Rainfall-Runoff Modeling in Arid Areas

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THESIS

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Preface

The present PhD dissertation “Rainfall-Runoff Modeling in Arid Areas, Jordan” has been submitted as a part of the requirement for the Ph.D. degree at the Technical University of Freiberg (TUBAF). The PhD supervisor was Professor Dr. Broder Merkel. The research was partially funded by Sächsisches Landesstipendium, DAAD, and BAFöG-Amt. The thesis is organized as a synopsis and an appendix, of which the synopsis contains an introduction, the objectives, review of existing work, and a short outline of three manuscripts in international journals with peer review in place. The study has taken place at the Department of Geology from October 2007 to March 2011. An external research stay of two months was spent at the Environment Centre, The Lancaster University/ England, with Professor Keith Beven. Three field campaigns were essential for developing cooperation with local partner universities: University of Jordan, and Al-Albyat University, gathering data of geo-referenced objects as well as from the Jordanian water authorities, and installing a stand alone weather station.

Freiberg, March 2011,

MSc. Eng. Eyad Hamad Abushandi

This thesis is dedicated to my mother, my wife, and to the soul of my father

Acknowledgements

I gratefully acknowledge my supervisor Prof. Dr. Broder J. Merkel for his inspiration, competent guidance, patience, and encouragement through all the different stages of this research. I really thank him for guiding me to conduct my PhD research in a challenging and enjoyable topic of hydrological modeling application in arid regions. A special thank goes to PD Dr. Volkmar Dunger, especially for his valuable comments and discussions to improve the research quality. My thanks also go to all colleagues of the hydrogeology team at the Geology Institute for many good discussions and for making my stay at TUBAF enjoyable: Sascha Kummer, Mandy Schipek, Robert Sieland, Hajo Peter, Mohammed Khattab, Iwona Woloszyn, Nadja Schmidt, Ramadan Abdel Aziz, Zheenbek Kulenbekov, Lotfallah Karimzadeh, Nair Sreejesh, Sameh Wisam, Wondem Gezahegne, Yvonne Lindig, Andrea Berger, Ali Alaoui, Samer Bachmaf, and Rudy Abo. A special thank to my officemates Sosina Shieleses and Raghid Sabri for creating a very nice atmosphere. My thanks also go to our technical and administration staff members of the department for their help during my PhD especially Tino Mai, Maja Merz, and Gisela Schmiedgen. I am really grateful to the university administration office especially Dagmer Heim, Corina Dunger, from the BAFöG-Amt Annette Kunze.

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I am forever indebted to my mother for her understanding, endless patience and encouragement when it was most required throughout the study-period. Thanks to my brothers and sisters specially Khalid, Ayman, Raghda, and Mai. I am deeply indebted for not

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Abstract

The Wadi Dhuliel catchment/ North east Jordan, as any other arid area has distinctive hydrological features with limited water resources. The hydrological regime is characterized by high variability of temporal and spatial rainfall distributions, flash floods, absence of base flow, and high rates of evapotranspiration. The aim of this Ph.D. thesis was to apply lumped and distributed models to simulate stream flow in the Wadi Dhuliel arid catchment. Intensive research was done to estimate the spatial and temporal rainfall distributions using remote sensing. Because most rainfall-runoff models were undertaken for other climatic zones, an attempt was made to study limitations and challenges and improve rainfall-runoff modeling in arid areas in general and for the Wadi Dhuliel in particular.

The thesis is divided into three hierarchically ordered research topics. In the first part and research paper, the metric conceptual IHACRES model was applied to daily and storm events time scales, including data from 19 runoff events during the period 1986-1992. The IHACRES model was extended for snowfall in order to cope with such extreme events. The performance of the IHACRES model on daily data was rather poor while the performance on the storm events scale shows a good agreement between observed and simulated streamflow. The modeled outputs were expected to be sensitive when the observed flood was relatively small. The optimum parameter values were influenced by the length of a time series used for calibration and event specific changes.

In the second research paper, the Global Satellite Mapping of Precipitation (GSMaP_MVK+) dataset was used to evaluate the precipitation rates over the Wadi Dhuliel arid catchment for the period from January 2003 to March 2008. Due to the scarcity of the ground rain gauge network, the detailed structure of the rainfall distribution was inadequate, so an independent from interpolation techniques was used. Three meteorological stations and six rain gauges were used to adjust and compare with GSMaP_MVK+ estimates. Comparisons between GSMaP_MVK+ measurements and ground rain gauge records show distinct regions of

correlation, as well as areas where GSMaP_MVK+ systematically over- and underestimated ground rain gauge records. A multiple linear regression (MLR) model was used to derive the relationship between rainfall and GSMaP_MVK+ in conjunction with temperature, relative humidity, and wind speed. The MLR equations were defined for the three meteorological stations. The 'best' fit of the MLR model for each station was chosen and used to interpolate a multiscale temporal and spatial distribution. Results show that the rainfall distribution over the Wadi Dhuliel is characterized by clear west-east and north-south gradients. Estimates from the monthly MLR model were more reliable than estimates obtained using daily data. The adjusted GSMaP_MVK+ dataset performed well in capturing the spatial patterns of the rainfall at monthly and annual time scales, while daily estimation showed some weakness for light and moderate storms.

In the third research paper, the HEC-HMS and IHACRES rainfall runoff models were applied to simulate a single streamflow event in the Wadi Dhuliel catchment that occurred in 30-31.01.2008. Both models are considered suitable for arid conditions. The HEC-HMS model application was done in conjunction with the HEC-GeoHMS extension in ArcView 3.3. Streamflow estimation was performed on hourly data. The aim of this study was to develop a new framework of rainfall-runoff model applications in arid catchment by integrating a re-adjusted satellite derived rainfall dataset (GSMaP_MVK+) to determine the location of the rainfall storm. Each model has its own input data sets. HEC-HMS input data include soil type, land use/land cover map, and slope map. IHACRES input data sets include hourly rainfall and temperature. The model was calibrated and validated using observed stream flow data collected from Al-Za'atari discharge station. IHACRES shows some weaknesses, while the flow comparison between the calibrated streamflow results agrees well with the observed streamflow data of the HEC-HMS model. The Nash-Sutcliffe efficiency (Ef) for both models was 0.51, and 0.88 respectively. The application of HEC-HMS model in this study is considered to be satisfactory.

Kurzfassung (German)

Das Untersuchungsgebiet Wadi Dhuliel im Nordosten Jordaniens hat wie alle anderen ariden Gebiete besondere hydrologische Eigenschaften mit begrenzten Wasserressourcen. Das hydrologische System ist durch hohe Variabilität der zeitlichen und räumlichen Verteilungen von Niederschlag, Durchfluss, des Fehlens einer Basisabflusskomponente und hohe Verdunstung charakterisiert. Das Hauptziel dieser Doktorarbeit ist Anwendung verschiedener Niederschlags-Abflussmodells (Lumped und distributed) um das Abflussverhalten im Einzugsgebiet des Wadu Dhuliel zu simulieren. Diese Modelle sind wichtig, um räumliche Zusammenhänge und Rückkopplungsmechanismen verschiedener hydrologischer Variablen in ariden Gebieten zu verstehen und die tatsächliche Wasserbilanz zu beschreiben. Dies erlaubt einen realistischen Überblick über alle Aspekte der Nachhaltigkeit. Die Dissertation ist in eine Synopse und einen Anhang eingeteilt. Die Synopse enthält eine Einleitung, die Ziele, die Literaturrecherche und einen kurzen Überblick über drei Publikationen. Die Anlage umfasst drei Publikationen, welche die eigentliche wissenschaftliche Arbeit dieser Dissertation bilden. Das Untersuchungsgebiet (Wadi Dhuliel) ist vor allem Ackerland; es befindet sich im Nordosten Jordaniens mit einer Fläche von 1985 km^2. Die Wahl Gebietes wurde auf der Grundlage der Kombinationen von ökologischen und anthropogenen Faktoren getroffen, die Einfluss auf die hydrologische Bilanz in diesem Gebiet Jordaniens haben. Darüber hinaus ist das Untersuchungsgebiet Teil des Badia Forschungs- und Entwicklungsvorhabens.

In der ersten Forschungsarbeit wurde das konzeptionelle Niederschlag-Abfluss-Modell IHACRES auf tägliche Zeitskalen und Starkregenereignisse unter Einbeziehung von Daten von 19 (Oberflächen)Abflussereignissen (Zeitraum 1986-1992) angewendet. Die ursprüngliche Struktur des Modells IHACRES verwendet einen exponentiell abklingenden Bodenfeuchte-Index, Infiltrationsrate und Evapotranspiration, um den Niederschlag in effektiven Niederschlag umzuwandeln. Eingabeparameter in IHACRES sind a) Niederschlag,

b) Temperatur (optional) und c) Abflussmessungen (zur Kalibrierung des Modells). Die zeitliche Auflösung erfolgt stündlich, täglich und monatlich ohne Lücken. Das IHACRES-Modell wurde für Schneefall erweitert, um solche Extremereignisse mit einzubeziehen. Während das Ergebnis des IHACRES-Modells auf der Basis täglicher Werte mangelhaft ist, zeigte die Modellierung für Starkniederschlagsereignisse eine gute Übereinstimmung zwischen gemessenen und simulierten Durchflusswerten. Das Modell reagiert sehr sensitiv für kleine Abflussereignisse. Die optimalen Parameterwerte wurden durch die Länge der Kalibrierungszeiträume und ereignisspezifische Änderungen beeinflusst.

In der zweiten Forschungsarbeit wurde der Datensatz der globalen Satellitenkartierung von Niederschlägen (GSMaP_MVK+) verwendet, um die Niederschlagsraten des Einzugsgebietes Wadi Dhuliel für den Zeitraum von Januar 2003 bis März 2008 zu bewerten. Aufgrund der geringen Zahl von an Niederschlagssammlern konnten die detaillierte Struktur der Niederschlagsverbreitung nicht angemessen bestimmt werden; deshalb wurde eine unabhängige Interpolationstechnik verwendet. Drei meteorologische Stationen und sechs Regensammler wurden benutzt, um Schätzungen des GSMaP_MVK+ Datensatzes zu optimieren. Ein Vergleich von GSMaP_MVK+ Messungen und Bodenniederschlags-messungen zeigt bestimmte Gebiete, die miteinander korrelieren, sowie Gebiete, in denen die GSMaP_MVK+ Daten systematisch die Bodenniederschlagsmessungen über- und unterschätzen. Ein multiples lineares Regressionsmodell (MLR) wurde angewendet, um die Beziehungen zwischen Niederschlag und dem GSMaP_MVK+ Datensatz, in Verbindung mit Temperatur, relativer Luftfeuchtigkeit und Windgeschwindigkeit abzuleiten. Die MLR-Gleichungen wurden für die drei meteorologischen Stationen definiert. Die beste Anpassung des MLR-Modells für jede Station wurde ausgewählt und dazu verwendet, eine zeitliche und räumliche Verteilung zu interpolieren. Die Ergebnisse zeigen, dass die Verteilung der Niederschläge über dem Wadi Dhuliel durch ein deutliches West-Ost- und Nord-Süd-Gefälle geprägt ist. Schätzungen aus dem monatlichen MLR-Modell erbrachten bessere Korrelationen als Schätzungen, die sich aus der Verwendung von Tageswerten ergaben. Die angepassten

GSMaP_MVK+ Daten eignen sich gut für die Erfassung der räumlichen Muster von Niederschlägen in monatlichen und jährlichen Zeitskalen, wohingegen tägliche Schätzungen Schwächen bei leichten und moderaten Starkregenereignissen zeigten.

In der dritten Forschungsarbeit wurden die hydrologischen Modelle HEC-HMS und IHACRES angewendet, um ein einzelnes Abflussereignis zu simulieren, das vom 30.-31.01.2008 im ariden Wadi Dhuliel-Einzugsgebiet auftrat. Beide Modelle werden als geeignet für aride Bedingungen eingeschätzt. Die Anwendung des Modells HEC-HMS erfolgte in Zusammenarbeit mit der HEC-GeoHMS-Erweiterung in ArcView 3.3. Oberflächenabflussschätzungen wurden auf der Grundlage von stündlichen Daten durchgeführt. Das Ziel dieser Studie war es, durch die Integration von modifizierten, satellitengestützten Daten der Niederschlagsmengen (GSMaP_MVK +) einen neuen Rahmen der Niederschlags-Abfluss-Modellanwendungen in ariden Einzugsgebiet zu schaffen, . Jedes Modell hat seinen eigenen Datensatz. Die HEC-HMS-Datensätze umfassen Bodenart, Bodennutzung/Bodenbedeckungkarte und eine Neigungskarte, die unter Verwendung von GIS enstanden. Die IHACRES-Eingangdatensätze umfassen stündliche Werte des Niederschlages und der Temperatur. Das Modell wurde kalibriert und validiert mit Hilfe beobachteter Durchflussdaten, die von der Messstation Al-Za'atari stammen. Das IHACRES-Modell zeigt einige Schwächen, wobei der Vergleich zwischen den kalibrierten Starkregendurchflüssen und den beobachteten Durchflussdaten im HEC-HMS Modell eine gute Übereinstimmung zeigt. Die Nash-Sutcliffe-Effizienz (Ef) für beide Modelle beträgt jeweils 0,51 und 0,88. Die im Rahmen dieser Studie realisierte Anwendung des HEC-HMS-Modells wird als zufriedenstellend angesehen.

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Appendix A

Abushandi E. & Merkel B. 2010 Application of IHACRES rainfall-runoff model to the Wadi Dhuliel arid catchment, Jordan. J. Water and Climate Change (Published) 43

Appendix B

Abushandi, E. and Merkel, B.: Rainfall estimation over the Wadi Dhuliel arid catchment, Jordan from GSMaP_MVK+, Hydrol. Earth Syst. Sci. Discuss., 8, 1665-1704, doi:10.5194/hessd-8-1665-2011, 2011. (Accepted for discussion).. 74

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Abushandi E., Merkel B. (2011) Modelling rainfall runoff relations using HEC-HMS and IHACRES for a single rain event in arid region, Jordan. Water Resources Management Journal (Ready for submission).. 111

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Introduction

1 Background and significance

The scarcity of water and threats of flash floods in Jordan require further understanding the natural processes of water resources in order to manage and sustain current and future water resources. If current population and water consumption trends continue, by the year 2025, water supply per capita will fall from current 145m3/yr to 91m3/yr (Hadadin et al 2010). To make matters worse, rainfall fluctuation and climate change are expected to increase water scarcity in Jordan (Freiwan and Kadioglu 2008a). These combined factors will drive Jordan to severe water stress. Around 91% of Jordan lies in arid and semi-arid regions, which receive less than 200 mm of annual rainfall. The rainfall distribution displays a sharp west-east gradient, from relatively wet west regions with about 600mm per annum to dry east regions (the Jordanian desert) with rainfall less than 100mm per annum (Figure 1).

Both the arid climate and topographic variations contribute to the variation in rainfall. However, only small fraction of the rainfall (8.5%) can be captured, while the rest is lost due to evapotranspiration (87.9%) and floods (3.7%) (*JMWI*). With rapid depletion of ground water resources, flood management could provide a potential means for futher optimize water resources. Since agriculture comprises much of the Jordanian economy, water availability is the vital factor controlling the economic growth in Jordan. Moreover, the management of infrequent flash floods requires detailed hydrological information about catchment.

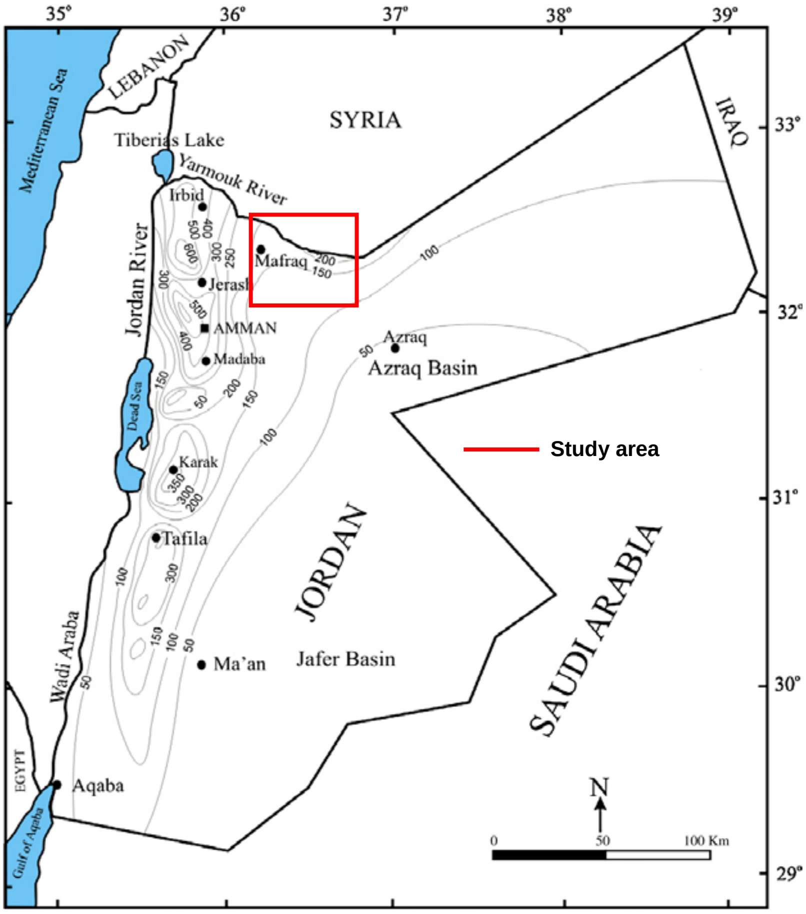

Figure 1. Average distribution of long-term (1938–2005) rainfall in Jordan (Hadadin et al 2010), modified. The red square outlines the area studied within this thesis.

Despite the importance of water resource management in Jordan, a substantial number of short-term flood flow studies have not yet been conducted for several reasons. (i) lack of awareness of the importance in monitoring floods (ii) cost of flood monitoring devices and (iii) difficulty of securely installing measurement devices within the study area. Even in the rare cases where gauging stations exist, measurement problems may occur during intense flood events, reducing the quality and completeness of the data (Lange et al 2000).

The term aridity describes a dry hot climate, with a precipitation threshold less than 250 mm per year. Arid zones can be classified according to the degree of aridity.

de Martonne suggested the following expression for use as an aridity index (Lin 1999):

$$X = P/(10 + T)$$

where X is the aridity index, P is the annual precipitation in mm, and T is the mean annual air temperature in ^{o}C.

Another aridity metric, the UNEP Aridity Index (Al) takes the ratio of average annual precipitation (P) to potential evapotranspiration (PET) (Safriel 2006) to determine the degree of aridity. Based on the UNEP classification, the study area in this research is classified as an arid region.

2 Research objectives

The general objectives of this research are to:

1. collect high quality rainfall and runoff data for hydrological modeling,
2. assess the feasibility of lumped and distributed rainfall-runoff models in arid region, where monitored data are rare.
3. critically analyze the selected models' performance in the study area,
4. develop a comprehensive analysis of spatial rainfall in the Wadi Dhuliel arid catchment using remote sensing data,
5. provide a platform on which future research can be developed using the available hydrological data.

The following specific objectives are addressed in different appendices:

1. evaluate all available rainfall-runoff models in order to find two which perform adequately for the boundary conditions of a Jordanian arid catchment.

2. analyze the accuracy of the calibration method in that region.
3. investigate rainfall characteristics of the Wadi Dhuliel catchment in north-eastern Jordan by comparing remote sense data with ground-based rain gauge data
4. develop a technique to enhance remote sense data of rainfall variability in arid regions using rain gauge data and standard interpolation techniques
5. reduce the potential errors of rain gauge estimates and produce improved catchment scale rainfall distribution maps
6. examine the performance of different models during a single heavy rainstorm event that caused streamflow in the Wadi Dhuliel sub-basin
7. parameterize the Wadi Dhuleil terrain using a high resolution digital terrain model (ASTER)

3 Study area description

Wadi Dhuliel, located in northeast Jordan, fulfils two important water management-related functions: the discharge of the Al-Zarqa River and natural groundwater recharge. Most of the catchment area belongs to the Al-Zarqa Basin. In Arabic, the term *Wadi* is defined as a channel of water that is dry except during heavy rain events. Around 10% of the upper part of Wadi Dhuliel catchment is situated on Syrian territory (Figures 1 and 2). The region has an arid climate with cold, rainy winters and a hot, dry summer.

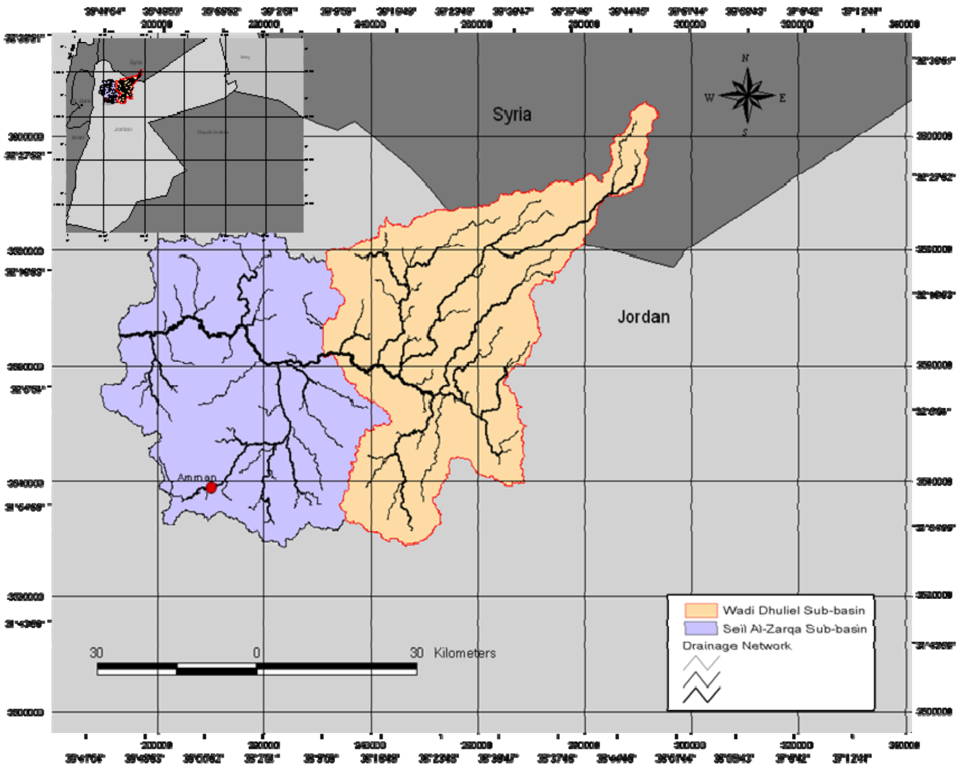

Figure 2. Map of Al-Zarqa basin, including Seil Al-Zarqa subbasin and Wadi Dhuliel sub-basin (map datum: WGS 84)

The Wadi Dhuliel catchment, a typical example of an arid catchment, passes floodwater from northern Jordan into the Al-Zarqa River. The area is characterized by a very gently undulating topography with elevation varying from 512 m in the south-west to 1400 m in the north. The area of interest is approximately 1985 km^2 (Figure 3).

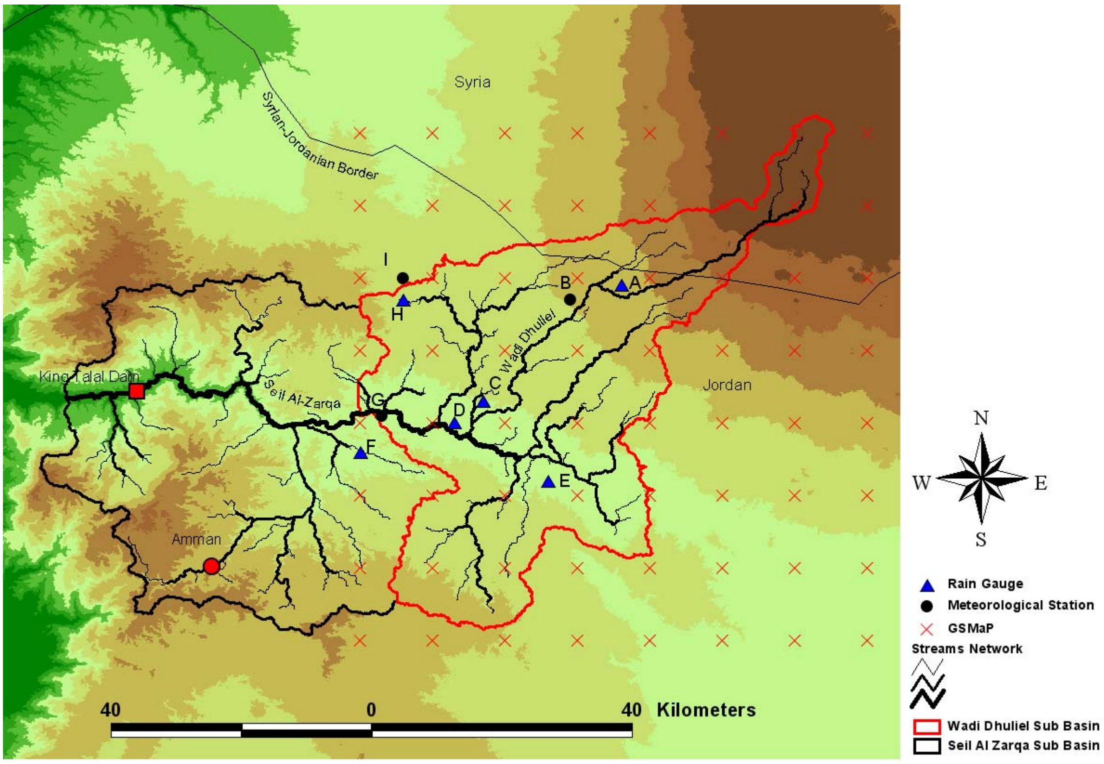

Figure 3. Al-Zarqa basin including the study area (Wadi Dhuliel) and the Seil Al-Zarqa sub-basin

Besides Wadi Dhuliel, there are a number of side-wadis in the catchment area such as Wadi Al-Za'atari, Wadi Al-Ajeb and Wadi Alghar. The flow direction is from the north towards the Seil Al-Zarqa subbasin in the southwest. Irrigation for agriculture in the Wadi Dhuliel taxes existing groundwater resources and strongly distorts hydrological features of this arid catchment.

The following general arid region characteristics describe the Wadi Dhuliel arid catchment:

(i) Stream flow characterized by absence of base flow and flash-floods during infrequent high-intensity rain events.

(ii) High evaporation rates.

(iii) Highly-localized spatial rainfall distribution (Wheater et al 1991)--the storm rainfall correlation coefficient decreases rapidly with distance (Osborn et al 1979).

(iv) Sparse plant cover and organic matter (McIntyre and Al-Qurashi 2009; Pilgrim et al 1988).

3.1 Rainfall

Short, high-intensity rain storms account for the dominant contribution to the low annual total rainfall in arid regions. Rainfall in the Wadi Dhuliel tends to vary markedly from year to year with an irregular distribution in time and space. As an illustrative example of the extreme yearly variability in Wadi Dhuliel, one rain gauge measured the annual rainfall to be 275.7, 93.1, 111.1, 230.4, 194.8, 63.1, and 209.5 mm over seven years. On one single day, 62 mm of rainfall occurred, even though the total annual rainfall in the same year was 100 mm (Sukhnah rain gauge). These kinds of rainfall events can generate significant surface runoff, resulting in severe soil erosion. Weather behavior and topographical characteristics play important roles in this variation. Around 73% of the total annual rainfall (mean 123 mm) occurs during November, December, January, and February.

3.2 Temperature

The area of interest is characterized by warm and dry summers (May to September) and moderate cold and wet winters (October to April) (Table 1). The average annual temperature is 16.8 C (1976–2005).

Table 1. Temperature description for the period of 1976–2005 (Um-Aljimal Meteorological Station)

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**
Average (°C)	7.4	8.6	11.5	16.2	20.4	22.9
Average maximum (°C)	12.7	14.2	18	24	28.7	31.6
Average minimum (°C)	2.1	2.9	5.1	8.5	12.0	14.1
	Jul.	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Average (°C)	24.7	24.6	23.1	19.5	13.6	9.0
Average maximum (°C)	33.1	33	31.3	27.2	20.2	14.5
Average minimum (°C)	16.32	16.31	14.9	11.73	6.92	3.51

3.3 Surface runoff

The Wadi Dhuliel catchment is exemplified by ephemeral wadis, where a stream runs fully for a short period of time, usually during and after heavy rain events (Figures 4 and 5), and is dry most of the year. Flash floods events fill desert dams and may recharge groundwater resources. The complex relationship between rainfall and streamflow is influenced by many factors, such as catchment slope, land cover type and density, soil type and infiltration rate, and evapotranspiration. Moreover, the quality and quantity of streamflow are strongly affected by urbanization and agricultural activity.

Figure 4. Dry condition in the Wadi Dhuliel/ Northern Jordan (13.04.2008)

Figure 5. Wadi Dhuliel, northern Jordan after a storm event (14.11.2008)

Flash flood hydrographs are generally sharp with durations between three hours and three days following the rain storm. In general, the runoff coefficient in the study area was 2.3% on average. Some flood flow events show more than one peak during a single rainstorm (Figure 6).

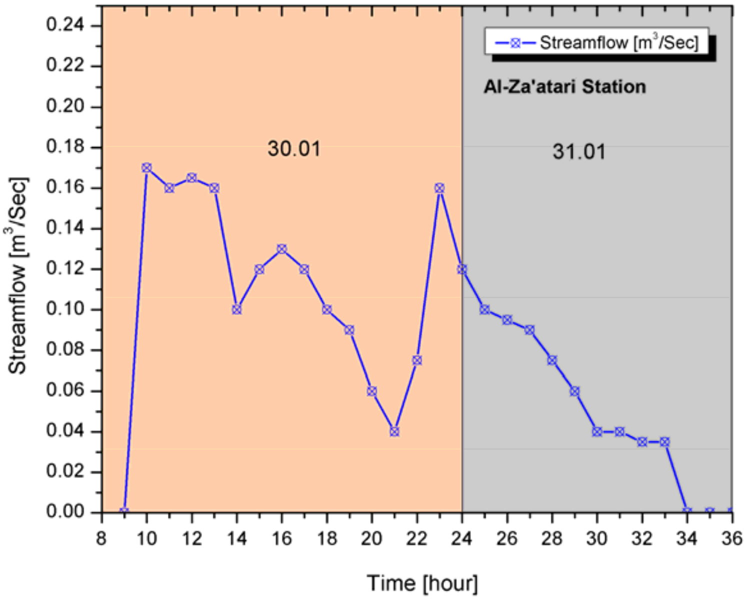

Figure 6. Typical Stream flow event in the Wadi Dhuliel (January 30-31, 2008)

The only flood records available from the study area are provided from the Al-Za'atari gauging station, which is located on the lower part of the catchment area (Figure 7).

Figure 7. Al-Za'atari gauging station including chart recorder (Stevens Type A)

3.4 Land use and soil types

The regional ecology, typified by vegetation cover, soil characteristics, plant and anthropogenic densities, affects the infiltration characteristics and influences the storage coefficient and runoff behaviour. Images from the Landsat Thematic Mapper (TM) allow categorization of land use in the Wadi Dhuliel into six classes (Figure 8 and Table 2). Much of the upstream land in the Wadi Dhuliel (36.3% of the total) of is largely cultivated while bare soil and settlements typify downstream surface cover.

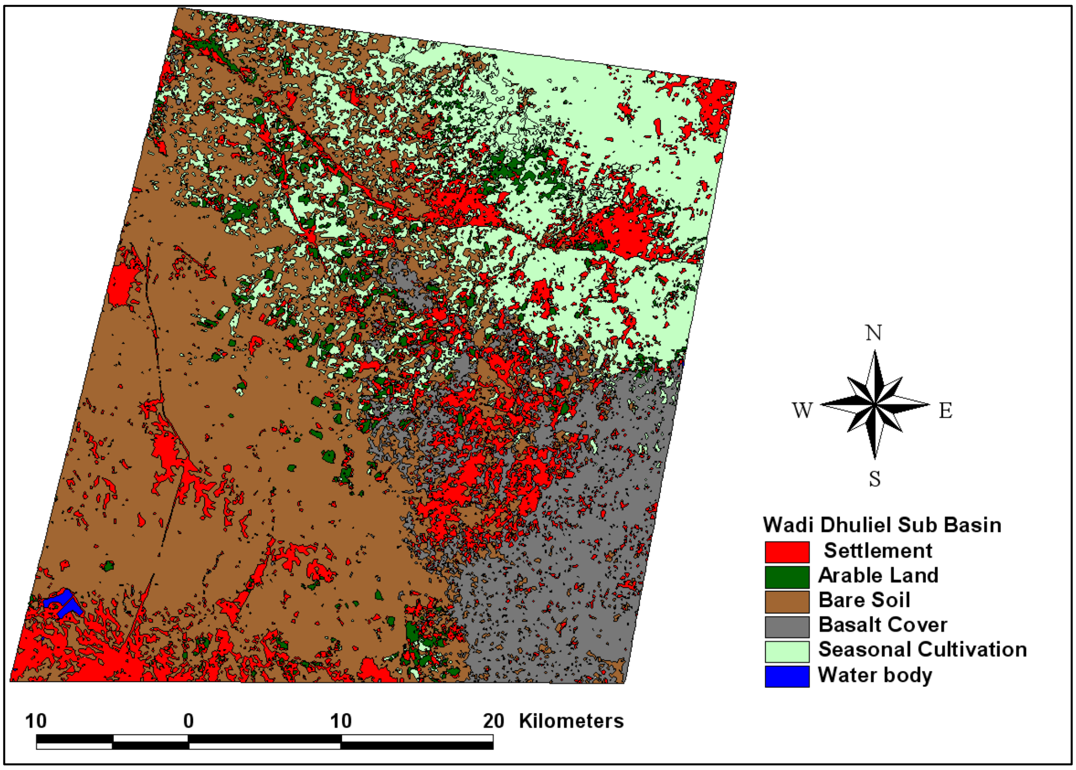

Figure 8. Land use map of Wadi Dhuliel sub-basin, Landsat Thematic Mapper (TM) of the year 1987, 30 m resolution.

Table 2 Land use features for the Wadi Dhuliel area derived from TM (1987)

Land use type (%)	**Settlement**	**Arable land**	**Bare soil**	**Basalt cover**	**Seasonal cultivation**	**Water body**
Contribution (%)	**34.2**	**13.17**	**19.7**	**9.6**	**23.11**	**0.23**

The physical properties of the catchment soil govern water flow potential. The soil within the study area is primarily classified as Aridisols and belong to loam or silty loam. Aridisols contain high concentrations of lime (Al-Qudah 2001) withlow gypsum and basalt content in the subsoil and parent materials. Soil crusting most often occurs due to the high silt content in this type of soils.

4 Literature review

4.1 Hydrological modeling in arid region

Hydrological models provide a simplified mathematical representation of the hydrological system and are designed to model surface flow and/or groundwater processes and comprise essential tools for controlling and managing water resources. Additionally, hydrological models may increase our understanding of streamflow frequency (Reed et al 2007). Hydrological models are often employed due to the limitations of hydrological measurement techniques (Beven 2001b).

Hydrological studies are often aimed at establishing rainfall-runoff relationships (Shah et al 1996). Rainfall-runoff models cover a wide range objectives and applications. Due to harsh climatic conditions and the lack of high quality observations, flood simulation in arid environment, especially flash flooding scenarios, is one of the greatest challenges facing hydrological modelers today. Different types of hydrological models exist to represent hydrological processes at a wide range of climatic and time scales.

Rainfall-runoff models can be categorized according to the model type. The most common models are data-driven. Within this category, the rainfall-runoff models falls into three sub-categories: (i) metric, (ii) conceptual, and (iii) physical-based models (Wheater et al 1993). The models vary in complexity, amount of observational data required as input parameters, and performance for different catchment types.

Knowledge-driven systems comprise the second category. These rainfall-runoff models fall into two sub-types: lumped and distributed models. Lumped models treat the catchment as single homogenous unit. Previous published lumped models include the IHACRES model (Jakeman and Hornberger 1993), AWBM (Boughton and Chiew 2007), GR4J (Perrin et al 2003), and NAM (DHI 1993). Lumped models require limited amounts of input data at the expense of model resolution; detailed spatial fluctuations can not be resolved by these models.

At the opposite end of the spectrum, distributed models make predictions by discretizing the catchment into a large number of grid squares (Beven 2001b). Available grid models include USDA SWAT (Arnold et al 1998b), TOPMODEL (Beven et al 1995), and HEC-HMS (Scharffenberg and Fleming 2010). Lumped models can be applied into catchments of limited data. Distributed models allow detailed description of hydrological processes which may fluctuate in space and time. Additionally, distributed models have the opportunity for parameterization with respect to geo-referenced objects within the catchment. Therefore, a great amount of spatially-related hydrological and physical data sets need to be prepared in order to run the model. Figure 8 shows the general classification of hydrological models.

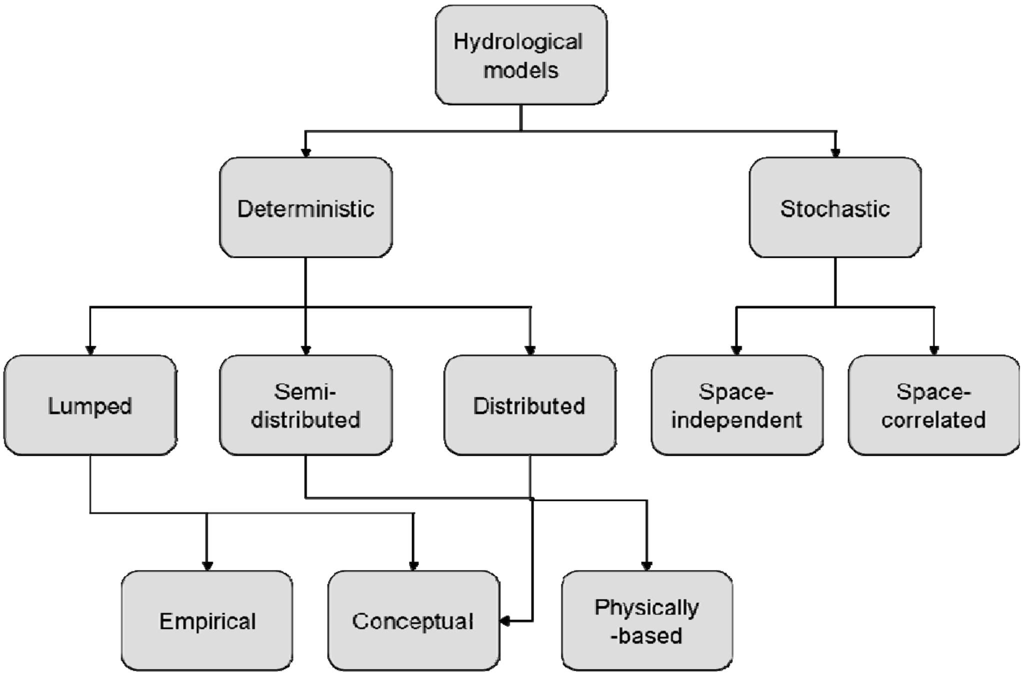

Figure 9. General classification of hydrological models (Chow et al 2005) modified

The choice of the model depends on the study objectives; several considerations when must be taken into account when selecting a rainfall-runoff model:

1 Availability and the quality of hydrological data, especially rainfall and runoff data,

2 Model structure and model ability of regionalization,

3 Catchment characteristics and flow homogeneity.

Many researchers recognize that rainfall-runoff models cannot give a full picture of reality (Al-Qurashi et al 2008; Beven 1984; Bronstert 2004; McIntyre and Al-Qurashi 2009; Pilgrim et al 1988); the spatial and temporal fluctuations in arid regions only intensify this dilemma for hydrologists working in these regions.

Flash floods in arid regions result from extreme,irregular rainfall events. These events occur when conditions, such as soil moisture , infiltration conditions, steep slope (Rodier and Roche 1978), and high rainfall intensity (Gheith and Sultan 2002), are fulfilled. The extreme irregularity of yearly flood events reduces the effectiveness of flood prediction methods. Flow measurement is particularly difficult in arid zones for several reasons:

(i) low population density (Pilgrim et al 1988; Rodier and Roche 1978)

(ii) few driveable roads, especially during in rainy (Pilgrim et al 1988) and flooding seasons

(iii) lack of suitable natural control sections in streams with movable beds, and high cost of artificial control (Pilgrim et al 1988)

(iv) harsh climatological and physical conditions (Pilgrim et al 1988)

(v) moving rocks and debris may damage instruments placed in the Wadi (Kilpatrick and Cobb 1985)

The quick rise and fall of the water level during flash floods makes flow measurements difficult (Lin 1999). Measuring flash floods in such areas are generally conducted via the velocity-area method (Rodier and Roche 1978) (e.g. Tunisia and China, Lin 1999). This method depends on measuring the average velocity of flow and calculating the cross sectional area of the Wadi. However, under unstable Wadi beds, this traditional flow measurement technique is problematic. Furthermore, turbulence and moving rocks pose could damage instruments for tracers and/or current-meter techniques. Therefore, new techniques of stream flow for arid environments should be developed to meet the project budget and overcome these challenges. Although a new diver from the Schlumberger Water Services Company was installed in the Wadi Dhuliel to measure water level during streamflow events (Figure 10), the resulting data set is rather short.

Figure 10. Diver installation in the study area to measure streamflow magnitudes

Only a limited number of rainfall-runoff models have been developed and modified for arid environments. Osborn and Hickok published the first scientific research on characterization of rainfall-runoff relationships in 1968. They analyzed the effect of rainfall variability in producing runoff for the Alamogordo Creek watershed in New Mexico. For areas the size of the Wadi Dhuliel catchment, a few potential available rainfall-runoff models demonstrated acceptable performance in arid regions: the IHACRES model in Australia and South Africa and Oman (Croke et al 2006; Dye and Croke 2003; McIntyre and Al-Qurashi 2009), The KINEROS2 model in Oman and India (Al-Qurashi et al 2008; Sharma and Murthy 1996), the RORB3 model in Australia (Kotwicki 1987), the Pitman model in South Africa (Hughes et al 1997), the AHYMO model in the New Mexico (Schoener 2010), the HEC-HMS model in the UAE, West Bank-Palestine (Al-Rawas and Valeo 2008; Schoener 2010; Shadeed and Almasri 2010; Sherif et al 2011), , and the SWAT model in the UAE (Al Mulla 2005).

Abdulla et al. (2002) developed and applied a simple single event watershed model to simulate and predict the surface runoff hydrograph in the western part of Iraq. Their model was based on the water balance equation and their results showed good agreement between simulated runoff hydrograph and observed data. In Saudi Arabia, Al-Turbak (1996) applied a geomorphoclimatic model, where rainfall intensity and duration are calculated from physically-based infiltration components, in three arid catchments. Their results showed that this model could successfully reproduce surface runoff hydrographs, at least for events in which detailed and accurate data were available. In Israel, Lange et al., (2000) studied the importance of single events in arid zone rainfall-runoff modeling. The study concluded that separate analysis of single events is crucial for the understanding of high magnitudes floods in arid regions.Finally, the Spatial Water Budget Model (SWBM) and HEC-HMS / HEC-GeoHMS extension model were applied for managing water resources in the Zarqa River basin. The study of Al-Abed and Abu Khyara (2005) showed satisfactory results from both models.

In this Ph.D. research study, the IHACRES and HEC-HMS rainfall runoff models were selected for several reasons: (i) model availability and structure, (ii) data availability, and (iii) model applicability in arid catchments. The model IHACRES (Identification of unit Hydrograph And Component flows from Rainfall, Evaporation and Stream flow data) is a simple model, parametrically efficient, and statistically rigorous (Dye and Croke, 2003). The IHACRES input requirements are only precipitation and temperature, and streamflow for calibration purpose. The other model, HEC-HMS (Hydrologic Engineering Center’s Hydrologic Modeling System), requires inputs for the basin model, meteorologic model, and control specifications but then allows several different techniques to be used to model the rainfall-runoff process.

4.2 Rainfall derived from remote sensing data

Hydrologists are extending their models to incorporate new data from remote, satellite-based rainfall (Geographic Information System or GIS) estimates for arid regions. GIS-compliance has already been implemented in many physical models, such as SWAT, HEC-HMS, and WEPP, not as data preparation tools but as a procedural step (Figure 11).

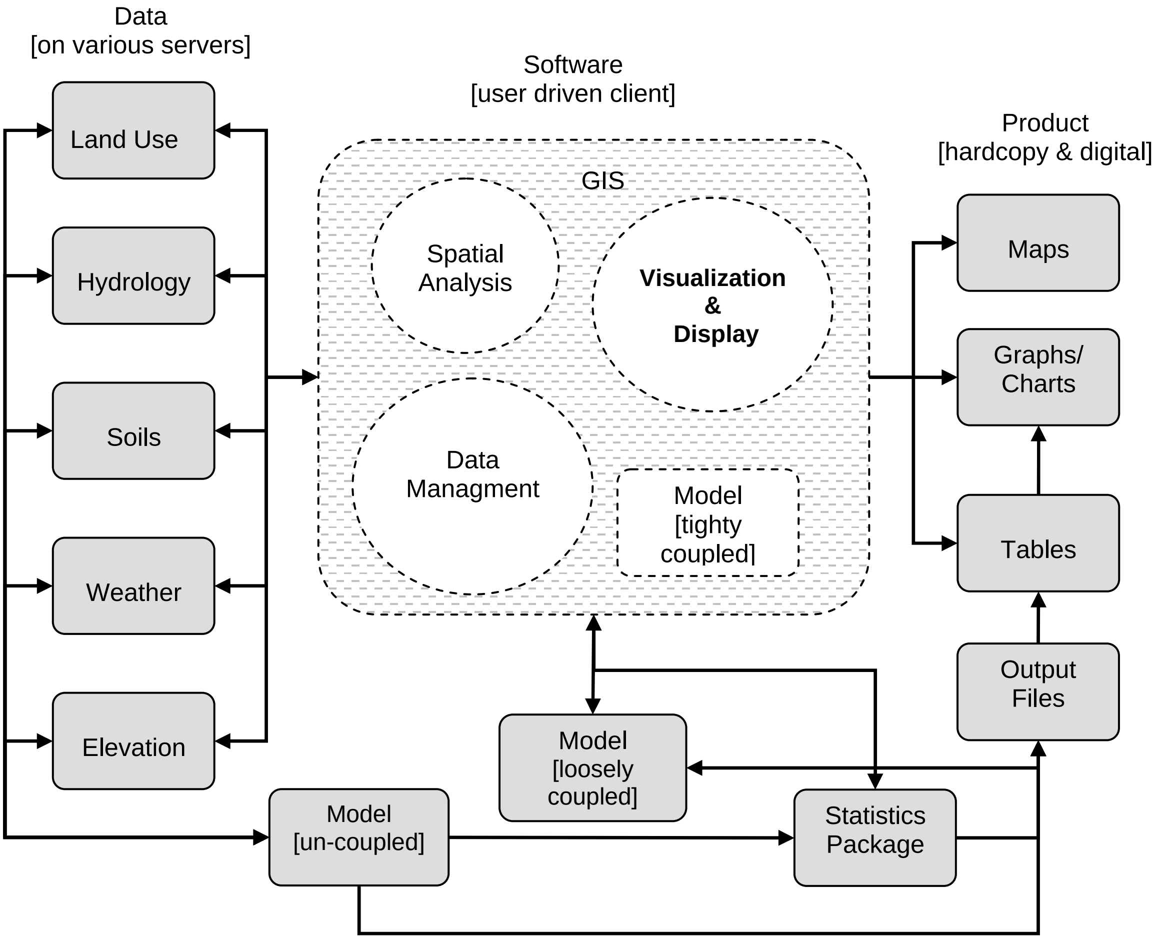

Figure 11. Integrating GIS with hydrological modeling (Matson et al 1995)

Satellite-based rainfall estimates could compensate for the lack of high quality observational rainfall data as an input for rainfall runoff models in arid regions. Recently, a number of global precipitation determination systems have been developed to meet scientific demand, such as PERSIANN (Sorooshian et al 2000), Global Precipitation Climatology Project (GPCP) (Adler et al 2000; Huffman et al 2001; Xie et al 2003), and Multi-satellite Precipitation Analysis (TMPA) (Huffman et al 2007). Global or near-global satellite datasets are important to identify temporal and spatial rainfall changes in arid regions. Global Satellite Mapping of Precipitation (GSMaP) technique employs passive microwave radiometer data to estimate rainfall rates with mm/h precision (Ushio et al 2009). GSMaP combines precipitation retrievals from polar-orbiting satellites and cloud motion vectors derived from infrared images.

5 Deliverables

- generate a weather parameters data set (rainfall, temperature , relative humidity, barometric pressure, and soil moisture) with 10 minute time steps over a range of 2 years by installing a stand alone weather station within the campus of Al-albayt University,
- improve IHACRES model by adding an option for snow precipitation
- develop a new methodology to re-adjust satellite-derived rainfall datasets (GSMaP_MVK+) using ground based rainfall data
- optimize the use of acquired weather data from the study area for present and future studies by designing a database management system (DBMS)
- develop a water resource management plan for the Wadi Dhuliel.

The above-mentioned deliverables will improve the understanding of hydrological processes not only in the Wadi Dhuliel, by also in regions with different climatic and topographic variations. At a more general level, it could lead to a better understanding of the correlation between all weather variables.

Despite limitations from the availability of input data, the results of this study help establish criteria for simulating streamflow in arid regions at different time scales. Specifically, this research explains how hydrological models should be used to model streamflow in arid regions when there is a dearth of observational data. The choice and quality of input data, model section, model parameters, model modifications, and applicability of results to different arid catchments on different timescales are discussed. The main research question was: what are the 'best' hydrological models that can be applied to assess stream flow in arid regions under the lack of observational data. More specific questions have been addressed by this PhD research study:

a. Which data should be collected to achieve research objectives?
b. What is the quality of available data from local water authorities?
c. What are the optimal sets of model parameter values?
d. How can the research modify the model to meet the catchment characteristics?
e. How can the research improve the accuracy of spatial rainfall estimation in arid regions?
f. Is there any significance of using different rainfall runoff models in assessing same event or period?

The first four questions were answered in the first paper; the fifth question was addressed in the second paper, and the last question was answered in the third research paper.

6 Summary of appendices

The above targets have been achieved via publication of three articles in peer-reviewed journals. The first publication was already published, the second has been accepted as a discussion paper, and the third is currently under review. The first author in all 3 papers is Eyad Abushandi. His contribution was 90% while the coauthor (Prof. Dr. Broder Merkel) contributed to 10% to the papers (ideas, proofreading).

In the first paper, the metric conceptual IHACRES model was applied to daily time scales for storm events and was also extended for snowfall in order to cope with such extreme events. The detailed descriptions of the model, including model structure, formulation, data preparation, parameter identification, model calibration and evaluation, etc. were presented. Additionally, a general literature review on the subject was also incorporated.

In the second paper, the investigation of rainfall characteristics over the Wadi Dhuliel catchment was madeutilizing Global Satellite Mapping of Precipitation GSMaP data and ground based rain gauge data. This study aimed to develop a technique to adjust or re-calibrate the GSMaP data by means of ground-based weather variables data and standard interpolation techniques. The study began with a detailed history recounting hydrological study in Jordan, then moved to the concept of using GSMaP_MVK+ in both arid reasons in general and the Wadi Dhuliel specifically. A statistical re- process was presented by which GSMaP_MVK+ data could be modified to account for complex terrain is the effects of rainfall variation with altitude were briefly described. Finally, the influential factors for the over- or underestimation of the GSMaP_MVK+ in arid regions were summarized.

The third paper discussed the advantages and the disadvantages of using distributed and lumped models. The applicability of GIS to hydrological modeling was highlighted and particular attention was given to explain the benefits of geo-referenced datasets. The HEC-HMS distributed model and IHACRES lumped model were applied to simulate a single event streamflow in the Wadi Dhuliel arid catchment occurring from March 30-31, 2008. The paper began with a brief discussion about the concepts of both models and how GIS was integrated into the HEC-HMS model. The mathematical background of the models was then presented. The models were calibrated and validated using observed stream flow data set collected from Al-Za'atari discharge station and results presented.

7 Conclusions

In this study, a distributed hydrological model (HEC-HMS) and a lumped model (IHCRES) are applied to the Wadi Dhuliel arid catchment to simulate streamflow on different time scales. Both models are applicable in arid areas of Jordan, which are dominated by ephemeral streams and rapid responses to storm events. The results indicate that both models can adequately simulate streamflow in arid catchments on the time scale of a single storm event but overall accuracy depends on the length of the chosen time interval.

This study concluded that longer calibration periods were needed in order to reduce the uncertainty in model parameters, as well as predict long-term climate change and anthropogenic impact on the study area. A major source of uncertainty for the hydrological modeling is the lack of spatial rainfall input, despite the fact that a new parameter (snow melt) was added to the IHACRES model. Therefore, the second publication focused on the incorporation of GSMaP_MVK+ data to simulate rainfall distribution. Although the GSMaP_MVK+ data proved extremely valuable for hydrological modeling, the new, satellite-derived rainfall data requires additional improvements for modeling continuous hydrological variables in arid catchments.

In the third paper, the HEC-HMS and IHACRES models were applied for estimating the streamflow volume for a single rainfall event. The HEC-HMS rainfall-runoff model included the effects of terrain using GIS satellite data, which proved advantageous for describing for the variety land-use patterns and soil types.. On the other hand, the less-complex IHACRES model required minimal input data. The GSMaP_MVK+ dataset was used to determine the rain storm location and to quantify the amount of the rain in each sub-basin. Estimated and observed streamflow volumes of the single event were close enough to assume the applicability of the HEC-HMS model approach for the region.

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Appendix A

Abushandi E. & Merkel B. 2010 Application of IHACRES rainfall-runoff model to the Wadi Dhuliel arid catchment, Jordan. J. Water and Climate Change (Published)

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Abstract

With increasing stress on water resources in Jordan, application of rainfall-runoff models can be part of the solution to manage and sustain the water sector. In this paper, the metric conceptual IHACRES model is applied to the Wadi Dhuliel arid catchment, north-east Jordan. Rainfall-runoff data from 19 storm events during 1986 to 1992 have been used in this study. Flood estimation was performed on the basis of daily scales and storm events scales. The model was extended for snowfall in order to cope with such extreme events. Although the best performance of the IHACRES model on a daily basis is poor, the performance on storm events scale showed a good agreement between observed and simulated streamflow. Apart from model parameter values, the principal reasons for IHACRES model success in this region are thought to be based on antecedent soil moisture conditions, rainfall duration and rainfall intensity before and during each storm. The model outputs were likely to be sensitive when the monitored flood was relatively small. The optimum parameter values were influenced by the length of calibration data and event specific changes.

Key words: arid regions, effective rainfall, IHACRES, rainfall-runoff, snow

1 Introduction

Around 95% of Jordan lies on arid and semi-arid terrains between the latitudes of 29°11′ N and 33°22′ N and the longitudes of 34°59′ E and 39°12′ E. Water scarcity is the major problem in Jordan, which has one of the world's fastest growing populations with a growth rate of 4.5% annually (Al-Halasah and Ammary 2006; Jaber et al 1997). Due to both population increase and rising of general prosperity the use of water resources in Jordan is dramatically increasing. Sporadic and unpredictable severe rainstorm events, flash floods and droughts are the main characteristics of the hydrological system in Jordan. Only 9% of Jordan's territory receives more than 200 mm of the annual rainfall (Al-Halasah and Ammary 2006). In comparison to some of Jordan's neighbouring countries, Jordan has the lowest annual water share. Therefore, an urgent need to focus on water resource sustainability management is essential.

With the exception of the Yarmouk River, surface water flow in Jordan is extremely rare and occurs in the following three ways:

1 a few creeks fed from groundwater through springs;

2 streamflow or floodwater formed after significant rainstorms in winter;

3 discharge of treated wastewater.

The average annual floodwater for the entire Jordan area is 255×10^6 m^3 (Al-Halasah and Ammary 2006), which contributes 3% of the total annual rainfall. Although the quantity of floodwater is relatively small, it might increase the water availability at the catchment scale. There are a few short-term projects on flood flow measurements but long-term flow data are generally not available for arid sites in Jordan. The major reason for this situation is a lack of awareness of the importance of monitoring flood flows in the governmental authorities. In addition, even in the rare cases where gauging stations exist, general measurement problems occur during intense flood events reducing the quality and completeness of the data (Lange et al 2000). Thus for arid regions in general and for Jordan in particular two requirements can be stated:

1 improved monitoring systems for flood flows;
2 evaluation tools based on limited data.

Rainfall-runoff models have been widely used for the last 50 years (Nash 1959) as a means of describing hydrological processes. Hundreds of rainfall-runoff models have been developed throughout the world, especially in Europe to provide river flow forecasting (Beven 2001). However, most of these models are designed to estimate runoff from persistent rainfall (Pilgrim et al 1988), making most of them appropriate tools for humid environments only.

Arid and semi-arid areas have particular challenges that have received less attention (Wheater et al 2008). A comprehensive review of modelling rainfall-runoff in arid and semi-arid regions and related difficulties was made by Pilgrim *et al.* (1988). Because of harsh climatological and physical conditions, modelling the rainfall-runoff relationship has been the dilemma for hydrologists working in arid regions. Obviously, only a limited number of rainfall-runoff models have been developed and modified for arid and semi-arid environments. Perhaps the first published research on characterizing the rainfall-runoff relationship in a semi-arid area was given by Osborn & Hickok in 1968. They analysed the effect of rainfall variability in producing runoff for Alamogordo Creek watershed in New Mexico.

Lane & Renard (1971) evaluated stochastic modelling for ephemeral runoff from Walnut Gulch semi-arid experimental watershed in Arizona.

The model was based on five statistical distributions of actual flow events to generate synthetic individual flows. The basic assumption of linear correlation between the starting date of the wet season and the number of thunderstorm runoff events per season was considered. The authors concluded that the length of runoff season plays an important role in the variability of the results. Ultimately, the typical application of rainfall-runoff models to arid and semi-arid regions is limited to parametric models (Drissel & Osborn 1968; Osborn & Hickok 1968; Lane & Renard 1971; Croke & Jakeman 2008; McIntyre & Al-Qurashi 2009).

Although it is recognized by many hydrologists that the rainfall-runoff models cannot give a full picture or 'plethora' of reality (Beven 1984; Pilgrim *et al.* 1988; Bronstert 2004; Al-Qurashi *et al.* 2008; McIntyre & Al-Qurashi 2009), modelling the rainfall-runoff relationship is a very useful tool to predict streamflow in arid catchments.

In general, the choice of rainfall-runoff model is based on three main roles:

2 The availability and the quality of hydrological data, especially rainfall and runoff data;

3 Model structure and model ability of regionalization;

4 Catchment characteristics and flow homogeneity.

These roles can be slightly different depending primarily on the catchment type and secondarily on the catchment size. For instance, the challenge of modelling urbanizing catchments is how to link the population growth and the effect of growing in industrialization. Aucharova & Khomich (2006) have mentioned that the type and concentration of urban runoff contaminants are primarily based on seasonal period and type of functional zones, therefore it is necessary to consider this conclusion in modelling urbanizing catchments. Attention has been paid to the effect of urbanization proceeds and manmade drainage system characteristics on the variability of runoff magnitudes (Rao *et al.* 1971; Hall 1977). In addition urban rainfall-runoff models require more spatial details of overland flow, rain-dependent inflow and infiltration (Dongquan *et al.* 2009).

On the other hand, applications of rainfall-runoff models for agricultural catchment have to deal with specific problems such as land degradation (Bulygina et al 2009), leaching fertilizers and their impact on surface and ground water quality (Sten Bergström & Brandt 1987) and soil erosion assessment (Lopezbermudez 1990; Hrissanthou *et al.* 2003). This usually requires some implementations or modifications of rainfall-runoff models.

The IHACRES rainfall-runoff model has been successfully applied to many arid and semi-arid catchments all over the world (e.g. Australia, Oman, Jordan and many parts of Africa). IHACRES stands for Identification of unit Hydrograph And Component flows from Rainfall, Evaporation and Streamflow. It has been used to predict streamflow in ungauged catchments (Kokkonen et al 2003), study land cover effects on hydrologic processes (Croke and Jakeman 2004; Kokkonen et al 2001) and investigate dynamic response characteristics and physical catchment patterns (Kokkonen et al 2003; Sefton and Howarth 1998).

In a particular study IHACRES has been applied to the Wadi Faynan area of south-western Jordan as part of the Water Life and Civilization Project. Monthly flow data from the River Jordan gauging station in conjunction with monthly rainfall data from Mt Kenaan, Israel, were used to apply IHACRES for the period 1988–1993. A calibrated version of IHACRES was able to explain 96% of flow records variability (Whitehead et al 2006).

The Zarqa River is the second-largest river in Jordan after the Yarmouk River. The total area of the river drainage network is around 3882 km^2 (the total area may differ slightly from one author to another). It is divided into two sub-basins: the Seil Al-Zarqa sub-basin and the Wadi Dhuliel sub-basin with a lower outlet near the King Talal Dam (Figure.A 1). The river receives water from two main sources: rainwater during winter, contributing approximately 47.4% of the annual yield, and approximately 52.6% due to treated wastewater from the Khirbet Al-Samra, Al-Baqa'a, Jarash, Abu-Nsair and Almafraq Wastewater Treatment Plants. In addition, there is a very limited contribution of groundwater through surrounding springs. Unfortunately this amount of groundwater contribution is not well cited.

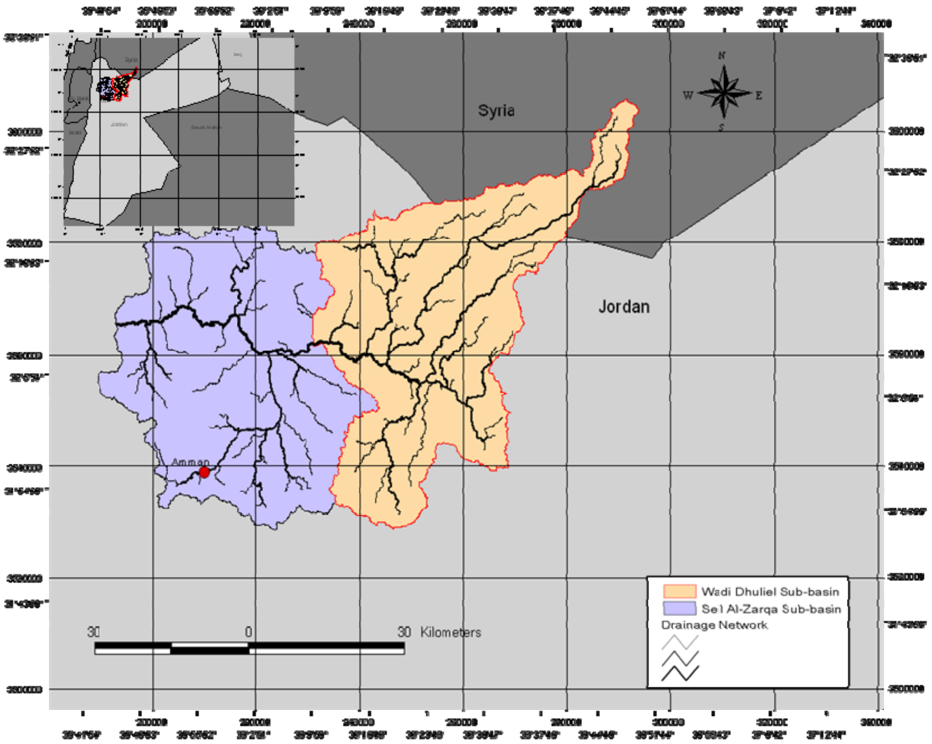

Figure.A 1| Location map of Al-Zarqa basin: including Seil Al-Zarqa sub-basin and Wadi Dhuliel sub-basin (map datum: WGS 84).

Wadi Dhuliel catchment is an appropriate example of an arid catchment and an important source for passing floodwater from the northern part into the Al-Zarqa River. In comparison to other hydrological models, the IHACRES model only requires three data sets (rainfall, temperature and streamflow) per time unit and a small number of parameters. This, however, may overcome the problem of the observed data scarcity for arid regions. In addition the structural simplicity of the IHACRES model assists the good performance of the model for many types of catchment.

This paper examines the application of the IHACRES model into 19 rainstorm events that caused streamflow obtained from the Wadi Dhuliel sub-basin by using daily rainfall, temperature and streamflow data to evaluate the accuracy of the calibration method in that region.

2 Methodology

2.1 IHACRES model structure

Model developers divide rainfall-runoff models into three categories: metric, conceptual and physics-based models (Beck 1991; Croke et al 2006; Kokkonen et al 2001). Metric rainfall-runoff models are the simplest models based on observed data including rainfall and runoff records to characterize the catchment interaction. Conceptual models describe many internal aspects to characterize the catchment interaction. Physics-based models couple mathematical-physical theories and flow equations (Navier-Stokes) to achieve precise simulations.

IHACRES (Jakeman and Hornberger 1993; Jakeman et al 1990) is a hybrid conceptual-metric model, using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models (Croke and Jakeman 2005).

The main objective of IHACRES is to characterize catchment-scale hydrological behaviour using as few parameters (often about six parameters) as possible (Littlewood 2003). Therefore, it can successfully be applied to arid regions where hydrological data sets are very rare.

The original structure of IHACRES uses the exponential soil moisture drying rate index. Several versions of IHACRES have recently been developed and improved to achieve a good simulation of ephemeral streams in arid regions. The model contains a non-linear loss module followed by a linear module; the non-linear loss module converts rainfall into effective rainfall, while the linear module transfers effective rainfall to streamflow. Figure.A 2 shows the model components.

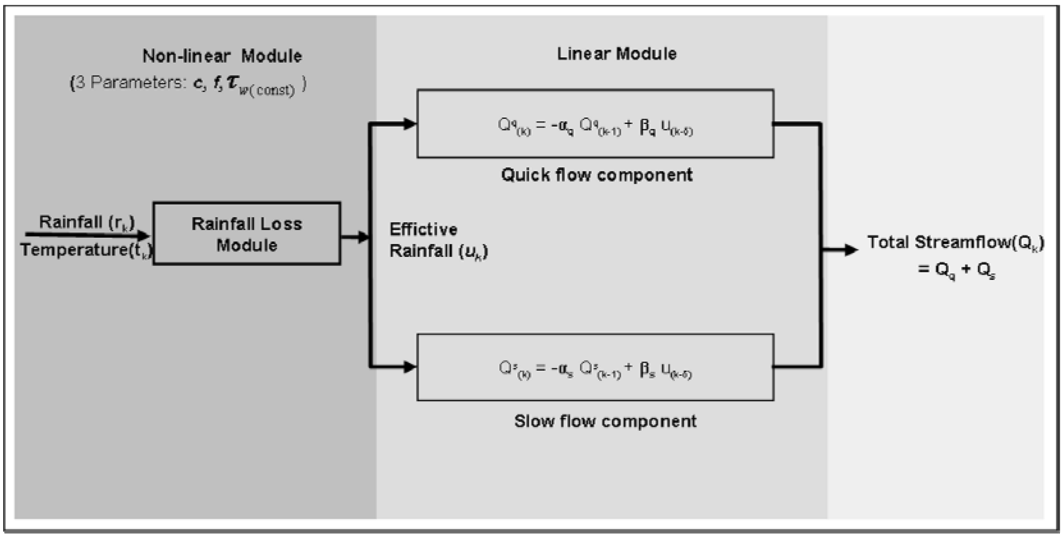

Figure.A 2| Generic structure of IHACRES model.

In this study the classic redesigned IHACRES version (Croke et al 2006; Jakeman and Hornberger 1993) has been used. The non-linear loss module converts rainfall (r_k) into an effective rainfall (u_k) by considering both the infiltration rate and evapotranspiration. In order to obtain the effective rainfall, a catchment wetness index or antecedent precipitation index, representing catchment saturation, is calculated for each time step. Usually, a non-linear loss module within IHACRES includes three parameters: c is the adjustment parameter, f is a temperature modulation parameter and $\tau_{w(const)}$ is the rate at which catchment wetness declines in the absence of rainfall.

The initial stage is to determine the drying rate τ_w, and the catchment moisture index s_k at each time step, which is given by:

$$\tau_w = \tau_{w(const)} \times e^{(20-t_k)} \times f \tag{1}$$

where τ_w is the drying rate at each time step, $\tau_w(const)$ is the rate at which catchment wetness declines in the absence of rainfall, t_k is the temperature at time step k and f is a temperature modulation parameter (°C^{-1}), which determines how τ_w changes with temperature.

Catchment wetness index s_k is computed for each time step on the basis of recent rainfall and temperature records. The loss module is used to account for the effect of antecedent weather conditions on the current status (s_k) of soil moisture and vegetation conditions, and evapotranspiration effects (Schreider et al 1995).

$$S_k = c \times r_k + (1 - \frac{1}{\tau w_{(k)}}) \times S_{k-1} \tag{2}$$

where c is the adjustment parameter and controls the amount by which s_k is increasing by a rainfall event (Post and Jakeman 1999), r_k is the rainfall at time step k.

Finally the effective rainfall (u_k) in the model is given by:

$$u_k = r_k \times s_k \tag{3}$$

if $r_k \times s_k \rangle 0$.

Since the study area is characterized by ephemeral streams where there is no runoff if there is no rainfall, computing effective rainfall if r_k is >0 for ephemeral streams can make equation (3) true, both physically and dimensionally. In the linear routing module, the effective rainfall is converted into streamflow (Q_k). The storage configurations of two parallel storage components have been applied. The linear model employs discrete-time intervals, transfer function and a representation of the Unit Hydrograph (UH).

$$Q_{(k)}^{q} = -\alpha_q Q_{(k-1)}^{q} + \beta_q u_{(k-\delta)} \tag{4}$$

$$Q_{(k)}^{s} = -\alpha_s Q_{(k-1)}^{s} + \beta_s u_{(k-\delta)} \tag{5}$$

where $(Q_{(k)}^{q}, Q_{(k)}^{s})$ are quick and slow streamflow components. Delta in the $u_{(k-\delta)}$ is the delay between rainfall and streamflow response. The parameters (α_q, α_s) are the recession rates for quick and slow storage, whereas the parameters (β_q, β_s) represent the fraction of effective rainfall. The UH of total streamflow is the total of both quick and slow flow UHs. As an external parameter, snow melt parameter (*Cmelt*) was added into the β_q fraction in the case of snowfall events:

$$Q_{(k)}^{q} = -\alpha_q Q_{(k-1)}^{q} + \left[(\beta_q)(Cmelt)u_{(k-\delta)}\right] \tag{6}$$

The snow melt parameter (*Cmelt*) will be automatically blocked if there are no snowfall events; it is actually connected to the temperature gradient. In other words; the *Cmelt* parameter is not functioning if the temperature is higher than the freezing degree.

To predict flood flow for ungauged catchments by means of calibrated rainfall-runoff models, a technique for estimating parameter values is required. There are numerous studies for determining these values. (Merz and Bloschl 2004) estimated parameter values based on regression analysis between proposed parameter values and catchment attributes. However, this regression application requires parsimonious models that have strong relationships between parameter and catchment attributes (Croke and Littlewood 2005). In addition, the Nash-Sutcliffe efficiency (E_f)

has frequently been applied to assess the goodness of modelled streamflow to observed records:

$$E_f = 1 - \frac{\sum (q_i - \hat{q}_i)^2}{\sum (q_i - \overline{q})^2} \tag{7}$$

where q_i is observed streamflow, $\hat{q}_i$ is modelled streamflow and $\overline{q}$ is the mean value of observed streamflow. The E_f will be used in this study to estimate the goodness of model outputs.

In order to measure the reliability of simulated values the Relative Error of Estimate was calculated.:

$$REE = \frac{\sqrt{\frac{1}{M}\sum_{1}^{M}(Q_{sim} - Q_{obs})^2}}{\overline{Q}_{obs}} \times 100 \tag{8}$$

2.2 Study area and available data

Wadi Dhuliel has always played a key role in increasing water levels in the Al-Zarqa River and being a valuable source of natural groundwater recharge. It is located in the north-east part of Jordan. Most of the catchment area belongs to the Al-Zarqa Basin. Around 10% of the upper part of Wadi Dhuliel catchment is situated on Syrian territory (Figure.A 3). The area is characterized by a very gently undulating topography with an elevation varying from 512 m in the south-west to 1400 m in the north. The area of interest is approximately 1985 km^2.

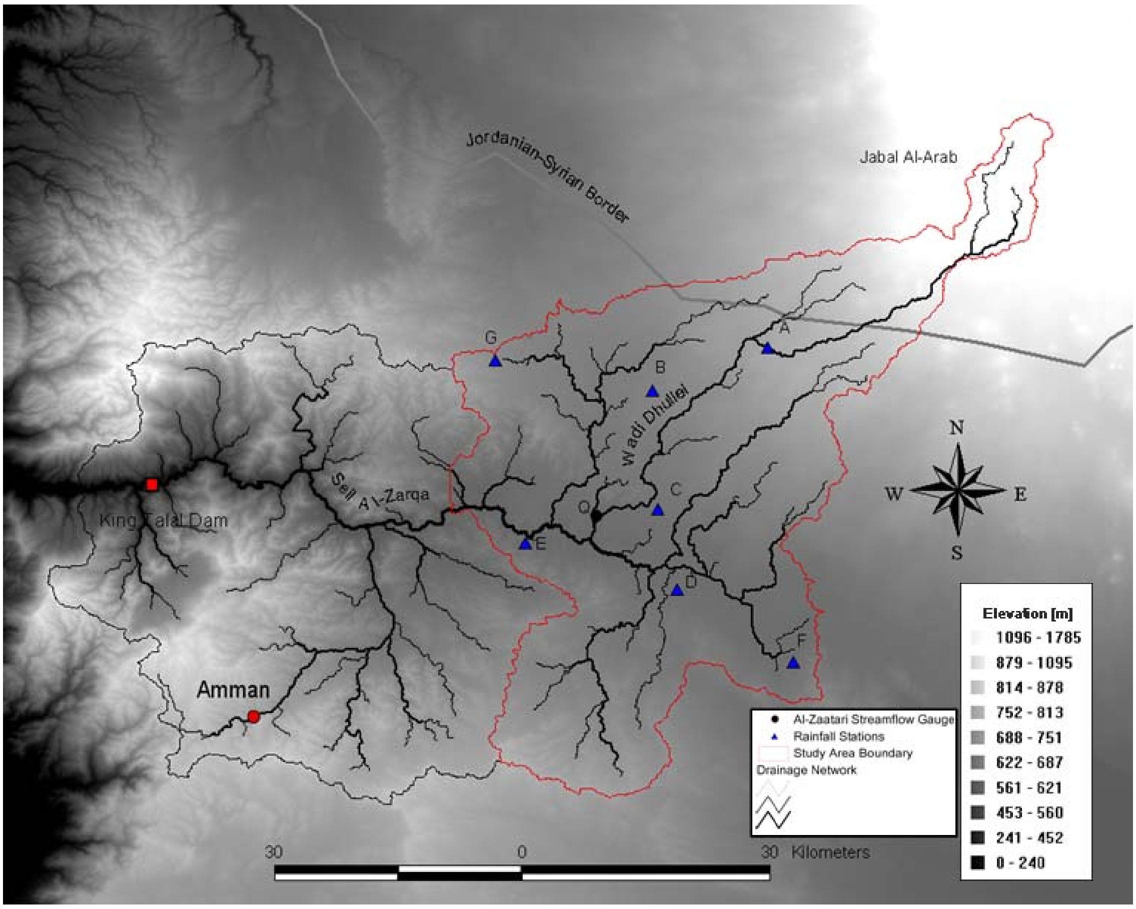

Figure.A 3| Wadi Dhuliel sub-basin: location map, drainage network and rainfall and discharge stations. DTM based on 90 m SRTM.

Besides Wadi Dhuliel, there are a number of wadis in the catchment area such as Wadi Al-Za'atari, Wadi Al-Ajeb and Wadi Alghar. The flow direction is from the north towards Seil Al-Zarqa sub-basin in the south-west. Hydrological features of the Wadi Dhuliel catchment are disturbed by a strong influence of agricultural activities and high pressure on groundwater resources.

The area of interest is characterized by warm and dry summers (May to September) and moderate cold and wet winters (October to April). The overall annual rainfall is 123 mm on average (Figure.A 4). The average annual temperature is 16.8 °C (1976–2005). Table.A1 shows average temperature and standard deviation during the driest and wettest months. The data for this table were compiled by Almafraq meteorological station at an elevation of 675 m above sea level.

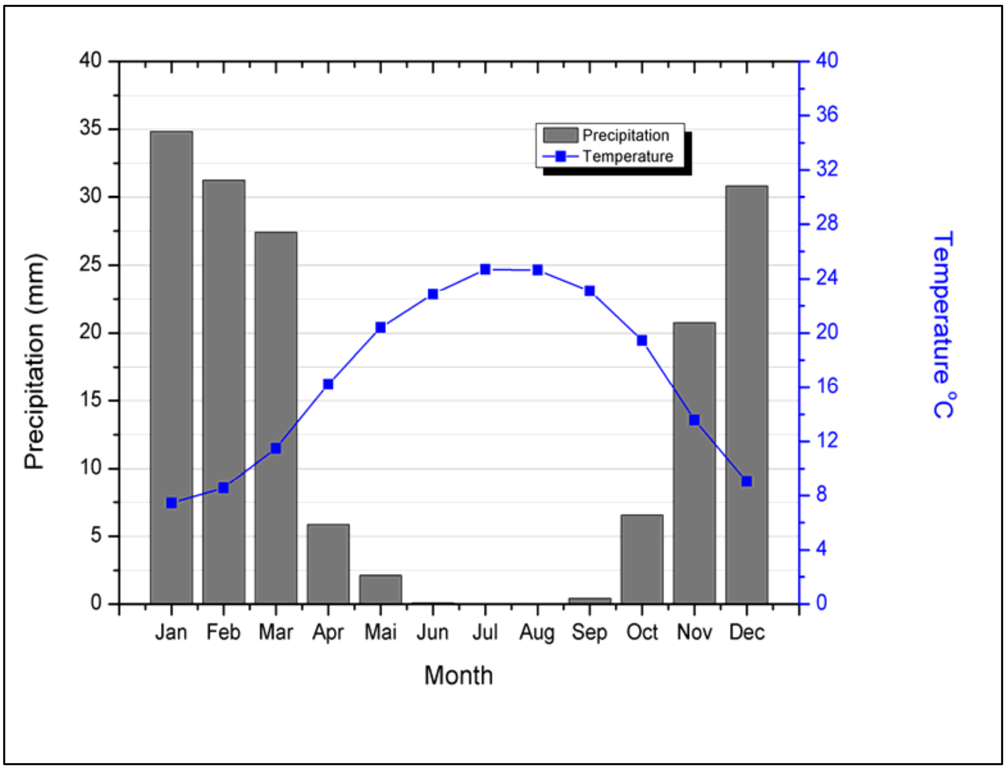

Figure.A 4| Climograph for Almafraq Meteorological Station/north-east Jordan, the period from 1976–2005 (Jordan Meteorological Department).

Table.A 1| Temperature description for the period of 1976–2005

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**
Average (°C)	7.4	8.6	11.5	16.2	20.4	22.9
Average maximum (°C)	12.7	14.2	18	24	28.7	31.6
Average minimum (°C)	2.1	2.9	5.1	8.5	12.0	14.1
PET (mm)*	145	185	310	566	842	1034

	Jul.	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Average (°C)	24.7	24.6	23.1	19.5	13.6	9.0
Average maximum (°C)	33.1	33	31.3	27.2	20.2	14.5
Average minimum (°C)	16.32	16.31	14.9	11.73	6.92	3.51
PET (mm)*	1186	1181	1054	779	415	204

* Potential evapotranspiration (PET) is calculated by the Thornthwaite equation.

The annual rainfall magnitudes show a distinct west-east gradient from the relatively wet west regions with about 600 mm to the Jordanian desert or Al-Badia with less than 100 mm.

Based on average annual precipitation (P) and potential evapotranspiration (PET) for the period of 1976 to 2005 of Almafraq Meteorological Station (Figure.A 5), the degree of aridity was calculated by the UNEP Aridity Index (Al) (Safriel 2006).

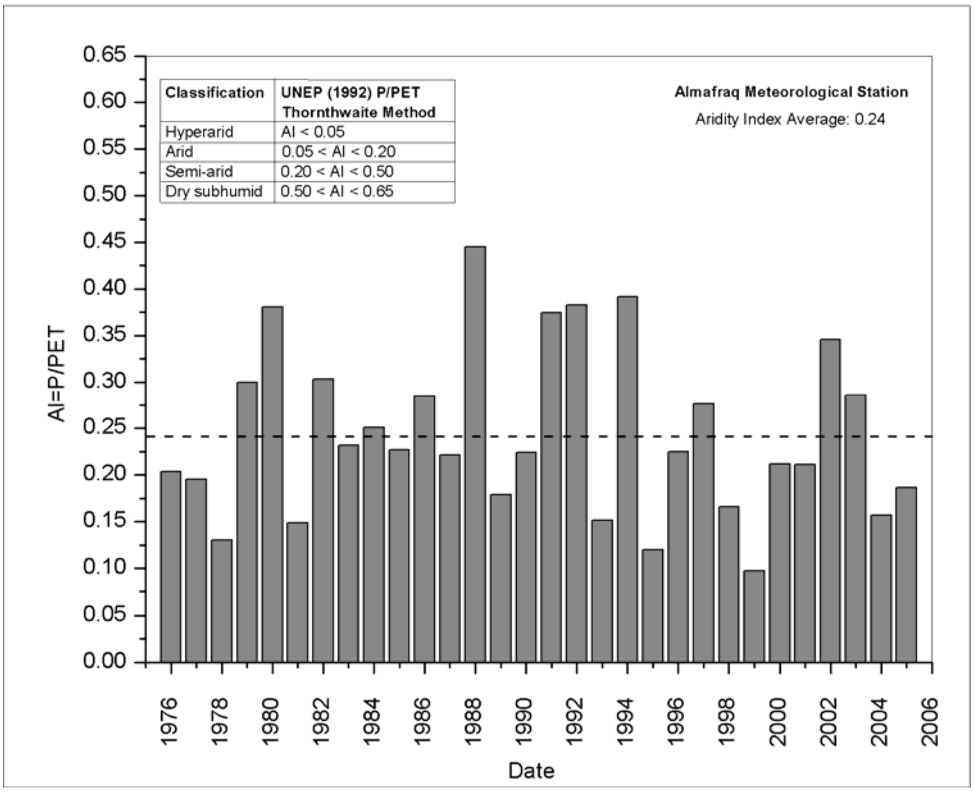

Figure.A 5| UNEP Aridity Index for the study area. Dashed line represents the aridity index of Almafraq Meteorological Station.

IHACRES model requires three data sets per time unit: (a) rainfall, (b) streamflow for calibration purpose and (c) temperature or potential evapotranspiration.

Typically, data sets for arid areas are limited to daily rainfall, temperature and in lucky cases short periods of flood flow records. The data sets used in this research were derived from the Surface Water Resources Unit at the Jordan Ministry of Water and Irrigation (JMWI) and Jordan Meteorological Department (JMD). The initial step was a careful screening with respect to errors and missing values in the datasets. Daily rainfall data are available from seven rainfall gauging stations, which are fairly well distributed over the entire catchment area. Recently, new rainfall gauges were added; however, their recording period is less than five years. Almafraq station has the highest annual rainfall (158 mm) while Qasr Al-Hallabat station has the lowest rainfall (79.2 mm). Seventy-three per cent of the annual rainfall occurs during November, December, January and February. An average rainfall was calculated from seven rainfall and meteorological stations. Table.A 2 presents detailed rainfall information and period of records for each station.

Table.A 2| Detailed information about rainfall stations utilized for the study

Station code on the map (Fig. 3)	**Station code in JMWI**	**Station name**	**Height (asl in metres)**	**Mean annual precipitation (mm)**	**Period of records**	**Total of period (years)**
A	AL0058	Sabha and Subhiyeh	843	108.1	1968–2002	35
B	AL0059	Um-Jimal [*]	670	119.3	1969–2002	35
C	AL0048	Al-Khaldiya	600	125.4	1968–2002	35
D	AL0055	Wadi Dhuliel Nursery	580	137	1968–2002	35 [a]
G	No Code	Almafraq [*b]	675	158	1975–2005	30
F	AL0049	Qasr Al-hallabat	590	79.2	1968–2002	35
E	AL0012	Sukhnah	556	135.3	1968–2002	52

[*] Meteorological station.

[a] Missing data in the years 1968–1971.

[b] Almafraq station is the only meteorological station from Jordan Meteorological Department, all others belong to the Jordan Ministry of Water and Irrigation.

Since availability of daily temperature records was limited, daily temperature data were taken from Um-Aljimal Meteorological Station only. The station is located at the upper part of Wadi Dhuliel catchment with an elevation of 676 m asl. Daily stream flow records were collected between 1986 and 1992 from Wadi Al-Zaatari streamflow gauging station close to the junction with Wadi Al-Dhuliel. This flow record has been used to test IHACRES performance during the calibration stage. Table.A 3 provides a very brief summary of the flow measurements.

Table.A 3| Summary of discharge from field measurements (JMWI)

Cross section width (m)	**Mean depth (m)**	**Max depth (m)**	**Cross section area (m^2)**	**Mean velocity ($m\ s^{-1}$)**	**Gauge reading (m)**	**Observed discharge ($m^3\ s^{-1}$)**
6.00	0.16	0.35	0.98	0.478	0.02	0.469
36.00	0.18	0.27	6.38	1.342	0.225	8.56
35.80	0.90	1.00	32.30	0.786	0.845	25.4
38.00	0.91	1.05	34.6	1.066	0.91	36.9
35.80	1.20	1.36	43.00	1.102	1.15	47.4

The stage-discharge relation was developed from direct discharge measurements carried out by the JMWI team by means of a current meter during the first and the second significant rainstorms in November 1986 and January 1987. Figure.A 6 shows the developed rating curve from a series of observed flow measurements plotted versus gauge heights at each time step. Most often the discharge in this area is characterized by flash flood waves of very short durations ranging from a few hours to five days within an average of three days. The discharge varies from $Q = 0$ to $Q = 125.2\ m^3\ s^{-1}$.

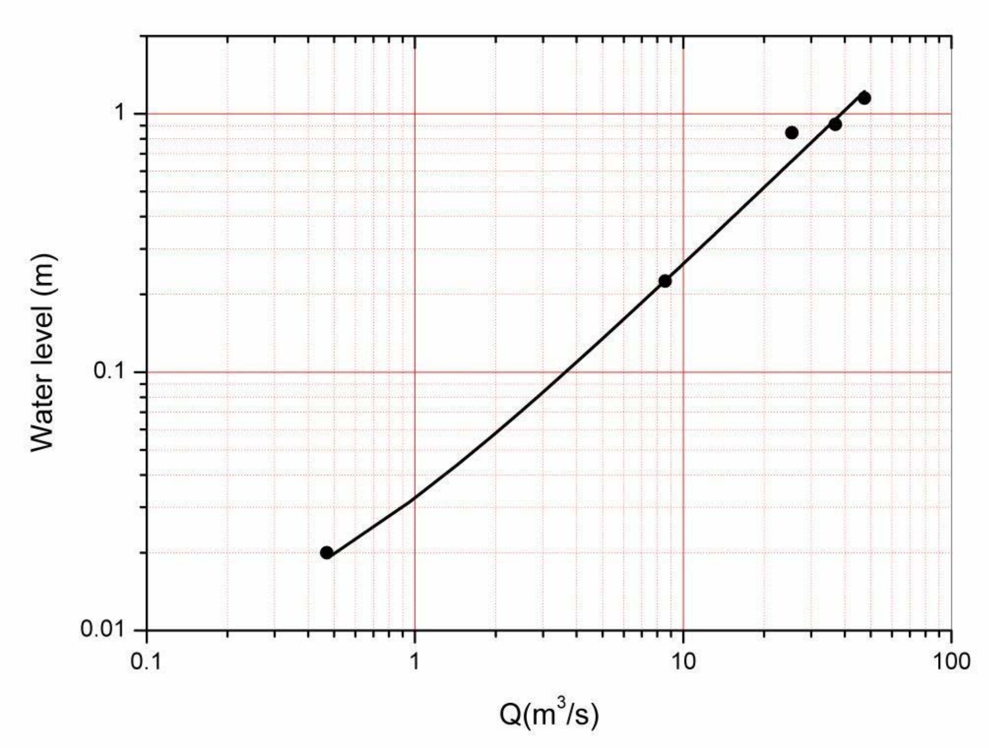

Figure.A 6| The rating curve for Wadi Al-Zaatari in the period of 1986–1987.

Application of IHACRES was limited to the flow measurements period. As explained by (Hansen et al 1996) effective rainfall (u_k) is calculated from the accumulated rainfall depth (r_k) in the non-linear loss module at each time step, where the catchment wetness index S_k values at this stage represent soil moisture characteristics in arid regions and runoff generation thresholds. To understand soil moisture characteristics, additional data sets were collected from a recently installed weather station in the study area (since January 2008). The data included rainfall, temperature and soil moisture. The point was to study the changes of rainfall and temperature in parallel with soil moisture changes. Since soil physical properties are fixed (i.e. infiltration rate), the potential values of the catchment wetness index S_k for the years between 1986 and 1992 were adjusted at both daily and storm event scales.

Simple linear interpolation method was used to develop daily and storm event time series of soil moisture for the years between 1986 and 1992 based on the additional data sets.

3 Results

Flood flow records from the Al-Za’atari gauging station show the main characteristic of surface water flow in the area. The runoff coefficient in the study area was 2.3% on average. Some flood flow events show more than one flow peak during a single rainstorm (Figure.A 7) and are characterized by steep rising peaks. The results show that the catchment tends to have only very few flood flow events (19 events during the period of 06.11.1986 to 11.02.1992, with an average of 3 storms per year).

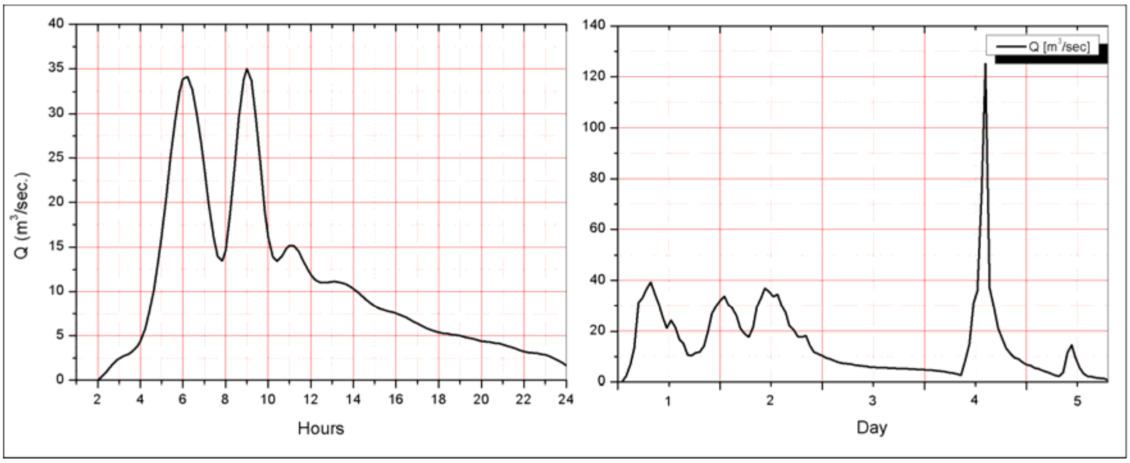

Figure.A 7| Representative behaviours of continuous streamflow: one day (29 November 1986) and five days streamflow (08 November–14 November 1986) respectively.

The IHACRES model was calibrated by using the Al-Zaatari daily flood flow records over a period from 06.11.1986 to 11.02.1992. The best parameter values containing the best fit between modelled and observed streamflow are listed in Table.A 4.

Table.A 4| Optimized IHACRES parameter values

C	$\tau_{w(\text{const})}$	F	α_q	β_q	α_s	β_s	$Cmelt$
0.002	120	0.09	–0.07	0.04	–1	0	0.1

In general, it is unusual for north-east parts of Jordan to receive a heavy snowfall. However, the snowstorm that began in January 1990 and ended in February of the same year was heavy enough to reach the arid parts crossing the Wadi Dhuliel arid catchment. This snowstorm changed the streamflow magnitudes and behaviour in 1990. A fraction of snow melt parameter (*Cmelt*) was added for such particular events to reduce the quick fraction (β_q) influence.

The total flood magnitude from each rainstorm was calculated as a single unit by the mean of total streamflow of each day recorded. The application of IHACRES to both daily and storm events basis gave a better view of streamflow behaviour in the catchment. The goodness of fit between observed flood flow (q_i) and modelled flood flow ($\hat{q}_i$) was estimated using the Nash-Sutcliffe efficiency (E_f).

A good performance of IHACRES was obtained with E_f equal to 0.86 on the storm events scale, while E_f was 0.43 on the daily scale using the same parameter values. This, however, shows a poor performance of the IHACRES model on daily basis application.

The result of IHACRES simulations in comparison to monitored data on both daily and storm events scales are shown in Figures.A 8 and 9.

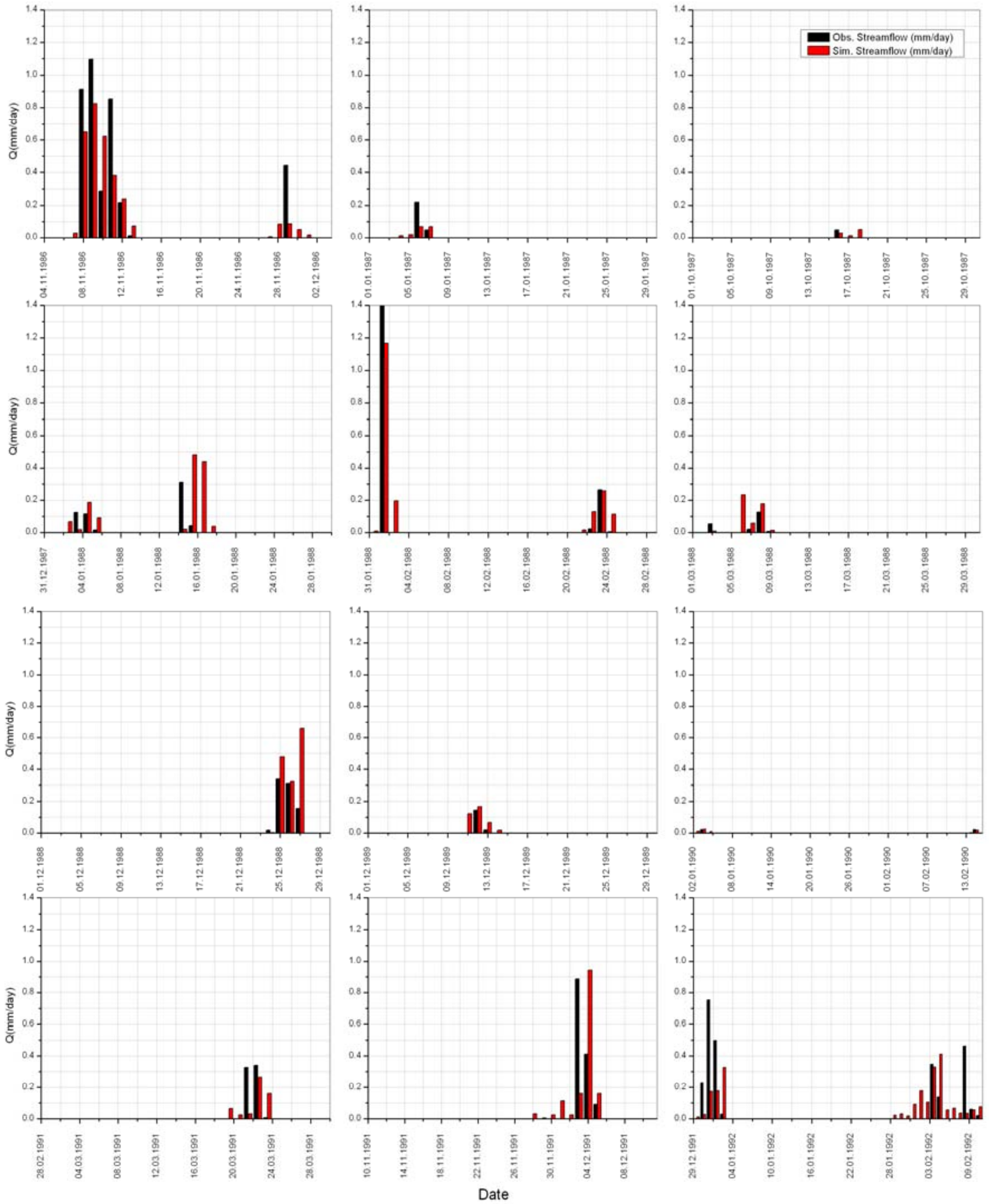

Figure.A 8| Observed and simulated flood flow on a daily basis.

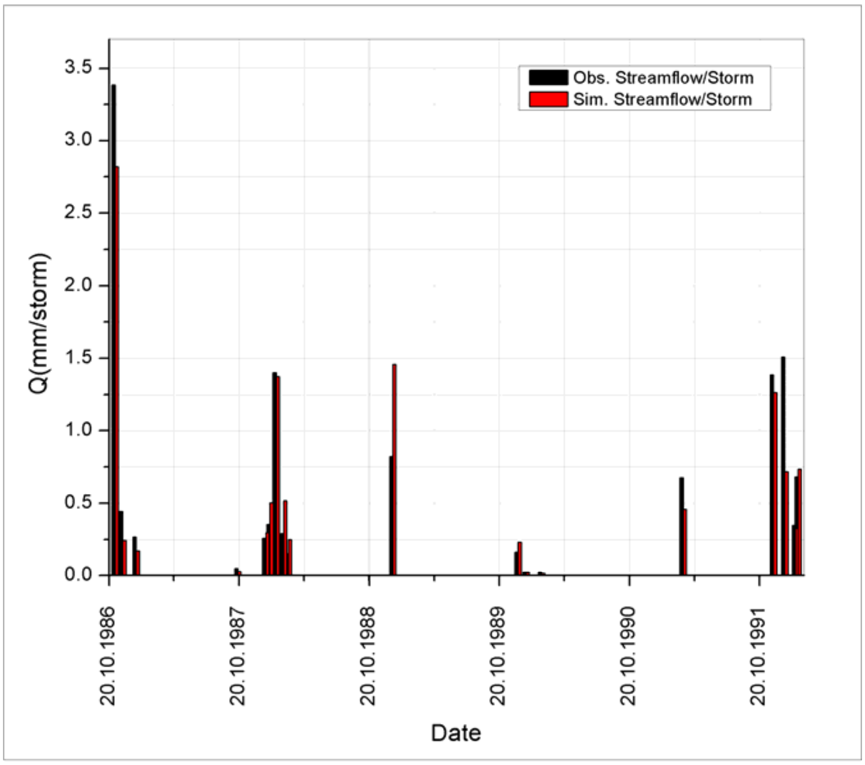

Figure.A 9| Observed and simulated flood flow based on storm events.

The average observed flood on a daily basis was 0.14 mm day^{-1} while the average of simulated flood was 0.16 mm day^{-1}. In contrast, the average observed flood per storm event was 0.65 mm storm^{-1} while the average of simulated floods of all storms was 0.62 mm storm^{-1}. As expected from E_f the Relative Error of Estimate of daily simulated-observed streamflow was 1.45% while in storm events the basis was 0.44%.

4 Discussion

Rainfall behaviour tends to be asymmetric in both space and time, thus affecting the streamflow magnitudes. For this reason, arid catchments are more amenable to simplified models. Because IHACRES is a parametric efficient rainfall-runoff model it is applicable in arid areas, which are dominated by rapid responses to weather variables. Since the model is a lumped model, it has the capability to avoid the spatial variability of the rainfall and streamflow. Furthermore the model requires only a few input data.

In general, rainfall-runoff models have many limitations and aim to achieve a high accuracy. Errors during simulations often occur because of missing data, or complexity of hydrological behaviour. The time step calculation is very important for IHACRES modelling in an arid region. As the results show, it is crucial to change the calculations from daily time steps to storm event time steps at the same parameter values due to the dependency of the present value on previous records. Apart from IHACRES structure there are many other reasons that may increase the relative error such as the flood fluctuation from one storm to another or stage-discharge errors. The Relative Standard Error is likely to be significant when the monitored flood is relatively small.

During the rainy season of the year 1990, the residuals were extremely high in both daily and storm event scales, which can be explained by two reasons: the occurrence of snow instead of rain, and the relatively very small monitored streamflow (0.04 mm storm^{-1}).

This snowstorm changed the entire behaviour of rainfall and temperature gradients. In this particular case the IHACRES model converted the total precipitation (including snow) into effective rainfall and then into streamflow through a quick flow linear module. The identification of optimum model parameters at this specific event was difficult; therefore, a snow melt parameter was added to identify snow melt-runoff conditions. This extreme event happened only once during the last 50 years as it is recorded, therefore it was challenging to study the IHACRES model simulation abilities under such conditions. Relatively, the period of observed and simulated data is not short as in many other related studies. Therefore, it can provide a higher accuracy of the calibration parameters which might be extended to test streamflow for the periods where no observed data are available. Particular attention has been paid to the rainfall patterns after the snow storm in 1990 (Figure.A 10). Tracking the rainfall rate shows that the average annual rainfall across the entire Wadi Dhuliel catchment is 112.7 mm for the years 1990–2008 while the average annual rate for the years 1969–2002 is 123.2 mm. This generally shows that the annual rainfall totals are declining but there have been no snowfall events so far.

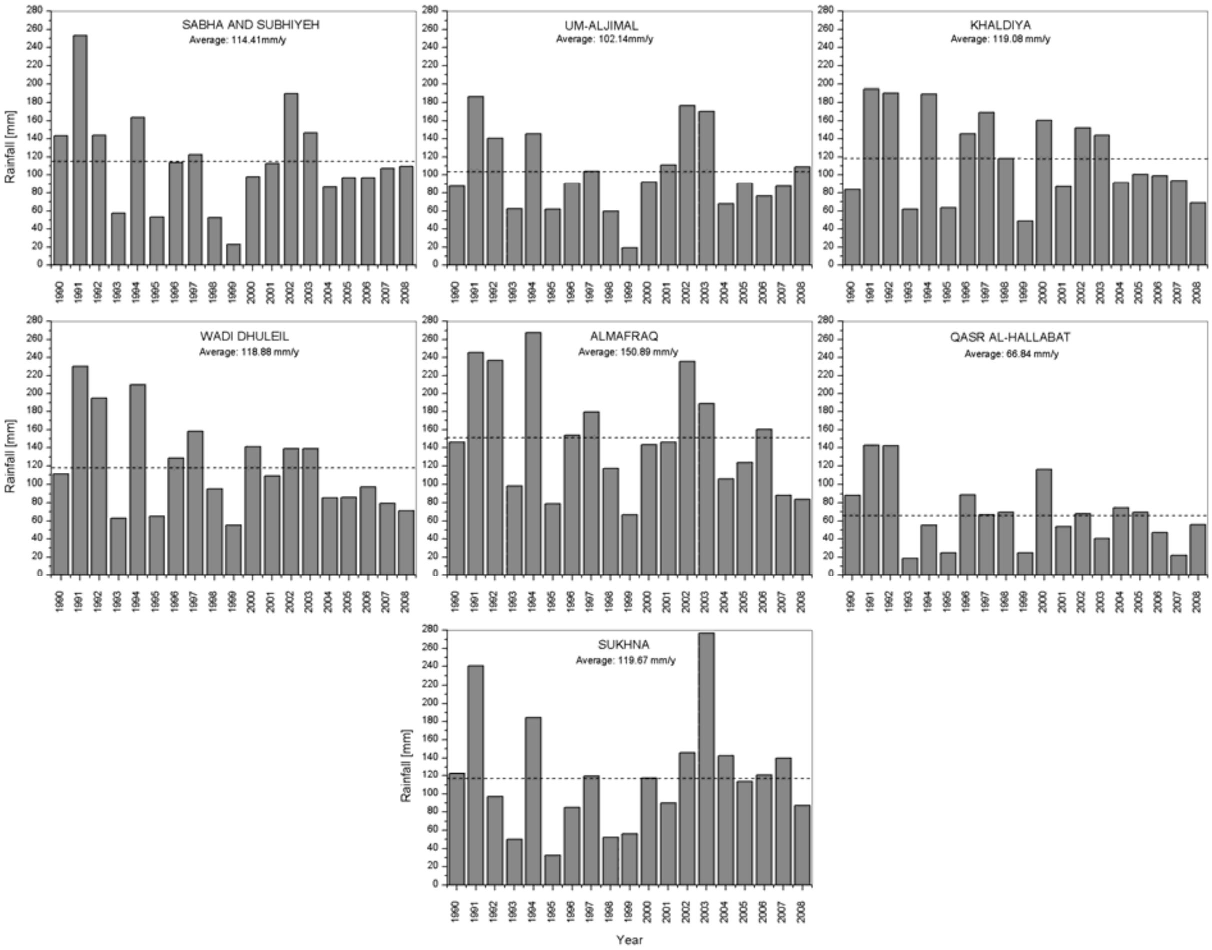

Figure.A 10| Annual rainfall rate measured in Wadi Dhuliel Catchment for the years 1990–2008. Dashed line represents the mean annual rainfall of the same period.

Based on the land use map derived from a Landsat Thematic Mapper (TM) imagery of the year 1987 (Figure.A 11) the agricultural area contributes approximately 36.2% from the total catchment area. Due to this fact, significant quantities of agrochemicals are expected to be transferred from the Wadi Dhuliel catchment to the Seil Al-Zarqa catchment, and end in the King Talal Dam. Therefore it is necessary to predict the potential contaminations in future research.

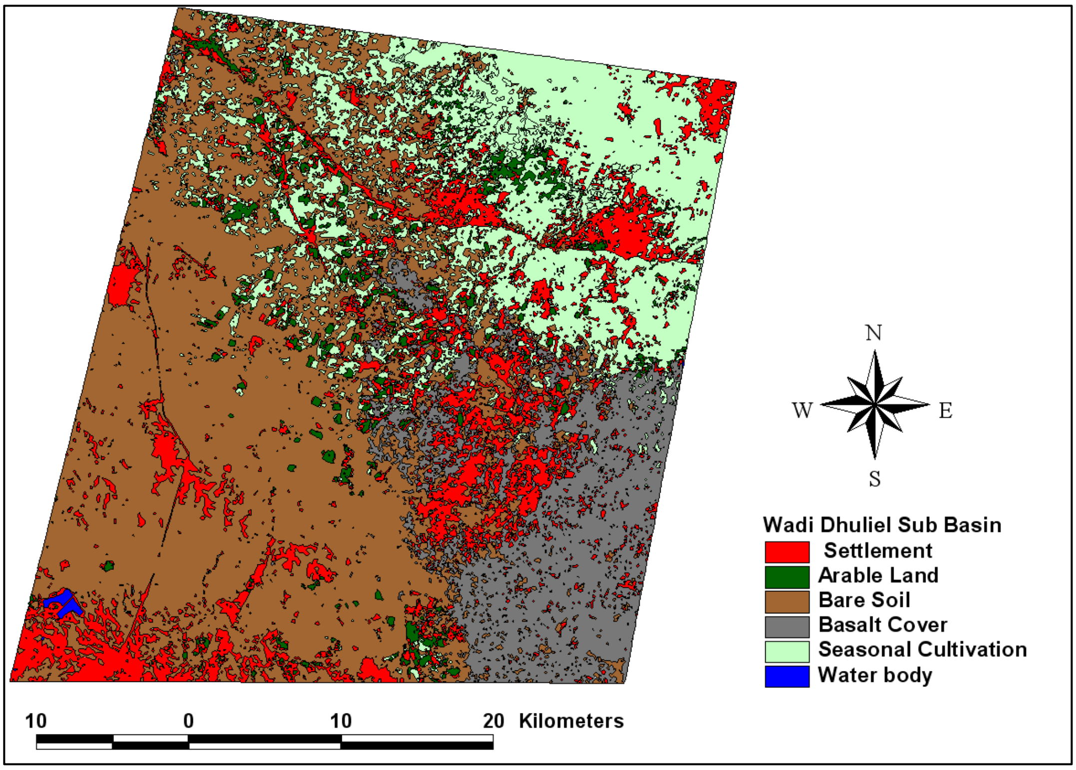

Figure.A 11| Land use map of Wadi Dhuliel sub-basin, Landsat Thematic Mapper (TM) of the year 1987, 30 m resolution.

Moreover, application of rainfall-runoff models in Jordan is a challenging task because of data scarcity and the complex interaction between climate variables. Apart from applying IHACRES rainfall-runoff model for the first time to arid parts of Jordan, the paper added three new aspects:

1. Adding and testing a new parameter in IHACRES model, the snow melt parameter, because arid regions do not have snowfall events.
2. Dividing the data into daily and storm event simulation, not just daily simulation.
3. Taking advantage of a data set obtained recently to correlate historical data, i.e. the soil moisture data set from our weather station.

5 Conclusion

The IHACRES rainfall-runoff model is applicable in the Jordanian arid areas, which are dominated by ephemeral streams and rapid responses to storm events. According to the obtained results, the model is able to adequately simulate streamflow in arid catchments when applying the model on a storm event scale. Dividing the same data into daily and storm event was a good option to evaluate IHACRES at different scales. A good performance of the IHACRES model showed E_f equal to 0.86 on the storm events scale, while E_f was 0.43 on a daily scale. The results therefore depend on the chosen time interval. A new parameter (snow melt) has been added into the IHACRES model. By adding a snow melt parameter the model could be enforced significantly. Changes in rainfall and temperature significantly affect soil moisture capacity, therefore calibration methods of IHACRES models need to be extended. The extension of calibration methods might include automated techniques instead of manual. Longer calibration periods are needed in order to reduce the uncertainty in model parameters and predict both climate change and anthropogenic impact on the study area. A key role of runoff generation can be concluded in four points: (1) antecedent soil moisture conditions, (2) rainfall intensity, (3) rainfall amounts before and during streamflow events and (4) the period of rainfall storms which affect soil storage capacity.

Acknowledgment

The authors are thankful to the Jordan Ministry of Water and Irrigation, particularly the Surface Water Unit, and the Jordan Meteorological Department for providing the necessary data sets.

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Appendix B

Abushandi, E. and Merkel, B.: Rainfall estimation over the Wadi Dhuliel arid catchment, Jordan from GSMaP_MVK+, Hydrol. Earth Syst. Sci. Discuss., 8, 1665-1704, doi:10.5194/hessd-8-1665-2011, 2011. (Accepted for discussion)

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Abstract:

The GSMaP_MVK+ (Global Satellite Mapping of Precipitation) dataset was used to evaluate the precipitation rates over the Wadi Dhuliel arid catchment in northeast Jordan for the period of January 2003 to March 2008. The scarcity of the ground rain gauge network alone did not adequately show the detailed structure of the rainfall distribution, independent form interpolation techniques used. This study combines GSMaP_MVK+ and ground rain gauges to produce accurate, high-resolution datasets. Three meteorological stations and six rain gauges were used to adjust and compare GSMaP_MVK+ estimates. Comparisons between GSMaP_MVK+ measurements and ground rain gauges records showed distinct regions where they correlate, as well as areas where GSMaP_MVK+ systematically over- and underestimated ground rain gauge records. A multiple linear regression (MLR) model was used to derive the relationship between rainfall and GSMaP_MVK+ in conjunction with temperature, relative humidity, and wind speed. The MLR equations were defined for the three meteorological stations. The 'best' fit of MLR model for each station was chosen and used to interpolate a multiscale temporal and spatial distribution. Results show that the rainfall distribution over the Wadi Dhuliel is characterized by clear west-east and north-south gradients. Estimates from the monthly MLR model were more reasonable than estimates obtained using daily data. The adjusted GSMaP_MVK+ performed well in capturing the spatial patterns of the rainfall at monthly and annual time scales while daily estimation showed some weakness in light and moderate storms.

Keywords: Rainfall, Arid Regions, IDW, GSMaP_MVK+, MLR

1 Introduction

Jordan has one of the world's lowest levels of available water resources (WHO, 2011). Due to this scarcity, Jordanian scientists and government have taken an increasingly active role in studying and managing water within Jordan during the last decade. Around 91% of Jordan lies on arid and semi-arid ground which receive less than 200 mm of total annual rainfall (Figure.B 1). Precipitation occurs primarily as rainfall with relatively high intensity in limited range of space and time. Since precipitation is Jordan's first source of water, it is important to investigate and analyze the rainfall behaviour. The rainfall distribution in Jordan varies with location mainly due to arid climatic conditions and topographic variations. Rainfall controls domestic and agricultural activities, especially in the rural area where the percentages of water use are 31% and 65% respectively (Aquastat-FAO, 2009). In comparison to other Middle Eastern countries, Jordan has the lowest magnitude of annual rainfall coincident with high evaporation rates.

Rainfall is also the most important input parameter in rainfall runoff models (Beven 2001a; Croke and Jakeman 2008), groundwater recharge models (Abdulla and Al-Assa'd 2006; Merkel and Sperling 1993), climate change scenarios (Dolman and Gregory 1994) and hydro-chemical models (Brezonik and Stadelmann 2002).

Additionally, rainfall information is a critical component in efficient management of urban drainage systems (Vieux and Vieux 2005). Consequently, an accurate assessment of rainfall variability is essential to reduce models uncertainty in the input data of these models.

Due to the arid climate, topographic variations, and a complicated land cover structure temporal and spatial rainfall distributions in Jordan are characterized by a high degree of variability. The annual rainfall magnitudes distinctly include a sharp west-east gradient from relatively wet west regions with about 600mm per year, to the Jordanian desert (Al-Badia), with rainfall less than 100mm per year.

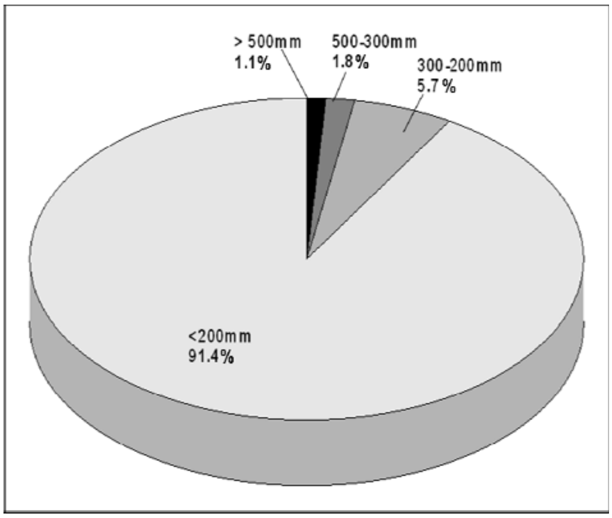

Figure.B 1| Rainfall distribution in Jordan *(JMWI)*

The surface water resources and ground water recharges in the country depend on the magnitude of yearly rainfall. The total annual rainfall on Jordan is approximately 8500 $\times 10^6 m^3$ (Abu-Zreig et al 2000). According to the Jordan Ministry of Water and Irrigation *(JMWI)*, the majority of the rainfall is lost through evapotranspiration (87.9%), 8.5% is groundwater recharge, while the smallest portion is surface runoff (3.6%) (Figure.B 2A). These distributions are slightly different in drier regions of north east Jordan (Figure.B 2B).

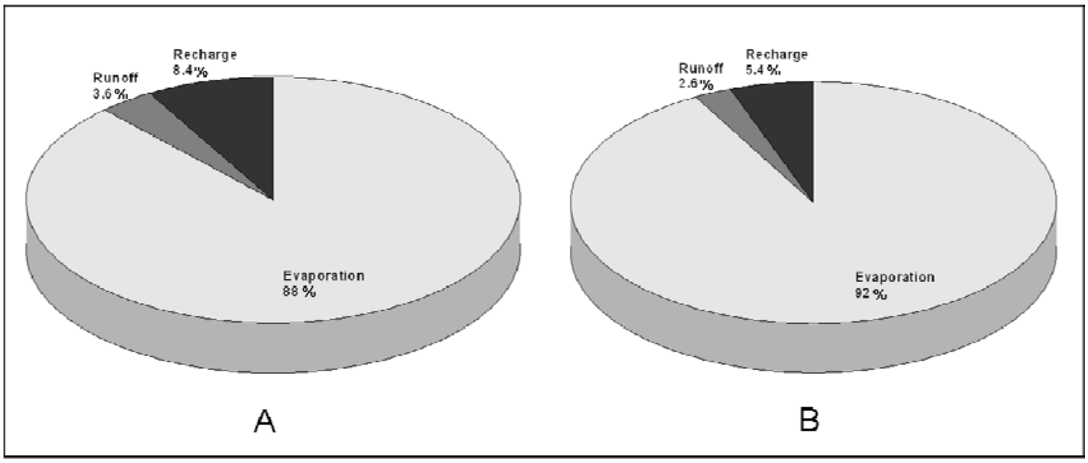

Figure.B 2| The percentages of hydrologic water balance for Jordan (A) and particularly the Wadi Dhuliel in northeast Jordan (B) *(JMWI)*

Rainfall temporal analysis may include rainfall periodicity (Gajiccapka 1994), risk of drought (Akhtari et al 2009; Pal and Al-Tabbaa 2009; Wong et al 2010), chance of rain and frequency (Goldreich 1995), and time series analyses (Momani 2009). In contrast, spatial rainfall analysis focuses on the rainfall distribution within a watershed. Many different rainfall interpolation methods, such as Arithmetic Average, Isotheral method, and the Grid method are employed in current scientific literature. Thiessen polygons are the simplest interpolation method to estimate areal rainfall at a sample point (Thiessen 1911), These methods may not be the optimal to estimate the temporal and spatial rainfall changes in arid regions without additional information or techniques. In some cases, these methods were included in a hybrid approach that utilized other datasets and techniques in order to ensure output quality or to avoid rainfall observation scarcity.

A relatively limited number of rainfall analysis techniques have been developed and modified for arid and semi-arid environments. Perhaps the earliest published research on rainfall magnitudes analysis in arid regions was performed by Winkwort (1967) in Australia and Osborn and Hickok (1968) in the United States.

Generally, the few published studies available from Jordan have tried to analyze rainfall characteristics in the entire country, rather than for individual catchments (Freiwan and Kadioglu 2008b; Tarawneh and Kadioglu 2003), even though many arid drainage basins might be smaller than 10 km^2 (Pilgrim et al 1988).

Two studies have focused on the techniques of optimizing the number and location of rain gauges (Manik and Sidle 2003; Tarawneh and Kadioglu 2003). Comprehensive surface hydrology studies including rainfall characteristics with respect to temporal and spatial variability have been carried out in Jordan for the last decade. Some of these studies examined the changes of rainfall temporal patterns only; other cases analyze both spatial and temporal patterns.

In 2009, Momani analyzed the monthly rainfall temporal variation by applying ARIMA time series analysis to data recorded at the Amman airport. In order to achieve a proper rainfall forecast of his research, ARIMA model parameters were adjusted (Momani 2009).

Smadi and Zghoul (2006) examined the recent rainfall temporal trends and fluctuations for three meteorological stations, Amman, Madaba, and Al-Mafraq. They observed a direct interrelationship between rainfall levels at these stations.

Dahamsheh and Aksoy (2007) studied the structural characteristics of annual precipitation data for 13 meteorological stations distributed across Jordan and utilized the Isohyetal method to plot rainfall distribution. They employed a number of tests, such as consistency, randomness, best-fit distribution, and others in order to characterize the annual precipitation. There was no evidence of negative or positive precipitation trends at any station. However, these results can not be directly compared with previous studies.

Tarawneh and Kadiolgu (2003) selected seventeen meteorological stations corresponding to different climatic regions of Jordan in order to depict spatial monthly precipitation characteristics. The frequency amplitude, periodicity phase angle, and basic statistical parameters from the meteorological stations were calculated as steps of harmonic analysis of the precipitation. The results showed that the variance percentage of harmonic analysis is changing rapidly by moving to the east.

According to the results of local studies water harvesting is one possible future solution to capture and store rainfall in Jordan (Abu-Zreig et al 2000; AbuAwwad and Shatanawi 1997; Oweis and Taimeh 1995). In order to achieve highest efficiencies, a thorough knowledge of rainfall distribution is essential.

Spatial rainfall analysis requires a network of rain gauges or meteorological stations. The accuracy of spatial rainfall interpolation method depends on the density distribution and the distance between rainfall rain gauges. Frequently, rain gauge density is not sufficient in arid regions (Pilgrim et al 1988), leading to biased analyses of rainfall temporal and spatial distributions at the catchment scale. State-of-the-art techniques may solve this issue by matching precipitation data from ground-based rain gauges and high-resolution satellites in hybrid interpolation analysis.

Recently, a number of global precipitation systems have been developed to meet scientific demand, such as PERSIANN (Sorooshian et al 2000), Global Precipitation Climatology Project (GPCP) (Adler et al 2000; Huffman et al 2001; Xie et al 2003), and Multi-satellite Precipitation Analysis (TMPA) (Huffman et al 2007).

Global or near-global satellite datasets are important to identify temporal and spatial rainfall changes in arid regions. Global Satellite Mapping of Precipitation (GSMaP) is based on passive microwave radiometer data and has shown to be effective for accurately estimating rainfall rate in mm/h (Ushio et al 2009). GSMaP combines precipitation retrievals from polar-orbiting satellites and cloud motion vectors derived from infrared images. GSMaP_MVK+ uses four different types of satellite sensors as shown in table.B 1 and an algorithm combining the CMORPH technique and Kalman filter (Tian et al 2010).

Table.B 1| Input datasets to produce GSMaP_MVK+ from four different types of satellite sensors

Input data	**Sensor**	**GSMaP near-realtime system**	**GSMaP standard system**
Passive microwave radiometer	TRMM/ The Tropical Rainfall Measuring Mission (TMI)	NASA/GSFC Real-time Version	NASA/GSFC Standard Version
	Aqua/AMSR-E	JAXA/EORC	JAXA/EORC
	DMSP/SSMI(F13, 14, 15)	NOAA/NWS	Remote Sensing Systems
GEO Infrared radiometer	MTSAT, METEOSAT-7/8,GOES-11/12	Globally-merged pixel-resolution data by JWA	Globally-merged pixel-resolution data by GSFC/DAAC
Atmospheric information	---	JMA Global Analysis (GANAL) Real-time Version	JMA Global Analysis (GANAL)
Sea Surface Temperature	---	JMA MGDSST	JMA MGDSST

The aim of this paper is to investigate rainfall characteristics of the Wadi Dhuliel catchment in northeastern Jordan by utilizing GSMaP data and ground based rain gauge data. Moreover, this study aims to develop a technique to adjust the GSMaP data by means of rain gauge data and standard interpolation techniques to perceive a good understanding of rainfall variability in arid regions, reduce the potential errors of rain gauge estimates, and produce improved catchment scale rainfall distribution maps.

2 Materials and methods

2.1 Study area description

The Wadi Dhuliel is an appropriate example of an arid catchment in which rainfall and rainfall intensity varies significantly both with with time and space. The total area of the Wadi Dhuliel is approximately 1985 km^2 and is located in northeast of Jordan. Most of the catchment area belongs to the Al-Zarqa river basin. Around 10% of the upper part of Wadi Dhuliel catchment passes over the Syrian border (Figure.B 3). The altitude in the area is characterized by a very gentle undulating topography varying between 512m in the southwest to 1400m in the north.

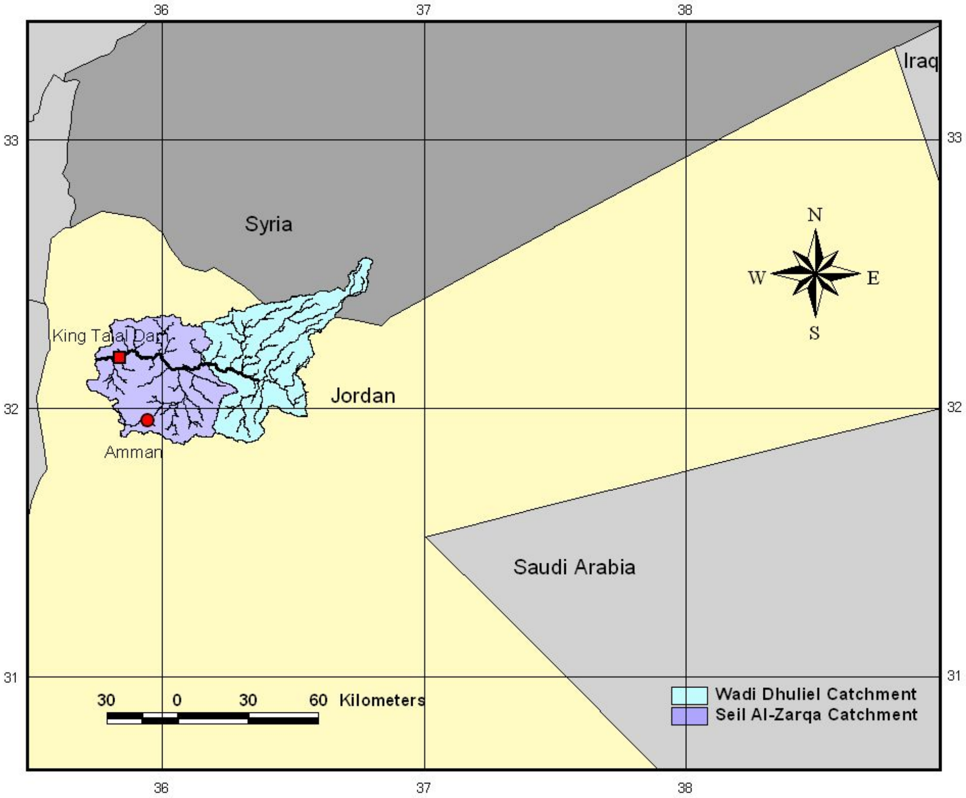

Figure.B 3| Study area location map of Al-Zarqa basin including the sub-basins Seil Al-Zarqa and Wadi Dhuliel.

Rainfall temporal magnitude in the Wadi Dhuliel tends to vary markedly from year to year with an irregular distribution over the year. As an example of the extreme yearly variability in Wadi Dhuliel one rain gauge measured the annual rainfall to be 275.7, 93.1, 111.1, 230.4, 194.8, 63.1, and 209.5 mm over seven years. In one single day, a 62 mm rainfall event occurred, though the total annual rainfall in the same year was 100 mm (Sukhnah rain gauge). These kinds of rainfall events can easily generate significant surface runoff, resulting in severe soil erosion. Weather behaviour and topographical aspects play important roles in this variation.

The region has essentially an arid climate with cold, rainy winter and a hot, dry summer. The average monthly rainfall showed that around 73% of the annual rainfall occurs during November, December, January, and February (Figure.B 4).

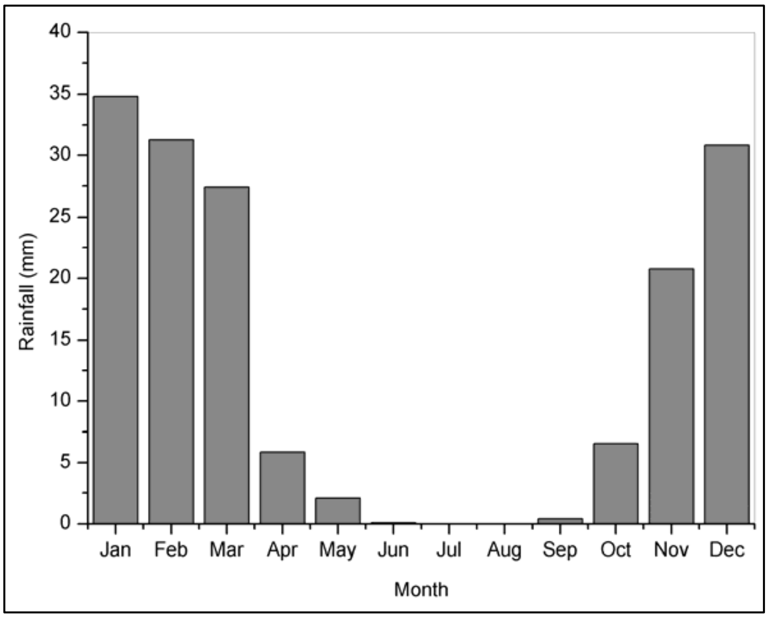

Figure.B 4| Monthly average rainfall (1976-2005)

Almafraq station has the highest rainfall magnitudes per annum with 158mm, Qasr Al-Hallabat station has the lowest rainfall with 79.2mm. Overall, the annual rainfall is around 123mm on average. In addition, the lowest temperatures are also during the winter months, with an average annual temperature (1976-2005) of 16.8 ºC (Figure.B 5).

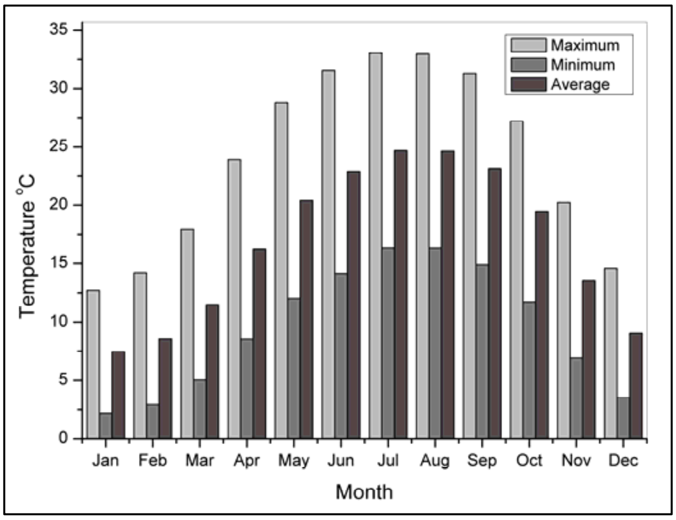

Figure.B 5| Monthly average of the minimum and maximum temperature (1976-2005)

2.2 Data and method of data analysis

The datasets used in this work included ground rainfall data of nine gauging stations at daily, monthly, and annual time steps between January 2003 and March 2008. A complementary Global Satellite Mapping of Precipitation dataset, currently known as GSMaP_MVK+ version 4.8.4 (short for GSMaP moving vector with Kalman filter method), was also examined.

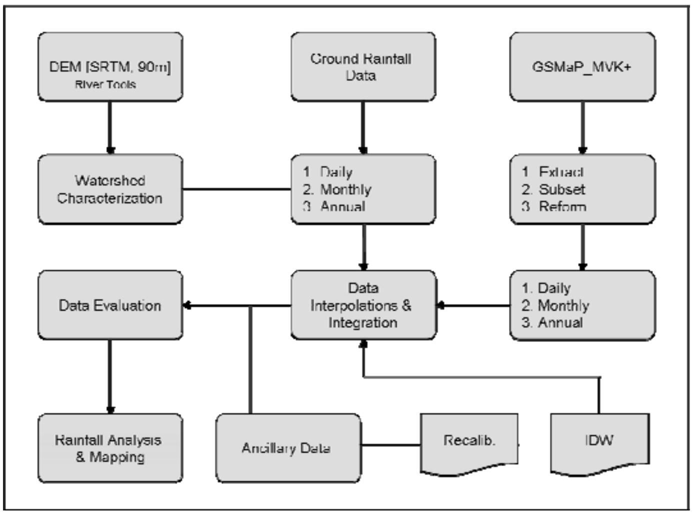

Figure.B 6| Research process flowchart

The rain gauges dataset (Table.B 2) was gathered from the Surface Water Resources Unit at the Jordan Ministry of Water and Irrigation (JMWI), and the Jordan Meteorological Department (JMD). Eight rain gauges are distributed in and near to Wadi Dhuliel I, and one station is located in Wadi Dhuliel II (Figure.B 7). Almafraq meteorological station has records only until 2005. However, only these nine stations produced a sufficient length of reliable data appropriate for this study.

Table.B 2| Information about meteorological and rain gauging stations utilized for the study

Station code on the map (Figures.B 3 and 7)	Station code (*JMWI)*	Station name	Altitude [above M.S.L. in meters]	Data type	Mean annual rainfall [mm]
A	AL0058	Sabha and Subhiyeh	843	Monthly and daily	109.3
B	AL0059	Um-Jimal*	670	Monthly and daily	110
C	AL0048	Al-Khaldiya	600	Monthly and daily	123.9
D	AL0055	Wadi Dhuliel Nursery	580	Monthly and daily	130.3
E	AL0049	Qasr Al-hallabat	590	Monthly and daily	72.4
F	AL0054	Hashimiya	566	Monthly and daily	135.3
G	AL0066	Khirebit Es Samra Evap. St.*	564	Monthly and daily	131.9
H	No code	Almfraq	675	Monthly	158
I	No code	Mafraq_60*	675	Hourly	143

[*] Meteorological station

The Global Satellite Mapping of Precipitation (GSMaP) project started in 2002 with support of the Japan Science and Technology Agency (Ushio et al 2009). A frame from 31.95^{o}N - 32.55^{o}N and 36.15^{o}E – 36.85^{o}E was extracted from the GSMaP_MVK+ dataset to cover the entire Wadi Dhuliel catchment area with 64 knots (8×8) and a spatial resolution of 10.8 km (Figure.B 7). Based on the altitudes, rainfall magnitudes, and land cover characteristics, the area was divided into two distinct sub-catchments Wadi Dhuliel I and Wadi Dhuliel II.

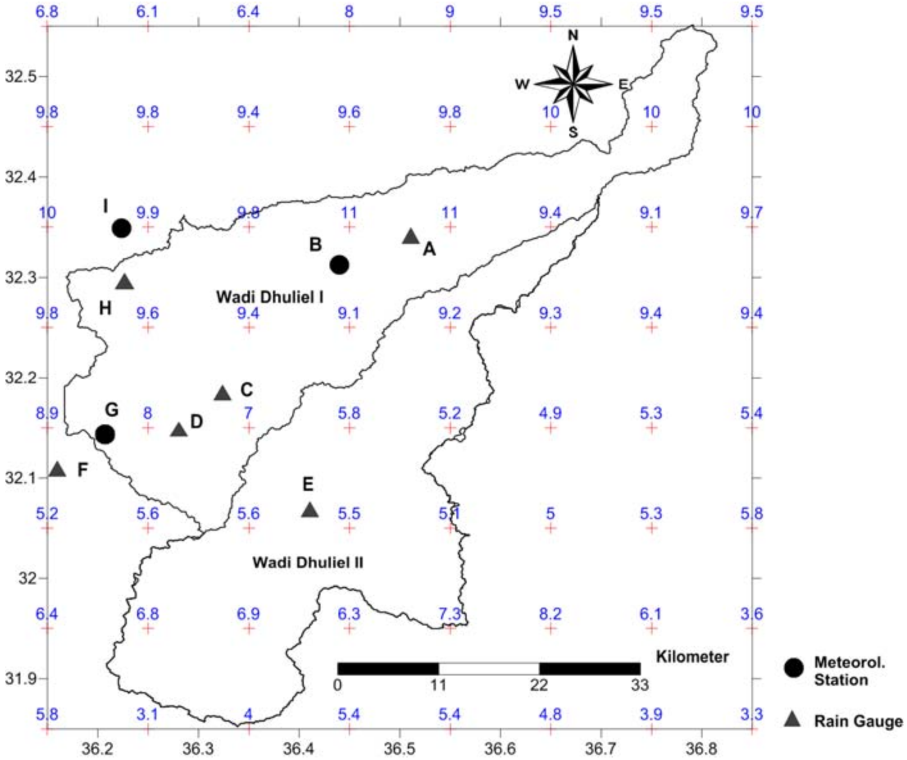

Figure.B 7| The GSMaP_MVK+ pixels distribution around and over Wadi Dhuliel catchment (Rainfall mm/month, [January 2003])

Rainfall ground dataset was based upon the acquisition period of GSMaP_MVK+ data, from January 2003 to April 2008. In order to assess at which time scale the GSMaP_MVK+ estimates have sufficient match, the daily datasets from the GSMaP_MVK+ and ground rain gauging station were aggregated to monthly and annual records.

For the comparison between ground rain gauges and GSMaP_MVK+ datasets values of all ground rain gauge station were calculated from the four neighbouring GSMaP_MVK+ knots using inverse distance weighting (IDW) interpolation method.

2.3 Satellite measurements adjustment with rain gauges

Since the GSMaP_MVK+ algorithm has been developed for precipitation over tropical and subtropical regions (Iwasaki 2009); ground observations are required to adjust the satellite information. Furthermore, the input data to the GSMaP_MVK+ is based upon brightness temperature and cloud microphysical properties, and therefore gives relatively indirect information about rainfall rate. This adjustment process is needed to tune the residuals between local observation datasets and GSMaP_MVK+ estimates.

The adjustment process was based on remapping GSMaP_MVK+ pixel values with respect to rain gauge observations. Datasets from three meteorological stations were used to adjust GSMaP_MVK+ dataset. Khirebit Es Samra and Um-Jimal meteorological stations provide monthly rainfall, temperature, and wind speed data sets from 2003 and 2008, while Mafraq_60 meteorological station provides 1-hourly rainfall, temperature, and relative humidity records for the period between 2004 and 2006. Unfortunately, some hourly records are missing from Mafraq_60 meteorological station. As observed from Mafraq_60 station, most of the rain events are related to low temperature and high relative humidity (Figure.B 8 and table 3).

Furthermore, a significant correlation between rainfall, temperature and relative humidity (RH) was observed. The Spearman correlation coefficient (rho) between hourly temperature and rainfall rate is -0.28 (two tailed P =0.48), while Spearman’s rho is 0.089 (two tailed P=0.026) between rainfall rate and RH. Hourly wind speed records have also a positive correlation coefficient with rainfall records but not significant (rho =0.122, two tailed P =0.002). However, some anomalous satellite pixel values are detected and skipped from the adjustment process.

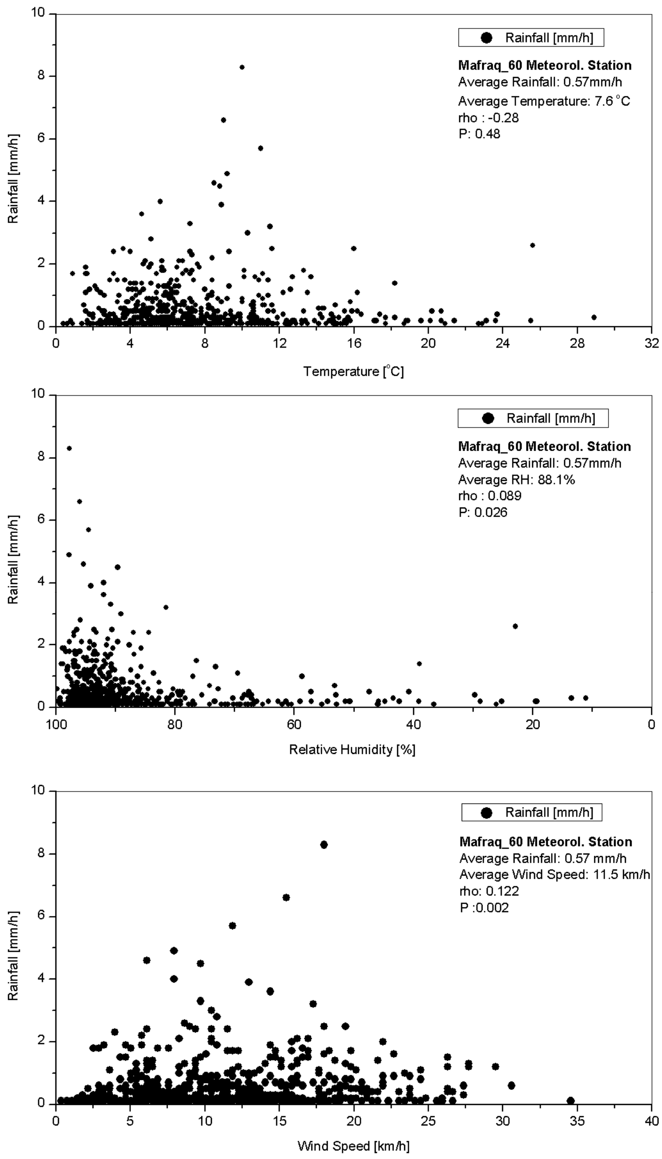

Figure.B 8| Comparison between hourly rainfall rate with air temperature, relative humidity and wind speed from Mafraq_60 meteorological station (2004-2006)

The next step towards adjustment is to aggregate 1-hourly dataset into daily, monthly, and annual datasets. For this the daily rainfall rates have been categorized into three groups: (i) Light 0.1-1.0 mm/day (ii) Moderate 1.1-5.0 mm/day, and (iii) Heavy >5.0 mm/day. Zero values from both ground gauges and GSMaP_MVK+ were excluded. Consequently, GSMaP_MVK+ pixel estimates were compared to daily and monthly ground rain, temperature, wind speed, and relative humidity (Figures.B 9 and 10). The comparison shows three groups:

1. GSMaP_MVK+ estimates matched the rain ground records rather fairly
2. GSMaP_MVK+ values are underestimates
3. GSMaP_MVK+ values are overestimates

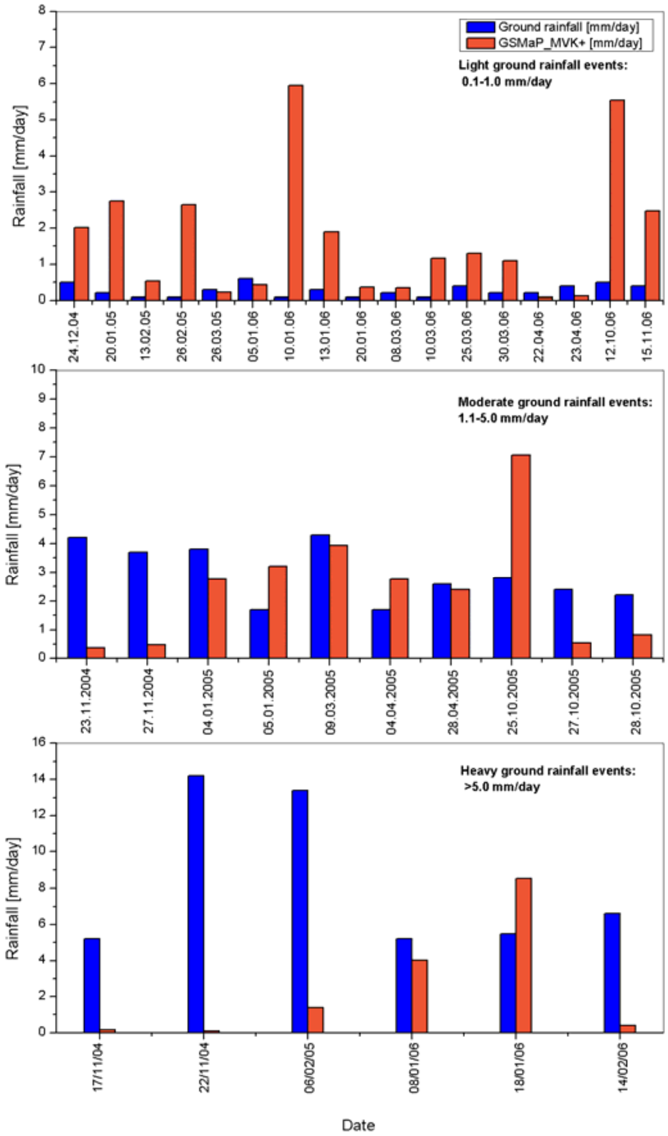

Figure.B 9| The daily rainfall rates at the ground and their estimates by GSMaP_MVK+ from Mafraq_60 (2004-2006)

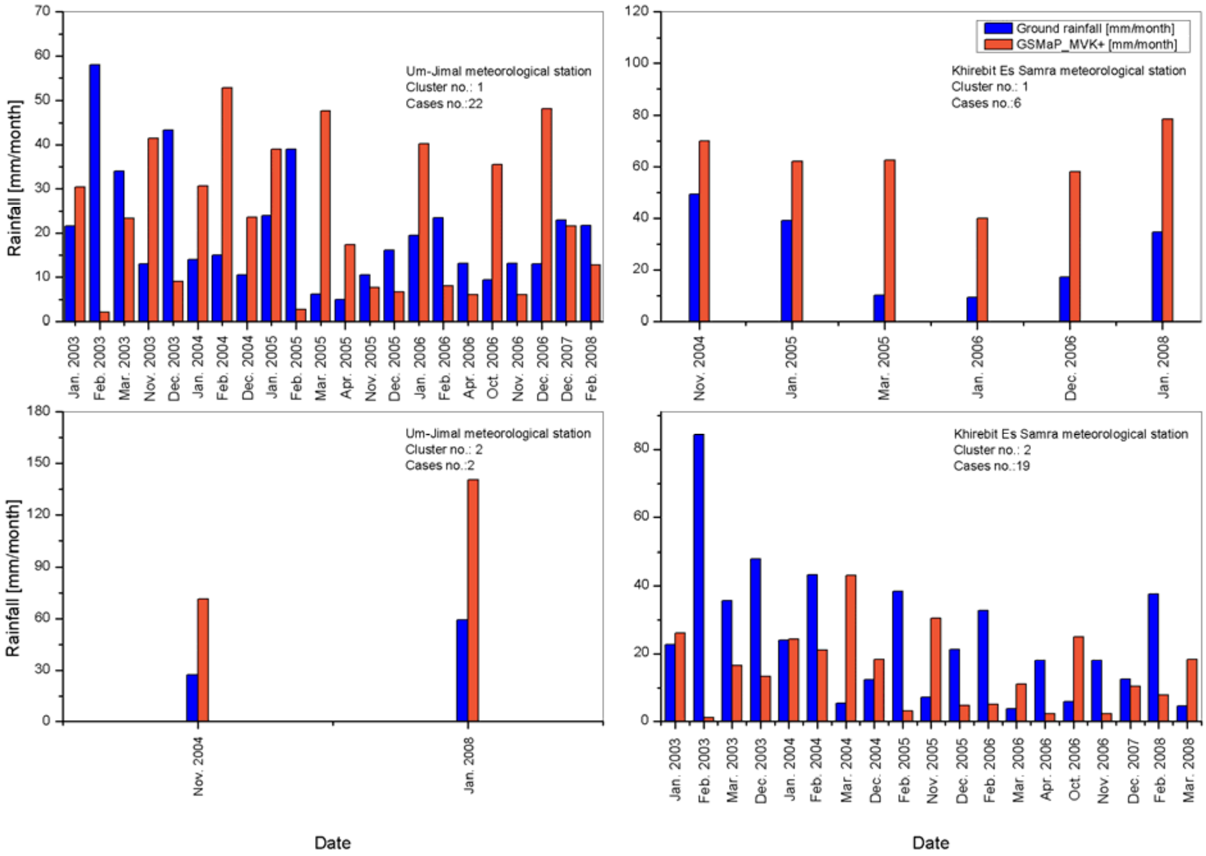

Figure.B 10| The monthly rainfall rates monitored at ground and their estimates by GSMaP_MVK+ from Um-Jimal metrological station (Left) and Khirebit Es Samra metrological station (Right) (2003-2008)

In order to categorize monthly rain events into groups of similar trajectories K-means clustering was applied (Tables.B 3 and 4). The aim of this categorization was to assess the effect of external variables on rainfall rates to GSMaP_MVK estimates, air temperature, and wind speed records. The events with totals less than 2mm/month were excluded.

Table.B 3| K-means cluster analysis of monthly air temperature, wind speed, and GSMaP_MVK+ for Um-Jimal metrological station (2003-2008)

Variable	Cluster No 1*	Cluster No 2**	Std. Deviation [Cluster1]	Std. Deviation [Cluster2]
Average Temperature [°C]	11.3	10.0	3.56	6.4
Wind Speed [km/h]	9.3	5.54	5.54	1.6
GSMaP_MVK+ [mm/month]	23.3	105.9	16.6	48.8

* The number of cases in cluster number 1 is 22
** The number of cases in cluster number 2 is 2

Table.B 4| K-means cluster analysis of monthly air temperature, wind speed, and GSMaP_MVK+ Khirebit Es Samra metrological station (2003-2008)

Variable	Cluster No 1*	Cluster No 2**	Std. Deviation [Cluster1]	Std. Deviation [Cluster2]
Average Temperature [°C]	10.77	13.3	3.52	2.87
Wind Speed [km/h]	2.5	2.7	1.17	0.9
GSMaP_MVK+ [mm/month]	86.45	15.6	12.92	20.1

* The number of cases in cluster number 1 is 6
** The number of cases in cluster number 2 is 19

Multiple linear regressions (MLR) method was carried out to estimate convective and stratiform rain rates from GSMaP_MVK+ among temperature, relative humidity, and wind speed of daily and monthly records. The relationship between the ground rainfall records and the explanatory variables is represented for each station by the following equations:

1. The MLR model for Mafraq_60 meteorological station daily records:

$$Rf_{Light} = GSMaP \times 0.012 + Temp \times 0.023 + RH \times 0.002 - C_1 \qquad \text{(Equation 1)}$$

$$Rf_{Moderate} = GSMaP \times 0.027 - Temp \times 0.068 + RH \times 0.01 + C_2 \qquad \text{(Equation 2)}$$

$$Rf_{Heavy} = -GSMaP \times 1.7 + Temp \times 1.03 + RH \times 0.99 - C_3 \qquad \text{(Equation 3)}$$

Where Rf_{Light} stands for the rainfall rate between 0.1-1.0 mm/day, $Rf_{Moderate}$ is the rainfall between rate between 1.1- 5.0 mm/day, Rf_{Heavy} is the rainfall rate more than 5.0 mm/day, *GSMaP* is the GSMaP_MVK+ estimates version 4.8.4 recorded in mm/day, Temp is the temperature records in Celsius degree, RH is the relative humidity in percentage, C_1 is the Rf_{Light} constant and equal to 0.164, C_2 is the $Rf_{Moderate}$ constant and equal to 4.46, and C_3 is the Rf_{Heavy} constant and equal to 71.8.

2. The MLR model for Um-Jimal meteorological station monthly records:

$$Rf_{cluster1} = -GSMaP \times 0.29 - Temp \times 1.85 + WS \times 1.008 + C_{cluster1} \qquad \text{(Equation 4)}$$

$$Rf_{cluster2} = -GSMaP \times 3.53 + C_{cluster2} \qquad \text{(Equation 5)}$$

Where $Rf_{cluster1}$ stands for the rainfall rate in mm/month for the first group of cluster, $Rf_{cluster2}$ is the rainfall rate in mm/month for the second cluster, and $C_{cluster1}$ is the first cluster constant and equal to 38.8, $C_{cluster2}$ is the second cluster constant and equal to 78.42, and *WS* is wind speed in km/h.

3. Monthly records of Es Samra meteorological station:

$$Rf_{cluster1} = GSMaP \times 1.03 + Temp \times 1.86 - WS \times 5.13 - C_{cluster1} \qquad \text{(Equation 6)}$$

$$Rf_{cluster2} = -GSMaP \times 0.64 - Temp \times 2.77 + WS \times 5.12 + C_{cluster2} \qquad \text{(Equation 7)}$$

Where $C_{cluster1}$ is equal to 44.2 and $C_{cluster2}$ is equal to 56.1

Then, the MLR equations were chosen from all these combination to adjust GSMaP_MVK+ estimates:

$$GSMaP\_MVK_{recalibrated} = GSMaP\_MVK_{original} \pm (GSMaP\_MVK_{original} \times RE)$$

(Equation 8)

RE is the relative error and can be determined by using the following equation:

$$RE\% = (Rf_{recalibrated} - GSMaP\_MVK_{original}) / GSMaP\_MVK_{original} \qquad \text{(Equation 9)}$$

In order to measure the reliability of simulated values the bias calculation assesses the average difference between GSMaP_MVK+ and ground rain gauges:

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(GSMaP\_MVK_{recalibrated} - Gauge)$$

Where $GSMaP\_MVK_{recalibrated}$ is the GSMaP_MVK+ estimates after the adjustment process at the station location, $Gauge$ is the observed rainfall ground. N is the number of elements.

3 Results

Using the available weather records between 2003 and 2008 from nine meteorological and rain gauge stations over the Wadi Dhuliel complementary with GSMaP_MVK+ rainfall data showed a complex rainfall pattern in the Wadi Dhuliel.

The evaluation of daily and monthly GSMaP_MVK+ datasets exhibited good performance in capturing relative values of rainfall pattern but poor results with respect to estimating the absolute values of the rainfall. The comparison of daily and monthly GSMaP_MVK+ and ground records showed significant under- and overestimations in both spatial and temporal distributions. Separate from cases where GSMaP_MVK+ and ground records are correlated, in general GSMaP_MVK+ records showed overestimation. Daily records of the GSMaP_MVK+ are showing 84% overestimation while in monthly records it is 59%. Most of the annual rainfall magnitudes of GSMaP_MVK+ were overestimates (85.7%); only the year 2003 exhibited correlation (Table.B 5).

Table.B 5| Annual rainfall of GSMaP_MVK+ compared to 8 ground rain gauge stations

Data Type	Date	Hashimiya	Khirebit Es-Samra	W. Dhuliel Nursery	Um El-Jumal
GSMaP	2003	114.02	136.44	125.71	162.08
Ground Record		184.2	194	138.9	172.8
GSMaP	2004	365.44	400.99	396.99	597.43
G Record		114.6	130	85.4	74.2
GSMaP	2005	232.68	256.72	231.26	455.99
Ground Records		122.9	124	86.2	105
GSMaP	2006	321.61	334.07	308.5	367.56
Ground Records		102.8	86.8	97.5	79.2
GSMaP	Dec-07*	10.04	10.4	9.65	21.58
Ground Records		14	12.6	8.5	23
GSMaP	2008	112.35	109.03	123.22	181.09
Ground Records		77.7	77	46.8	83
Data Type	Date	Khaldiya	Sabha and Subhiyeh	Qasr El-Hallabat	Al-Mafraq
GSMaP	2003	127.37	161.7	80.43	162.95
Ground Record		143.9	146.9	40.8	54.6
GSMaP	2004	374.49	567.42	295.48	385.96
G Record		91.5	86.7	74.7	105.7
GSMaP	2005	248.58	412.07	153.67	466.42
Ground Records		100.7	97.1	69.7	123.7
GSMaP	2006	309.86	361.51	311.34	396.41
Ground Records		99.3	96.8	47	NA
GSMaP	Dec-07	11.46	20.8	10.24	20.5
Ground Records		8.5	16.5	6	NA
GSMaP	2008**	124.68	164.18	120.67	122.7
Ground Records		62	105.1	30.4	NA

* The available month from 2007 is December only

**Jan, Feb, and March in 2008 have no error estimates

In order to match GSMaP_MVK+ values in all cases within some acceptable error, an adjustment was performed based on ground data based on multiple linear regressions. For daily time step, MLR equations were calculated for Mafraq_60 meteorological station and derived from temperature and relative humidity records as well as from GSMaP_MVK+ daily estimates. Clustering rain events into light, moderate, and heavy storm helped to reduce the relative error. For monthly time step, explanatory variables used to develop MLR equations were calculated from two meteorological stations: Um-Jimal and Khirebit Es Samra. Here, the MLR equations derived from temperature and wind speed records as well as from GSMaP_MVK+ monthly estimates.

Unfortunately monthly relative humidity is not available for these two stations. If the relationship between variables is not clear, clustering of monthly rainfall to groups with respect to the variation of temperature, wind speed, and GSMaP_MVK+ estimates is a primary step to develop MLR models. The results of daily and monthly rainfall rates including under- and overestimates corresponding to each meteorological station after the calibration process are shown in Figures.B 11 and 12. The results showed good agreement between adjusted rainfall rates with ground station observations. The Spearman's correlation coefficient between adjusted and observed values for daily records shows significant correlation. The heavy storm events correlation coefficient was 0.75 (P =0.084), while for light and moderate storm events rho was 0.62 (two tailed P =0.008) and 0.66 (two tailed P =0.071), respectively. This may reflect the effect of extreme rain rates on Spearman's correlation coefficient.

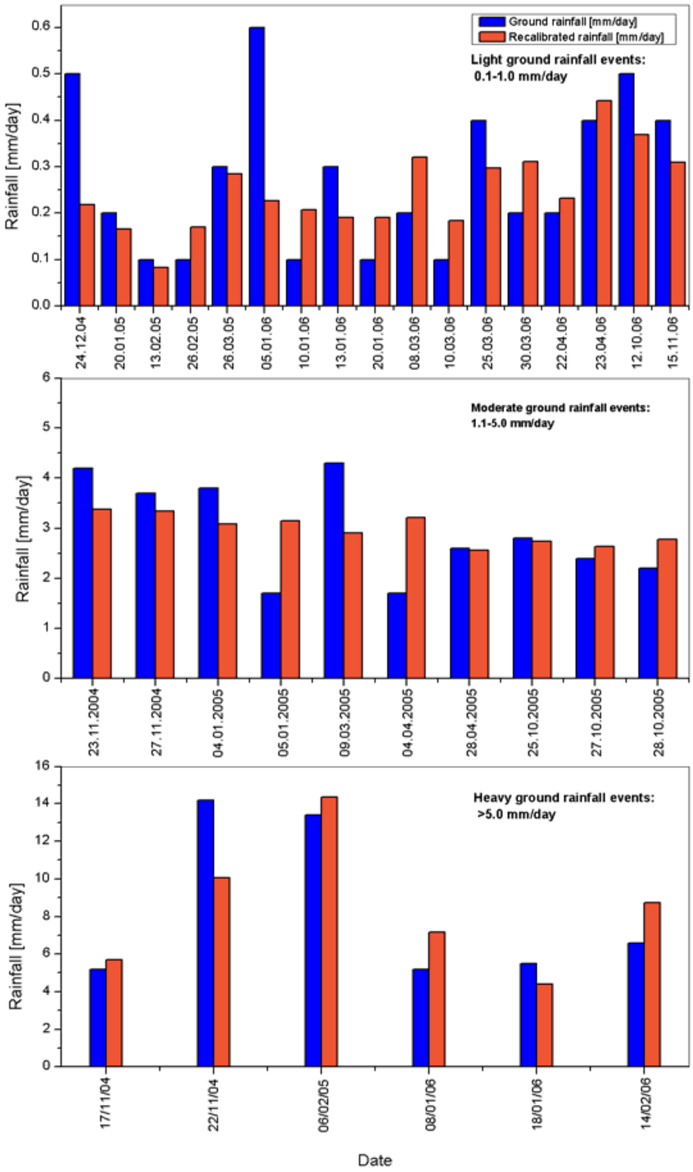

Figure.B 11| Comparison between daily adjusted rainfall rates from Temperature, relative humidity, and GSMaP_MVK+ records with ground rainfall rates obtained from Mafraq_60 meteorological station (2004-2006)

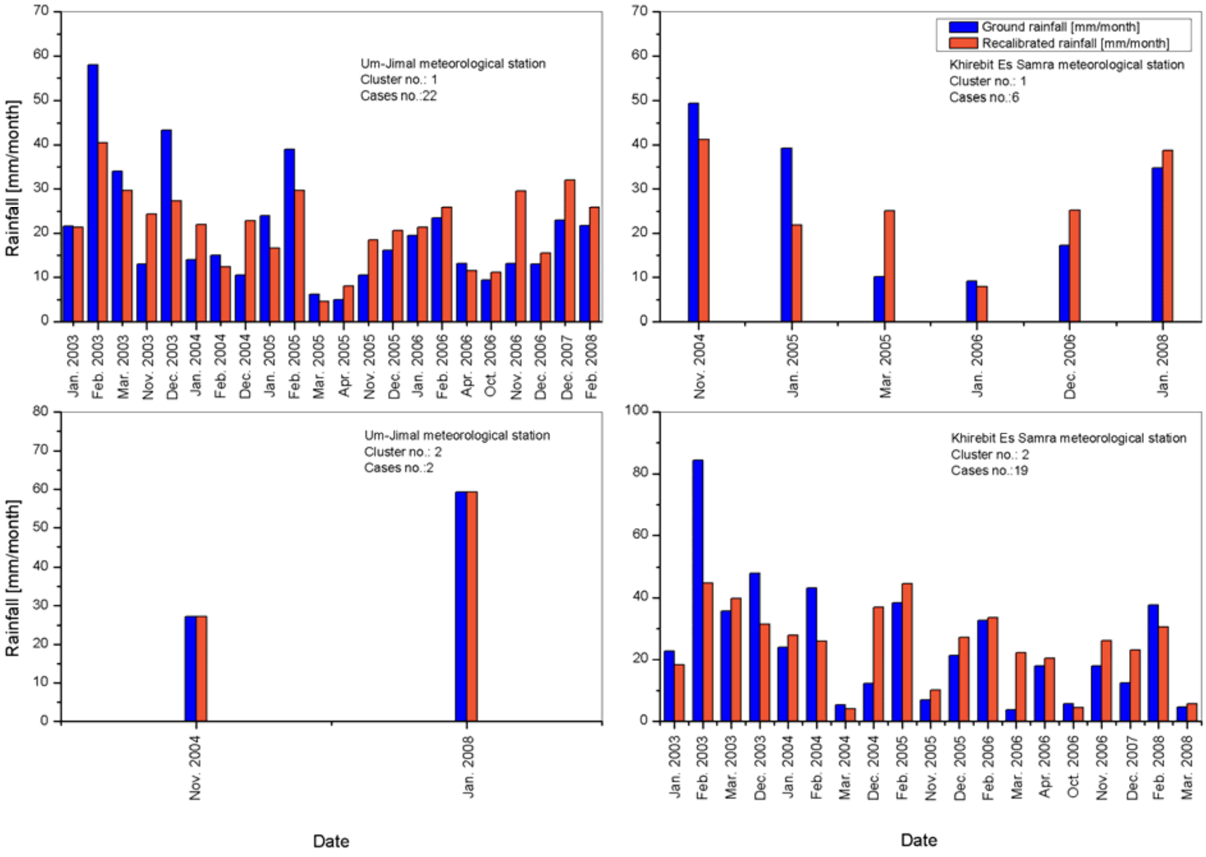

Figure.B 12| Comparison between monthly adjusted rainfall rates from Temperature, wind speed, and GSMaP_MVK+ records with ground rainfall rates obtained from Um-Jimal metrological station (Left) and Khirebit Es Samra metrological station (Right) (2003-2008)

Spatial rainfall analysis was based on Inverse Distance Weighting (IDW) interpolation method. Daily results included one meteorological station (Mafraq_60) and seven rain gauges. The MLR model was carried out for Mafraq_60 meteorological station and extended to the daily GSMaP_MVK+ pixel values (equations 8 and 9). Adjusted daily GSMaP_MVK+ performed well in capturing the spatial patterns of the rainfall distribution, and showing more details especially on extreme rainfall events, while some weakness in light and moderate storms spatial distributions (Figure.B 13).

The MLR model was computed for monthly records acquired from Khirebit Es Samra and Um-Jimal meteorological stations for the time between 2003 and 2008. For ground interpolation, six other rain gauges were also used. The adjustment of GSMaP_MVK+ was primarily based on the average of equations 8 and 9 calculated from both stations. The MLR model monthly rainfall estimates were found to be more reasonable than estimates obtained using daily MLR.

The evaluation of spatial patterns shows that monthly GSMaP_MVK+ does well in capturing the topographic effect on precipitation distribution pattern, in particular for the west-east and north-south precipitation gradients (Figure.B 14). A key outcome of the spatial and temporal analyses is the advantage of aggregating the fine scale data to coarser resolution (Figure.B 15).

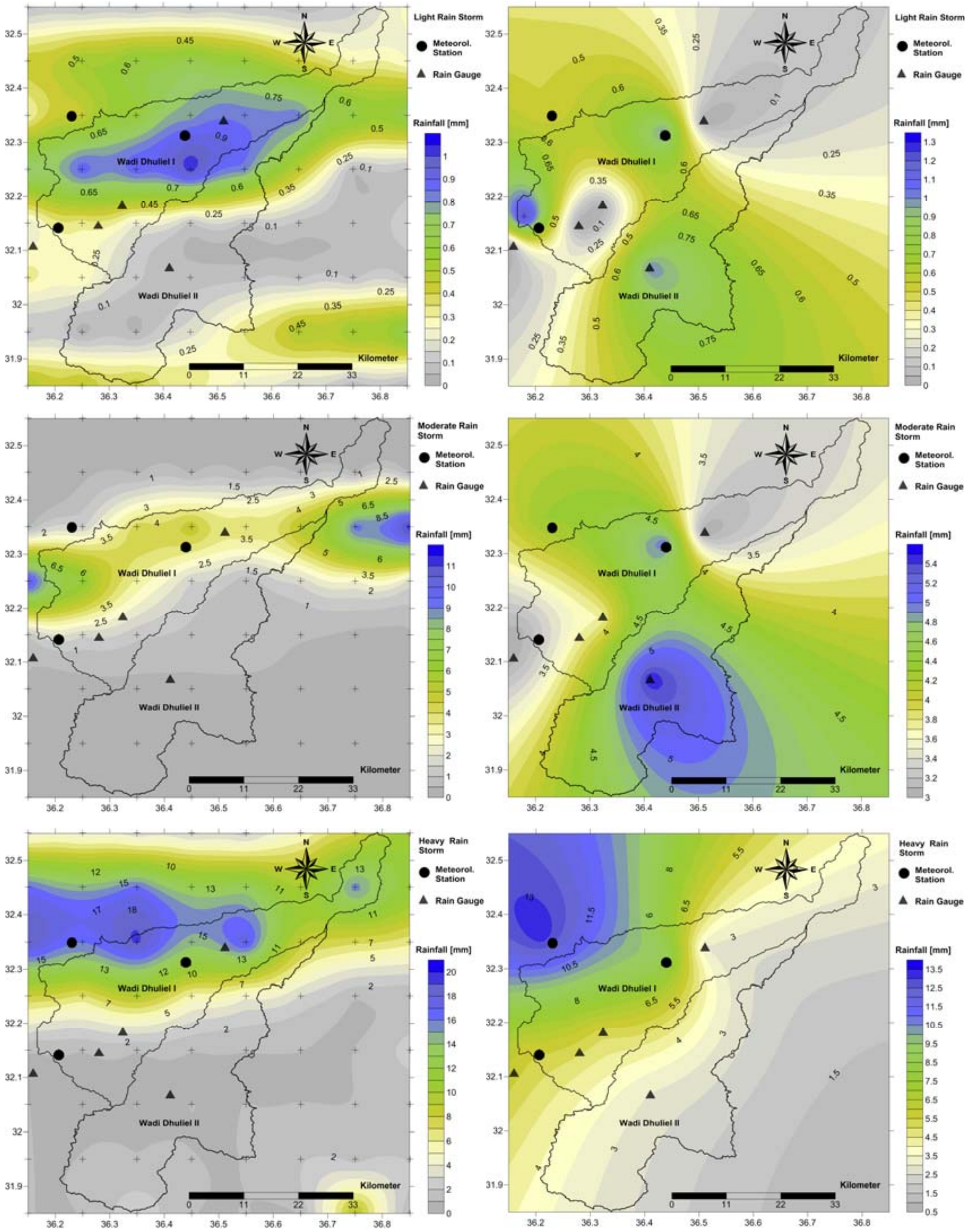

Figure.B 13| Spatial comparison of daily rainfall between re-calibrated GSMaP_MVK+ estimates (Left) and eight ground rainfall station records (right) using IDW method, light storm in 24.12.2004, moderate storm in 09.03.2005, and heavy storm in 06.02.2005

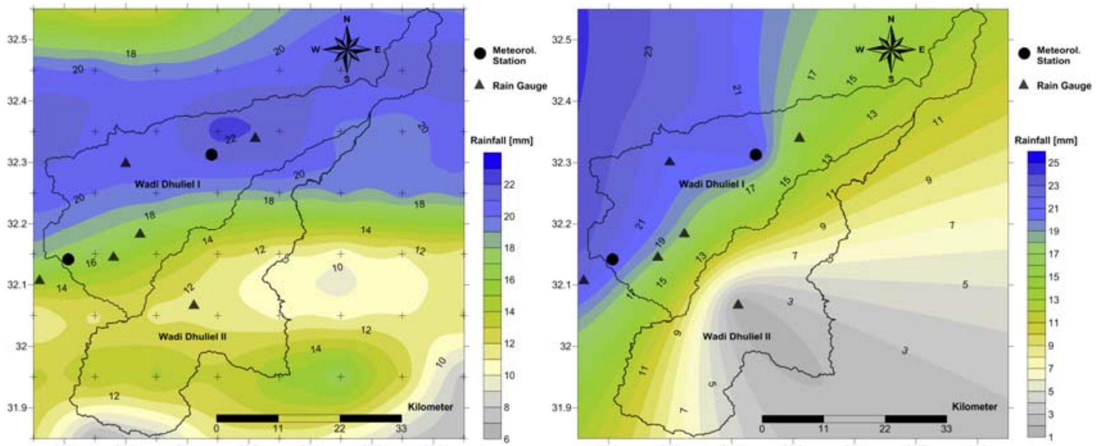

Figure.B 14| Spatial comparison of mean monthly rainfall between adjusted GSMaP_MVK+ estimates (Left) and eight ground rainfall stations records (right) using IDW method, an example from January 2003

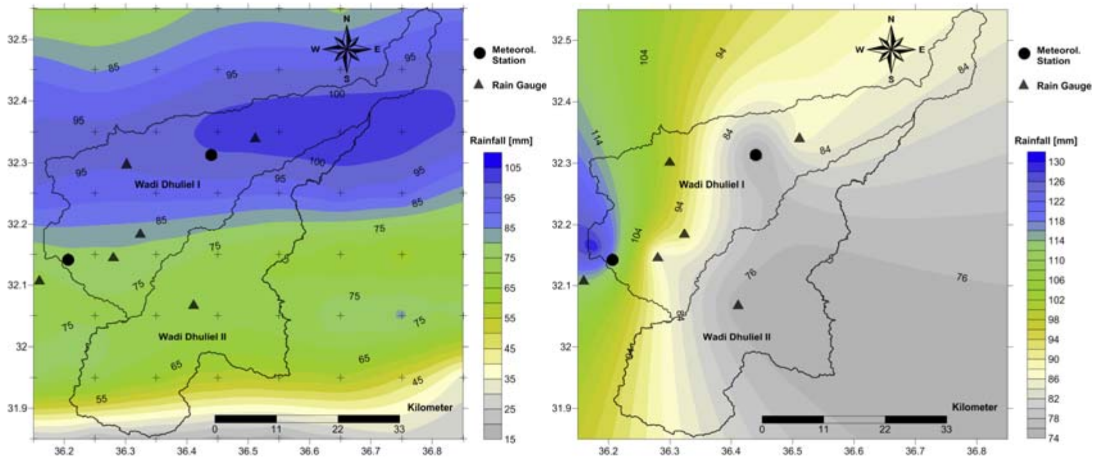

Figure.B 15| Spatial comparison of average annual rainfall between adjusted GSMaP_MVK+ estimates (Left) and eight ground rainfall stations records (right) using IDW, an example from 2004

4 Discussion

Drawing conclusions from two disparate datasets may improve the quality of the combined data. Due to the sparseness of the rain gauge networks, interpolated data often are biased by the interpolation algorithms. In some cases, the ground rainfall gauges reveal slight homogeneity of rainfall magnitudes but the spatial distributions are, in general, heterogeneous. Furthermore, the number of stations and the length of historical records affect both spatial and temporal correlation structures. The results of this study are in agreement with previous works which showed that the characteristic of rainfall in arid catchment varies in space and time (Abu-Zreig et al 2000; Lange et al 2000; Pilgrim et al 1988). Overall, GSMaP_MVK+ showed the best performance in comparison with other satellite products. This conclusion has been proven by several authors (Dinku et al., 2010a; Dinku et al., 2010b; Iwasaki, 2009; Ushio et al., 2009).

The results of (Dinku et al 2010a; Dinku et al 2010b; Iwasaki 2009; Ushio et al 2009) motivated us to use the GSMaP_MVK+ in our study. Results of GSMaP_MVK+ were crosschecked against nine rain gauges observations assuming to represent reasonable and reliable point data. The compatibility between GSMaP_MVK+ and the ground rain gauges was limited to specific months. The over- or underestimation of the GSMaP_MVK+ in estimating rainfall in arid regions may be influenced by the following factors:

a) The sensors detected the rainfall aloft, meaning the rain may have evaporated before reaching the ground (Dinku et al 2010a; Rosenfeld and Mintz 1988).
b) The moving vector Kalman filter algorithm was developed for precipitation over the tropical and sub-tropical regions (Iwasaki 2009) using IR data as a means to move the precipitation estimates from microwave observation during

periods when microwave data are not available. Obviously this estimate does not work always properly in arid areas.

c) The available GSMaP_MVK+ product was originally calibrated using ground based radar data located in tropical and sub-tropical regions of Japan, which may have different weather regime or covered by different cloud systems (Petty 2001) than in arid regions.

d) An abrupt change in wind speed or wind direction below the cloud may have affected the rainfall area. A study conducted in Israel and Jordan by Sharon (1978) showed that the expansion of rainfall area may not be fully represented by point measurements. An increase of 10 km/h would constitute 12-15% of total rainfall.

e) The rainfall duration varied from storm to storm. The rainfall storm over the study area was characterized by high rainfall intensity (Figure.B 16). This, however, might have occurred at the time when no satellite was overhead.

f) Desert dust and other aerosols may suppress rainfall and alter cloud microphysical properties (Han et al 2008; Rosenfeld et al 2001). The desert dust above and in the cloud could have distorted the satellite measurements (Rosenfeld et al 2001). However, most of the previous related studies were usually based on homogenous water cloud models(Schutgens and Roebeling 2009).

Generally, there is no doubt that remote sensing capability to monitor rainfall is still under development and has -in particular- some weaknesses related to arid regions application. However, there are on-going projects to improve the correlation between Satellite based rainfall retrieval algorithms and the real rainfall magnitudes (e.g. The Wet-Net Precipitation Inter-comparison Project, and the NASA GPM

Project). As previously explained, it was seen that GSMaP_MVK+ over the Wadi Dhuliel arid catchment exhibited poor performance in compare with ground data. Therefore, developing a new framework to re-adjust the GSMaP_MVK+ data by means of ground data and standard interpolation techniques was logically necessary. This new concept has caught our attention in order to achieve a reasonable representation of the true rainfall distribution.

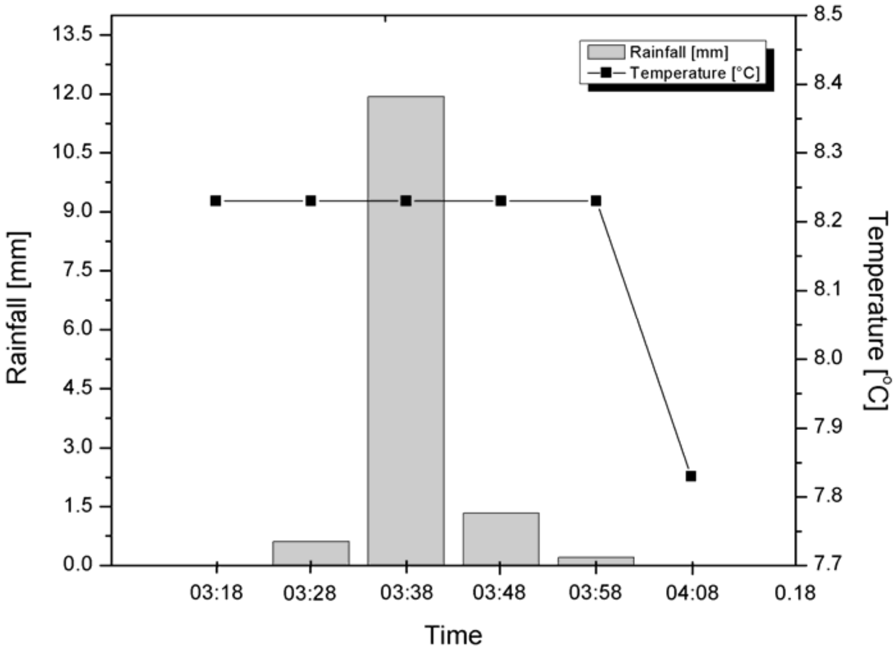

Figure.B 16| The duration of a single storm event recorded at 10 minute intervals (25.12.2008)

Precipitation in this area is very spotty in both time and space. The datasets in figure.B 16 were obtained from our station which was newly installed in the study area. In addition, global warming increases the rainfall variability and change the rain form at global and regional scales, moreover, might cause extreme events. A study made by Abushandi and Merkel (2011) showed that the study area received unusual snowstorm in 1990. This snowstorm might give an indicator of global warming crossing the Wadi Dhuliel arid catchment. Since rainfall is highly fluctuated in arid regions, the rising of temperature gradients is pretty much obvious than the rainfall variability. However, studying the impact of climate change on rainfall variability from space requires longer period datasets.

We are fully aware of the uncertainties associated with satellite derived rainfall maps and the original calibration from ground radar. Therefore an adjustment process for GSMaP_MVK+ results was needed to achieve better match with ground observations in arid regions. Multiple linear regression analysis proved to be an appropriate technique using additional weather data. As expected, rainfall events showed higher intensities in the western parts, while eastern parts are characterized by lower rainfall rates.

In some cases the rainfall distribution did not show the west-east gradient, as can be seen in the Appendix. This may be related to climatic and topographic variations. The high-resolution GSMaP_MVK+ dataset allowed us to evaluate and estimate the amount of rainfall in regions where no ground rainfall stations were available. Thus, the gridding interpolation method provided a qualitative view of the rainfall distribution. However, it is important to note that the interpolation technique explicitly derived new spatial values based on the number of present rain gauges, and, if the number of the gauges is limited, the unknown points may not be interpolated properly.

Allowance for other weather variables such as radiation, evaporation, and would improve the accuracy of Global Satellite Mapping of Precipitation estimates. Furthermore, employing other satellite and aircraft observation for retrieving clouds properties may enhance our understanding of the microphysical impact of aerosols on water clouds. However, the quality of this rainfall analysis will be affected by paucity of data in the region.

In this study, an attempt was made to apply a multiple linear regression (MLR) model to derive the relationship between rainfall and GSMaP_MVK+ in conjunction with temperature, relative humidity, and wind speed. The application of MLR seems to do consistently well under varying time scales. Since there is a very limited number of studies on using MLR in arid region, these results will confidently let us apply the MLR model in further research.

In a further research, a new framework of hydrological models application in arid catchment will be developed by integrating re-adjusted satellite derived rainfall dataset (GSMaP_MVK+) as an input dataset.

5 Conclusion

The climate in the Wadi Dhuliel area is characterized by high rainfall variability. Hence, it is difficult to estimate the spatial rainfall variability by a simple gridding method. Rainfall records from different rain gauges showed a complex rainfall regime in the area. Rainfall distribution in the Wadi Dhuliel varies with location mainly due to topographic variations as one move from semi-arid to arid regions. A Global Satellite Mapping of Precipitation dataset, currently known as GSMaP_MVK+ Version 4.8.4, was compared with eight rain gauge stations at monthly and annual time steps. The performance of GSMaP_MVK+ over arid regions in general and over the Wadi Dhuliel arid catchment in particular is limited and requires a re-adjustment process. The results showed how topographic variation can influence the rainfall distribution, especially in the northern part of the catchment. Higher rainfall rates in the western parts and the lower rainfall rates in eastern parts may explain the change in climate from arid area to desert area. Moreover, aggregating hourly rain rate into coarser time step, daily and monthly, will contribute to more accurate rain estimation.

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Appendix C

Abushandi E., Merkel B. (2011) Modelling rainfall runoff relations using HEC-HMS and IHACRES for a single rain event in arid region, Jordan. Water Resources Management Journal (Ready for submission)

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Abstract:

The HEC-HMS and IHACRES rainfall runoff models were applied to simulate a single streamflow event in the Wadi Dhuliel arid catchment occurring on 30./31.01.2008. The HEC-HMS model application was using the HEC-GeoHMS extension in ArcView 3.3. Streamflow estimation was performed on the basis of hourly scale. The aim of this study was to develop a new framework of rainfall-runoff model applications in arid catchment by integrating re-adjusted satellite derived rainfall dataset (GSMaP_MVK+) to determine the location of the rainfall storm. Each model has its own input data. HEC-HMS input data include soil type, land use/land cover , and slope. IHACRES input data sets include hourly rainfall and temperature. The model was calibrated and validated using observed stream flow data set collected at Al-Za'atari discharge station. The performance of IHACRES showed some weaknesses, while the flow comparison between the calibrated streamflow results fits well with the observed streamflow data in HEC-HMS model performance. The Nash-Sutcliffe efficiency (E_f) for both models was 0.51, and 0.88 respectively. The application of HEC-HMS model is considered to be satisfactory.

Keywords: *HEC-HMS, GIS, Arid regoin, Jordan, Wadi Dhuliel SCS-CN method;*

Introduction

Poor availability of hydrologic studies for the Wadi Dhuliel arid catchment in the northern Jordan leads to miss planning and inadequate water recourses management strategies not only at the catchment scale but also for the entire Al Zarqa Basin. Implementation of storm water management is essential in the Wadi Dhuliel to increase water availability especially for agriculture and livestock sectors. However, most of the existing water monitoring projects in Jordan are evaluated as lacking comprehensive hydrologic data or accessibility. Based on this fact, there is a growing realization of the importance of water management in Jordan from both scientists and politicians during the last decade (Abushandi and Merkel 2011b).

The water availability is the most vital factor controlling the economic growth in Jordan as a country based on agriculture and cropping (Figure.C 1). This situation drove the Jordanian government to implement new projects to provide Jordan with fresh water. The proposed Dead Sea - Red Sea canal project is one of these projects to produce hydro-energy, increase the level of Dead Sea to the state of 1960, and produce fresh water. The length of this channel would be about 325 km canal length (Beyth 2007; Hadadin et al 2010). The second proposed project is the exploitation of the Disi aquifer groundwater in the southern desert of Jordan by means of a 2000mm diameter pipeline with a length of 300 km to convey additional water (100×10^6 m^3y^{-1}) to Amman (Abu Qdais and Batayneh 2002). In addition, the government tries to enhance the use of treated wastewater for irrigation instead of groundwater. Moreover, water harvesting at the catchment scale is one of the solutions to increase water availability for agriculture (Abdulla et al 2002; Al-Adamat et al 2010; Alkhaddar et al 2005).

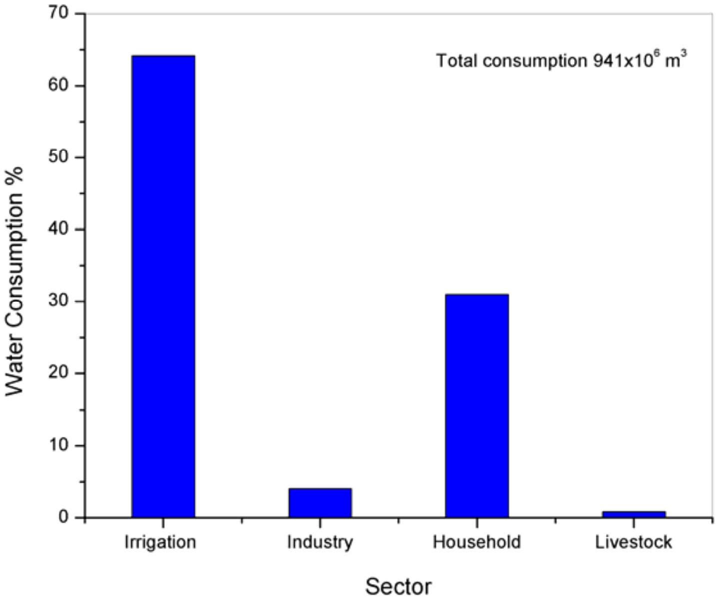

Figure.C 1 Water use percentage in Jordan (*Hadadin et al 2010*)

The Wadi Dhuliel arid catchment shares general arid regions characteristics, which can be summarized by:

(v) stream flow is characterized by flash flooding during high intensity rain events only, absence of base flow, and low flood frequency components,

(vi) high evaporation rates,

(vii) spatial rainfall distribution is highly localized (Wheater et al 1991) and the correlation coefficient of storm rainfall decreases more rapidly with distance (Osborn et al 1979),

(viii) plant cover and organic matter are sparse (McIntyre and Al-Qurashi 2009; Pilgrim et al 1988).

However, studying the complexity of hydrological process in arid region is basically based on understanding rainfall characteristics and watershed properties. The research community is facing challenges of applying rainfall runoff models in arid zone. The main challenge is the lack of monitored data (Pilgrim et al 1988) specially rainfall spatial distribution over the catchment area, because the rainfall is the primary input in any hydrological model. This may force the researcher to minimize the research questions or will increase the model uncertainty.

In hydrological modelling, conceptual-lumped rainfall runoff models usually require less input data than distributed models. However, a distributed rainfall runoff model may offer a better approach for flood hydrograph simulation in catchments characterized by the heterogeneity of rainfall distribution (Yu and Jeng 1997). Consequently, spatial rainfall dataset is required for a successful distributed rainfall runoff model analysis. In the present time, the availability of spatially distributed data sets such as Digital Elevation Model (DEM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and soil type allow the regionalization of model parameters. Additionally, the open access into rainfall data obtained from satellite-borne derive microwave radiometers is increasing the use of physically-based distributed models.

It has been clearly stated the advantage of using Geographic Information System (GIS) in hydrological management by many researchers (Jayakrishnan et al 2005; Martin et al 2005; Reinelt et al 1991). Efforts have also been made on integrating some of hydrological models with GIS environment. Most of these models are physically based distributed, e.g. HEC-HMS, SWAT, TOPMODEL, and WEPP model. This integration allows assessing and predicting the impact of watershed management practices (Arnold et al 1998a; Verma et al 2010; Wheater et al 1999; Zhang et al 2008).

On other hand, lumped rainfall runoff models require less input data. Furthermore, the analysis can be performed much faster in Lumped model. The IHACRES rainfall-runoff model (Jakeman and Hornberger 1993) has been successfully applied to several climatic zones.

The Hydrologic Engineering Center-the Hydrologic Modeling System (HEC-HMS) is a physically based distributed model, designed to simulate the rainfall-runoff processes of dendritic watershed systems (Scharffenberg and Fleming 2010). The model was developed by the US Army Corps of Engineers. HEC-HMS model has been widely applied for humid, tropical, sub tropical and arid watersheds to simulate and forecast stream flow. Previous studies on HEC-HMS proofed the ability of HEC-HMS model to simulate and forecast stream flow based on different datasets and catchment types (Anderson et al 2002; Bournaski et al 2009; Chu and Steinman 2009; Cydzik and Hogue 2009; Knebl et al 2005; Yusop et al 2007).

More closely, a study conducted by (Al-Abed et al 2005) on Al-Zarqa Basin using monthly streamflow proved that the HEC-HMS model gave more acceptable results than other models. In contrast, a study by Abushandi and Merkel (2011b) proved that the IHACRES rainfall-runoff model is applicable in the Jordanian arid areas. According to the obtained results, the IHACRES model was able to adequately simulate streamflow in arid catchments when applying the model on a storm event scale. In this context, it is important to note that the results quality depends on the chosen time interval.

In this research paper, the IHACRES and HEC-HMS rainfall runoff models were selected for several reasons: (i) model availability and structure, (ii) data availability, and (iii) model applicability in arid catchments. The model IHACRES (Identification of unit Hydrograph And Component flows from Rainfall, Evaporation and Stream flow data) is a simple model, parametrically efficient, and statistically rigorous (Dye and Croke 2003). The IHACRES input requirements are only precipitation and temperature, and streamflow for calibration purpose. The second model, HEC-HMS (Hydrologic Engineering Center’s Hydrologic Modeling System), requires inputs for the basin model, meteorologic model, and control specifications but then allows several different techniques to be used to model the rainfall-runoff process.

To answer the question of what parameter levels will lead to a desired modelled output, the sensitivity analysis (SA) will be carried out to study the behaviour of modelled streamflow with respect to the change of parameter values. This method is useful for complex hydrological models that involve a large number of parameter (Liu and Sun 2010). In addition, it is particularly important for arid catchment to identify the local controlling parameters.

The examination of these two models will based on the application into a single heavy rainstorm event that caused streamflow obtained from the Wadi Dhuliel sub-basin on 29./31.01.2008 by using hourly rainfall, temperature and streamflow data. The key issue of the paper is evaluating whether the distributed HEC-HMS model perform sufficiently better than the lumped IHACRES model. The objectives of this study are to (i) proof the ability of HEC-HMS and IHACRES rainfall-runoff models to simulate stream flow for the Wadi Dhuleil from a single storm event, (ii) parameterize the Wadi Dhuleil using a high resolution dataset including the Global Satellite Mapping of Precipitation (GSMaP_MVK+) and ASTER data, and finally (iii) correlate land activities to water variability through HEC-HMS model.

Materials and method

Study area description and data analysis

The Wadi Dhuliel arid catchment is located in the northeast part of Jordan as a major sub-basin of the Al-Zarqa Basin (Figure.C 2). The total area of the Wadi Dhuliel drainage network is around 2687 km^2. The size of the area may differ slightly from one author to another basically because of the resolution of the DEM image used to determine the catchment area, the delineation method, and the software used for the catchment delineation. Al-Zarqa, a city of one million people, is located in the outlet section of the Wadi Dhuliel Sub-basin. The climate in the area is arid with an average rainfall of 123mm per annum.

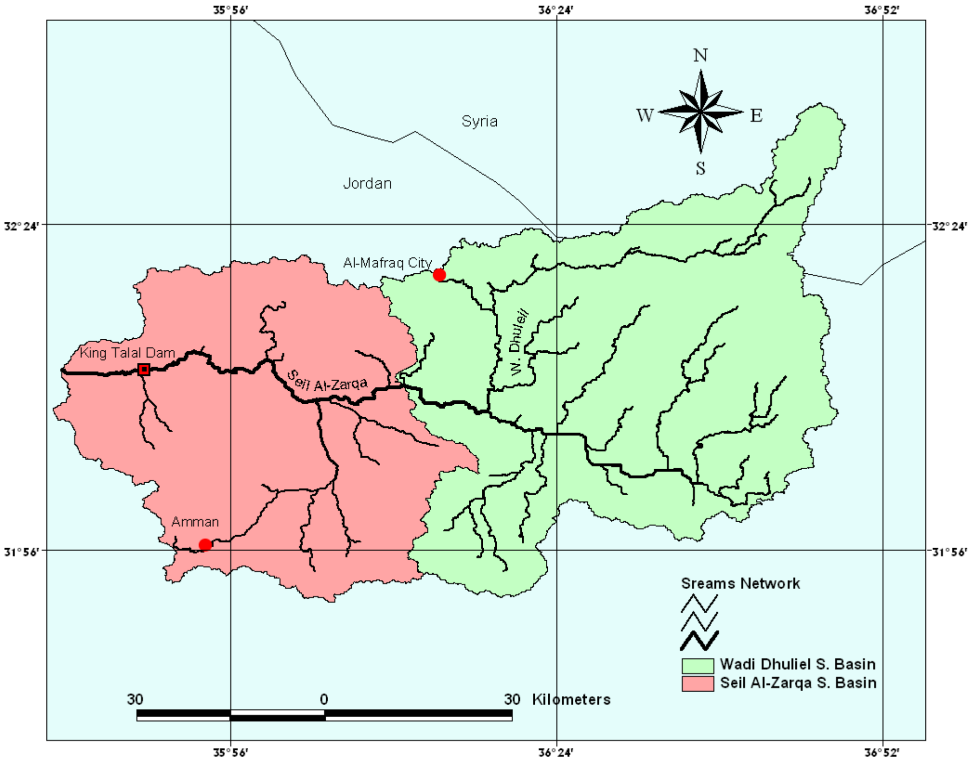

Figure.C 2 Location of the Wadi Dhuleil arid catchment area in Jordan (ASTER, 30m resolution, Map datum: WGS 84)

Land use and soil types

The ecological infrastructure such as vegetation cover type, soil characteristics, plant and settlement densities affect the infiltration characteristics and influence the storage coefficient and runoff behaviour. Derived from Enhanced Landsat Thematic Mapper Plus (ETM+) imagery, the land use categories of the Wadi Dhuliel area were classified into six classes (Figure.C 3) ERDAS Imagine (V8.4) software was used to develop a land use supervised classification. This procedure was based on the Maximum Likelihood Classification method with training area based on ground survey and land cover maps (Table.C 1). The ground cover is largely cultivated area in the upstream of the catchment and contributes around 36.2% from the total area. Bare soil and settlements are the main surface cover in the downstream.

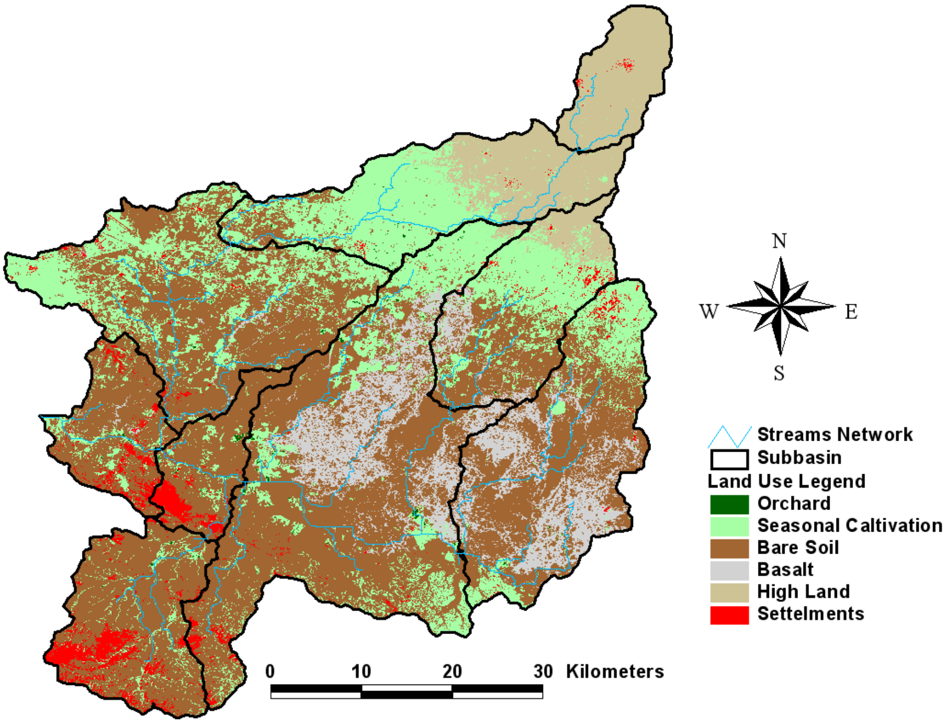

Figure.C 3 Land use map of the Wadi Dhuleil (ETM+ 10.04.2005)

Table.C 1 Land use features for each sub basin derived from ETM+ 10.04.2005

Land use type (%) / Sub basin No.	Orchard	Seasonal cultivation	Bare soil	High land	Basalt	Settlements
1	1	11.8	0	66.2	0	21.2
2	3.2	57.5	12.6	14.8	4.9	7.1
3	1.2	44.1	27.7	0.1	17.1	9.7
4	0.9	42	24.2	15.2	7.7	10
5	1.1	43.5	28.6	0.6	17.2	9.0
6	5.1	39.1	18.3	1.0	3.7	32.7
7	0.4	27.4	31.9	1	31.3	8.0
8	0.5	36.6	21.5	0	0	41.4
9	1.6	37.5	17.3	0.2	10.9	32.6
Basin total (%)	1.2	40.0	25.4	4.1	15.0	14.4

Most of the soil types within the study area is classified as Aridisols and contains high amount of lime (Al-Qudah 2001) low gypsum and basalt in the subsoil and in the parent materials. Soil physical properties and it is relationship to soil moisture have important implications in water flow potential. Spatial soil physical properties data (e.g. sand, silt, and clay %) are obtained from the soil and terrain database, regional project (SOTER) developed by FAO and the International Soils References and Information Center (ISRIC) (Figure.C 4 and Table.C 2). Soil crusting most often occurs due to the high silt content in this type of soils

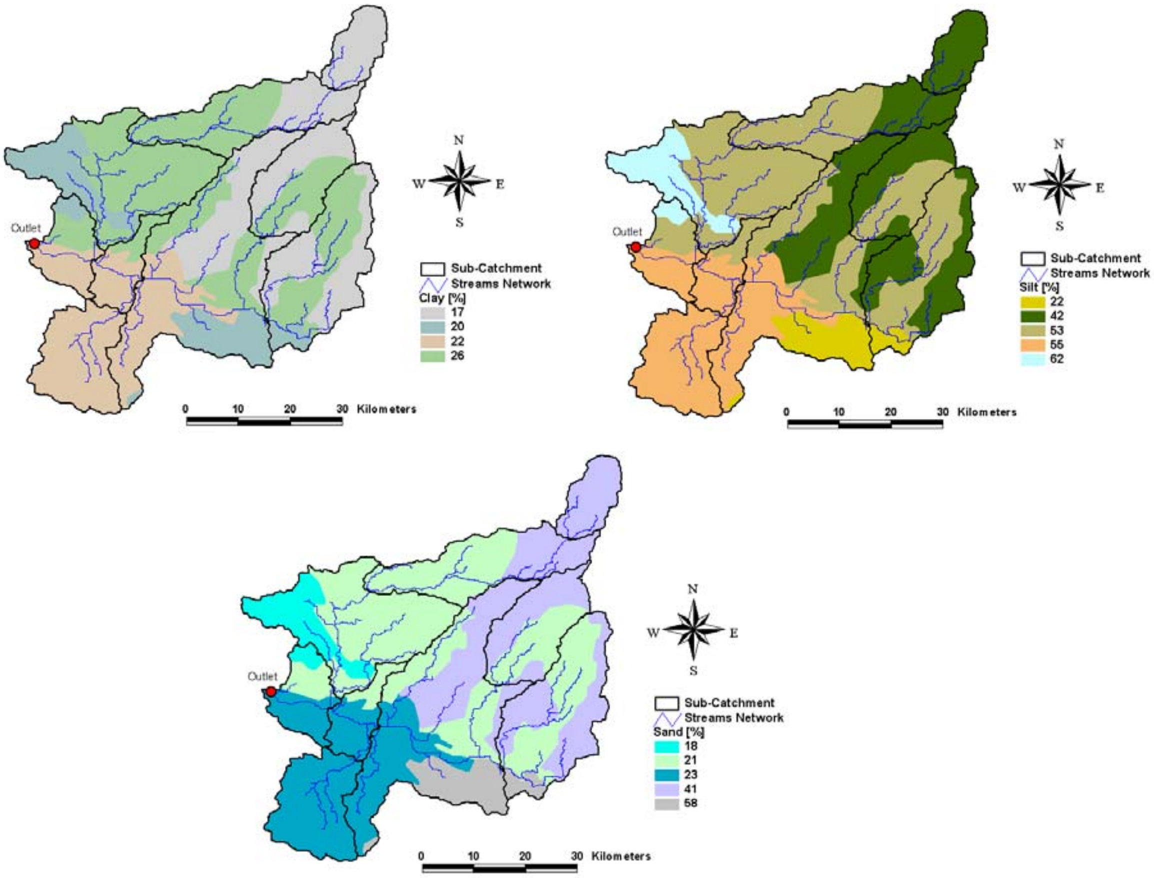

Figure.C 4 Soil classification maps based on ISRIC

Table.C 2 Soil Texture and percent composition (sand, silt, and clay) for each sub-basin

Sub basin No.	**Clay [%]**	**Silt [%]**	**Sand [%]**	**Textural Triangle***
1	17	42	41	Loam
2	21	48	31	Loam
3	24.2	55.7	20.1	Silt loam
4	21	47	32	Loam
5	21.25	47.25	31.5	Loam
6	23.4	54.3	22.3	Silt loam
7	19.8	49.6	30.6	Loam
8	22	55	23	Silt loam
9	22.7	55.7	21.6	Silt loam
Average	21.4	50.5	28.1	Silt loam

*Textural classification in various soil classes (Jackson 1965)

The main wet season is between October and March, while the dry months are between April and September. Topographic data were generated from Advanced Spaceborne Thermal Emission and Reflection Radiometer images (ASTER), and show that the area is characterized by a gently undulating with an elevation varying from 460 m in the southwest to 1400 m in the north (Figure.C 5) with an average slope between 5-30%. The area is considered as the main source of agriculture in Jordan arid regions and groundwater is the main source of irrigation. Irrigation for agriculture in the Wadi Dhuliel taxes existing groundwater resources and strongly distorts hydrological features of this arid catchment.

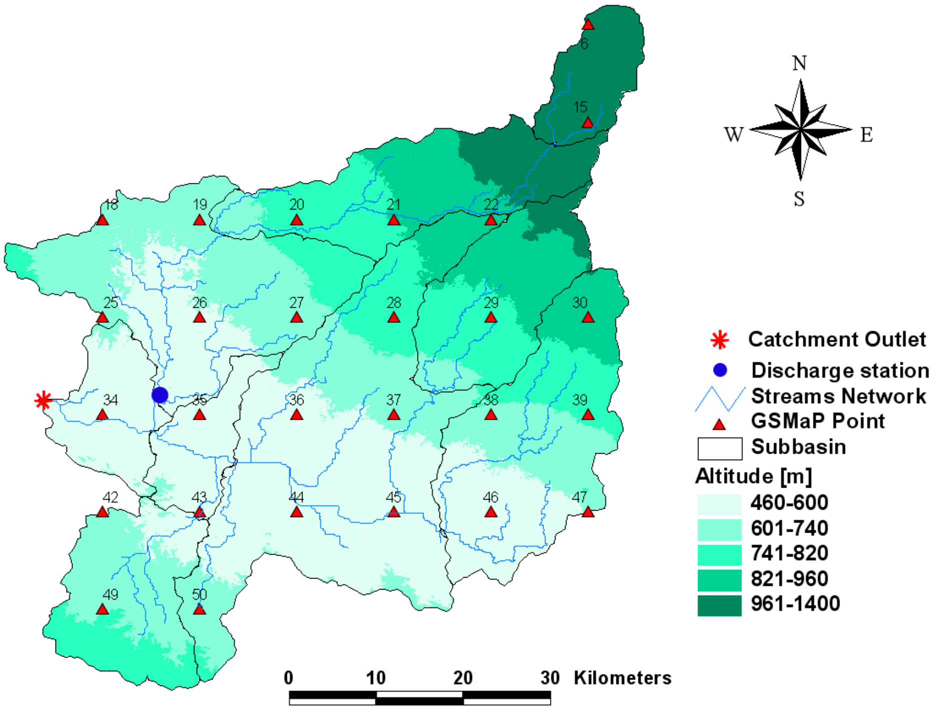

Figure.C 5 The Wadi Dhuleil sub basins altitude (ASTER, 30 m resolution) and GSMaP_MVK points

HEC-HMS model description

The HEC-HMS can be used to simulate a single watershed or a system of multiple hydrologically connected watersheds. The first step in the application of HEC-HMS is to define the basin area and sub basins, a stream network, and diversions, junctions. As any physically based hydrologic model, HEC-HMS simulate most of the key hydrologic processes at watershed scale. The HEC-HMS model requires different datasets including Digital Elevation Model (DEM), weather data, soil type, and land use. A detailed map of land surface elevation was obtained from ASTER with 30 m resolution (Figure.C 5). A comprehensive description of all components in HEC-HMS can be found in the user manual (Scharffenberg and Fleming 2010).

The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) along with ArcHydro extension in ArcView was used to delineate the physical properties from ASTER data and generate a stream network. HEC-GeoHMS was also used to create the input file in the form of sub-catchment boundaries, meteorologic model etc. for the use in HEC-HMS. Figure.C 6 is showing the output of HEC-GeoHMS with the basin being divided into 9 sub-catchments. The Sub-catchments characteristics are summarized in Table.C 3.

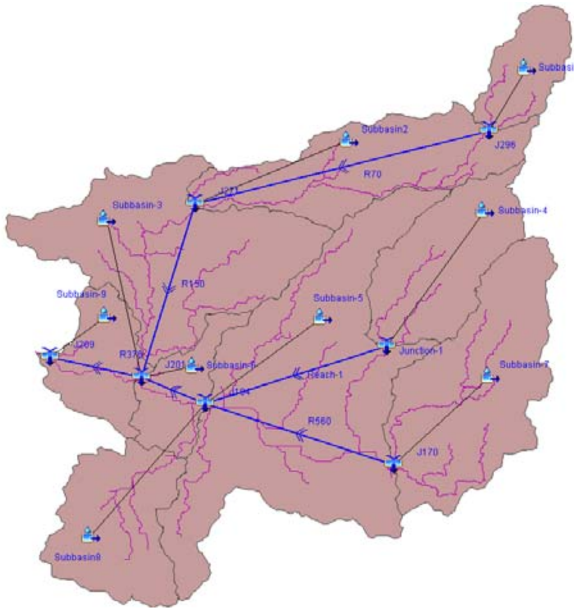

Figure.C 6 HEC-GeoHMS generated the Wadi Dhuliel catchment (9 sub-catchments)

Table.C 3 Sub-catchments characteristics

Sub-catchment No.	**Area [km^2]**	**Mean Altitude [m]**	**Total Rainfall [mm]***	**Number of GSMaP Points**
1	96	1100	22.6	2
2	508.2	825	26.8	3
3	596.1	580	76.1	5
4	258.7	735	17.7	1
5	575.4	520	133.7	6
6	84.01	490	50	2
7	251.4	663	106.2	5
8	189.46	605	19.7	1
9	127.83	483	21.2	1

*Rainfall for three days period derived from GSMaP_MVK+ (mm)

The HEC-HMS model includes three main components: basin model, meteorologic model, and control specifications. Basin model stores the physical datasets describing the catchment properties. Meteorologic model includes the precipitation; evapotranspiration and snowmelt data. Six different historical and synthetic precipitation methods, two evapotranspiration methods, and one snowmelt method are included. The time span of a simulation is controlled by control specifications including a starting date and time, ending date and time, and computation time step. However, the stream flow simulation requires carful identifications of each model. The loss rate model which has been used in this study is the Soil Conservation Service (SCS) Curve Number (CN) method to compute the volume of streamflow. The SCS-CN method accounts for most of the runoff producing watersheds characteristics such as soil type, land use, hydrologic condition, and antecedent moisture condition (Mishra and Singh 2004) using the following formula:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \qquad \text{Equation 1}$$

Where P_e is the accumulated rainfall excess at time t ($P_e = 0 \text{ if } P < 0.2S$), P is the accumulated rainfall depth at time t, I_a is the initial abstraction, S is the potential maximum retention.

The SCS developed an imperial relationship between I_a and S as $I_a = \lambda S$, where $\lambda = 0.2$, and then the equation 1 will be:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{Equation 2}$$

Where the parameter S is mapped to the curve number CN as

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

The model of direct flow which includes the transformation of precipitation into surface runoff was accomplished by SCS Unit Hydrograph. Since the area has no base flow, the model of base flow was not used. Transform method requires a lag time determination as an input. The SCS developed a relationship between the time of concentration (T_c) and the lag time (T_{lag}). The time of concentration can be estimated based on subbasin characteristics including topography, length of the reach (Kirpich's formula).

$$T_{lag} = 0.6T_c$$ Equation 4

$$T_c = 0.0078 \times \left(\frac{L^{0.77}}{S^{0.385}} \right)$$ Equation 5

Where, L is the reach length in feet, and S is slope in %.

IHACRES model description

IHACRES is the abbreviation of **I**dentification of unit **H**ydrograph **A**nd **C**omponent flows from **R**ainfall, **E**vaporation and **S**treamflow. IHACRES (Jakeman and Hornberger 1993; Jakeman et al 1990) is a hybrid conceptual-metric model, using the simplicity of the metric model to reduce the parameter uncertainty inherent in hydrological models (Croke and Jakeman 2004). The main objective of IHACRES is to characterize catchment-scale hydrological behavior using as few parameters, often about six parameters. The IHACRES model only requires three data sets (rainfall, temperature, and streamflow) per time unit.

The classic redesigned IHACRES version(Croke et al 2006; Jakeman and Hornberger 1993) has been used in this study. The original structure of IHACRES includes non-linear and linear modules. The non-linear loss module converts rainfall (r_k) into an effective rainfall (u_k) by considering both the infiltration rate and evapotranspiration. In order to obtain the effective rainfall, a catchment wetness index or antecedent precipitation index, representing catchment saturation, is calculated for each time step. Usually, a non-linear loss module within IHACRES includes three parameters: c is the adjustment parameter, f is a temperature modulation parameter and $\tau_{w(const)}$ is the rate at which catchment wetness declines in the absence of rainfall. The initial stage is to determine the drying rate τ_w, and the catchment moisture index S_k at each time step, which is given by:

$$\tau_w = \tau_{w(const)} \times e^{(20-t_k)} \times f \qquad \text{Equation 6}$$

where τ_w is the drying rate at each time step, $\tau_{w(const)}$ is the rate at which catchment wetness declines in the absence of rainfall, t_k is the temperature at time step k and f is a temperature modulation parameter (°C–1), which determines how τ_w changes with temperature.

Catchment wetness index S_k is computed for each time step on the basis of recent rainfall and temperature records. The loss module is used to account for the effect of antecedent weather conditions on the current status (S_k) of soil moisture and vegetation conditions, and evapotranspiration effects.

$$S_k = c \times r_k + (1 - \frac{1}{\tau w_{(k)}}) \times S_{k-1} \qquad \text{Equation 7}$$

where c is the adjustment parameter and controls the amount by which S_k is increasing by a rainfall event (Post and Jakeman 1999), r_k is the rainfall at time step k.

Finally the effective rainfall (r_k) in the model is given by:

$u_k = r_k \times s_k$ Equation 8

if $r_k \times s_k \rangle 0$

Since the study area is characterized by ephemeral streams with no runoff if there is no rainfall, computing effective rainfall if r_k is >0 for ephemeral streams can make equation (3) true, both physically and dimensionally. In the linear routing module, the effective rainfall is converted into streamflow (Q_k). The linear model employs discrete-time intervals, transfer function and a representation of the Unit Hydrograph (UH).

$Q^q_{(k)} = -\alpha_q Q^q_{(k-1)} + \beta_q u_{(k-\delta)}$ Equation 9

$Q^s_{(k)} = -\alpha_s Q^s_{(k-1)} + \beta_s u_{(k-\delta)}$ Equation 10

where $Q^q{}_k, Q^s_m$ are quick and slow streamflow components. Delta in the $u_{(k\delta)}$ is the delay between rainfall and streamflow response. The parameters (α_q, α_s) are the recession rates for quick and slow storage, whereas the parameters (β_q, β_s) represent the fraction of effective rainfall. The UH of total streamflow is the total of both quick and slow flow UHs.

Rainfall data

The data set of single heavy rainstorm event that caused streamflow in the Wadi Dhuliel catchment was collected from the Surface Water Resources Unit at the Jordan Ministry of Water and Irrigation (JMWI). The only available climatic data from the

JMWI are based on a daily time resolution. However, the hourly data sets were obtained directly from the raw chart of Umm-Aljimal meteorological station (Figure.C 7).

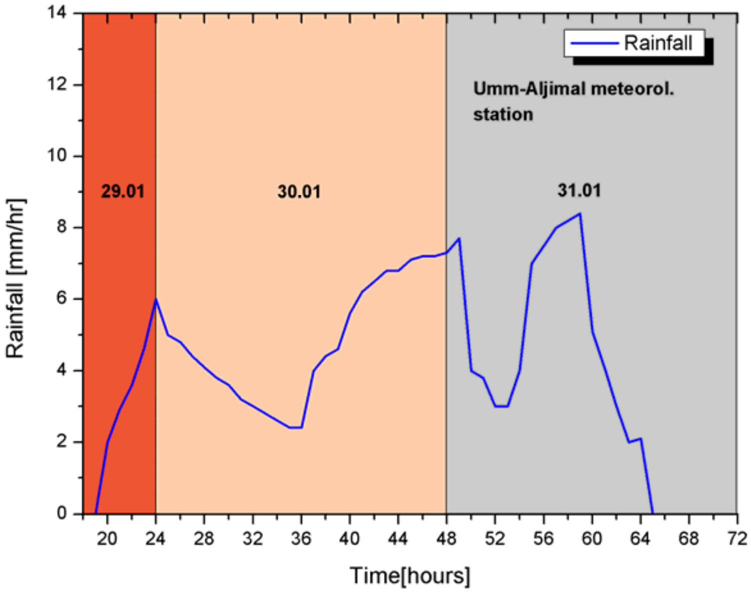

Figure.C 7 Rainfall bar chart for a single storm event in mm (Umm-Aljimal meteorological station, JMWI.)

To overcome the problem of spatial rainfall dataset scarcity and ensure the uniformly distribution over the catchment area, re-adjusted satellite derived rainfall dataset known as the Global Satellite Mapping of Precipitation (GSMaP_MVK+) version 4.8.4 was used to determine the rain storm location. It has also been used to determine the ratio of rainfall in each sub-catchment. The GSMaP_MVK+ dataset of a heavy storm event in January 29-31 with 26 grid points covering the basin was used (Figure.C 8).

The GSMaP project started in 2002 with support of the Japan Science and Technology Agency (Ushio et al 2009) to produce high resolution rainfall dataset. A frame from 31.95°N - 32.55°N and 36.15°E – 36.85°E was extracted from the GSMaP_MVK+ to cover the entire area Wadi Dhuliel catchment with 24 knots and a spatial resolution of 10.8 km. To consider the spatial distribution of rainfall, standard Kriging interpolation (linear variogram) was used to calculate estimates for the representative area of each GSMaP_MVK+ pixel (Figure.C 8). Detailed information about GSMaP_MVK+ dataset processing and application for the Wadi Dhuliel are given by Abushandi and Merkel (2011b). Furthermore, the GSMaP_MVK+ datasets show that the highest magnitude of rainfall was during the first day of the storm (29.01.2008) (Figure.C 9).

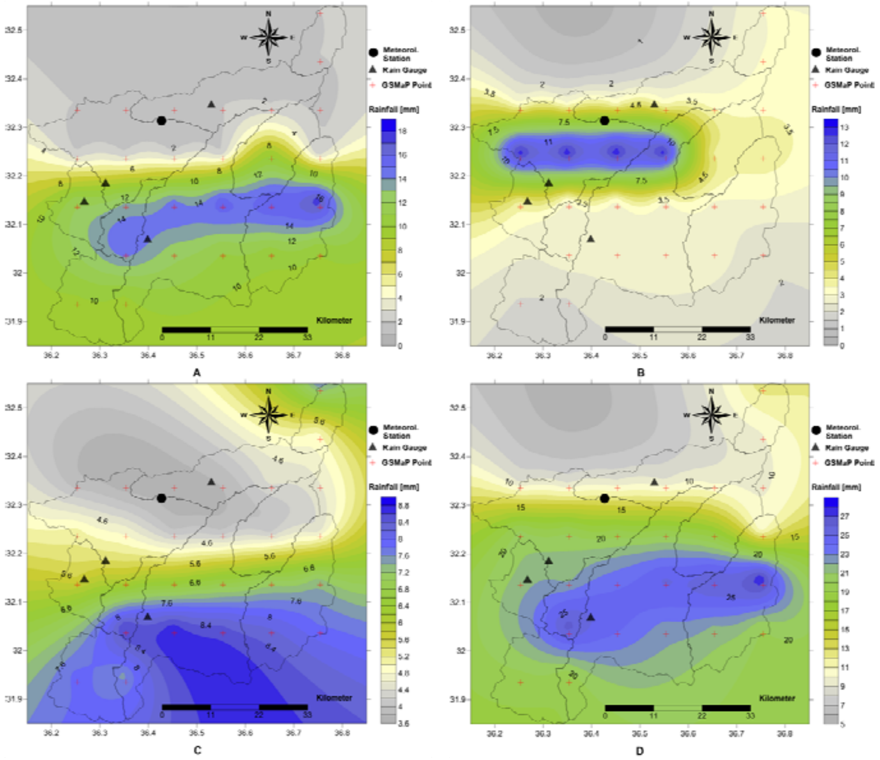

Figure.C 8 GSMaP_MVK+ estimates using standard Kriging interpolation for rain storm between 29-31.01.2008, and the average for this storm event respectively

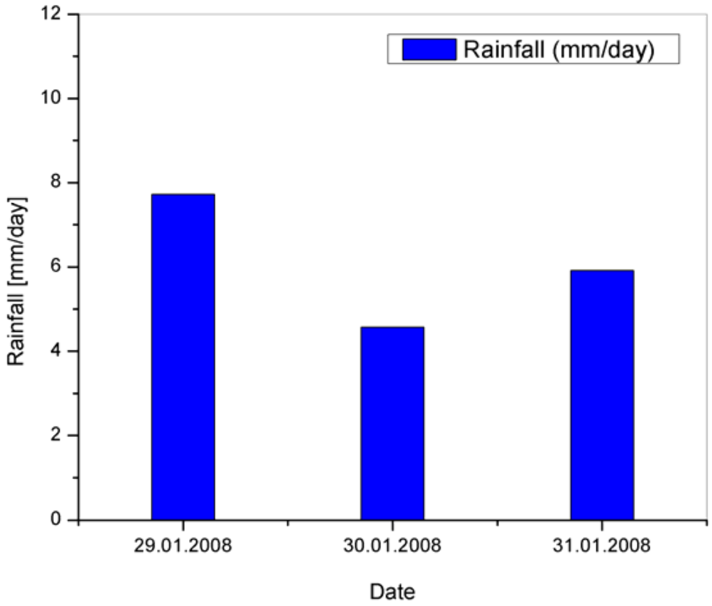

Figure.C 9 Average rainfall rates from all GSMaP_MVK+ pixel values for the three days storm (29-31.01.2008)

Streamflow data

Generally, the runoff production in the Wadi Dhuleil arid catchment is totally different from one storm to another. Therefore, the capability of simulating individual storms is important for models to adequately capture hydrologic processes at different conditions. The rate of rainfall was found to be non-linearly related to streamflow on the rising limb of the stream hydrograph.

The scarce streamflow gauging is common in the Wadi Dhuleil. Only one streamflow gauge exists in the Wadi Al-Za'atri (subbasin no. 3) with daily dataset covering limited periods. Hourly data can be extracted from the row charts. Due to the limitation of calibration and validation data, hourly streamflow data from Al-Za'atari gauging station was used to calibrate the HEC-HMS and IHACRES models. The objective of the model calibration is to match simulated streamflow volumes with the observed ones. Flash flood hydrograph is generally sharp with timing between 3-24 hours during and after the rain storm (Figure.C 10).

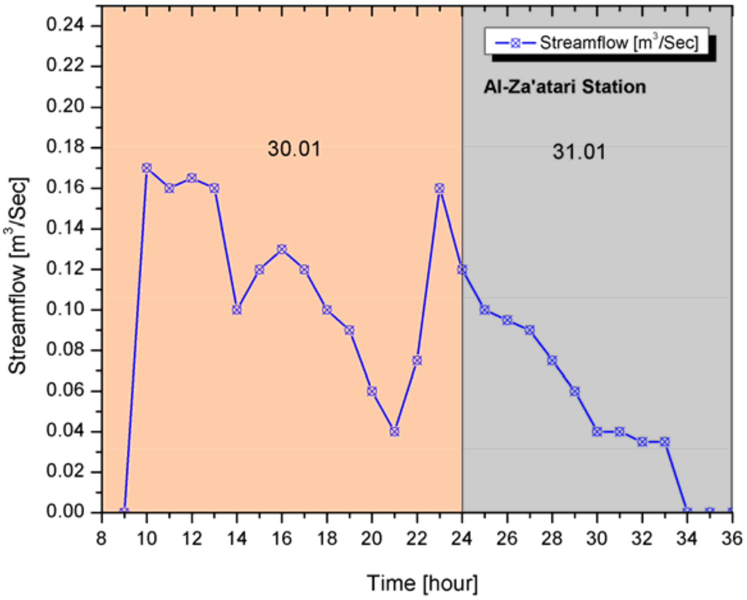

Figure.C 10 Stream flow event in January 30-31, 2008, (Al-Za'atari Gauging Station, Jordan Ministry of Water and Irrigation)

It is recognized that the stream flow volumes in the Wadi Dhuliel have recently very limited magnitudes and dramatically decreased over time. For example, in the years between October 1986 and February 1992, the average flood was 7.6 m^3/Sec., while in the years between 2001 and 2008 was 1.2 m^3/Sec. This might happen due to urbanization, increasing agricultural activity especially in the upper part of the catchment, and/or drought events. The runoff coefficient in the study area was 2.3% on average (Abushandi and Merkel 2011a).

A single rainfall-runoff event dataset in 29-31.01.2008 was used to calibrate and validate HEC-HMS and IHACRES models. Parameter values were tested manually during the calibration processes to reach the best fit between observed and simulated values. This calibration was performed by applying different curve numbers in the HEC-HMS simulated model.

The HEC-HMS offers automated and manual calibration. In this study the automated calibration procedure was used. The Nash-Sutcliffe efficiency (*E_f*) was used to quantify the goodness-of-fit between modelled streamflow to observed records:

$$E_f = 1 - \frac{\sum (q_i - \hat{q}_i)^2}{\sum (q_i - \overline{q})^2} \qquad \text{Equation 11}$$

where q_i is observed streamflow, $\hat{q}_i$ is simulated streamflow and $\overline{q}$ is the mean value of observed streamflow.

The relative sensitivity analysis (*R*) was carried out using the following equation (Al-Abed et al 2005):

$$R = \left[\left((FY2 - FY1)/Y\right)/\left((FX2 - FX1)/X\right)\right] \qquad \text{Equation 12}$$

where FY1 is the output result for the original case, FY2 is the output result for the new parameter with specific change, FX1 is the original parameter value, and FX2 is the new parameter value with specific change.

Results and Discussion

Based on the hydrologic soil groups (HSGs) and vegetation type, the CN value of each subbasin was determined (Table.C 4)

Table.C 4 Soil Curve Number (CN) method parameters values for each sub basin

Sub basin No.	**Curve Number**	**Soil Type**	**Land Use Description***
1	89	Loam	High land , settlements, and seasonal cultivation
2	82	Loam	Seaosnal cultivation, high land, and bare soil
3	87	Silt loam	Seasonal cultivation, bars soil, and baslat
4	85	Loam	Sesonal cultivation , bare soil, and high land
5	86	Loam	Sesonal cultivation, bare soil, and basalt
6	87	Silt loam	Sesonal cultivation, settlement, and bare soil,
7	87	Loam	Baslat, bare soil, and sesonal cultivation
8	86	Silt loam	Settelments, Sesonal cultivation, and bare soil
9	88	Silt loam	Sesonal cultivation, Settements and bare soil, basalt

*only main land use cover is presented

The Initial loss, Imperviousness, and the lag time of concentration have also been estimated based on subbasin characteristics including topography, length of the reach (Table.C 5)

Table.C 5 Transform model parameter values

Sub basin No.	Initial Loss [%]	Imperviousness [%]	Slope [%]	Lag Time [h]
1	24.7	21.2	25	3.5
2	43.9	12	23	10.7
3	29.9	26.8	21	7.4
4	35.3	17.7	18	8.5
5	32.6	26.2	15	6.8
6	29.9	36.4	9	5
7	29.9	41.4	17	9.3
8	32.6	43.5	16	6.6
9	27.3	29.4	5	8.1

The hydrologic soil groups (HSG) classification reflects soil characteristics and the range of infiltration rates (Table.C 6). Based on this classification, the infiltration rate in the Wadi Dhuliel catchment was assigned to group C.

Table.C 6 Summary of HSG characteristics (McCuen 1997)

Group	Minimum Infiltration Rate [mm/hr]	Surface Runoff Potential
A	7.6-11.4	Low
B	3.8-7.6	Moderately low
C	1.3-3.8	Moderately high
D	0-1.3	High

The shape of the simulated hydrograph is generally following the observed hydrograph in HEC-HMS Model (Figure.C 11), while the application of IHACRES to the same data sets showed some sever weaknesses and overestimation (Figure.C 12). Generally HEC-HMS, with few exceptions, tends to overestimate observed streamflow only slightly. Parameters for best fit of HEC-HMS are listed in Tables.C 4 and 5, while best fit parameters of IHACRES are listed in Table.C 7.

Table.C 7 Optimized IHACRES parameter values

C	$\tau_{w(\mathrm{const})}$	F	α_q	β_q	α_s	β_s
0.00	40	0.15	–0.05	0.04	–1	0

The relative sensitivity analysis was carried out by adjusting different parameter values in both HEC-HMS and IHACRES models for the subbasin no 3 (where the discharge station is located). After running the models repeatedly, the simulated streamflow results were compared with monitored values at each change of parameters. The most sensitive parameters in HEC-HMS model were the CN with an average of 2.7, while the imperviousness relative sensitivity value was 3.1. The results, however, showed sensitivity to input initial loss parameter (3.3). The rest of parameters in the HEC-HMS model showed a weak effect on the modeled outputs. In contrast, most of the IHACRES model parameters are having a strong influence on the modeled outputs except the adjustment parameter (*c*). The most sensitive parameter in IHACRES was β_q (0.5)

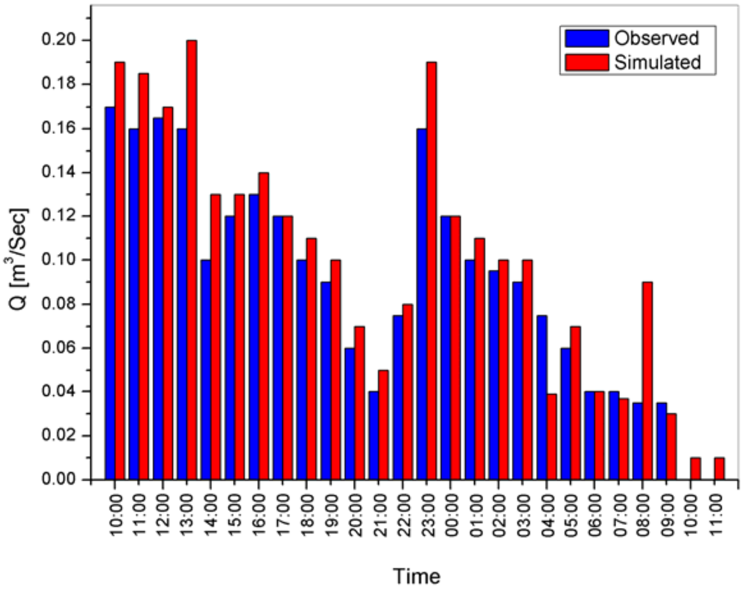

Figure.C 11 Wadi Dhuliel catchment observed vs. simulated streamflow hydrographs for the calibration 30-31/01/2008) using HEC-HMS

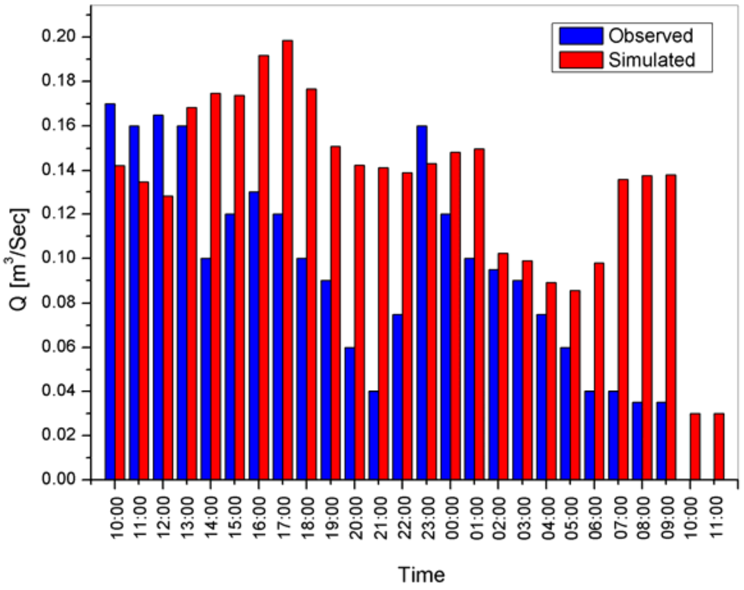

Figure.C 12 Wadi Dhuliel catchment observed vs. simulated streamflow hydrographs for the calibration 30-31/01/2008) using IHACRESl

To estimate the goodness of fit between observed stream flow (q_i) and modeled stream flow ($\hat{q}_i$) was estimated using the Nash-Sutcliffe efficiency (E_f).

A good performance of HEC-HMS was obtained with E_f equal to 0.88, while E_f was 0.51 in IHACRES application. This, however, shows a poor performance of the IHACRES model on hourly basis application. The applications of HEC-HMS model is considered to be satisfactory.

HEC-HMS and IHACRES are models widely applied for estimating streamflow. The major advantage of employing a GIS based approach in rainfall-runoff modeling is the use of different land use patterns especially in regions with complex mix of land use features and different soil types. While the major advantage of using IHACRES is the minimal input data requirements. HEC-HMS and IHACRES models were applied in this study to calculate the streamflow volume in a single storm of the Wadi Dhuliel arid catchment. GSMaP_MVK+ dataset was used to determine the rain storm location. However, it has also been used to quantify the amount of the rain in each subbasin. Estimated and observed streamflow volumes of a single event was close enough to assume the applicability of the HEC-HMS model approach for the region. However, this was not the case in IHACRES model performance.

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