Sensitivity Analysis

In order to assess the TRAIN-ZIN model sensitivity to different parameter variations, a series of sensitivity analyses was undertaken. Performing sensitivity analyses is a method to identify the input parameters that have the biggest impact on model predictions. De Roo (1993) used a simple index for describing the sensitivity of a variable in the following form:

$$S = \frac{|R_i - R_d|}{R_b} \tag{8.1}$$

Where S is the sensitivity index, R_i and R_d are model results with a variable being increased or decreased by a certain uncertainty range and R_b is the baseline simulation.

It is becoming common practice in rainfall-runoff modeling to estimate prediction uncertainty and represent it using prediction ranges. Uncertainty ranges are usually simply a pair of upper and lower values for the prediction variable. Ideally, the uncertainty ranges should be accurate and narrow, so that the actual value lies between these ranges. Lange (1999) for his rainfall-runoff study assessed parameter uncertainty and carried out sensitivity analysis by determining the uncertainty ranges of each parameter. In this study, parameters uncertainty ranges proposed by Lange (1999) were used to examine the sensitivity of the coupled TRAIN-ZIN model for the Faria catchment.

Event 1 with mostly SEOF (62%) and event 2 with mostly IEOF (98%) were used for model calibration on Al-Badan sub-catchment and are used herein. These two events were selected to study the sensitivity of the coupled TRAIN-ZIN model since they are big enough to expect sound sensitivity effects. The sensitivity analysis has been undertaken based on the sensitivity index defined by equation (**8.1**) for the Faria catchment by simulating the effects of three parameter groups (runoff generation, runoff concentration, and channel routing and transmission losses) containing 12 different model parameters. In different model runs, as each parameter was allowed to vary over its maximum rate of uncertainty, all others were kept constant. While each parameter was varied, the effects on the simulated peak flow rate, time to peak and volume were analyzed and compared.

For the initial loss, the uncertainty was assumed to be ±2.5 mm while the infiltration rate has been increased or decreased by ±20%. Uncertainty range of ±10 minutes was assigned for the hydrological time lag parameter. The length of channel segments was determined from the digitizing 1:50,000 topographic maps. Therefore uncertainty range of ±100 m could result from a digitized error of ±2 mm. Uncertainty range of ±0.2 m for the bankfull stage and Manning's coefficient ±0.01 were assigned. For the other parameters of routing an uncertainty range of ±20% from the basic parameter range have been run. For the transmission losses parameters an uncertainty range of ±0.5 m, ±50 mm hr-1 and ±10% have been assumed for the depth of active alluvium, the infiltration rate of alluvium and antecedent moisture index respectively. Finally, for model input, uncertainty range of ±20% in rainfall intensity created by the IDW method for both events (1 and 2) was assumed.

8.3 Results and Discussion

Assuming the aforementioned uncertainty ranges, a sensitivity analysis was accomplished for event 1 and event 2. The results of this analysis are depicted in **Tab. 8.1** and **Tab. 8.2** for model parameter error. For better visualization, the relative importance of the single parameter error is plotted for both events as shown in **Fig. 8.1**. In **Tab. 8.3** model input error (rainfall) is tabulated. The sensitivity analysis showed that the sensitivity of the coupled TRAIN-ZIN model varies considerably from event to event. It is obvious from the obtained results that the runoff generation mechanism is the driving force that determines the model response for different parameter uncertainties.

Tab. 8.1 Sensitivity Index of Parameters Affecting Simulated Peak, Time to Peak and Volume, Event 1

Model Parameter (ID)	Parameter uncertainty range	Sensitivity to simulated peak		Sensitivity to simulated time to peak		Sensitivity to simulated volume	
		m^3/s	%	min	%	MCM	%
Runoff generation							
Initial loss (1)	±2.5 mm	±0.86	±4.80	±0.00	±0.00	±0.04	±3.95
Infiltration rate (2)	±20%	±0.43	±2.40	±0.00	±0.00	±0.06	±5.59
Runoff concentration							
Hydrological time lag (3)	±10 min	±3.91	±21.82	±0.00	±0.00	±0.01	±1.41
Routing parameters							
Channel length (4)	±100 m	±1.07	±5.97	±10	±0.29	±0.08	±7.87
Channel width (5)	±20%	±0.87	±4.85	±10	±0.29	±0.09	±9.50
Channel slope (6)	±20%	±0.00	±0.00	±10	±0.29	±0.00	±0.12
Manning n (7)	±0.01	±0.99	±5.52	±10	±0.29	±0.07	±7.52
Bankfull stage (8)	±0.2 m	±0.21	±1.17	±10	±0.29	±0.00	±0.16
Percentage of inner channel (9)	±20%	±0.80	±4.46	±0.00	±0.00	±0.10	±9.97
Transmission losses							
Depth of alluvium (10)	±0.5 m	±2.26	±12.61	±0.00	±0.00	±0.18	±18.06
Infiltration rate of the alluvium (11)	±50 mm hr^{-1}	±0.05	±0.28	±0.00	±0.00	±0.01	±0.88
Antecedent moisture index (12)	±10%	±0.04	±0.22	±0.00	±0.00	±0.05	±4.89

Tab. 8.2 Sensitivity Index of Parameters Affecting Simulated Peak, Time to Peak and Volume, Event 2

Model Parameter (ID)	Parameter uncertainty range	Sensitivity to simulated peak		Sensitivity to simulated time to peak		Sensitivity to simulated volume	
		m^3/s	%	min	%	MCM	%
Runoff generation							
Initial loss (1)	±2.5 mm	±0.33	±2.14	±0.00	±0.00	±0.03	±7.53
Infiltration rate (2)	±20%	±4.98	±32.32	±20	±0.81	±0.16	±46.62
Runoff concentration							
Hydrological time lag (3)	±10 min	±3.23	±20.96	±60	±2.42	±0.01	±2.83
Routing parameters							
Channel length (4)	±100 m	±1.29	±8.37	±10	±0.40	±0.04	±11.23
Channel width (5)	±20%	±0.97	±6.29	±0.00	±0.00	±0.05	±15.62
Channel slope (6)	±20%	±0.37	±2.40	±10	±0.40	±0.01	±2.29
Manning n (7)	±0.01	±0.63	±4.09	±20	±0.81	±0.05	±13.53
Bankfull stage (8)	±0.2 m	±0.02	±0.13	±0.00	±0.00	±0.00	±1.16
Percentage of inner channel (9)	±20%	±0.80	±5.19	±0.00	±0.00	±0.06	±17.02
Transmission losses							
Depth of alluvium (10)	±0.5 m	±2.74	±17.78	±10	±0.40	±0.09	±26.03
Infiltration rate of the alluvium (11)	±50 mm hr^{-1}	±0.25	±1.62	±0.00	±0.00	±0.01	±1.95
Antecedent moisture index (12)	±10%	±0.01	±0.06	±0.00	±0.00	±0.01	±2.86

Tab. 8.3 Model Input Data (rainfall) Error for Event 1 and Event 2

Input Data (Rainfall)	Input data uncertainty range	Sensitivity to simulated peak		Sensitivity to simulated time to peak		Sensitivity to simulated volume	
		m^3/s	%	min	%	MCM	%
Event 1	±20%	±22.59	±126.06	±20	±0.58	±1.12	±112.97
Event 2	±20%	±15.17	±98.44	±10	±0.40	±0.42	±121.21

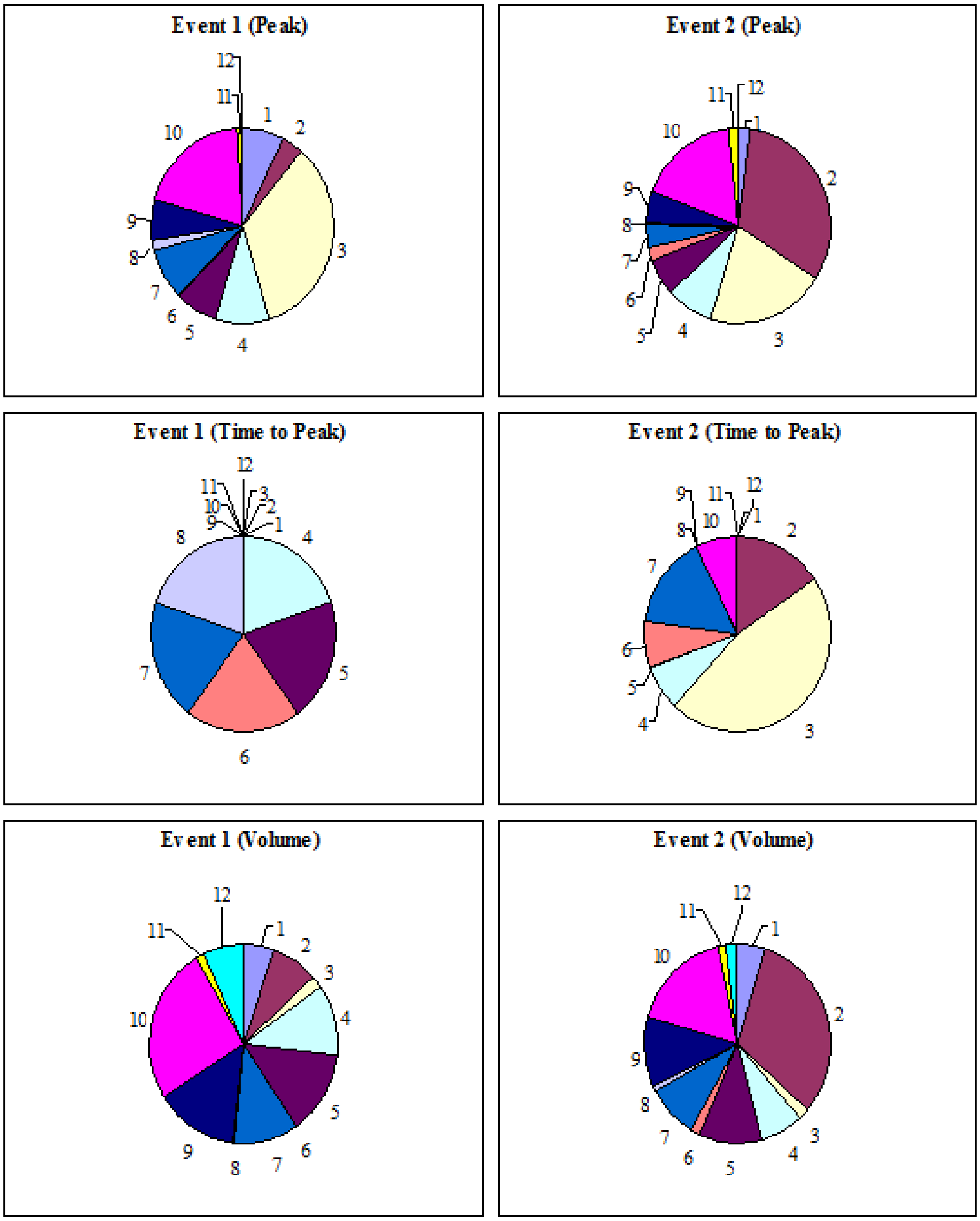

Fig. 8.1 The Relative Importance of the Single Model Parameter Error (Numbers refer to the ID in Tab. 8.1 and Tab. 8.2)

For event 1 where the SEOF is the dominant runoff generation mechanism it is clear that the model is less sensitive to the runoff generation parameters compared to event 2 which was made up mainly from IEOF. The uncertainty of runoff generation parameters (initial loss and infiltration rate) caused 34% of the peak uncertainty during event 2 and 54% of the volume uncertainty. For flood arrival of event 2 it was less important (0.8%). In contrast to event 2, runoff generation parameters were of minor importance for event 1 (7% uncertainty on the peak, 0% on the time to peak and 9% on the volume). For runoff concentration mainly the time lag parameter, the model uncertainty on the peak flow is almost the same for event 1 (21%) and event 2 (22%) while the uncertainty on the volume was minor for both events. The model didn't show any effect on flood arrival for event 1 whereas for event 2 the model was sensitive to the time lag uncertainty (2.4%).

The routing parameters had greater effects on the peak (22% for event 1 and 26% for event 2) than time to peak (1.5% for event 1 and 1.6% for event 2). For the flood volume, the model was very sensitive to routing parameters uncertainty but for event 2 the uncertainty was nearly double (60%) that of event 1 (35%).

For event 1 the transmission losses parameters are dictated the uncertainty of the peak (13%) and volume (24%) rather than the runoff generation parameters. During event 2 the transmission losses parameter were less important than those of runoff generation and routing parameters (19% for the peak and 31% for the volume).

The sensitivity analysis that was carried out for the model input error indicates that the TRAIN-ZIN model is highly sensitive to the uncertainty in rainfall data. For event 1, this error source increased the uncertainty of the peak flow rate and flood volume by more than 126% and 113% respectively whereas the uncertainty of the time to peak was insignificant (0.58%). The same trend is noticed for event 2 (98% for the peak, 0.4% for the time to peak and 121% for the flood volume). This indicates that the model input uncertainty error is significantly affecting the simulated runoff. For event 1, the uncertainty of the peak flow resulted from the 12 model parameters (64%) is nearly half of the uncertainty resulting from the model input error (126%). For the flood volume, the model input uncertainty (112%) is more important than those of model parameters uncertainty (70%). This demonstrates the dire need to have a representative areal rainfall distribution over the catchment. For this, it is recommended to have enough rainfall stations to produce a clear picture of spatial rainfall distribution over the catchment.

Although the obtained results are combined with subjectivity which was involved in assessing the maximum uncertainty ranges of some input parameters, this results may help to judge the model workability and consistency and may lead the future efforts to improve the model accuracy.

In general, it can be concluded that in case of IEOF (event 2) the overall model parameter uncertainty was higher than the SEOF case (event 1). As already stated, in the case of IEOF the runoff generation was controlled by the rainfall intensity and infiltration rate. For the central and the lower parts of the Faria catchment, the rainfall is less than the upper part. Thus only the upper catchment was contributed to the generated runoff (see **Fig. 7.11**). In such case the generated runoff on the upper part traveled for long distances on almost dry channels. Therefore transmission losses parameters dominate model parameters error (see **Fig. 7.14**). Hence for such events more field information on the infiltration processes that take place during a real flood will increase the model accuracy.

9 Scenario Modeling

9.1 General Aspects

Predicting the hydrological effects of changes of land use and climate is indeed a currently stylish indoor game. Recently, hydrologists have employed rainfall-runoff models to predict the effects of future land use and climate changes on catchment rainfall response, mainly extreme events. This has been one of the most important uses of rainfall-runoff models (Beven, 2001).

Hydrologic response is an integrated indicator of catchment condition where significant changes in land cover and climate may affect the overall health and function of a catchment. Rainfall-runoff relationships within a catchment are the result of the interaction of climate, land cover and soils. Catchment response in the form of runoff depth and peak discharge can therefore be used as indicators of condition and as predictors for the consequences tied with changes of land use and climate (Hernandez et al., 2000).

A quantitative assessment of the impacts of changes of land use and climate on flooding conditions requires simulations of climatological-hydrological system. This means that both the relevant internal processes of climatological-hydrological system and the relevant external forces (changes in land use and climate) must be part of the system to be modeled. This calls for an integrated, coupled, approach of climatological and hydrological model application (Bronstert et al., 2002). Rainfall runoff models (in particular the physically-based, spatially distributed models) can serve as a powerful tool to achieve such a purpose, because they transform the meteorological forcing (the rainfall) into the hydrological response of a catchment (the runoff) (Bronstert, 2004).

In recent years, a wide range of rainfall-runoff model applications have been used to assess impacts of land use and climate changes on the hydrological cycle (e.g. Bronstert et al., 2002 and Niehoff et al., 2003). In fact applying a rainfall-runoff model is the only economically possible way (land use change impact assessment) or even the only feasible way (climate change impact assessment) to obtain some quantitative figures about the impact of such environmental changes on the hydrological cycle (Bronstert, 2004). This will help the decision-makers to develop a comprehensive plan to mitigate the predictable future environmental changes.

The strong interactions between climate and land cover conditions make the link between climate and land use scenarios possible. However, in rainfall-runoff models application for environmental changes impact assessment, the mostly applied procedure is a one-way mode. That means a set of climate or land use scenarios are used for a rainfall-runoff model without bothering about feedback effects, neither direct climate land-surface feedbacks nor the effects of changed forcing on the relevance of different hydrological processes. For example, a change of characteristics in rainfall intensity (climate change) may result in different consequence of the IEOF, or a change of soil surface conductivity caused by different land cover (land use change) may alter infiltration conditions. A two-way mode (the climatological model depends on feedback information from the hydrological model) is commonly used for flooding analysis (Bronstert, 2004).

In the one-way mode, it is assumed that under the scenarios the catchments will continue to behave as they do at the present, which may be misleading especially in the arid and semi-arid regions, like the Faria catchment.

It has to be emphasized that the natural variability of hydrological systems in space and time, and the generally short periods of available observations, makes it very difficult to study, understand and assess the effects of environmental changes, even with the most accessible physically distributed and process-oriented models. Recently, through improvement in measurement of physical parameters and a better understanding of hydrological processes, models are able to depict reality more accurately. The advances in automatic data processing make it possible to handle complex models with a high resolution. Even so, care should be taken with model results handling. This is because the climatic and hydrological modeling is accompanied by a high degree of uncertainty (data, process and parameter).

Bronstert et al. (2002) suggested some criteria for the selection of hydrological models that are suitable for the assessment of the effects of land use and climate changes. These are:

1. **Representation of the soil zone:** The behavior of the soil surface and unsaturated zone is essential for the appearance of the quick rainfall-runoff process. If the land use change effects are investigated, models that lump different runoff generation process are not advisable.
2. **Spatial distribution:** The selected model should be able to operate in a spatially distributed manner. If the runoff generation processes are highly variable in space, a distributed approach is crucial especially if this variability can be attributed to soil and vegetation characteristics. This is typically the case if the IEOF is the dominant runoff generation mechanism.
3. **Temporal resolution:** When the runoff generation is controlled by rainfall intensity (e.g. IEOF), the selected model should be able to reflect the temporal resolution of both the meteorological data and the modeling time step.
4. **Dynamics of the landscape:** If the climatic conditions have a second order impact on the runoff generation conditions (causing crusting of the soil, altering the characteristics of the vegetation cover, etc) this needs to be taken into account, particularly for long term projections of the development of flood generation.
5. **Scale:** The transformation from rainfall to runoff is highly non-linear and, as a result, scales dependent.

It was one purpose of this study to evaluate how and to what extent hydrological modeling can contribute to a quantitative analysis of the effects of land use and climate changes on catchment hydrology. To achieve this purpose, the coupled TRAIN-ZIN model (which matches the criteria mentioned above) is used in a one-way mode to assess the effects of land use and climate changes on the availability of water resources in the Faria catchment.

9.2 Modeling the Impacts of Land Use Change

A prevailing principle of land management is that changes in land cover and land use are followed by changes in catchment condition and hydrologic response. It is true that methods for transforming various land cover and land use characteristics into distributed hydrologic model parameters are not well developed for a wide range of conditions. For management purposes, many approaches rely largely on empirical studies of small plots and catchments to relate land cover and land use to hydrologic model parameters (Hernandez et al., 2000). The curve number method (USDA-SCS, 1972) is an example of this type of approach to relate land cover and land use to hydrologic model parameters. However, since the period of industrialization and rapid growth of population, land use change phenomena have accelerated in many regions (Bronstert, 2004). Acceleration of recent human activities is producing some changes, such as urbanization, deforestation, reforestation, reservoir or detention pond construction and the effects of wild fires (Beven, 2001).

In fact, the change in land use is of major relevance for rainfall-runoff processes, especially if runoff generation processes are influenced by the land surface conditions of the investigated catchment. IEOF is affected by crop cultivation and management practices; relevant for storm runoff generation in the case of high rainfall intensities and low soil infiltration. Soil siltation and crusting may enhance the IEOF. On the other hand, the SEOF is slightly affected by land use changes, since the process is controlled by topography and subsurface conditions (Bronstert et al., 2002).

In this study the calibrated TRAIN-ZIN model is used to predict the effects of land use changes by assuming three different scenarios:

1. **Scenario 1:** Urbanization, urban areas, on the one hand, consist of asphaltic or paved surfaces and house roofs that generate a high amount of runoff and are often connected to a sewer system. On the other hand, they contain parks, green strips or gardens that allow a high amount of rainfall to infiltrate since soil storage conditions can be found. Lumping of soil parameters in these areas predictably leads to an overestimation of the influence of built-up areas on storm runoff generation and underestimates the compensating effect of green areas within settlements. For the exact modeling, built-up areas have to be mapped so that different surfaces can be grouped into sealed and unsealed surfaces. In this study built-up areas are generalized to a single land use class and no difference between sealed and unsealed surfaces was made since mapping the built-up areas in the Faria catchment into sealed and unsealed surfaces is too difficult due to the lack of spatial data needed to do this task. Thus as an example of the impact of urbanization on storm runoff generation, the simulated runoff response to an increase in built-up areas of 10% and 50% respectively is illustrated. In the Faria catchment, such an increase corresponds to a growth of built-up areas from 4.7% of the total catchment area to 5.2% and 7.1% respectively.

2. **Scenario 2:** Land reclamation, it is a common practice nowadays in the upper Faria catchment (mainly in Al-Faria sub-catchment) that farmers in cooperation with the Ministry of Agriculture are changing the grassed land cover (terrain type E) to agriculture areas (terrain type H). As already mentioned, this terrain type is covered by fragmented stone cover, and by removing these stones, fertile agriculture areas are produced. For this scenario, the agricultural areas in the Faria catchment will increase from 22.7% to 28.6%. Hence, it is expected that the runoff generation will be decreased due to the increase of the infiltration rate of the soil by agricultural practices.

3. **Scenario 3:** Extensions of the scattered and poorly managed olive areas (terrain type F) to more dense and well managed olive areas (terrain type G). This scenario will increase the olive plantation areas by 7.8%. As a result the generated runoff will be

also decrease due to management practices that enhance the soil infiltratibility (e.g. ploughing, soil tillage and terraces).

For the above three scenarios the two already simulated rainstorm events, event 1 with high antecedent soil moisture and low rainfall intensities (SEOF) and event 2 which is characterized by high rainfall intensities and low antecedent soil moisture (IEOF) were used. In **Fig. 9.1** the simulation results of scenario 1 for both events 1 and 2 are depicted.

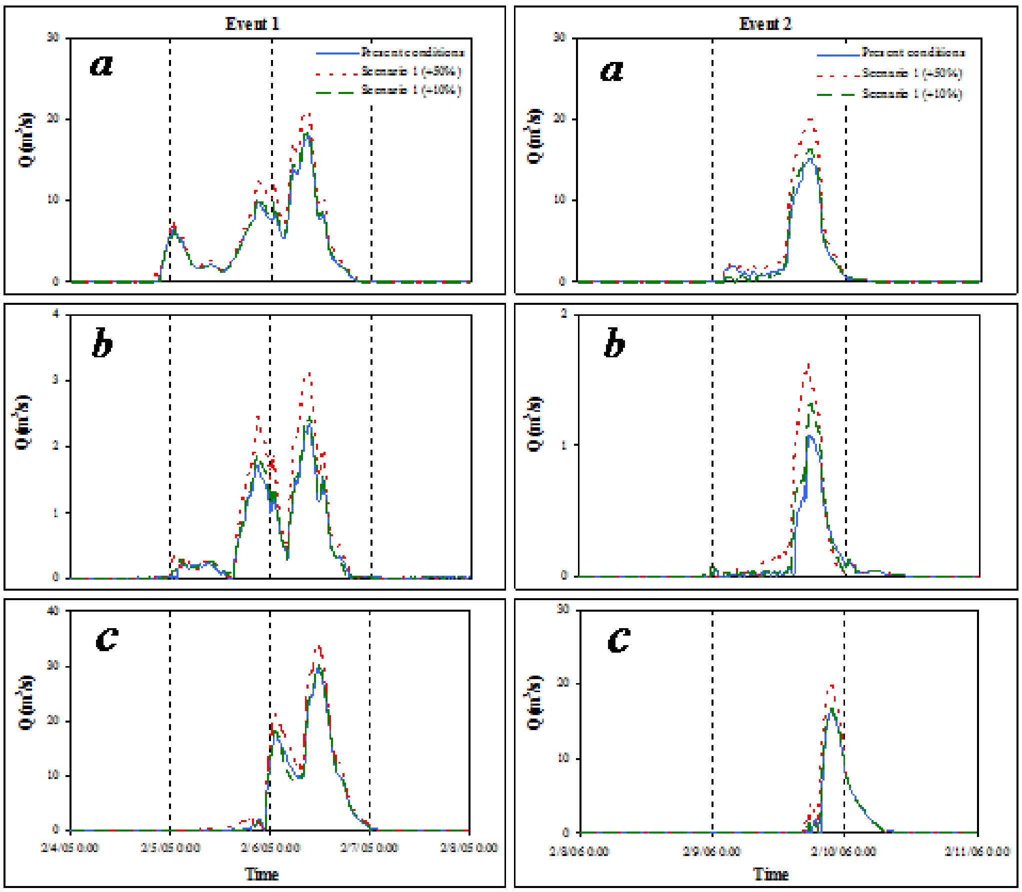

Fig. 9.1 Simulation of Event 1 and Event 2 for Present Conditions and Land use Change Scenario 1 (10% and 50% increase in built-up areas): (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment

Fig. 9.1 clearly illustrates that, the effect of urbanization on the rainfall events with lower rainfall intensities and higher antecedent soil moisture (event 1) is smaller than that of higher rainfall intensities and lower antecedent soil moisture (event 2). For event 2, an increase in built-up areas leads to higher peak flows and flood volumes.

The simulated results of land use change scenario 2 are as shown in **Fig. 9.2**. The effect of this scenario on the simulated runoff is minor. A little effect is seen for Al-Faria sub-catchment (b). This makes sense because the changed land use for this scenario is situated mainly in Al-Faria sub-catchment.

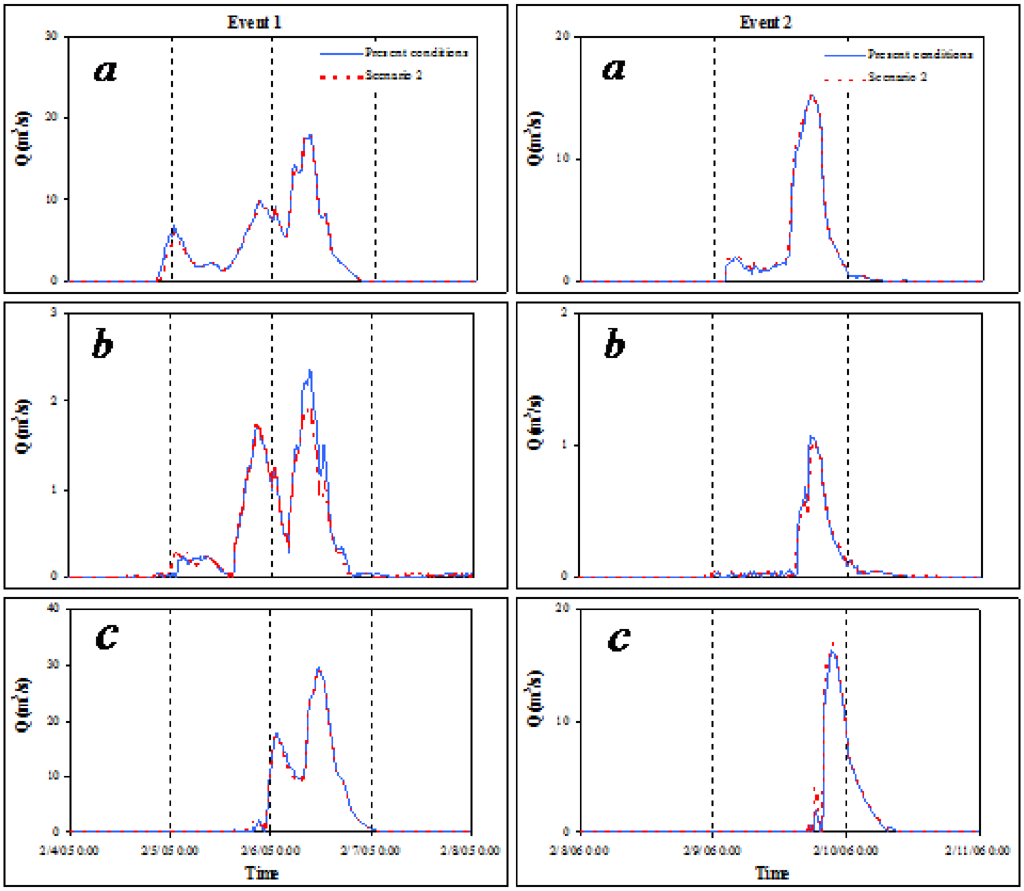

Fig. 9.2 Simulation of Event 1 and Event 2 for Present Conditions and Land use Change Scenario 2: (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment

As shown in **Fig. 9.3**, scenario 3 has no effect on the simulated runoff for both events. The two hydrographs are nearly identical. This could be due to the relatively high infiltration rate for this terrain (34 mm/hr) which is almost not reached by both events. Both events are expectedly produced on the built-up areas and the saturation of natural grassed areas (terrain type D), in case of event 1, which has infiltration rate of 14 mm/hr. Thus neither event 1 nor event 2 had rain that was able to generate runoff from these terrains. However it is expected to see the effects of this scenario for rainfall events with low rainfall intensities and long duration or for short duration events but with high rainfall intensities.

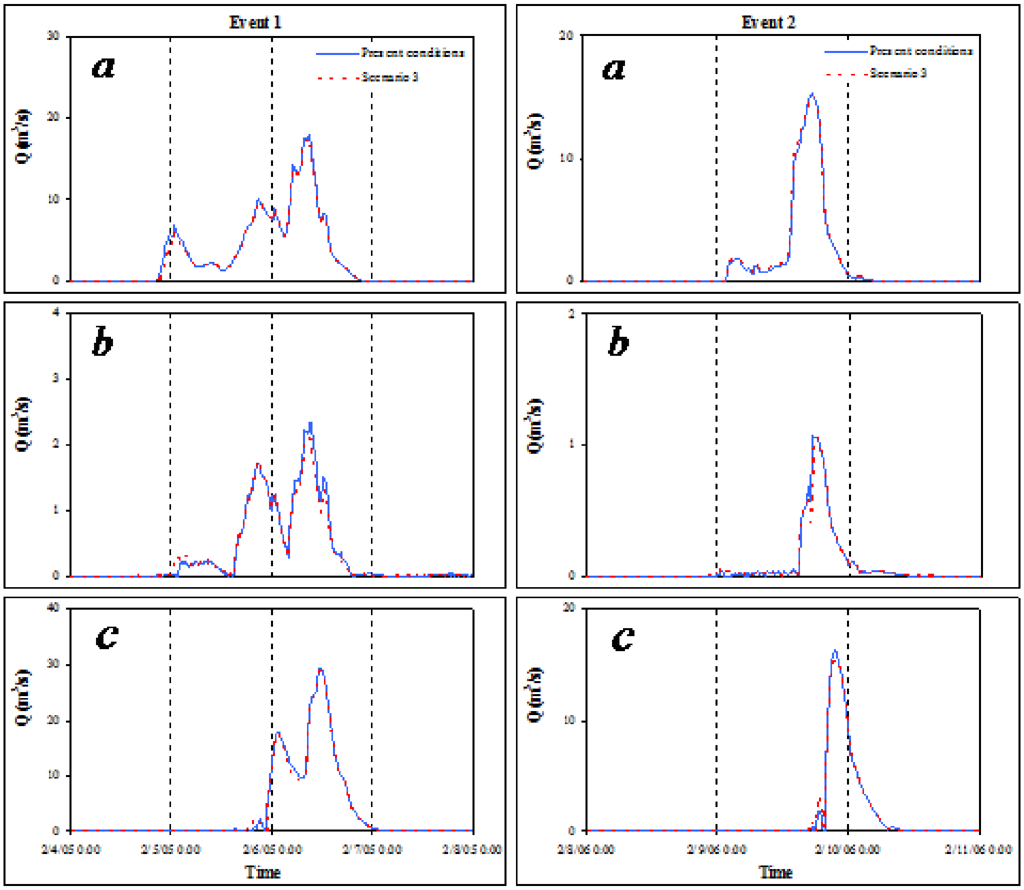

Fig. 9.3 **Simulation of Event 1 and Event 2 for Present Conditions and Land use Change Scenario 3: (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment**

In general and from the simulation results, it became clear that the TRAIN-ZIN model was able to characterize the runoff response of the Faria catchment due to changes in land cover. It is also clear that effects of land use changes on catchment rainfall response are observed when the IEOF is the predominant runoff generation mechanism in the catchment. In particular, the dominant runoff generation mechanisms and their relation to land use were distinguished within the process-oriented and physically distributed TRAIN-ZIN model.

9.3 Modeling the Impacts of Climate Change

It is widely accepted that the anthropogenic production of greenhouse gases will cause many changes in the natural environment. The most noticeable of these changes are on the climate, for example increased mean global temperatures and modified precipitation distributions (Houghton et al., 1995). The Intergovernmental Panel on Climate Change (IPCC), which involves hundreds of scientists from the United States and other nations in assessing the state of climate change science, concluded in a 2001 report that, by 2100, average global surface temperatures will rise 1.4 to 5.8°C above 1990 levels. A key question is how much of the observed warming is due to human activities and how much is due to natural variability in the climate. An analysis of data sets that cover the period since 1970 (IPCC 2007) leaves no doubt on the existence of a man-made climate change. One of the most significant potential consequences of changes in climate may be alterations in regional hydrological cycles and consequent changes in catchment rainfall response (Xu, 2000). Worldwide, there has been growing concern to assess the effects of these changes (e.g. Labat et al., 2004; Legates et al., 2005).

The available global climate models (GCMs) were originally created for the analysis of large scale circulation systems and are much too coarse in their spatial resolution (10^4-10^5 km^2) to generate usable input data for high resolution hydrological catchment scale models (10^{-1}-10^3 km^2) (Hostetler, 1994). Therefore the degree of uncertainty of the simulated regional metrological parameters is very high. This demonstrates the weaknesses of the present state of the art of the research studies of the climatic change and its impacts on the hydrological cycle. The uncertainties are very strong and relate to the lack of knowledge and understanding of the processes in their complex and interconnected form. Accordingly, two conclusions could be drawn from such finding; either science has no chance of arriving at any results of importance in reasonable time, due to the enormous lack of knowledge, data, understanding, etc.; or science has a great challenge to evaluate the situation and to improve quantitative assessments which would be of value in practice (Kundzewicz and Somlyödy, 1997).

It has been observed that the current generation of GCMs is not well suited for the evaluation of catchments water resources problems. Furthermore, different GCMs are still giving different values of climate variable changes and so do not provide a single reliable estimate that could be advanced as a deterministic forecast for hydrological planning (Xu, 1999). This demonstrates the need to develop and test other impact assessment techniques and tools. Hydrologic models provide a conceptual framework to conceptualize and investigate the relationships between climate and water resources. Xu (2000) reviewed the different methodologies for simulating hydrological responses to global climate change by using hydrologic models which may be described using three categories: (1) Coupling high resolution regional climate models (RCM) with hydrologic models (e.g. Hostetler and Giorgi, 1993; Nash and Gleick, 1993); (2) Coupling GCMs with hydrologic models through statistical downscaling techniques (e.g.Wilby and Wigley, 1997) and (3) Using hypothetical scenarios as input to hydrologic models (e.g. Arnell, 1992).

Hence, in most climatic change scenarios, methods of simple alteration of the present conditions, i.e. hypothetical scenarios methods, are often used. Rough expectations of future temperature and rainfall changes are incorporated into hydrological models.

For the Middle East, GCMs simulations indicate higher future temperatures that will increase evapotranspiration and changes in climate patterns that might reduce rainfall in the region as a whole (IPCC-DCC, 1999; IPCC-WGI, 1997). On the other hand, an increase in extreme daily rainfall and a decrease of annual rainfall is a widely accepted prediction for the Eastern Mediterranean region (Alpert, 2004).

Pe'er and Safriel (2000) studied the climate change in Israel (Historical Palestine) under the United Nations Framework Convention on Climate Change (UNFCCC) (Impact, Vulnerability and Adaptation). After a survey of recent literature, evaluation of available GCMs and based on the climate scenario of Dayan and Koch (1999) they summarized the currently most likely climate scenarios for the region. The following are the first two scenarios proposed:

1. **Scenario 1:** By 2020, mean temperature will increase of 0.3-0.4^{o}C and reduction in precipitation by 2% to 1%.
2. **Scenario 2:** By 2050, mean temperature will increase of 0.7-0.8^{o}C and reduction in precipitation by 4 % to 2%.

Moreover, regional climate simulations for the Near East and the Jordan River Region were studied under project 3 of the GLOWA-JR project. Consequently, meteorological time series for both the reference period 1961-1990 and the scenario period 2021-2050 were developed by the project. The climatic scenarios are based on the IPCC, A1B and A2 emissions scenarios. Two different GCMs were used. At Tel Aviv University, Israel (Historical Palestine), the ECHAM5-RegCM3 model was used by the working group leaded by P. Alpert for A1B scenario. At Forschungszentrum Karlsruhe, Garmisch-Partenkirchen, Germany, the GLOWA-working group leaded by H. Kunstmann used the A2 scenario driven by the ECHAM4-MM5 model. The spatial resolution is 50 km (ECHAM5-RegCM3) and 54 km (ECHAM4-MM5). For both scenarios, change in mean annual temperature (^{o}C) and mean annual precipitation (mm) for the projected period (2021-50) versus the reference period (1961-90) are available on 14x12 km grids. The raw data of the GLOWA partners were processes by Giebl in his ongoing master thesis at the Institute of Hydrology, Freiburg University (Giebl, 2008). Out of these grids and to achieve the aim of the overall GLOWA-JR project, the following scenarios were taken for the Faria catchment:

3. **Scenario 3 (A1B):** By 2021-50, mean temperature will increase 1-1.25^{o}C and reduction in mean annual precipitation by (50-0 mm) which equivalent to (12-0%).
4. **Scenario 4 (A2):** By 2021-50, mean temperature will increase 1.75-2^{o}C and increase in mean annual precipitation by (50-100 mm) which equivalent to (12-24%).

These four scenarios were assessed in this study. The average values for both temperature increase and precipitation decrease/increase were used. This makes it possible to compare directly the different hydrological response on storm weather periods under present and future climatic boundary conditions.

The TRAIN-ZIN model was used here to assess the impact of future climate change for both events 1 and 2. **Fig. 9.4** through **Fig. 9.7** show the resulting hydrographs gained from the aforementioned scenarios. From **Fig. 9.4** and **Fig. 9.5**, it can be seen that the first two climate change scenarios proposed for the region will have insignificant effects on the runoff generation. However, small effects will be expected from scenario 3 (A1B) where the expected reduction in rainfall will reduce the generated flood by 2050 (**Fig. 9.6**). Generally, the obtained results from the first three scenarios indicate that small changes of the meteorological forcing can’t cause much stronger changes in catchment runoff. In contrast to the first three scenarios, the result of scenario 4 (A2) shows that a considerable future climate change with no doubt leads to a noticeable change in catchment runoff (**Fig. 9.7**). Hence results of both scenarios A1B and A2 proved that the GCMs contain with high uncertainty since for the same reference period 1961-1990 and the scenario period 2021-2050, these models produced different values of climate variable changes. This confirms the limitations of the present GCMs for providing a single reliable estimate that could be used for the evaluation and management of the catchment water resources under the forecasted future climate changes.

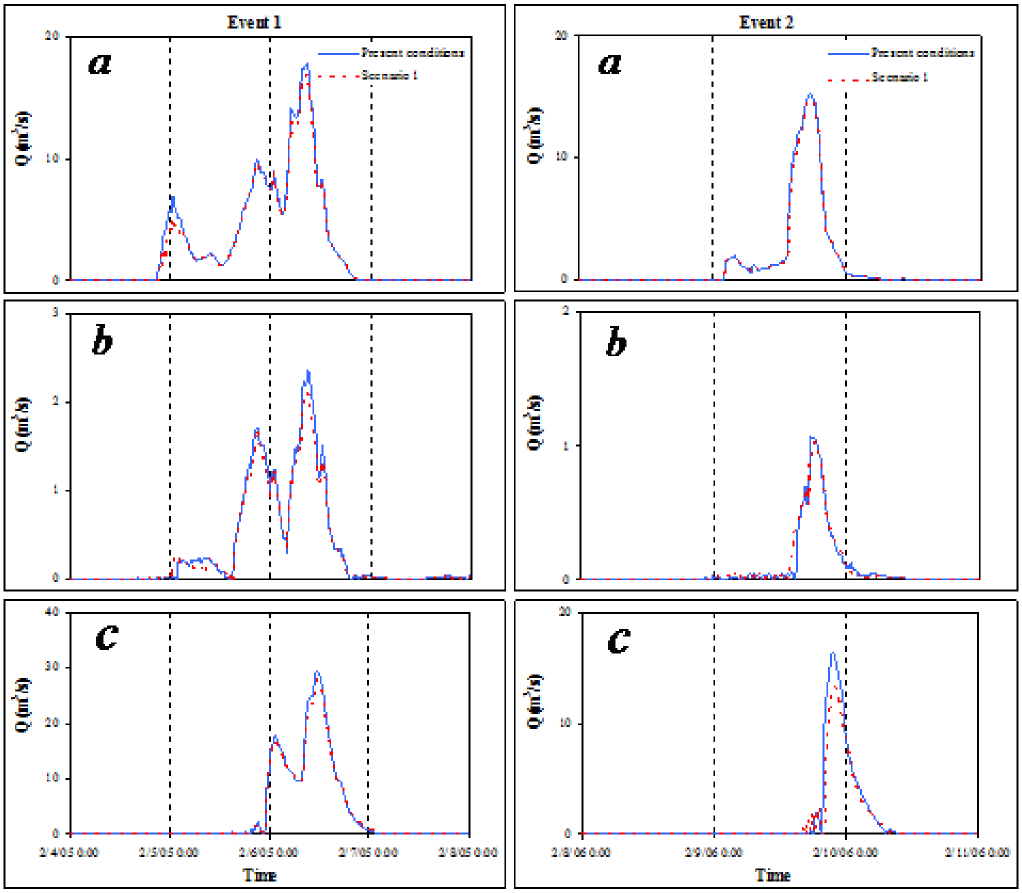

Fig. 9.4 **Simulation of Event 1 and Event 2 for Present Conditions and Climate Change Scenario 1: (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment**

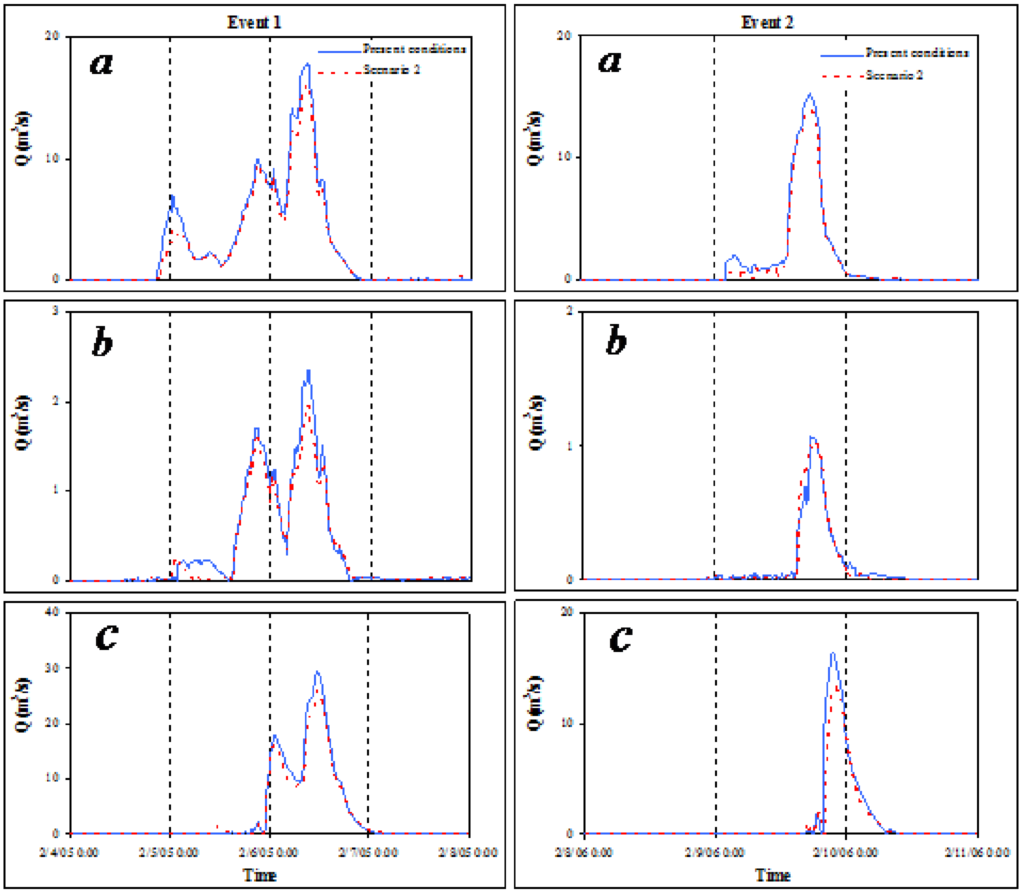

Fig. 9.5 Simulation of Event 1 and Event 2 for Present Conditions and Climate Change Scenario 2: (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment

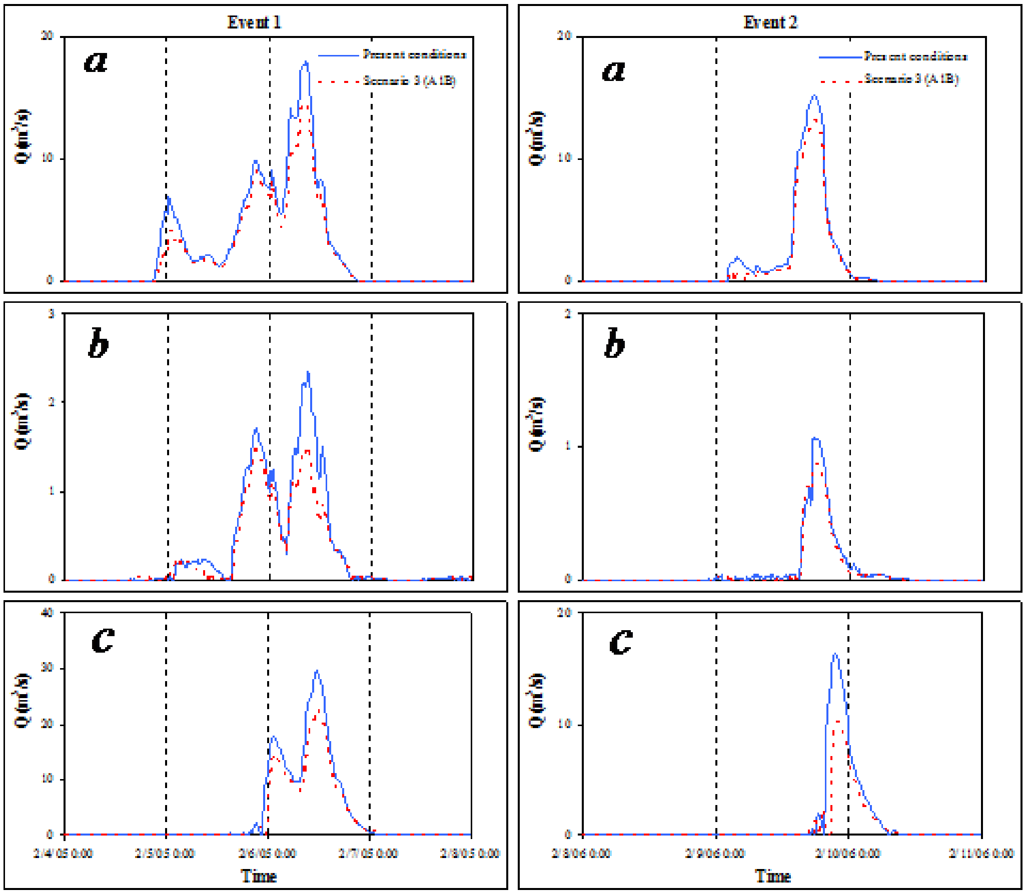

Fig. 9.6 **Simulation of Event 1 and Event 2 for Present Conditions and Climate Change Scenario 3 (A1B): (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment**

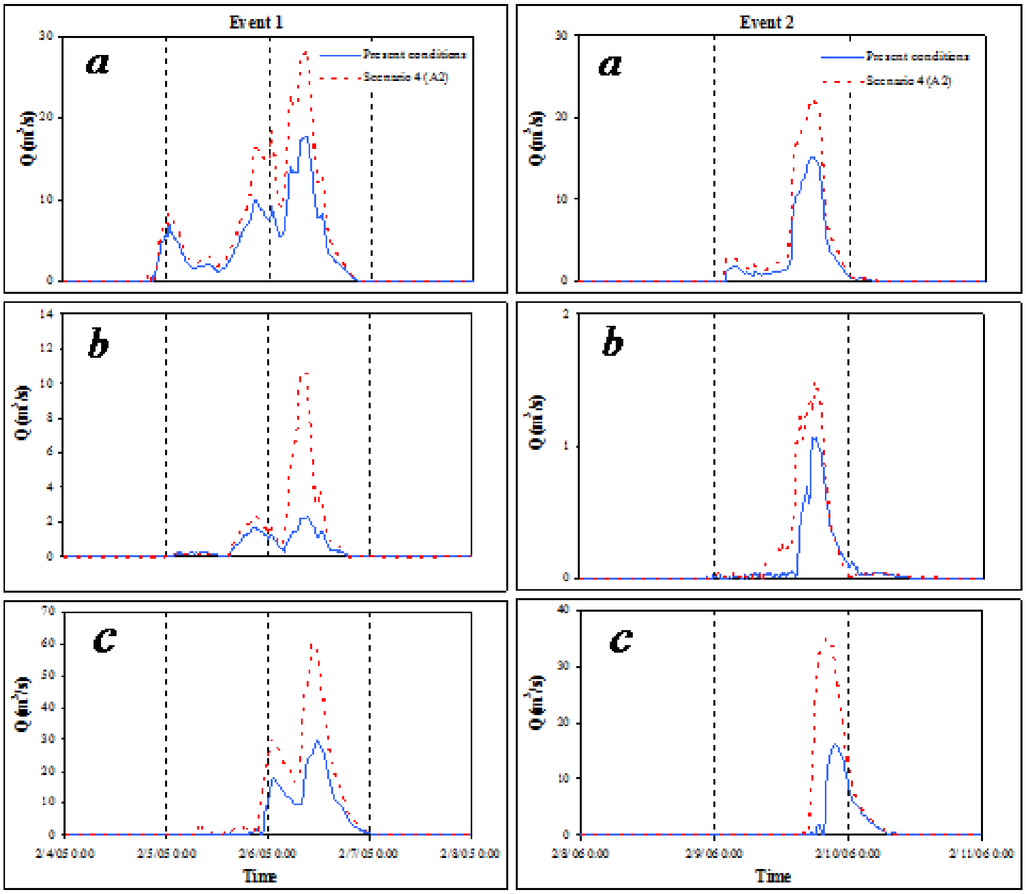

Fig. 9.7 Simulation of Event 1 and Event 2 for Present Conditions and Climate Change Scenario 4 (A2): (a) Al-Badan Sub-catchment; (b) Al-Faria Sub-catchment and (c) the Entire Faria Catchment

To expect a sound catchment response to the future climate change, a hypothetical scenario method (**Scenario 5**) was assumed and used. In this scenario, rough expectations of extreme future rainfall changes are assumed and incorporated into the TRAIN-ZIN model. For both events, the model was run one time with half rainfall and second time with doubled rainfall. In **Fig. 9.8**, the simulation results on Al-Badan sub-catchment of scenario 5 is presented for event 1 and event 2.

Fig. 9.8 indicates that a considerable future climate changes can have an important impact on flood generation in the Faria catchment. For the double rainfall scenario, rainfall with all intensities can produce runoff. For event 2 (IEOF) this scenario has longer effects than on event 1 (SEOF). Produced runoff volumes of the double rainfall scenario are 5.8 and 6.48 times higher than the simulated runoff volume under the present conditions for event 1 and event 2 respectively. However these volumes are unrealistic and have never experienced for the Faria catchment. For both events, half rainfall scenario will generate insignificant runoff.

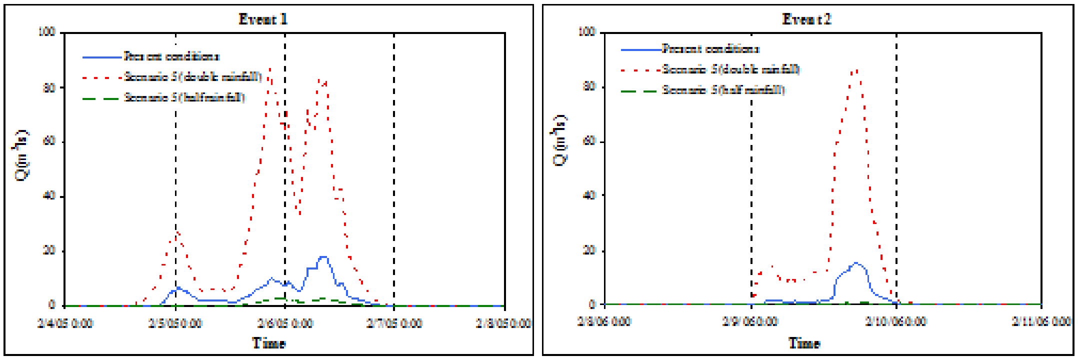

Fig. 9.8 Simulation of Event 1 and Event 2 for Present Conditions and Climate Change Scenario 5 for Al-Badan Sub-catchment

9.4 Discussion

The land use and climate changes impacts study conducted for the Faria catchment shows how changes of land cover and climate (temperature and rainfall) can sometimes lead to significant changes in floods and in some cases the impacts are insignificant. Modeling results for the Faria catchment indicate that rainfall characteristics and antecedent soil moisture are crucial for the relative importance of different storm runoff generation mechanisms (SEOF and/or IEOF). Therefore, the runoff generation mechanisms were controlled the relative importance of changes in land use and climate conditions. Eight scenarios were assessed by the calibrated TRAIN-ZIN model, three scenarios for land use changes and five for climate changes. For the Faria catchment a 50% increase in built-up areas significantly affected simulated runoff while the other two scenarios had insignificant impacts on generated floods. The impacts of the projected climate change scenarios for the region by 2020 and 2050 were examined by the model. The first three scenarios insignificantly affected the generated floods while significant effects were attained on the fourth scenario (A2). As a result, it became clear that a change in climate can have both aggravating and mitigating effects. This depends on the change in rainfall patterns (intensities and duration). However the hydrologists thought that the process-oriented and physically distributed models are an adequate tool to investigate the environmental change impacts on flooding conditions. It has to be emphasized that there are limitations to such modeling studies, since climatic and hydrological modeling are accompanied by a high degree of uncertainty. Thus the choice of climatic scenario is very important in studying the impacts of climate changes on flood generation. Consequently, it has to be recommended that a comprehensive method should be applied, taking into account the general climatic conditions of the studied catchment and possible future changes of these (average) conditions. For the process-oriented models, like the TRAIN-ZIN model used in this study to assess the impacts of changes of land use and climate, a systematic and inclusive technique for uncertainty analysis still needs to be developed.

10 Surface Water Management Options

10.1 Introduction

It is broadly accepted that the most appropriate unit for planning water resources development and management is the catchment. Resources development and management in one part of the catchment will consequently have impact elsewhere on the catchment (Prinz and Singh, 2000). In arid and semi-arid regions of the Mediterranean fresh water resources are finite and most of the economically viable development of these resources has already been implemented (Hamdy et al., 1995). There is a growing disparity between water supply and demand in arid and semi-arid regions. This disparity necessitates the development of management options to close the supply-demand gap. The problem of allocating scarce water among competing uses and users is the most serious issue among the matters that water resources management has to consider (Lee, 1999). Water resources management is often seen as a potential answer to the water availability problems in areas facing serious water shortage, either periodically or throughout the year (Athens, 2005). Worldwide, many arid and semi-arid catchments suffer from the population growth and increasing demand for water, deteriorating water quality, increasing environmental degradation and impending climate change. This situation needs more effort to assess water resources for national planning and management in order to sustain development.

Sustainable water resources management needs a combination of complementary technical, economic, environmental, social and political measures, adapted to the particular local contexts (GWP, 2000). Water resources management should deal with both groundwater and surface water resources. Since this study emphasized with the surface water modeling, best surface water management options are studied and developed. In the Faria catchment, surface water resources are commonly referred to as direct runoff and spring baseflow. Therefore, surface water management options developed in this study include both direct runoff and baseflow.

The overall objective for developing surface water management options is to protect surface water and ensure sustainability use for all beneficial uses. In the Faria catchment, beneficial uses include drinking water supplies, recreational use and agricultural use. Sustainable use of surface water resources will help to bridge the supply-demand gap in the Faria catchment.

10.2 Surface Water Assessment

To assess and manage the surface water (streamflow) in the Faria catchment, the measured streamflow was separated into two components, the direct runoff and the baseflow components (**Section 4.4.3**). For the three modeled seasons (2004-2007), the volume of streamflow (Q_i), direct runoff (q_i) and baseflow (QB_i) in addition to baseflow index (BF_{Index}), which is the volume of baseflow divided by the volume of streamflow, are summarized in **Tab. 10.1**.

Tab. 10. 1 Volumes of Q_i , QB_i , q_i and BF_{Index} of Faria Catchment for the Years (2004-2007)

Parameter	Season 2004/05		Season 2005/06		Season 2006/07	
	Al-Badan	Al-Faria	Al-Badan	Al-Faria	Al-Badan	Al-Faria
Q_i (MCM)	4.20	1.66	3.10	0.52	2.00	0.05
q_i (MCM)	1.46	0.37	0.75	0.10	0.54	0.02
QB_i (MCM)	2.75	1.29	2.34	0.41	1.46	0.03
BF_{Index}	0.65	0.78	0.75	0.79	0.73	0.60

The streamflow in Al-Badan stream is larger than that of Al-Faria stream. This is because of the reasons mentioned in **Section 4.5** for the direct runoff, as well as the following two reasons:

1. Most of Al-Faria springs discharges are used for drinking purposes and agricultural activities while a considerable amount of Al-Badan springs discharges are delivered to the stream; and
2. A considerable amount of wastewater effluent from the eastern part of Nablus city is discharged to Al-Badan stream compared to the small amount of wastewater effluent discharged to Al-Faria stream from Al-Faria Refugee camp.

It is clear also from the table that streamflow varies from year to year as a result of rainfall variation. In addition it can be inferred from the table that estimated baseflow index in the Faria catchment is in the range between 0.60 and 0.79. These values of baseflow contribution are expected to be higher than the adjacent catchments in the West Bank, Palestine. This is due to the fact that the Faria catchment has a perennial stream in which 8 fresh water springs contribute to the baseflow in the upper Faria catchment until the point where the measuring flumes are situated. Statistical analysis has been applied to the baseflow data and spring yield time series as an attempt to investigate the relationship between them. Average monthly streamflow volume of the three seasons (2004-2007) was estimated for the 5 months from November to March for both Al-Badan and Al-Faria streams and the result is illustrated in **Fig. 10.1** and tabulated in **Tab. 10.2**. From the figure it is obvious that the streamflow increases from November to February then decreases slightly afterwards. From the time series of the springs monthly yield discharge, the average monthly volumes are estimated for Al-Badan and Al-Faria spring groups (**Tab. 10.2**).

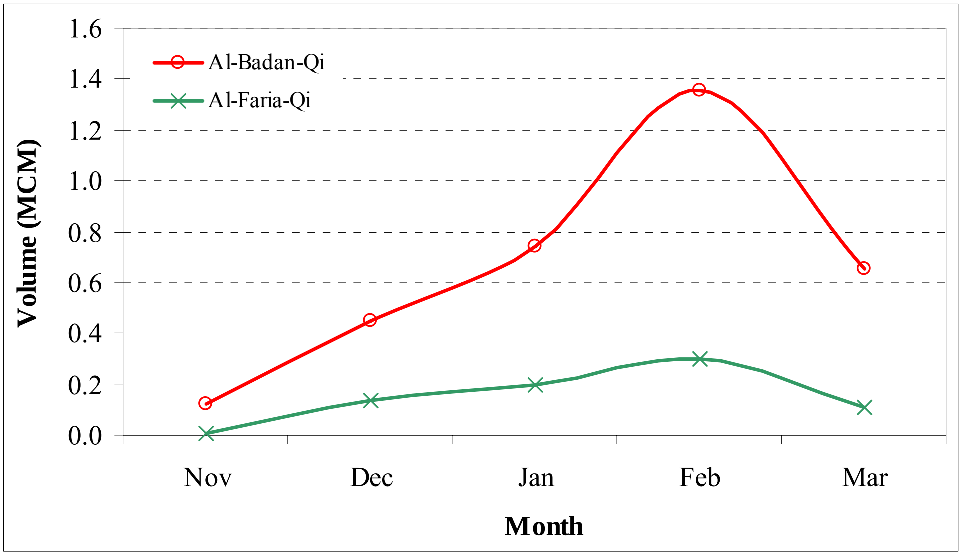

Fig. 10.1 Average Monthly Volumes of Al-Badan and Al-Faria Streamflow

Tab. 10.2 Average Monthly Volumes of Springs and Baseflow

Average Monthly Volumes (MCM)				
Month	**Al-Badan Baseflow**	**Al-Badan Springs**	**Al-Faria Baseflow**	**Al-Faria Springs**
Nov	0.09	0.25	0.01	0.43
Dec	0.26	0.43	0.08	0.50
Jan	0.61	0.37	0.17	0.56
Feb	0.84	0.43	0.23	0.61
Mar	0.58	0.59	0.10	0.70
Sum	**2.37**	**2.07**	**0.59**	**2.80**
Springs - Baseflow	**-0.30**		**2.21**	

Tab. 10.2 indicates that the sum of the average volume of spring yields of Al-Badan group for 5 months is less than the corresponding baseflow volume for the same period. This is due to the wastewater effluent from eastern part of Nablus city entering Al-Badan stream. Depending on the number of inhabitants living in the eastern side of the city (about 75,000) and assuming the water demand to be 70 litter/capita/day, on average and assuming 80% of water demand becomes wastewater, the volume of wastewater coming from Nablus city during the above mentioned 5 months is estimated at about 0.60 MCM, which makes the difference between springs and baseflow to equal 0.30 MCM. Using the same concept, it is estimated that the average volume of wastewater effluent from Al-Faria Refugee camp to Al-Faria stream during the 5 months (November-March) is about 0.04 MCM. Generally, it can be concluded that the abstraction and withdrawal from Al-Badan and Al-Faria streams are 0.30 MCM and 2.25 respectively. The average direct runoff for the five months from November to March for the three seasons (2004-2007) was estimated at about 0.95 MCM and 0.16 MCM for Al-

Badan and Al-Faria streams respectively. Considering the April flood of the season 2005/06 which is simulated but not measured, the annual average direct runoff for the three seasons is increased to 1.05 MCM and 0.163 MCM for Al-Badan and Al-Faria streams respectively. In general, the streamflow variability in the recorded three years in the Faria catchment is high due to the high variability in rainfall that contributes the direct runoff and in spring flows that contribute to the baseflow. This indicates the necessity of continuing the measurements of streamflow in the catchment. This will help to clarify the streamflow variability and trend in the catchment. In **Fig. 10.2**, the seasonal water budget for the upper Faria catchment has been estimated.

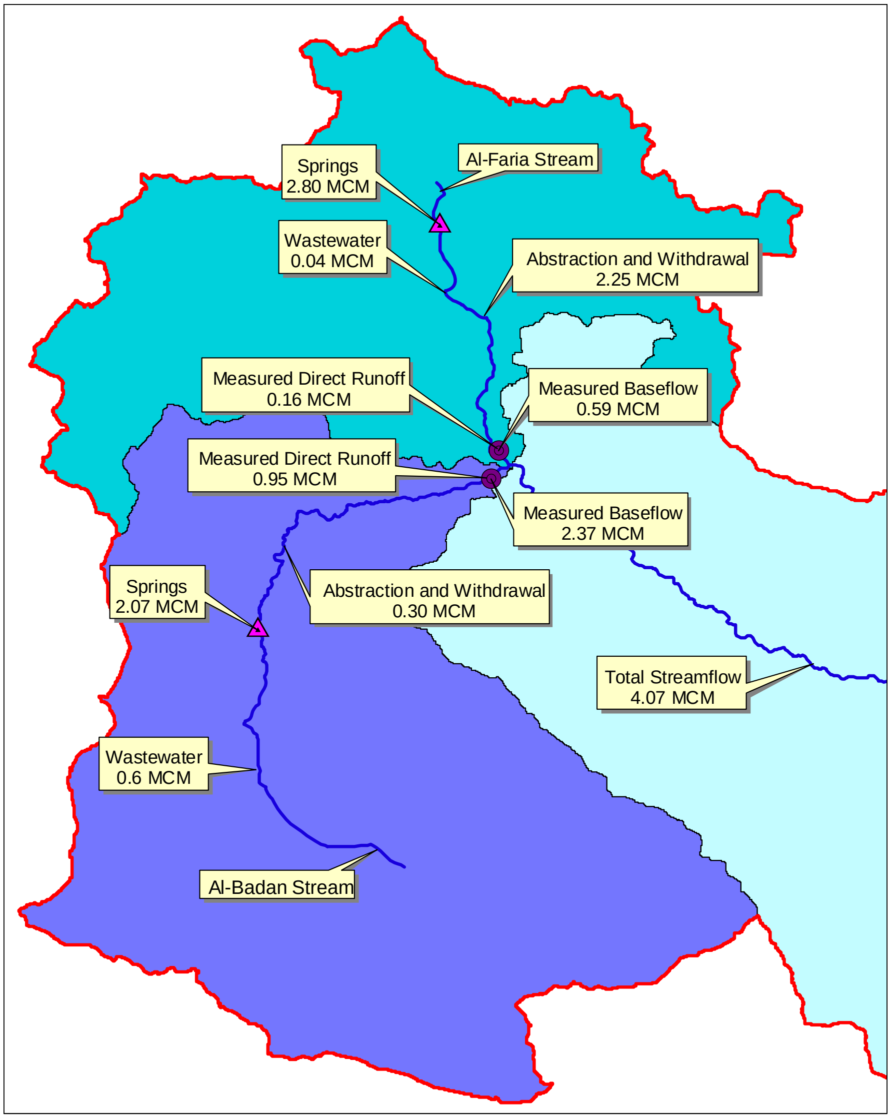

Fig. 10.2 Seasonal Average Water Budget of Al-Badan and Al-Faria Streams

From the figure, it can be concluded that the available volume of streamflow that can be utilized, in winter season, downstream of Al-Malaqi Bridge is about 4 MCM. Besides the surface water resources in the Faria catchment, on average the annual water resources from springs and groundwater wells are 14 MCM and 8 MCM respectively. About 3 MCM of springs discharges are included in the estimated seasonal water budget. This means that nearly 22% of annual springs yield which contribute to the baseflow are lost in winter from November to March. In addition, the direct runoff is also lost in winter due to the lack of storage facilities in the catchment. This makes the annual obtainable water resources in Faria catchment decrease from 23 MCM to about 19 MCM. The total annual irrigation and domestic water demand in the catchment are 15.3 and 5.7 MCM respectively resulting in a deficit of approximately 2 MCM between supply and demand. This situation is becoming worse due to drought that leads to water scarcity and increased competition for water between all beneficial uses. Analysis of rainfall data for the last 30 years from the NMS, one of the rainfall stations located in the upper Faria catchment, proved that drought occurred in 7 out of the last 30 years (Shadeed and Almasri, 2007). By 2015, the annual domestic water demand is estimated to be about 8.3 MCM (EQA, 2004). Assuming that the irrigation water demand stays the same as the current conditions, this means that by 2015, the annual supply-demand gap in the Faria catchment will be increase up to 4.5 MCM.

From the previous calculation, it can be summarized that the water resources in the Faria catchment are not sufficient to fulfill the demand for both agricultural and domestic uses neither in the present nor in the future. Additionally, there is a potential for additional quantities of water (4 MCM) in the catchment to be utilized. Thus it is essential to set a proper surface water management options to save water to be used in dry periods where the gap between demand and supply is high.

Modeling the climate change scenarios (see **Chapter 9**) indicates that changes in climate insignificantly affected the sustainable yield of the surface water resources in the Faria catchment. In contrast, modeling the land use change scenarios showed that urbanization will significantly increase the runoff generation in the catchment. Thus the development of optimal alternative options for surface water resources management could close the supply-demand gap under the current conditions, where the gap is 2 MCM, and also under the inevitable future population growth and climate scenarios projected for the catchment by 2020, where the gap will exceed 4 MCM.

The next sections will focus on the formulation of the best surface water management options to improve the utilization and management of the scarce water resources to close the gap between supply and demand in the Faria catchment. Subsequently outstanding challenges for widespread adoption of surface water management options are identified.

10.3 Management Options

10.3.1 Proper Management Needs

In order to properly manage surface water resources, Nova Scotia (2007) suggested the following steps:

1. **Surface water resources assessment for both quality and quantity:** Assessment of surface water quality and quantity starts by an inventory of the potential sources of surface water supply and specifying the pollution sources that affect those surface

water resources. This is necessary to assess capacity to accept potential changes as a result of human interventions or activities. In addition, there is an urgent need to fully update the hydrological data in terms of frequency and distribution of rainfall, quantity and quality of water resources. A centralized water data management system for information dissemination is essential for enhanced water resource assessment. In this study, location of different springs and streams, in the Faria catchment, were mapped and the sources of pollution were identified. Then, the naturally available surface water runoff is assessed by applying the up to date process-oriented modeling techniques (the coupled TRAIN-ZIN model).

2. **Allocate available water resources amongst various users:** Fair allocation of water resources is essential to make water available for different water uses. In the Faria catchment, surface water resources are not allocated properly. Most runoff is generated in the upper part of the catchment as a result of considerable rainfall, whereas there is limited rainfall in the lower part of the catchment. Additionally, 10 out of 13 springs are also located in the upper part of the catchment. Therefore, most of surface water is used in the upper part for recreational and agricultural activities and for drinking purposes as in the case of the Faria spring. This leaves the dwellers in the central and lower part of the catchment with too little water mainly in summer when the demand is maximal during minimum supply. This situation highlights urgent need for a new legal framework that would bring a more equitable balance of water rights to attain the fair distribution of the water resources in the catchment.
3. **Protect surface water from human impacts:** The aim of surface water protection is to protect water quality by minimizing contamination of the resource from the surrounding communities. Unfortunately, in the Faria catchment, the shortfall in water supplies has been compounded by a decrease in quality owing to the contamination of surface water resources. For instance, surface water mixes with wastewater coming from Nablus city and Al-Faria Refugee camp. Additionally, illegal and unmanaged solid waste dumping in some water courses adds additional complexity to the pollution problems in the catchment. In the catchments when water is plentiful, the quantity of water is enough to dilute these pollutants to insignificant levels. But, in the case of Faria catchment which is characterized by water resources scarcity, there is no natural filter for these pollutants with the result that the available surface water resources are further reduced due to water quality problems.
4. **Monitor surface water to track trends in water quality and quantity:** Monitoring programs are crucial to track long-term trends in surface water quality and quantity. Such monitoring programs are generally both costly and extremely necessary. It is an essential tool for checking the status of surface water, assessing the impact of human activities on this resource and evaluating long-term surface water trends associated with issues such as land use and climate changes. Consequently, monitoring programs generate data that can be analyzed to produce relevant information for best management options. The construction of the two Parshall Flumes in the Faria catchment to monitor the quantity of surface runoff is the first step in developing such a monitoring program. A better understanding of basic hydrological processes is critical for effective catchment management, mainly in arid and semi-arid areas where inadequacy of water supply is a major limitation for development. Reliable prediction of runoff generation from the catchment is therefore essential. Sampling the quality of

surface water in the Faria catchment is an ongoing activity by WESI of An-Najah National University in the context of project 8 of GLOWA-JR project.

5. **Evaluate effectiveness of management options:** According to the previous steps, best management options are developed. To evaluate the effectiveness (sustainability) of the developed options, predictive, evaluatory, and interpretive tools must be developed. This is an important component of the overall management of surface water. Unfortunately, in the Faria catchment these tools have not been developed.

From the above it is clear that management of surface water is a complex issue, especially in arid and semi-arid areas where water resources are very limited. In the Faria catchment, management of the surface water resources is difficult in the absence of protection programs and short-term monitoring programs. In addition, the existing political situation adds another complexity to manage scarce water resources in the catchment. Consequently, intensive efforts should be done at the national level to challenge the current orthodoxy. In general, managing the surface water in the Faria catchment as a considerable water resource will support the decision-making process regarding future sustainable development of its water resources.

10.3.2 Proposed Management Options

A management strategy is urgently required to optimally manage the surface water resources in the Faria catchment. Surface water analysis indicates that there is about 4 MCM of streamflow lost during the winter season when the water needs for agricultural purposes is very minimal and no storage structures exist to capture these flows. In the face of the outstanding difficulties and challenges for managing the surface water in the Faria catchment, the following management options are proposed.

10.3.2.1 Rainwater Harvesting

Rainwater harvesting is the practice of collecting and storing rainwater runoff for productive purposes (Siegert, 1994). In arid and semi-arid areas where it is already practiced, rainwater harvesting has been used for many years to solve water problem for agricultural and domestic uses (e.g. Boers et al., 1986; Brunis et al., 1986; Reij et al., 1988; Critchley and Siegert, 1991; Abu-Awwad and Shatanawi, 1997; Wesemael et al., 1998; Oweis et al., 1999; Li et al., 2000; Li and Gong, 2002 and Ngigi et al., 2005). Rainwater harvesting is an ancient technology that is gaining popularity in a new way. It traces its history to biblical times. Extensive rainwater harvesting apparatus existed 4000 years ago in Palestine and Greece (Evanari et al., 1971, cited by Critchley and Siegert, 1991). In India, simple stone-rubble structures for impounding rainwater date back to the third millennium BC. It was also a common technique throughout the Mediterranean and Middle East. Water collected from roofs and other hard surfaces was stored in underground reservoirs (cisterns) with masonry domes. In Western Europe, America and Australia, rainwater was often the primary water source for drinking water. In all three continents it continues to be an important water source for isolated homesteads and farms (Agarwal and Narain, 1997). Recently, growing scarcity and intersectoral competition for water between all users in arid and semi-arid regions, along with groundwater depletion and the problems facing major surface water control systems have raised interest in refreshing water harvesting systems that capture rainwater wherever it falls (Kerr and Pangare, 2001). Economically rainwater harvesting is viable (inexpensive), can be utilized by individuals or state-run agencies, is a reliable renewable resource with little investment or special management, is relatively easy to use, environmentally safe, and little energy is needed for water transport.

Gould and Nissen-Petersen (1999) categorized the rainwater harvesting system according to the type of catchment surface used as presented in **Fig. 10.3**.

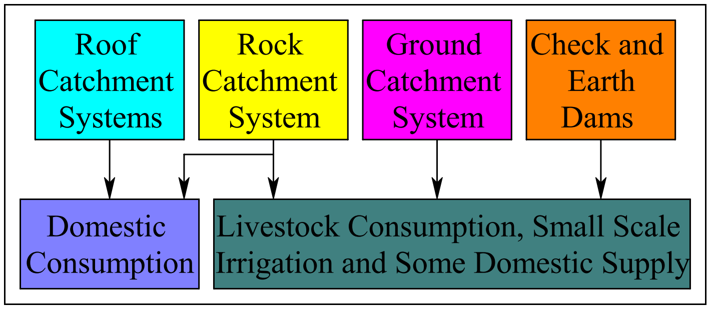

Fig. 10.3 Small-scale Rainwater Harvesting Systems and Uses

In this study, urban (roof catchment) and hillslopes (rock and ground catchment) rainwater harvesting systems were proposed.

1. Urban Rainwater Harvesting System

This system is commonly used in areas where water is scarce, either because it is rare or because it has been depleted due to heavy use. The storage of rainwater on the surface is a traditional technique and structures used include cisterns, underground tanks, ponds, check dams, weirs, etc. In Palestine, the family cistern is a traditional water harvesting technique used for several decades to capture the rooftop runoff for many purposes, including cooking, washing and in some cases for irrigation. In the Faria catchment, particularly in the upper part where the eastern part of Nablus city produces a considerable amount of rooftop runoff, family cisterns are proposed to capture rainwater. This will provide domestic water for families, especially in summer where inadequate municipal supplied. The long-term annual average rainfall in Nablus city is estimated at about 640 mm which is relatively high compared to the average rainfall in the Faria catchment. Thus, more potential for runoff generation is offered.

The coupled TRAIN-ZIN model was used to assess the runoff generation from the built-up areas of the eastern part of Nablus city for event 1 and event 2. Results are presented in **Tab. 10.3**.

Tab. 10.3 Simulated Runoff Volumes (MCM) for Event 1 and Event 2

Contribution	Event 1	Event 2
Al-Badan Sub-catchment	0.99	0.37
Built-up Areas (Nablus)	0.57	0.23
Percentage (%)	57	62

The results show that the contribution of the built-up areas of Nablus city to the generated runoff from Al-Badan sub-catchment is 57% and 62% for event 1 and event 2 respectively. As mentioned earlier, event 1 mainly came out of the SEOF, so most of the catchment contributed to the generated flood. For event 2, which consisted mainly of IEOF, partial area contribution is clear since the built-up areas of Nablus city made more than 60% of the generated flood. Therefore, it is of great important to harvest and manage this considerable amount of flood water lost in winter due to the lack of storage structures in the area.

For the two events, the generated runoff from the built-up areas was not separated to rooftop runoff and other surfaces (paved roads and parking areas) runoff. However, on average, it is assumed that the rooftops runoff represents about 50% of the generated built-up areas runoff. Therefore rooftops runoff becomes half of the simulated runoff volumes shown in **Tab. 10.3**. Simply, this means that a rooftop runoff which is 283,486 m^3 and 113,112 m^3 can supply an annual average daily amount of about 775 m^3 and 310 m^3 for event 1 and event 2 respectively. Assuming a consumption rate of 70 liters/capita/day, rainwater harvesting from rooftops, on average, can supply water for about 8,000 inhabitants for the whole year. In other words, this supply can fulfill the domestic demands for nearly 24,000 inhabitants for more than 4 months from May to September when the water resources are very limited. Hence, this can help to reduce the municipality stress to make water available for domestic use. To achieve this purpose, it is proposed to construct a cistern for each family wherever it is possible.

For the other surfaces runoff, which is assumed to be 50% of the generated runoff, it is proposed that the municipality of Nablus will construct enough underground reservoirs at some selected locations to harvest this amount of water. Therefore, this will also enhance the availability of water in the region for different uses.

For rural communities in the Faria catchment that get their domestic supply from either direct house connections to nearby irrigation wells or using tanker vehicles which fill from the Faria spring, rainwater harvesting will help to make water available for these communities and reduce competition between agricultural and household demands.

Generally, harvesting rainwater for domestic purposes has the following advantages:

- Saves money;
- Reduces demand on the municipal water supply;
- Makes efficient use of a valuable resource;
- Reduces flooding streets as well as reduces clogging the storm drains; and
- Reduces contamination of surface water with wastewater.

In the lower part of the Faria catchment where the water resources are very limited, green houses are commonly used for growing vegetables. It is proposed to collect rainwater from these houses to help meet their water needs.

2. Hillslopes Rainwater Harvesting System

This system has been developed to provide supplementary water for rain-fed agriculture in arid and semi-arid regions (e.g. Yair, 1983; Giraldez et al., 1988; Tabor, 1995; Lavee et al., 1997). This system is commonly used in Spain, northern Africa as well as in arid and semi-arid parts of India to provide the water needs of families and their livestock (e.g. Chapman, 1978; Samra et al., 1996). In arid and semi-arid regions, rainfall produces a discontinuous runoff that in many cases never reaches the valley bottom. Therefore, suitable sites where runoff is produced are limited and relatively small (Lavee and Yair, 1990; Brown and

Dunkerley, 1996). Lavee et al. (1997) have shown that rock outcrops produce runoff which tends to infiltrate further downslope in the colluvial mantle during the majority of events. These rock outcrops and thin, stony soils show a spatial distribution that depends on the topography and land use (Poesen et al., 1998).

In the case of Faria catchment, the runoff generation map was developed and areas of high potential runoff generation were delineated. For these areas it is proposed to construct underground reservoirs (cisterns) to capture runoff for future uses. Such cisterns are proposed to be very close to isolated rain-fed agricultural farms. Topographically, these farms are elevated and suffer from a shortage of water availability due to the difficulty in pumping water from the agricultural wells when there is a large variability in the topography. Having cisterns in these areas will increase the water availability and lead to improved agriculture productivity. In the central and lower parts of the catchment where Bedouins are living and mainly depend on livestock, hillslope rainwater harvesting system can save water for families and their livestock.

In this study, and depending on the developed runoff generation map and aerial photographs, an inventory of the best locations to generate runoff (rocky slopes, gentle slopes with a crusted surface and even complete headwater areas) was done. As a result 19 cisterns are proposed (**Fig. 10.4**).

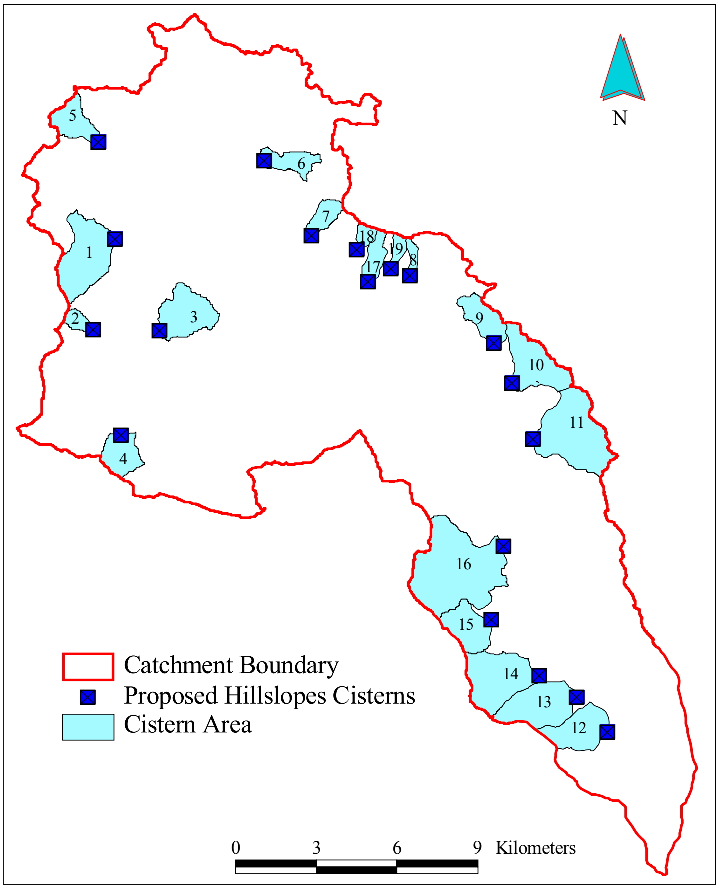

Fig. 10.4 Proposed Locations for the Hillslopes Rainwater Harvesting Cisterns

The most important characteristic of these hillslopes is their ability to produce runoff even during light rainfall (runoff is produced most rapidly). The TRAIN-ZIN model was used to assess the amount of runoff generation from these hillslopes for event 1 and event 2. This assessment is essential to determine the size of the proposed cisterns. Results are depicted in **Tab. 10.4**. Although the catchment areas of the proposed cisterns accounts only for 15% of the entire Faria catchment, the flood generation out of these areas are 30% and 62% for event 1 and event 2 respectively. This reflects the importance of runoff generation mechanisms that took place during these events. In case of SEOF, event 1, although the generated flood is greater than event 2, the percentage of the generated runoff is less than that of event 2 (IEOF). Two reasons made the generated runoff volume out event 1 greater than the one of event 2. These are the rainfall amount which is 1.5 times the rainfall amount of event 2 and high antecedent soil moisture of event 1 that increased the areas contributing to the generated flood as a result of SEOF. In contrast to event 1, the proposed cisterns can collect more than 60% of generated flood volume out of event 2 (IEOF).

Tab. 10.4 Runoff Volumes of the Proposed Hillslope Cisterns for Event 1 and Event 2

Cisterns ID	Coverage cistern area (km^2)	Event 1			Event 2		
		Rainfall (m^3)	Runoff (m^3)	Runoff coefficient (%)	Rainfall (m^3)	Runoff (m^3)	Runoff coefficient (%)
1	4.40	730,765	17,268	2.36	488,644	5,171	1.06
2	0.60	94,278	5,710	6.06	60,266	1,948	3.23
3	3.08	461,657	32,054	6.94	295,460	18,539	6.27
4	1.81	307,585	21,939	7.13	189,979	5,184	2.73
5	1.81	292,654	11,593	3.96	193,296	4,528	2.34
6	1.39	167,588	13,236	7.90	102,492	3,399	3.32
7	1.04	135,853	14,810	10.90	84,001	5,139	6.12
8	0.41	51,587	4,210	8.16	32,603	2,244	6.88
9	1.81	188,451	9,676	5.13	121,406	2,545	2.10
10	3.42	314,562	7,623	2.42	208,568	3,197	1.53
11	5.90	536,750	20,868	3.89	348,003	8,021	2.30
12	2.79	200,546	25,305	12.62	133,697	10,377	7.76
13	3.73	279,901	70,766	25.28	186,601	46,092	24.70
14	4.31	349,214	24,259	6.95	228,498	14,002	6.13
15	2.35	201,733	28,858	14.30	131,361	19,618	14.93
16	8.66	788,482	24,641	3.13	511,213	15,485	3.03
17	1.08	138,897	11,089	7.98	87,214	5,636	6.46
18	0.52	66,526	5,031	7.56	41,579	1,622	3.90
19	0.51	63,796	6,028	9.45	39,999	2,515	6.29
SUM	49.60	5,370,825	966,354	------	3,484,882	263,175	------
MAX	8.66	788,482	70,766	25.28	511,213	46,092	24.70
MIN	0.41	51,587	4,210	2.36	32,603	1,622	1.06
AVG	2.61	282,675	18,682	8.01	183,415	9,224	5.85

The volumes collected in the proposed cisterns vary between 4,210 and 70,766 m^3 with an average of 18,682 m^3 for event 1 while for event 2 about half of these values were estimated. This variation in runoff volumes reflects differences in rainfall characteristics from event to event and differences in the location of cisterns in the landscape regarding their possibility to frequently collect substantial runoff volumes. It is clear that the estimated runoff volumes are high. In this case a series of cisterns are proposed instead of just one for each area. Such big cisterns were constructed in Nyabushozi in South-Western Uganda. Nine cisterns with an average capacity of about 10,000 m^3 were built to save water for people and their livestock for more than three dry months (Mawami, 2005). This study is an attempt to assess the value of the hillslope rainwater harvesting technique. This technique can be adopted on small scales to avoid the large scale adaptation problems (e.g. capital cost, location and maintenance). In this regard, it is worth mentioning that the small scale hillslope rainwater harvesting system is an old technique used in Palestine. Furthermore, ground truthing combined with feasibility study are very important to examine the power of this management option to decrease the water shortage problems in arid and semi-arid regions.

Generally, this study shows that the hillslope water harvesting system is still viable provided that the runoff coefficient of the proposed cisterns catchments is high and the size of the cisterns is adapted to the size of the catchment so that water loss by overflow is minimal. In addition, a hillslope rainwater harvesting system can catch more runoff by minimizing the considerable transmission losses that take place in the Faria catchment. Indigenous techniques such as the hillslopes cistern system could provide an additional source of water to alleviate the ever increasing demand in arid and semi-arid regions.

10.3.2.2 Spring Water Harvesting

In the Faria catchment, springs water is a highly desirable source of community water supply. No pumping is required, given that the water comes out at the ground surface through cracks and loose joints in rocks under internal pressure of the groundwater system. This makes, on average, more than 14 MCM per year available without cost. Moreover the water is fresh and free from pollution obviating the need for artificial purification. However, these sources are under threat particularly at Al-Badan sub-catchment where the fresh spring water are mixed with the untreated wastewater coming from Nablus city causing noticeable pollution to water resources in the catchment. Part of water from these springs was used for recreation activities in the area where the swimming pools are filled from these springs while the remaining water is going to the natural stream and mixing with the wastewater. Spring water is conveyed in the natural stream to irrigation ditches, which convey water to different farms in the upper and central parts of the catchment. The irrigation ditches are lined with concrete to improve their efficiency. Although no measurements are available to quantify the conveyance efficiency, it is expected that efficiency is low and the system needs improvement.

From the above it is clear that the spring water of Al-Badan sub-catchment was not managed and most of water is not used properly. Therefore, it is proposed to harvest the springs discharge in order to use it for both domestic and agricultural purposes. One relatively easy means of storing and distributing spring water is through construction of a concrete reservoir (a spring box). It is proposed to build a deep enough box into a hillside of the spring mouth to access the spring water source. This box allows water to enter from the bottom and fill up to a certain level depending upon the spring yield and the filling time of the box. Depending on local water requirements and conditions, a number of these spring boxes may be constructed to provide year-round supply or used to recharge other community water storage systems. In case of Faria catchment, Al-Badan springs group which has annual yield of 5.2 MCM can fulfill the domestic and recreational needs of Al-Badan area. Instead of conveying the remaining water to the natural stream and mixing with the wastewater, it is proposed to convey it to the eastern part of Nablus city for domestic purposes. This will reduce the cost for dwellers that depend on the pumped groundwater resources for drinking purposes since pumping costs from such spring boxes are much less than pumping costs from groundwater wells. A second alternative is to use it for agriculture purposes in the lower parts of the catchment after improving the conveyance coefficient of the existing channel system. In this regard, it is proposed to replace the existing open channel system by a pipe network system. This will minimize the losses that take place in existing open channels by both natural evaporation and leakage and the pipe system will keep the fresh water away from the potential source of pollution. However to save the harvested spring water for dry periods, onsite water reservoirs are proposed to be built either in Nablus city for domestic purposes or in the central and lower parts of the Faria catchment for agricultural purposes. Thus the collected water will be conveyed to these reservoirs in a way to prevent over flooding of the proposed spring boxes. Therefore, depending on the local water requirements, a well designed scheme is needed to insure the effectiveness of this management option.

Al-Faria springs which produced 6.5 MCM per year is used for drinking purposes for Al-Faria Refugee camp where water is pumped to the local network distribution. In addition, tanker vehicles transport water from the Faria spring to the nearby villages during summer, when demand is at its peak. It is assumed that Al-Faria spring is managed to fulfill the domestic water needs for the nearby communities.

10.3.2.3 Construction of Irrigation Ponds

The previous management options are proposed to harvest the rainwater as well as the baseflow. In fact it is impossible to collect each drop of rainfall by means of urban and hillslopes rainwater harvesting systems. Therefore, a certain amount of runoff generated on built-up areas and hillslopes is not harvested and goes to the main stream of the catchment. Therefore, it is proposed to capture this amount of water in order to be used for irrigation purposes for the farms that exist along both sides of the water course. Although the farmers are neither hydrologists nor engineers, they have the common sense required to capture the streamflow. Hence, an irrigation pond is proposed to be built for each farm along the water course to collect the streamflow for irrigation use.

10.3.2.4 Wastewater Treatment and Reuse in Agriculture

There has been an increasing interest in reuse of wastewater in agriculture over the last few decades. This is due to increased demand for fresh water. Population growth, increased per capita use of water, the demands of industry and of the agricultural sector all put pressure on water resources. Treatment of wastewater provides an effluent of sufficient quality that it should be put to beneficial use and not wasted (Chen et al., 1998).

In arid and semi-arid regions like the Faria catchment, there is increasing water scarcity accompanied with major political implications of water scarcity. Therefore, water quantity and quality issues are both of concern. Recycling of wastewater is one of the main options when looking for new sources of water in the catchment.

Wastewater is used extensively for irrigation in certain countries e.g. 67% of total effluent of Israel (Historical Palestine), 25% in India and 24% in South Africa is reused for irrigation through direct planning, though unplanned reuse is considerably greater (Ursula and Peasey, 2000).

In case of Faria catchment, about 1.5 MCM per year of wastewater effluent from Nablus city and Al-Faria Refugee camp is discharged to both Al-Badan and Al-Faria streams and mixes with the fresh surface water without any treatment. This is one of the greatest threats to water resources in the catchment. Hence, it is proposed to construct a wastewater treatment plant to stop this increasing threat and to use the treated effluent for agricultural purposes. A wastewater treatment plant is proposed to be constructed in the eastern part of Nablus city to remove health risks from the use of wastewater for agriculture. A trunk line is proposed to convey the treated wastewater (by gravity) from the wastewater treatment plan to the downstream users in the central part of catchment in order to be used for irrigation purposes. For the wastewater coming from Al-Faria Refugee camp (estimated at about 0.1 MCM per year) a small treatment plant is proposed to be built and the treated effluent used for irrigation purposes locally in the upper part of the catchment.

The reuse of treated wastewater for agricultural purposes in the Faria catchment can be used as strategy to release the spring fresh water for domestic use and to improve the quality of stream water to reduce the environmental degradation in the catchment.

10.4 Outstanding Challenges

The sustainability of water resources management in the Faria catchment is being challenged by five important factors. The first is technical because, unfortunately, our scientific understanding of the physical phenomena of rainfall, runoff, evapotranspiration, seepage, sediment transport and flooding are still insufficient. These phenomena should be carefully observed, measured and analyzed. Understanding the physical phenomena in the Faria catchment is accompanied with several difficulties, including climatic conditions, difficulty in carrying out measurements and interdependency of the different processes that need more technical possibilities and further scientific research. Further, there has been a noticeable lack of coordination of data collection activities and propagation of information and techniques between the different projects which are ongoing in the catchment. The value of collected data describing the natural water resources in the Faria catchment becomes limited if these data are not made readily available to all potential users. The second challenge is financial because the existing water resources are poorly managed and the demands of the growing population are urgent. Hence, under this situation and in the absence of financial support, managing water resources in the Faria catchment is difficult. The third challenge is environmental because of declining water quality and increased urban and agricultural pollution. There is no success for any management plan in Faria catchment if the environmental aspects are not given their proper role. Thus, environmental legislation and laws require consolidation and updating to enable proper use, protection, and management of water resources and prevent further pollution. Most importantly, the enforcement of regulations is crucial to the success of any water policy. The fourth challenge is institutional and legal because of weak regulatory and legal framework required to implement policies efficiently regarding allocation, management and pollution of water resources in the Faria catchment. The existing institutional structure should be strengthened and new institutions should be established as needed to manage, operate and maintain water resources in the catchment. Clear legislation and enforcement mechanism should be applied to ensure the performance of institutions. This is essential to make each community and individual controlled by the laws and regulation. For example, these regulations should clearly make those producing pollutants responsible for pollution in the catchment. The last challenge is political because the political situation in the region is very complicated and constrains the development of water resources management in the catchment.

10.5 Discussion

The annual water balance for the Faria catchment indicated that the catchment has a water deficit under the current conditions of about 2 MCM and the situation will be worse with the inevitable growing water demands and hydrologically limited and uncertain supplies. By 2015, it is expected that the annual water deficit will be increase to 4.5 MCM. Consequently, water resources management in the catchment is a complex issue to face the outstanding challenges. As such, the establishment of a clear and well-defined local water policy is imperative. Since this study focused on the surface water, special concerns were made to set the proper surface water management options in trying to solve the ongoing water shortages in the Faria catchment. From the analysis of surface water, it is found that there is a potential for additional quantities of water (4 MCM) in the catchment to be utilized. Thus it is essential to set proper surface water management options to save water to be used in dry periods where the gap between demand and supply is comparatively high. Rainwater harvesting system of urban areas and hillslope as well as the spring water harvesting is very useful to bridge the supply-demand gap for both domestic and agricultural purposes. Resorting to unconventional water sources such as treated wastewater will be required in the future to meet the expected rise in water demands. However, wastewater treatment may become more necessary in order to keep pollutants out of the natural water resources and to use the treated effluent for irrigation purposes.

11 Conclusions and Perspectives

11.1 General

Hydrological models are standard tools increasingly used in catchment hydrology to understand the catchment rainfall response, mainly the surface runoff, and to what extent the changes in the catchment (land use and climate changes) may affect this response. Surface runoff is a significant component of the global water budget and is widely considered an important variable in managing water resources especially in arid and semi-arid regions. Therefore accurate information on the surface runoff over a study area is essential for developing sustainable and coherent water resources management options to mitigate the water scarcity related problems in the area. Surface runoff estimation is usually obtained either by monitoring or by modeling. Despite increasing advances in both observation technology and modeling techniques, the provision of surface runoff estimation at the right spatial and temporal resolution is not yet practical. This problem is mostly due to the high spatial and temporal variability of rainfall characteristics, especially in arid and semi-arid environments.

Understanding the runoff generation processes (SEOF and/or IEOF) is the most critical issue for rainfall-runoff modeling in arid and semi-arid catchments (**Chapter 2** and references therein). The TRAIN-ZIN is a process-oriented and physically-based distributed model used in this research study to gain an understanding of the runoff generation mechanisms in an arid to semi-arid catchment. Three years of monitoring rainfall and runoff combined with thorough field campaigns (e.g. measuring infiltration rates and channel geometry) are considered to be the cornerstones for the success of this study. Despite difficulties, limitations and uncertainties associated with obtaining observations and measured parameters, this study ended-up with optimistic results for the simulation of single events and entire seasons in continuous mode. The question arose of what is the best hydrological model that can be used to assess the active runoff generation process in arid and semi-arid regions. That was the main research question addressed by this PhD research study. More specifically, an answer was sought for the following supplementary research questions:

1. Which data should be collected and how should data acquired be in the fieldwork period? What is the quality of the data? (Spatial data and attribute data) If data availability is insufficient, how can synthetic data be generated?
2. How can we provide improved estimations of catchment initial conditions (e.g., soil moisture, infiltration rate, Manning coefficient, hydrologic conductivity)?
3. What is the optimal set of the input model parameters required to apply the coupled TRAIN-ZIN model?
4. What is the potential for distributed coupled TRAIN-ZIN model set up for catchment outlet simulations to generate hydrographs at interior locations for flood forecasting?
5. How do we characterize the coupled TRAIN-ZIN model uncertainties?
6. How can we use the coupled TRAIN-ZIN model in assessing the runoff generation under land use and climate changes scenarios?
7. What are the total available water resources in the Faria catchment?

8. What are the proper surface water management options for the most efficient water use in the Faria catchment?

The Faria catchment (320 km^2), which is a typical arid to semi-arid catchment located in the northeaster part of the West Bank, Palestine was used when investigating these research questions in details. Chapters 3 to 7 addressed the first four questions. Chapters 8 and 9 described in details the answer for question 5 and 6. The last two questions were answered in Chapter 10. In this Chapter, the findings presented in the previous Chapters will be integrated into a more general synthesis in order to highlight the achievements of this research study and also to identify future research needs.

11.2 The Rainfall and Runoff Monitoring

Monitoring of rainfall and runoff is a key factor for successful modeling of the catchment rainfall response. Highly accurate rainfall input is crucial to drive hydrological models accurately. A better description of the catchment rainfall inputs enhanced the model efficiency mainly in arid regions where the rainfall is highly variable in space and in time. Thus to capture the spatial rainfall distribution accurately over the catchment, several rain-gauges should be installed in different places.

As discussed in Chapter 4, the number of the existing rain-gauges in the Faria catchment is not enough to have a clear picture of the spatial distribution of the catchment rainfall. Four TBRs were installed in the upper part of the catchment while the central and lower parts are not gauged. To overcome this deficit, the ideal number of the rain-gauges required in case of the Faria catchment was estimated at 14. Dummy stations were proposed randomly at several locations in the central and lower parts of the catchment. Multiple regression analysis of long term average rainfall of the existing stations was used. Geographic location and topography (elevation) are two factors that were considered in the developed formula. The developed formula was used to estimate long term average of the proposed stations. Using the measured rainfall intensity of the existing four TBRs, the rainfall intensity of the proposed stations was estimated. The IDW method was used to average the rain-gauge pointwise measurements over the entire catchment. Despite the well-behaved results of the catchment rainfall distribution obtained from the used method, with no doubt, a certain amount of rainfall data uncertainty remains. Therefore it is highly recommended to install enough rain-gauges especially in the central and lower parts of the Faria catchment in order to have actual rainfall measurements. This can decrease the data uncertainty and increase the model efficiency.

Monitoring of runoff generation in several locations in the catchment is of great importance for model calibration and validation by comparing measured and simulated flows. Given that the Faria catchment was not gauged at its outlet, the upper Faria catchment which was gauged by two Parshall flumes was used for model calibration; subsequently the model was extended to the entire catchment. Conversely to the fact that the constructed flumes in the upper part of the Faria catchment help to examine the runoff generation processes in the catchment, it is recommended to install two more streamflow gauges, one at the central part and the second at the catchment outlet. By doing this, calibration and validation of the model will be more physically possible.

Three years of monitoring for both rainfall and runoff observations in the Faria catchment was the focal point for model calibration and validation. Consequently, three years of monitoring made it possible for the author of this research to deal with the catchment as a gauged catchment. Thus this is the first trial in the West Bank catchments. Before this study, all hydrological studies that were carried out in the Faria catchment used synthetic hydrographs methods (e.g. SCS, Clark and Snyder methods) since the catchment was un-gauged at that time. However, it is recommended to continue the monitoring of rainfall and runoff observations in the catchment in order to investigate the streamflow variations and trends as a result of the well characterized rainfall variation. This will make it easier for the follow up researchers to gain a better understanding of runoff generation mechanisms in the Faria catchment under present and future inevitable global changes.

11.3 The Coupled TRAIN-ZIN Model

As mentioned in **Section 5.3** of this thesis, the ZIN model simulates short term runoff generation processes whereas the TRAIN model simulates long term fluxes between soils, vegetation and atmosphere. The coupling layer of both models is the soil storage. The structure of the ZIN model combines the process-based runoff generation at sub-catchments scale with runoff routing. In general the Faria catchment modeling process is represented by: (a) Runoff generation by IEOF and/or SEOF, (b) Transmission losses (infiltration, percolation and storage) and (c) Evapotranspiration. The hydrological response units (model elements) which represent the spatial scale of hydrological process have been classified based on terrain and landscape units. The simple model structure and the lateral distribution of sub-catchments and channel segments has been linked to topographic position and thus to runoff generation and stream routing relationships. This has been important in view of incorporating sub-scale processes in an efficient and flexible way for a large scale catchment under limited data availability. The model has great advantages due to its flexibility to incorporate any hydrological and spatial information without much modification in the model code.

During times of rain, the ZIN model is active and describing the filling of the soil storage and runoff generation whereas during dry days the soil module of TRAIN is active and calculates the emptying of the soil storage by evapotranspiration using the Penman-Monteith equation and percolation using the Van-Genuchten method. These calculations are important for modeling the next event, as they describe initial filling of the soil storage. With time steps of one day, TRAIN provides the missing long term simulation of soil moisture to ZIN. This modifies the ZIN model to a combined model that can be run in a continuous mode instead of single event oriented. Channel routing has been done using Muskingum-Cunge flow routing technique in which the Green-Ampt infiltration model was integrated to simulate the transmission losses. The flow velocity in each sub-catchment has been calculated by Manning's equation which depends upon the slope, channel roughness and hydraulic radius. The generated runoff has been routed over the surface flow path and accounts for the differences in runoff and velocities due to changing slope, soil, land use and sub-catchment surface conditions. The total discharge at a given node has been obtained by superimposing all contribution from surface flow paths for each sub-catchment. The routing routine can be run separately with the results from prior model runs and so parameters for channel flow and transmission losses can be calibrated without running the whole model. This advantage makes it possible to output the hydrograph of any sub-catchment. This possibility saves time since the model is spatially distributed and runoff generation is time consuming and this facilitates the calibration of routing parameters focusing on different characteristics of sub-catchments.

The TRAIN model was developed for more humid environments. Thus, the built-in land cover classes and their evapotranspiration processes are suitable for the typical humid land use types. Typical land covers in the Faria catchment such as olive plantations are not included in the TRAIN database. Therefore, an approximation along with personal judgment and some field experiences were employed to select the suitable TRAIN land covers that represent the available land covers of the Faria catchment. This causes some model structure uncertainty which surely affects the evapotranspiration estimation as well as the model output. In this regard, it is recommended to incorporate the typical arid and semi-arid land use types in the TRAIN database in order to accurately mimic the evapotranspiration processes in the Faria catchment so that more accurate results can be obtained.

However, model results are hopeful for further applications. The TRAIN-ZIN model is available, at the moment, in a C++ shell. Thus the user should spend much effort to understand the source codes and to be aware with the code lines that must change to switch from one catchment to another or for the same catchment in case of model calibration. With a more user-friendly interface the coupled TRAIN-ZIN model will be a powerful and useful tool for further research and for operative catchment management under the present and forecasted changes in climate as well as in land cover conditions.

11.4 Parameterization

Before determining the input parameters for the coupled TRAIN-ZIN model, the thematic GIS database was developed for the three main components of the model (runoff generation, runoff concentration, and routing and transmission losses). The spatial sub-units (terrain types) for the model's runoff generation routine and the channel segments with adjacent polygons (1088 polygons) that represent the model elements for runoff concentration routine were mapped with the help of aerial photographs that cove the entire catchment. As a result, a detailed runoff generation map (combination of the land use and soil maps) which is classified into eight different terrain types was obtained for the Faria catchment. For the computation of the channel flow and transmission losses using the routing routine, the developed channel network (544 segments) was grouped into 5 different channel types according to their morphological feature similarities to reduce the large number of the input parameters. The mean channel segment flow length is on the order of 847 m with mean size of the contributing sub-catchments, on both sides of the channel segments, around 0.295 km^2. Due to the lack of information on the mean response function in the catchment, a uniform time lag for runoff concentration was assumed and calibrated for the catchment. Thus it is crucial to study the hydrological response function in the small scale; around the average size of the contributing sub-catchments (model elements) in order to have an actual time lag and representative hydrograph shape. The accuracy of the spatial subdivision of the three model units (terrain types, model elements and channel segments) used in the Faria catchment must be regarded as an uppermost boundary for a meaningful model parameterization. The GIS makes the spatial subdivision flexible; as a result the efficiency of model parameterization was maximized.

Based on the developed runoff generation map and channel network, the model parameters for various terrains and channel types were estimated. Infiltration rate, which is the most important parameter controlling runoff generation, was determined through physical measurements carried out directly in the field for different terrain types. For the different channel types, parameters such as width, inner channel, depth of full and alluvium depth were also measured directly in the field for several channels. The remaining parameters were determined from the SPAW soil water characteristics tool (e.g. hydraulic conductivity, permanent wilting point, field capacity) based on soil texture, from topographic maps (e.g. channels slope), aerial photographs (e.g. channels geometry) and from information in literature (e.g. porosity, Manning n, etc). Through model calibration, the un-measured model parameters were adjusted. Finally, two optimal parameters set values were obtained for both terrains and channels. With these values, good results were achieved after manual calibration. With a few additional measured data, the quality of simulation could be improved and parameters obtained through the calibration could be verified. Hence more field measurements are highly recommended to reduce the model parameter uncertainties.

11.5 Model Application

In this study, the coupled TRAIN-ZIN model was first calibrated and validated for selected single events, then the model was applied in continuous mode for the entire rainy seasons for the period from the first of October till the end of April. In the monitored three years (2004-2007), only four events were available for model calibration and validation. The first two events were used for model calibration, whereas the last two events were saved for model testing (validation). Rainfall characteristics, mainly the rainfall intensity and the initial soil moisture content, are the main parameters that controlled the runoff generation processes (IEOF and/or SEOF) in the Faria catchment. Low rainfall intensities and high initial soil moisture content made SEOF the dominant runoff generation mechanisms for event 1 whereas event 2 was produced mainly from IEOF since the rainfall intensities are relatively higher than that of event 1 combined with low initial soil moisture content.

The measured streamflow at both outlets of Al-Badan and Al-Faria sub-catchment were separated into two components, baseflow and direct runoff using the Lyne and Hollick filter method. The separated direct runoff was used to assess the model performance during the calibration and validation processes.

In light of the above, in **Chapter 7** of this thesis the question was raised on how model parameterization and model performance can be investigated throughout the model calibration and validation processes. To answer this question the predictive performance of the coupled TRAIN-ZIN model was evaluated by comparing the observed and simulated hydrographs using three performance statistics measures. These are the Nash-Sutcliffe efficiency coefficient (EFC), the volume error (VE) and the peak error (PE). Subsequently the model was calibrated successfully after several alternative runs of the first and the second rainfall events. Then the model was validated for both events 3 and 4. For Al-Badan sub-catchment, EFC was in the range of 0.74 to 0.91, while for Al-Faria sub-catchment the range varied between -2.77 to 0.9. A negative value can be explained by the very low flood generated out of Al-Faria sub-catchment in case of event 4 (the peak flow was 0.04 m3/s). However, visual inspections indicated the good agreement between the observed and simulated hydrographs for the four events for both sub-catchments. The runoff coefficient of Al-Badan sub-catchment is larger than that of Al-Faria sub-catchment. This identifies the potential of Al-

Badan terrain to generate large runoff compared to the low runoff generation potential of Al-Faria sub-catchment. As a result, it was found that the average runoff coefficient for the four simulated events for Al-Badan and Al-Faria sub-catchments is about 5% and 1%, respectively.

After the successful calibration and validation of the model with single events, the entire rainy seasons 2004/05, 2005/06 and 2006/07 were simulated. Continuous simulation of the entire rainy season evaluates the continuous behavior of the vertical fluxes and it provides an additional verification of the single event simulation.

For the entire Faria catchment, it was found that the annual runoff volume is in the range of 0.24 to 1.5 MCM. This is the first real number of the generated flood obtained in the Faria catchment using a physically-based rainfall-runoff model and confirmed with the observed values. All the hydrological studies carried out in the catchment so far using simple empirical formulas like the rational method concluded that the runoff generation in the Faria catchment was in the range of 4-6 MCM per year. Thus the result of this research study is of great importance as it reflects the actual situation of the runoff generation in the Faria catchment. The previous studies assumed that the entire catchment is contributing to the generated flood. In reality and as proved by this research study, the concept of partial area contribution is acceptable in the Faria catchment. In **Fig. 11.1**, the areas of high runoff generation potential are depicted. From these areas, which account for only 10% of the entire catchment, the flood generation is 73% and 117% for event 1 and event 2 respectively. This demonstrates to what extent the partial area contribution concept is acting in the Faria catchment. In the central and lower parts of the catchment, where there is less rainfall, IEOF contributes almost nothing to the generated runoff. In addition, a part of the generated runoff in the upper part of the catchment is lost because of considerable transmission losses taking place while the water is routed from the upper part to the catchment outlet. This explains the reason for higher runoff of event 2 which was 17% more than the one simulated at the catchment outlet. Generally, it can be concluded that it is not proper to use simple empirical formulas to estimate the amount of runoff generation in the Faria catchment as an arid to semi-arid region.

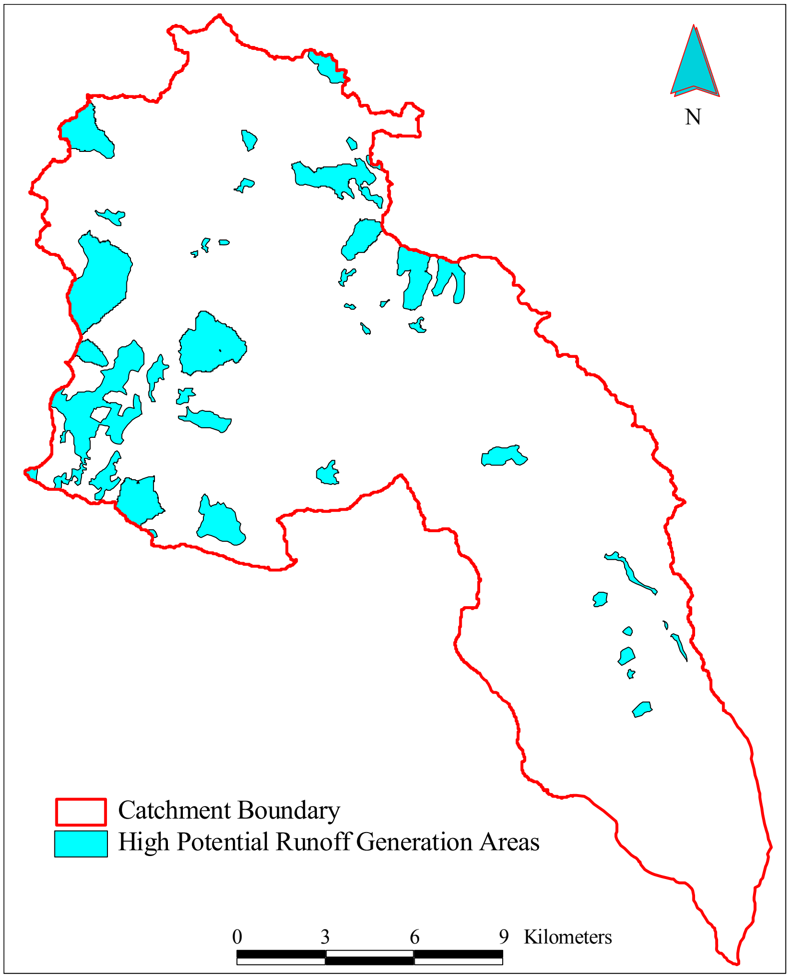

Fig. 11.1 High Potential Runoff Generation Map

From the coupled TRAIN-ZIN model the seasonal water balance was obtained. On average, it was found that circa 70% of the rainfall is stored in soil, of which, a certain amount is percolating and the remaining goes back to the atmosphere by means of evaporation and transpiration. The percolated water is replenishing the groundwater aquifers. In the Faria catchment, there are no observations of the soil moisture at appropriate spatial and temporal resolution, especially when soil moisture information on deeper layers is required. Thus it is difficult to estimate the actual volume of annual rainfall replenishing groundwater aquifers without groundwater modeling. Therefore it is recommended to link the coupled TRAIN-ZIN model with a suitable groundwater model to overcome this shortage.

Generally speaking, the coupled TRAIN-ZIN model proved its functionality and applicability for both event and continuous simulations in the Faria catchment as an arid and semi-arid catchment.

11.6 Uncertainty Assessment

Uncertainty in rainfall-runoff modeling arises from different interacting causes (natural, parameters, data and structure). In this research study the sensitivity of the coupled TRAIN-ZIN model to different parameter uncertainties and the uncertainty arising from the rainfall input data were studied. Natural and model structure uncertainties were not addressed. Rainfall events 1 and 2 were used for uncertainty assessments of the TRAIN-ZIN model.

The sensitivity analysis showed that the different event characteristics that control the runoff generation mechanisms directly affected parameter sensitivity and model uncertainty. For example, for event 1 where the SEOF is the dominant runoff generation mechanism, it was found that the model is less sensitive to the runoff generation parameters compared to event 2 which was made mainly of IEOF. In general, it can be concluded that in the case of IEOF (event 2) the overall model parameter uncertainty was higher than the SEOF case (event 1). As already stated, in case of IEOF the runoff generation was controlled by the rainfall intensity and infiltration rate. In the Faria catchment, most of the runoff is generated in the upper part of the catchment since the central and the lower parts receive less rainfall. In such cases the generated runoff on the upper part travels for long distances on almost dry channels. As a result, transmission losses parameters dominate model parameter errors. Therefore, future studies should concentrate on field measurements of flow processes and transmission losses during real flood events. This will increase model accuracy.

Sensitivity analysis carried out for the model input error indicates that the TRAIN-ZIN model is highly sensitive to uncertainties in rainfall data. For event 1 and event 2, this error source increased the uncertainty of the peak flow rate by more than 126% and 98%, respectively. This indicates that the model input uncertainty error significantly affected the simulated runoff. For event 1, the overall model parameters uncertainty of the peak flow (64%) is around half the uncertainty resulting from the rainfall input error (126%). This indicates that the rainfall input data uncertainty is a key factor for accurate flood estimates. Therefore, by having enough rain-gauges in the Faria catchment, the accuracy of the coupled TRAIN-ZIN model simulations may be further increased.

In conclusion for the uncertainty part of this study it can be stated that both input data uncertainty and model parameter uncertainty have a significant influence on the simulated runoff in the Faria catchment. Taking into account the limited data availability, the uncertainty range around the runoff simulation is acceptable and other quality measures such as model efficiency, peak error and volume error are sufficient. Even so the detected uncertainty needs to be quantified and set into relation to the expected results of land use and climate change scenarios.

11.7 Scenario Modeling

Hydrologists agree that significant changes in land cover and climate may affect the overall functioning of a catchment. There are several indications that changes in land cover and climate influence the hydrological regime, mainly by changing the runoff behavior of various catchments. However, currently it is uncertain how much and at which spatial extent these environmental changes are expected to affect the runoff generation and consequently the flood discharges of catchments.

In this research study, scenario modeling was applied to assess the impacts of land use and climate changes on the runoff generation of the Faria catchment. To achieve this aim, eight scenarios were assumed and assessed by the TRAIN-ZIN model using the rainfall events 1 and 2 including three scenarios for land use changes and another five for climate changes. As indicated by the modeling results, some of the proposed scenarios affected the runoff behavior in the Faria catchment. This depends on the runoff generation mechanisms which are controlling the relative importance of changes in land use and climate conditions. For example and as discussed in **Chapter 9**, a 50% increase in built-up areas significantly affects the simulated runoff whereas insignificant effects are attained from modeling results of the projected climate change scenarios for the region by 2020 and 2050 except for scenario 4 (A2) where the effects on the generated floods are noticeable. This demonstrates the weaknesses of the present state of the art of the research studies in climatic change and its impacts on flood generation in the region. This points to the urgent need for more precisely targeted research in the area, taking into account the general climatic conditions of the studied catchment and possible future changes of (average) conditions, according to the principle of the hydrological cycle, “what goes up must come down”. A systematic and inclusive technique for uncertainty analysis still needs to be developed for the TRAIN-ZIN model used in this study to assess the impacts of changes of land use and climate.

Finally, the results of this research study show that the impacts of land use and climate changes on runoff behavior are event-dependent and that event characteristics (intensities and duration) as well as the initial soil moisture content should be identified for different scenarios.

11.8 Management Options

The primary motivation for the hydrological model used in this research work has been the desire to assess the naturally available surface water resources in the Faria catchment in order to reduce the uncertainty in decision making where the scarce water resources availability may pose enormous costs for catchment management. Water-related problems within the Faria catchment are increasing as the population increases. Deteriorating quality of the limited available water resources results in an immediate reduced access to safe water for both domestic and agricultural activities in the catchment. Solving these problems is hampered by technical, financial, environmental, institutional and political constraints. Consequently, growing water demands and hydrologically limited and uncertain supplies make the sustainable water resources management in the Faria catchment very difficult for current and future situations. Therefore, under these constraints, sustainable and integrated management plans that are concerned both with supply and demand can help to close the supply-demand gap under present and future conditions. Such management plans should promote the use of water resources to ensure the satisfaction of society’s needs while preserving resources for the future. Simply, it can be concluded that all of us want a holistic approach to life; we need a holistic approach to manage our water resources.

As this study emphasizes the importance of quantification of naturally available surface water in the Faria catchment, special concerns were made to set the proper surface water management options. Four management options were proposed in which water harvesting is the focal point. These are, rainwater harvesting systems for both urban areas and hillslopes, springs water harvesting, construction of irrigation ponds and wastewater treatment. Water harvesting is certain to grow in importance in coming years as policymakers and planners seek cost-effective solutions to water supplies. For domestic use, urban (rooftop) rainwater collection is a simple system that can easily be put in place to overcome increasing water scarcity in the catchment, whereas the hillslope rainwater harvesting technique is a viable approach to meet irrigation demands of isolated farms. The optimal utilization of considerable amounts of spring water discharge will significantly bridge the supply-demand gap for both domestic and agricultural purposes. For agricultural purposes, the construction of irrigation ponds along both sides of the water course will help to solve part of the water shortage problems in the Faria catchment. As water becomes increasingly scarce in the Faria catchment, opportunities for wastewater reuse will have to be increased. Wastewater treatment will become more necessary in order to keep pollutants out of the natural water resources and to provide the treated effluent for irrigation purposes. Finally, integrating water harvesting with other systems, as well as improving the management of demand, will lead to reliable, cost-effective water systems.

For successful implementation of the proposed management options to achieve its main goals of bridging the supply-demand gap, concrete actions are required at national and local levels. Hence it is necessary to go beyond the basic research and undertake demonstration projects for possible application of the proposed management options in the Faria catchment.

Notations

LJRB	Lower Jordan River Basin
PWA	Palestinian Water Authority
WESI	Water and Environmental Studies Institute
IHF	Institute of Hydrology, Freiburg
DEM	Digital Elevation Model
MOPIC	Ministry of Planning and International Corporation
MOT	Ministry of Transportation
GPS	Global Positioning System
NMS	Nablus Meteorological Station
PET	Potential Evapotranspiration
IEOF	Infiltration Excess Overland Flow
SEOF	Saturation Excess Overland Flow
SVAT	Soil Vegetation Atmosphere Transfer
VTI	Variable Time Interval
WAB	Western Aquifer Basin
NEAP	Northeastern Aquifer Basin
EAB	Eastern Aquifer Basin
MCM	Million Cubic Meter
AVG	Average
STD	Standard Deviation
MAX	Maximum
MIN	Minimum
EQA	Environment Quality Authority
WHO	World Health Organization
TBRs	Tipping Bucket Rain-gauges
E_p	Allowable percentage of error in the estimation of mean areal rainfall
C_v	Coefficient of variation of the rainfall from the existing stations in percentage
IDW	Inverse Distance Weight
GSRD	Ground Station Rainfall Data
Q_i	Streamflow [m³/s]
q_i	Direct runoff [m³/s]
QB_i	Baseflow [m³/s]
BF_{Index}	Baseflow Index
H	Depth of water level [m]
K	Constant depends on the Parshall Flume size
i	Time step index
α	Streamflow separation parameter
$K(\theta)$	Unsaturated hydraulic conductivity [cm/h]

K_S	Saturated hydraulic conductivity [cm/h]
θ	Soil water content
θ_r	Residual soil water content
ϕ	Porosity
Q_{i+1}^{j}	Discharge at the next channel node at the present time step [m^3/s]
Q_{i}^{j}	Discharge at the present channel node at the present time [m^3/s],
Q_{i+1}^{j-1}	Discharge at the next channel node at the last time step [m^3/s],
Q_{i}^{j-1}	Discharge at the present channel node at the last time step [m^3/s],
K	Storage constant [s]
X	Weighting factor
Q_{ref}	Reference discharge [m^3/s]
V_k	Kinematic wave celerity [m/s]
Δt	Computational time step [s]
S_o	Energy/channel slope
ΔX	Distance step (channel reach length) [m].
R_h	Hydraulic radius [m]
n	Manning roughness coefficient
F_R	Final infiltration rate [mm/hr]
I_L	Initial loss [mm]
PWP	Permanent Wilting Point
FC	Field Capacity
B_Ω	Channel width at the catchment outlet
L_{c_i}	The i^{th} channel length [m]
D_A	Depth of active alluvium [m]
I_P	Percentage of inner channel width from total channel width
H_F	Depth to the bankfull stage [m]
k_i	Hydraulic conductivity (inner channel) [mm/hr]
k_b	Infiltration constant (bars, banks and floodplains) [mm/hr]
k_f	Final infiltration rate (hydraulic conductivity of the underlying strata) [mm/hr]
He	Effective suction head [m]
Vk	Critical flow velocity/shear stress
L	Infiltration reduction factor
AMI	Antecedent Moisture Index
EFC	Nash and Sutcliffe model coefficient

Q_{O_i}	Observed runoff [m³/s]
Q_{S_i}	Simulated runoff [m³/s]
$\overline{Q_O}$	Mean observed runoff [m³/s]
VE	Volume Error
PE	Peak Error
$Q_{O(\max)}$	Maximum observed runoff [m³/s]
$Q_{S(\max)}$	Maximum simulated runoff [m³/s]
RH	Relative Humidity
SSD	Sun shine duration
T	temperature [°C]
U	wind speed [m/s]
S	Sensitivity
R_i	Model results with a variable being increased
R_d	Model results with a variable being decreased
R_b	Baseline simulation

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Annexes (Figures, Pictures and Tables)

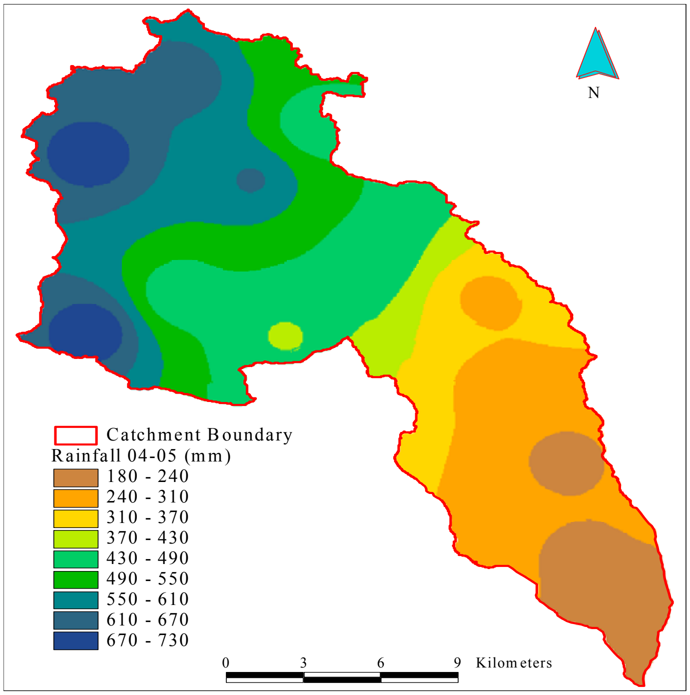

Fig. A1 Seasonal Rainfall Map of 2004/05 (mm)

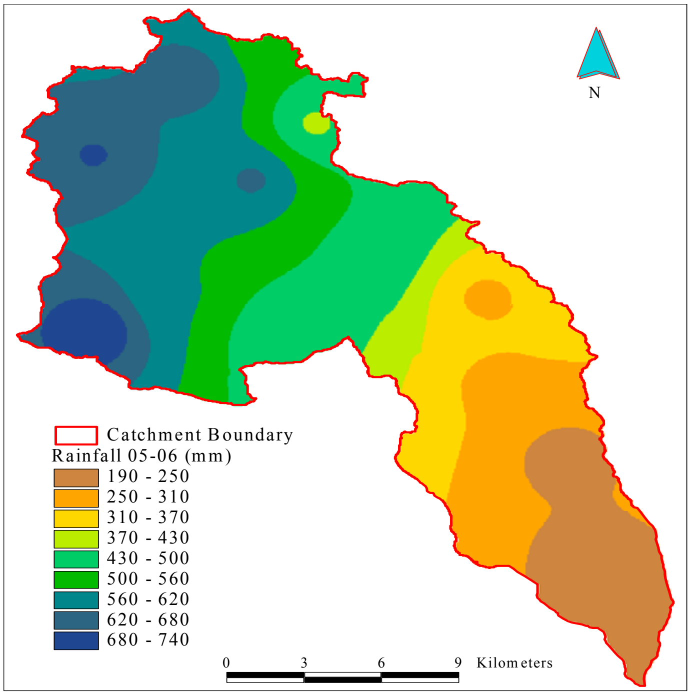

Fig. A2 Seasonal Rainfall Map of 2005/06 (mm)

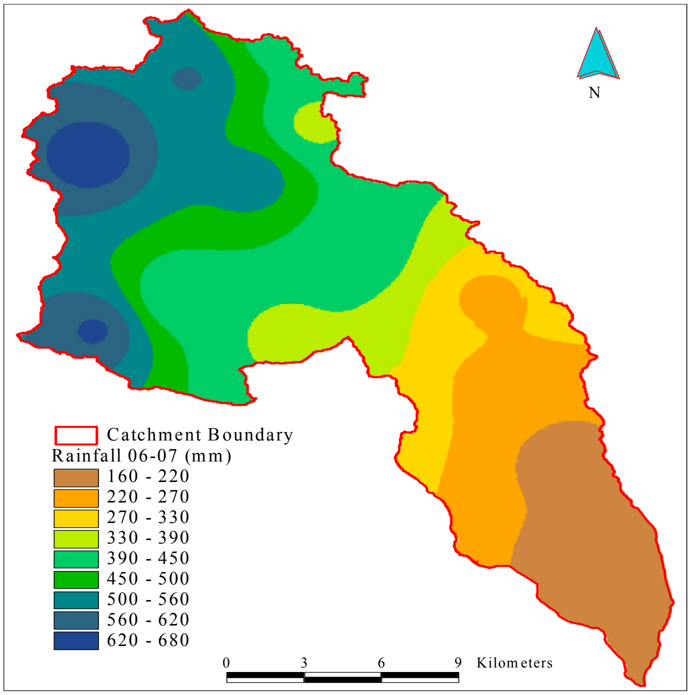

Fig. A3 Seasonal Rainfall Map of 2006/07 (mm)

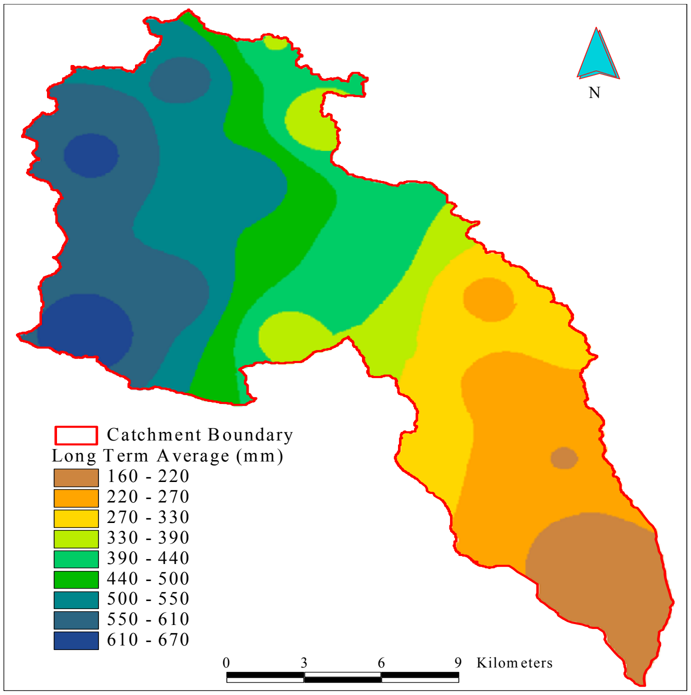

Fig. A4 Rainfall Map of Long Term Average Data (mm)

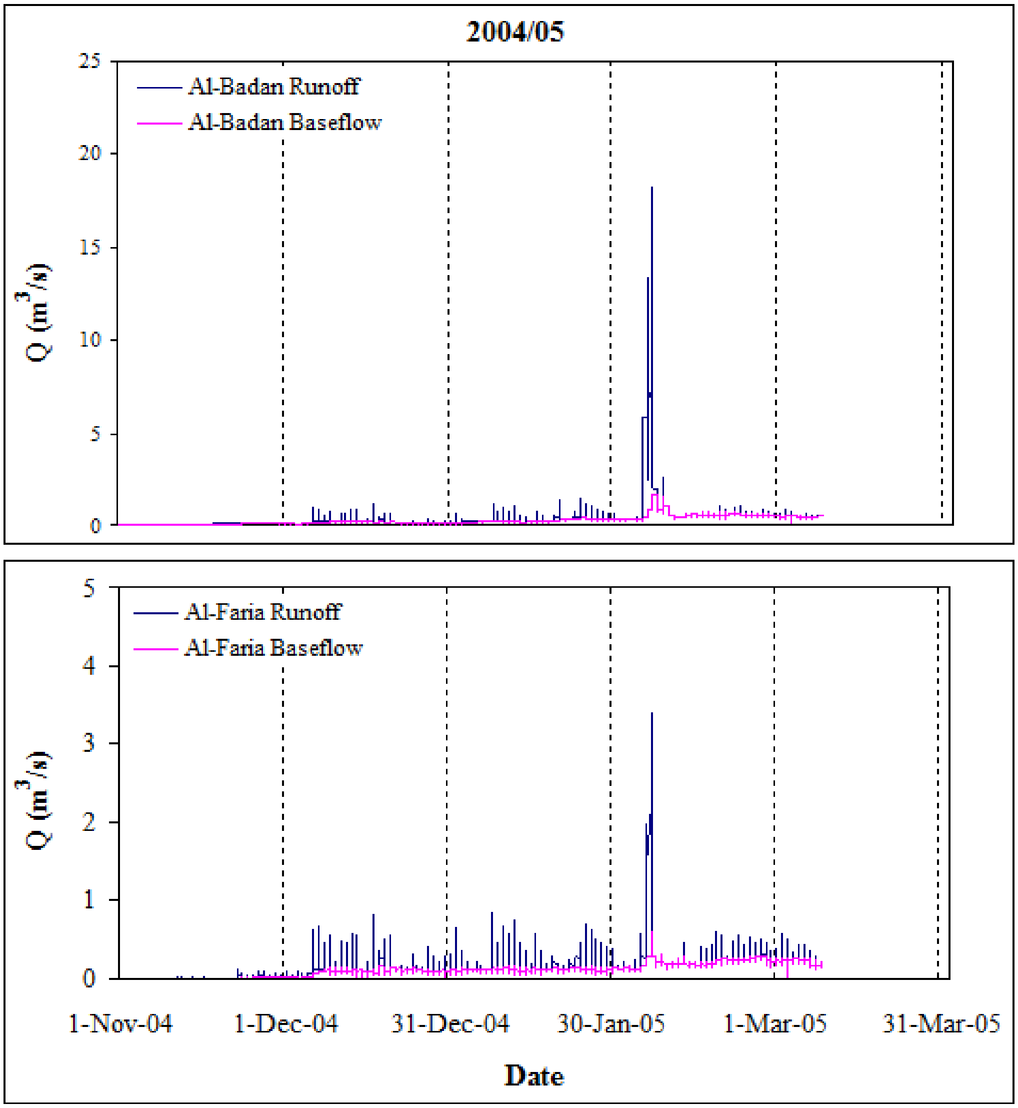

Fig. A5 Runoff and Separated Baseflow of Al-Badan and Al-Faria Sub-catchments for the Rainy Season 2004-2005

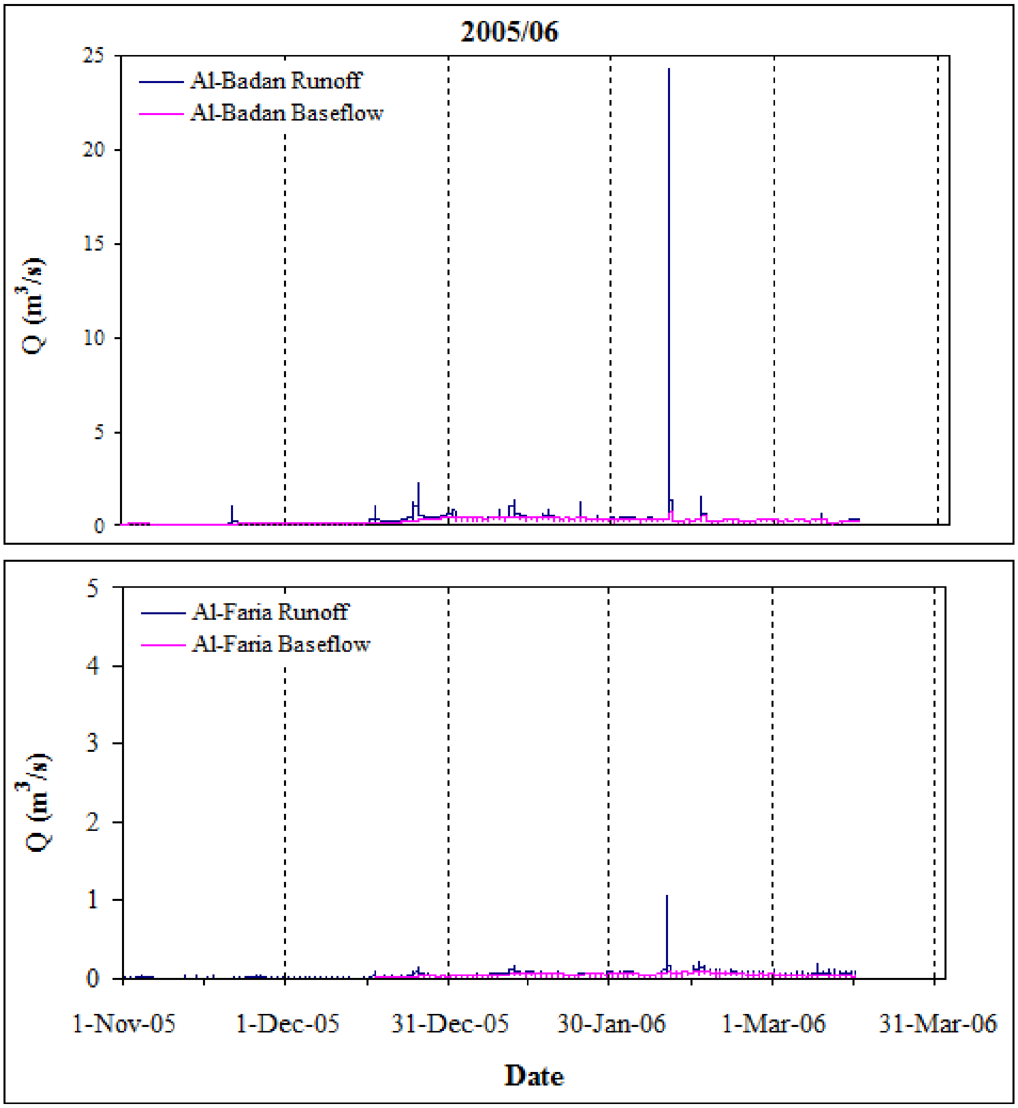

Fig. A6 **Runoff and Separated Baseflow of Al-Badan and Al-Faria Sub-catchments for the Rainy Season 2005-2006**

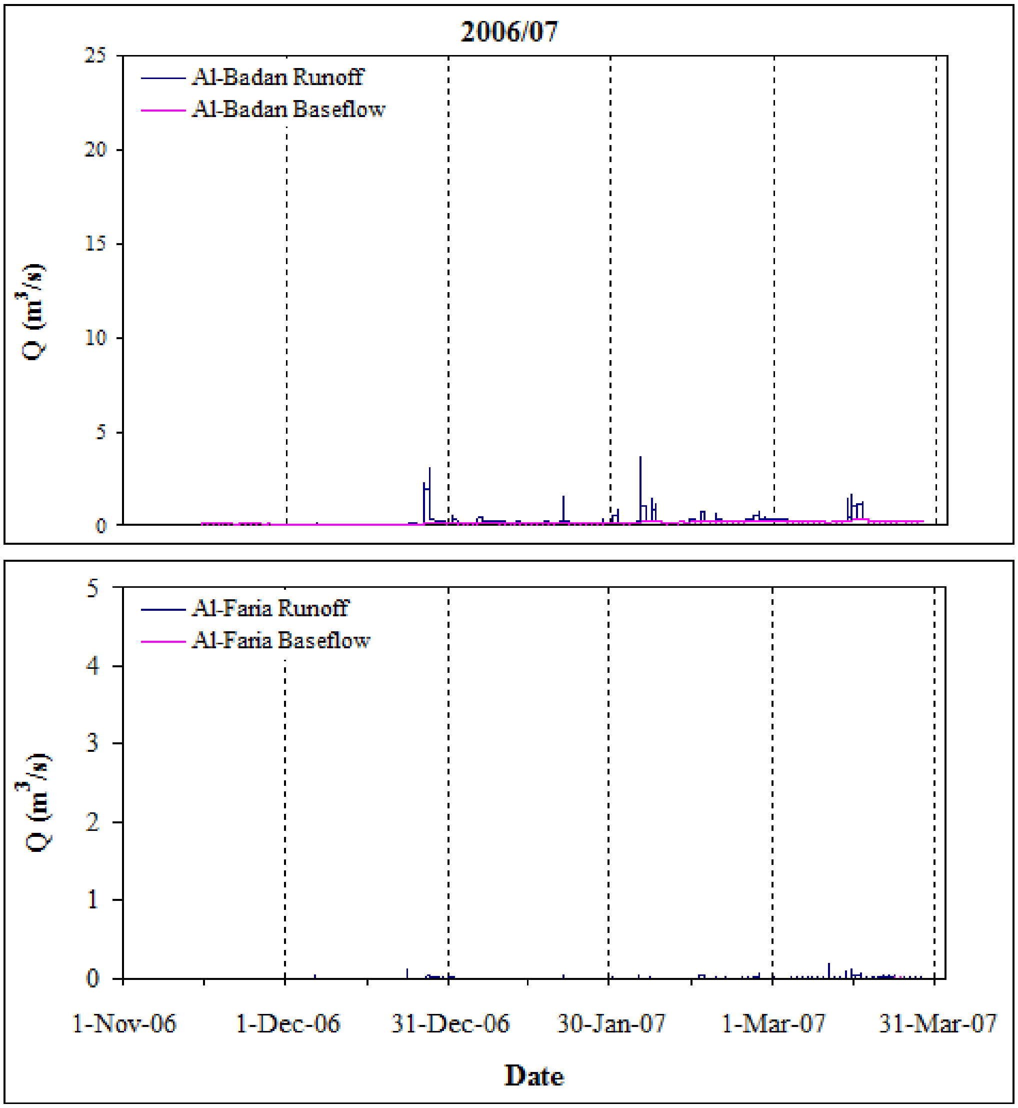

Fig. A7 Runoff and Separated Baseflow of Al-Badan and Al-Faria Sub-catchments for the Rainy Season 2006-2007

Pic. A1 Sample of Terrain Type A (Rocky Areas)

Pic. A2 Sample of Terrain Type B (Built-up Areas)

Pic. A3 **Sample of Terrain Type C** (Sparsely Vegetated Hillslopes)

Pic. A4 **Sample of Terrain Type D** (Natural Grassed Hillslopes)

Pic. A5 **Sample of Terrain Type E** (Natural Grassed Hillslopes with Fragmented Stones)

Pic. A6 **Sample of Terrain Type F** (Scattered Olive Plantation)

Pic. A7 Sample of Terrain Type G (Olive Plantation)

Pic. A8 Sample of Terrain Type H (Agricultural Areas)

Pic. A9 Sample of Channel Type 1

Pic. A10 Sample of Channel Type 2

Pic. A11 Sample of Channel Type 3

Pic. A12 Sample of Channel Type 4

Pic. A13 Sample of Channel Type 5

Tab. A1 Monthly Climatic Average Data of Al-Faria Station

Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Max. Temp. (^oC)	19.5	20.2	24.3	29.1	34.6	37.1	39.4	38.5	36.6	33.5	27.9	21.5
Mean Min. Temp. (^oC)	9.3	9.2	12.1	14.4	19.0	21.1	22.7	24.2	22.9	20.2	16.8	11.9
MeanTemp. (^oC)	14.4	14.7	18.2	21.7	26.8	29.1	31.1	31.4	29.8	26.9	22.4	16.7
Mean Wind Speed (Km/h)	4.6	6.5	6.1	3.6	3.3	3.6	6.8	6.5	5.0	2.5	2.5	2.1
Mean Sunshine Duration (h/day)	5.7	6.0	7.5	8.7	10.3	11.6	11.7	11.0	9.9	8.5	7.3	6.2
Mean RH (%)	73	73	63	63	52	51	51	52	43	54	55	67
Total Rainfall (mm)*	55.2	31.9	45	16.7	0	0	0	0	0.3	6.7	23.7	45.1
Max. Monthly Rainfall (mm)	204.1	79	84.4	78.4	0.2	0	0	0	3.6	27.9	51	106.2

* Average Monthly Total for the Period 1969-1981 (source: MOT)

Tab. A2 Monthly Climatic Average Data of Nablus Station

Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	sep	Oct	Nov	Dec
Mean Max. Temp. (^oC)	13.1	14.4	17.2	22.2	25.7	27.9	29.1	29.4	28.4	25.8	20.2	14.6
Mean Min. Temp. (^oC)	6.2	6.7	8.8	12.1	14.9	17.4	19.3	19.5	18.5	16.2	12.1	7.8
MeanTemp. (^oC)	9.6	10.5	13	17.1	20.3	22.6	24.2	24.4	23.4	21	16.1	11.2
Mean Wind Speed (Km/h)	8.7	9.5	10	10.2	10.7	12	12.4	11.7	10.3	7.7	7.8	7.7
Pressure (mbar)	953	952	951	949	948	946	944	945	948	951	953	953
Mean Sunshine Duration (h/day)	4.7	4.8	6.4	8.2	8.9	8.4	9.6	10.9	10.2	9.8	7	4.5
Mean RH (%)	67	67	62	53	51	55	61	65	64	57	57	67
Total Rainfall (mm)*	141.1	146.9	104	20.2	7.8	0	0	0	1.8	20.7	77.1	140.5
Max. Monthly Rainfall (mm)	389	389	220	225	65	3	0	1	22	83	249	472

* Average Monthly Total for the Period 1970-1998 (source: MOT)

Information about the Author

Sameer Shadeed was born on 9th of September 1978 in the village Ellar, Tulkarem in Palestine. After finishing his preparatory school at his birth place in 1995, he continued his secondary education at the nearest (~6 km) town named Atteel and in the year 1997 he got his Tawjehi. In 1997 he was accepted at the faculty of engineering of An-Najah National University, Nablus, Palestine. There he got his B.Sc. degree in the field of civil engineering in 2002. In February 2003, under a temporary contract, he was appointed as a supervisor engineer in the new campus of An-Najah National University. In September 2003 he attended his master programme at the same university. In the year 2005 he got his M.Sc. degree in the field of water and environmental engineering. The title of his master thesis was: "GIS-based hydrological modeling of semi-arid catchments (the case of Faria catchment, Palestine)". During the period September 2003-August 2005 he worked as research assistant for GLOWA-JR project, Phase-I at Water and Environmental Studies Institute of An-Najah National University. From 2006 to 2008 he was a PhD student in the field of hydrology at the Institute of Hydrology of Freiburg University. During that time he was working as a research assistant for GLOWA-JR, Phase-II at Water and Environmental Studies Institute of An-Najah National University. Within his M.Sc. and PhD studies, he attended several postgraduate courses and published several research papers. He speaks Arabic (native language) and English. After his PhD, he will start his new job as a senior researcher and lecturer at the Water and Environmental Studies Institute of An-Najah National University.

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