Floods As Water Resource and As a Hazard in Arid Regions: a Case Study in Southern Jordan

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ABSTRACT

Floods in arid and semiarid regions are considered the only hydrologic process that generates large volumes of water for surface storage and groundwater recharge. Floods in southern Jordan are associated with certain synoptic climatic conditions that are mainly influenced by the effect of the Red Sea trough. Geologic and geomorphologic factors significantly influence flood generation. The slack-water deposit and paleostage indicators' technique incorporated with gradually varied flow model HEC-RAS 4. 0 were used to estimate the large flood of February 2006 in the Wadi Ouhadah subcatchment in southern Jordan. Flood discharge was estimated to be 320 m^3/s, and this flood event is suspected to be the flood event of February 2006. Fast recharge to shallow groundwater aquifers occurred through channel bed transmission loss during the flood event. Floods pose a large threat to Ma'an city which is located downstream in flat topography.

KEYWORDS: Southern Jordan, Floods, Paleohydrology, Groundwater recharge, Climate.

INTRODUCTION

In arid and semiarid environments, large floods present the only hydrologic process that generates large volumes of water for surface storage and groundwater recharge. With this in mind, floods in arid and semiarid regions can be viewed as a potential water source for future use and sustainable development. In small arid watersheds, questions related to the frequency and magnitude of precipitation events and flows that contribute to the local aquifers are critical. For example, a small population of Bedouins inhabits ephemeral stream catchments in the remote area of Tulul al Ashaqif in northeastern Jordan. A small increase in the water resources in the shallow alluvial aquifer of that region could have a significant effect on their livelihood (Al-Qudah and Abu-Jaber, 2009).

In deserts, large floods are generated under an appropriate combination of rainfall characteristics of magnitude, intensity, duration and distribution over the drainage basin (Schick, 1971, 1988; Greenbaum et al., 1998, 2009). Large floods tend to be a product of the entire basin and are usually associated with preferred precipitation patterns (Enzel et al., 1993; Kahana et al., 2002; Greenbaum et al., 2009). Effective integration of flow from several tributaries occurs in desert regions only during extreme floods (Wolman and Gerson, 1987; Brouke et al., 1999; Greenbaum et al., 1998). Basin orientation in relation to storm movement also affects the peak discharge (Greenbaum et al., 1998). Therefore, an understanding of the different characteristics of appropriate climatic conditions, precipitation, basin morphometry and geomorphology is essential in understanding how floods are generated in a drainage basin.

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Very little documented information is available on floods in remote arid regions in general and in Jordan in particular. However, data about the frequency and magnitude of floods in desert areas is very important for management, as floods are considered a main source of surface water and risk planning for hazards associated with floods (Farhan, 1989; Robins et al., 2008). However, information about past floods (paleofloods) can provide an unprecedented data set that is essential to understanding the real behavior of extreme events, magnitude and frequency, as well as the relation to hydroclimatic variability and possible global climatic change (House et al., 2002; Redmond et al., 2002; Benito., 2003).

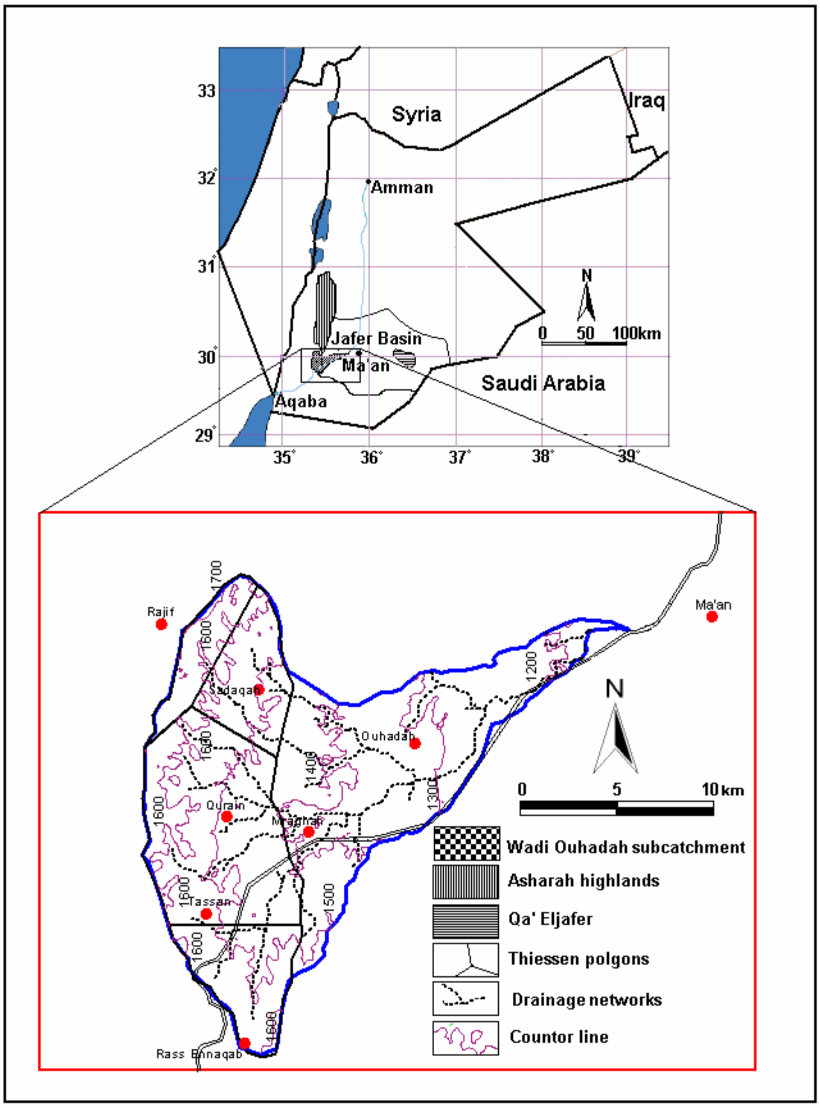

Figure 1: Location of the study area. Wadi Ouhadah subcatchment, red circles are raingage station locations

As in most arid and semi-arid regions, the technical literature on floods in Jordan and the Middle East region (except in Israel) is limited. Historic records and rainfall-runoff data in southern Jordan indicate that large floods occurred frequently in the past century. As late as 1940, a “terrific rain- and hail-storm“ literally washed away half of modern Aqaba (Schick,1971). The decade preceding the instrumental period, which started in 1950-1951, witnessed at least three major floods in southern Jordan; on January 7, 1944, in 1945 and a major flood on May 12,1950. In March 1966, a catastrophic flood struck the town of Ma’an in southern Jordan. It is reported that approximately 200 people were killed and over 250 were wounded. About half of the buildings of the town were destroyed and over three thousand people were rendered homeless (Falastine Daily Newspaper, 1966). The estimated flow of this flood reached a peak discharge of 540 m^3/sec (CWA, 1966). Schick (1971) mentioned in his study of Ma’an Flood that, in fact, a flood may be expected almost every year in southern Jordan based on observations of local residents.

In 1963, Petra was hit with a destructive flood, and 27 French tourists were killed and the Wadi el Yutim dam was destroyed (Abu Hussain, 1994). In the 1990s, two major floods occurred in Jordan; one in 1993 in northern Jordan, in which four people were killed and many properties were damaged, and the other one in 1996 in the Petra area, in which two people were killed and many properties were damaged. More recently, on February 2006, Aqaba and Ma'an witnessed a large flood where 2 people were killed. Property damage to airport and waste water treatment plant was estimated to be approximately 6 million JD (Al Rai Daily Newspaper, Feb. 8th, 2006).

The main objectives of this paper are to: (a) understand the hydroclimatic conditions that are most likely to generate floods in southern Jordan, (b) determine how geology, geomorphology and geometry of drainage basins influence flood development, (c) determine the magnitude of recent flood events in a basin using paleoflood hydrology techniques combined with hydrologic modeling software package HEC-RAS and (d) determine the flood threat potential to Ma'an city in southern Jordan.

GENERAL PROPERTIES OF THE WADI OUHADAH STUDY SITE

Location and Climate

The subcatchment of Wadi Ouhadeh is located in southern Jordan to the west of Ma'an city (Figure 1). The subcatchment is part of greater Jafr basin and represents the southwestern part of the basin. The western part of the subcatchment (headwaters) is part of Asharah highlands, which are relatively dense in vegetation cover of desert shrubs and become very sparse towards east. The mountainous part in the west is usually used by local inhabitants for growing crops, especially in wet seasons. Some fruit farms (mainly apples and peaches) are present in the western parts (irrigated by groundwater). The Desert Amman-Aqaba highway runs through the basin and provides the only major land access to the area.

The climate of the study area is arid to hyper-arid, with relatively higher average rainfall in the western parts, where it ranges from 120mm to 160mm and decreases dramatically to less than 50mm in the eastern parts towards Ma'an. There are noticeable seasonal variations, with summers tending to be hot and dry and winters cool and relatively wet. Precipitation in the area is subject to drastic fluctuations in both location and season. Higher precipitation in the western parts is influenced by the orographic effect of Asharah Mountains (1650m elevation). Most heavy rainfall events are the result of convective thunder storms occurring primarily in the transitional seasons of fall (October–November) and spring (March–May) and are influenced by the effect of the Red Sea trough (Abu Hussein, 1994). The southern parts of Jordan do not lie within the track of the usual frontal storms that pass over the Mediterranean Sea. Only few south-deepening depressions may influence this area from December to February. In some years, snow may fall in the western parts of the Wadi Ouhadah subcatchment at Ras Ennaqab. The mean annual maximum temperature is approximately 25°C and the mean annual minimum temperature is approximately 10°C. Absolute average yearly maximum is about 42. 2°C and absolute average yearly minimum may reach -8°C (JMD, 2008).

GEOMORPHOLOGY AND HYDROGEOLOGICAL SETTING

Wadi Ouhadah is an ephemeral stream with an approximate 242 km^2 catchement area (area calculated before it reached the bridge of Ma'an on the Ma'an-Aqaba highway) (Figure 1). Wadi Ouhadah and its tributaries drain part of the eastern edge of Asharah mountains at the Naqab area (average elevation is 1650m ASL) and steeply to moderately roll through carbonate rocks of the Upper Cretaceous age (Abed, 2000) into Qa’a El Jafr (El Jafr depression, which has an elevation of 850m ASL) in the east (Figure 1). The subcatchment has a mushroom-like shape. At the head water, it is elongated north-south with an axis of approximately 23km which is approximately equal to the long axis of the catchement (24km) that extends west-east. The shape and orientation of the subcatchment is significant. The north-south elongation of the headwater puts the subcatchment within the track of depressions which are coming either from west to east (frontal storms) or from south to northeast (Red Sea trough storms). In addition, the mushroom shape of the subcatchment provides a larger headwater area, which comprises highlands of elevations above 1400 m, receiving an annual average rainfall of about 140mm. The headwater represents about 56% of the total area of the subcatchment where higher rainfall occurs. Such characteristics, combined with a higher slope terrain yield high runoff potential. The subcatchement has a relief of about 800m and has a dendritic drainage network pattern (Figure 1).

The main aquifer in the basin is the B2/A7 aquifer (Upper Cretaceous carbonate rocks) which becomes confined to the east towards the central parts of El Jafr basin. The Wadi Sir Formation (A7) consists mainly of hard crystalline dolomitic limestone, chalky limestone with occasional chert bands and nodules (Bender, 1974). The Amman Formation (B2) consists of limestone with chert interbedded with phosphatic layers and marls.

This aquifer gets recharge at the headwater at Asharah highlands. The other aquifer is the B4 (Um Rijam chert limestone formation), which consists of limestone and chalky limestone of Paleogene (Abed, 2000). The B4 aquifer exists in an independent regional sedimentary basin which overlies the impervious Muwqqar Argillaceous Formation (B3). This aquifer (B4) has water table conditions and receives limited water recharge during occasional flood events (WAJ, 1990).

METHODOLOGY

The methodology is based on integrated hydroclimatic analysis of rainfall data and weather maps of the area. Rainfall data is available for five stations; three are located within the basin in the headwater (i. e., Ras Ennaqab, Qurain and Sadaqa) (Figure1), while two rain gauge stations are found outside and near the basin; one at Rajif in the northweastern corner of the headwater and the other one is located at Ma'an city to the eastern side of the basin (Figure 1). These stations collect accumulative daily rainfall. However, the quality of the data for these stations is dubious because of the poor control, and records have missing data. Still, those records can give an idea about the total annual rainfall and the general trends in rainfall distribution in the area.

Weather maps for both surface and 500mb were accessed through the NOAA web site and analyzed for recent flood events to understand the origin of rainstorm events that generated floods in the region and their subsequent movement (Figure 2).

As is the case for most southern wadies, Wadi Ouhadah has no stream gauge records. Therefore, information on runoff in the area is not available except as anecdotal observations of the local inhabitants. To overcome the problems of the lack of hydrologic data in arid regions, the paleohydrologic technique was applied to investigate the magnitude-frequency of flood history in the subcatchment of Wadi Ouhadah.

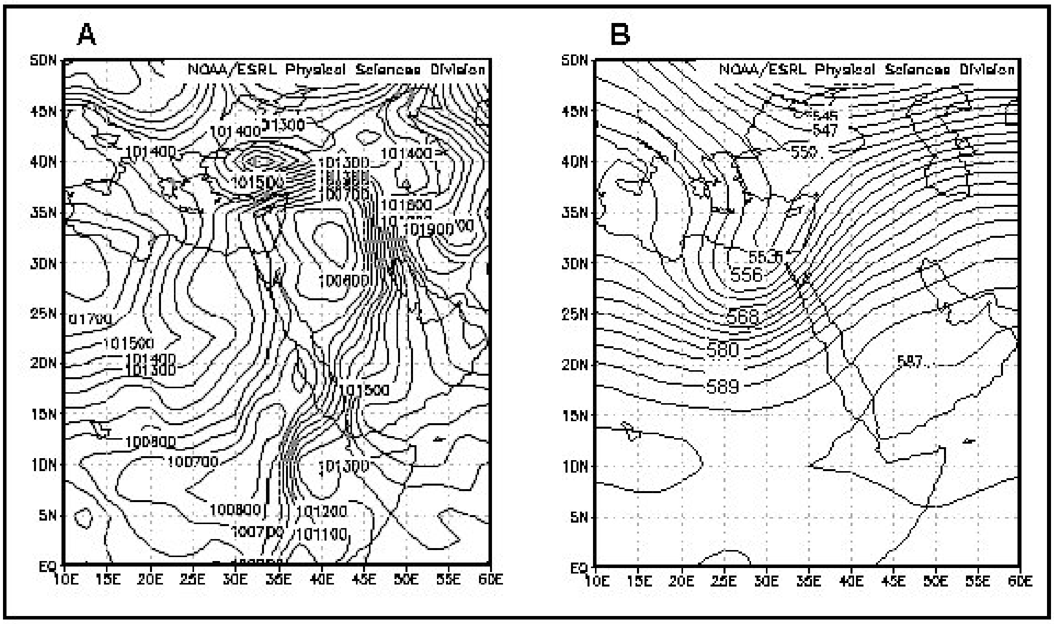

Figure 2: Weather maps of the rainfall event that occurred on February 3,2006 at 00Z(GMT). A) sea level pressure map showing the development of the Red Sea trough and its progression towards north. B) a 500-mb geopotential height showing the upper trough over the Mediterranean (NCAR-NCEP CDAS-1 archive)

The paleohydrologic technique using slackwater deposits (SWDs) and paleostage indicators (PSI) in combination with a gradually varied flow model (HEC-RAS 4) was used to estimate the peak discharges of the most recent floods in the basin. Paleoflood hydrology is defined as the integration of geologic principles, methods and data with those of hydrology, hydraulics, and even climatology for the determination of the magnitude and/or frequency of large floods that have occurred in the absence of direct documentation, observation or instrumentation (Baker, 1987).

Slackwater deposits (SWDs) are fine-grained (usually fine sand and silt) fluvial sediments that are deposited in floodplain areas sheltered from high-velocity flood flows (Kochel and Baker, 1988). A well-preserved SWD site may contain a stratigraphic record of multiple floods, formed by vertical accretion. Individual flow events can be separated using sedimentological criteria (Baker, 1987). Both relative and numeric ages can be often determined from the SWDs. Relative ages of flood deposits can be determined from the stratigraphic relationships, soil pedogenesis and age of buried flood debris such as soda cans and plastic bags… etc. Absolute ages can be determined by radiocarbon dating of organic materials embedded within the flood deposits (Kochel and Baker, 1988).

Paleoflood discharge estimates associated with these floods are determined using a step-backwater model such as HEC-RAS (Hydrologic Engineering Center, 1995). Discharges corresponding to the paleoflood evidence are determined by comparing calculated water surface profiles with the paleoflood evidence (O'Connor and Webb, 1988). Estimated discharges are generally minimal because the deposits accumulate under peak water stages. In this study, step-backwater hydraulic modeling was employed to determine discharge. O'Connor and Webb (1988) discussed the technique behind the step-backwater approach by using the basic energy equation for gradually varied flow:

$$Z_1+Y_1+(\alpha_1 V^2{}_1/2g) = Z_2+Y_2+(\alpha_2 V^2{}_2/2g)+h_L$$

where Z= channel elevation above datum, Y= flow depth, V= flow velocity, α=velocity head coefficient accounting for nonuniform velocity distribution in subdivided channel, g=gravitational constant and h_L=total head loss. The subscripts 1 and 2 represent the upstream and downstream cross-sections, respectively.

The sum of the flow's potential and kinetic energy must equal that of the downstream cross-section less any energy (head) losses between sections. Head loss is subdivided into frictional losses created by elements of flow boundary roughness, eddy losses, channel constrictions and expansion. The constriction and expansion losses are defined by $h_L = K_c\,\{(V^2{}_1/2g) - (V^2{}_2/2g)\}$ *and* $h_L = K_e\,\{(V^2{}_{1/2g}) - (V^2{}_2/2g)\}$, respectively, (reference). The frictional losses are evaluated depending on the variation in the Manning equation $S_f=n^2V^2/R^{4/3}$.

Finally, as Wadi Ouhadah encompasses shallow aquifers along reaches of the main channel, the water table in these shallow aquifers was monitored during the study and found in the range 6-18 m.

FLOOD SYNOPETICS IN SOUTHERN JORDAN

Rainstorms likely to generate floods in Jordan in particular, and in the east Mediterranean region in general, are associated with two dominant synoptic types: the western frontal storms that pass through the Mediterranean Sea and the south convective storms that are mainly influenced by the Red Sea trough (Abu Hussien, 1994; Al-Qudah, 2003; Kahana et al., 2002, 2004; Dayan and Morin, 2006; Greenbaum et al., 2009). The first synoptic type, an active cold front from the Mediterranean which is accompanied with high rainfall depths, is associated with midlatitude extra-tropical cold lows originated over east Mediterranean such as the Cyprus low (Kahana et al., 2004; Dayan and Morin, 2006). This type of cyclone has greater influence on the northeastern parts of the Mediterranean mainly during winter time (December-February). In some cases, when the Mediterranean lows are deepening while approaching Syria (called Syrian Lows), it may intensify and influence the central and southern parts of Jordan and Naqab desert. The Syrian lows are the second most frequent synoptic-scale cyclone type that causes floods in the southern parts of the east Mediterranean (Kahana et al., 2002, 4004).

The second synoptic type is the Red Sea Trough (RST), which accounts for the majority of the floods that occur in southern parts of east Mediterranean (Kahana et al., 2002, 2004). The RST can be defined as a surface low-pressure trough extending from eastern Africa along the Red Sea toward the east Mediterranean combined with upper cold trough in east Mediterranean (e. g., Ashbel, 1938). The influence of the RST on the climate of east Mediterranean Sea has long been recognized as one of the active cyclogenetic systems in the region (Ashbel, 1938; El-Fandy, 1948,1952; Abu Hussien, 1994; Kichak et al., 1997; Greenbaum et al., 1998). This synoptic system penetrates the area from south and dominates the southern and eastern parts of Jordan mainly during fall and spring times (Sharon, 1978; Abu Hussien, 1994; Dayan et al., 2001, Dayan and Morin, 2006).

Abu Hussien (1994) in his study of the major historic witnessed floods that occurred in the past 50 years found that there were at least 7 major historic floods. Six out of the seven floods occurred in the southern part of Jordan, and one in the northern part. Also, he found that all of these floods were combined with climatic conditions that are influenced by the Red Sea Trough (RST), and they were most likely to occur during the transition seasons; fall (October– November) and spring (March-May). Al-Qudah (2003) ivestigated the flood event that occurred in April, 2001 in the northeastern Badia of Jordan, and found that it was also influenced by the effect of the RST and mainly affected the southern and eastern parts of Jordan.

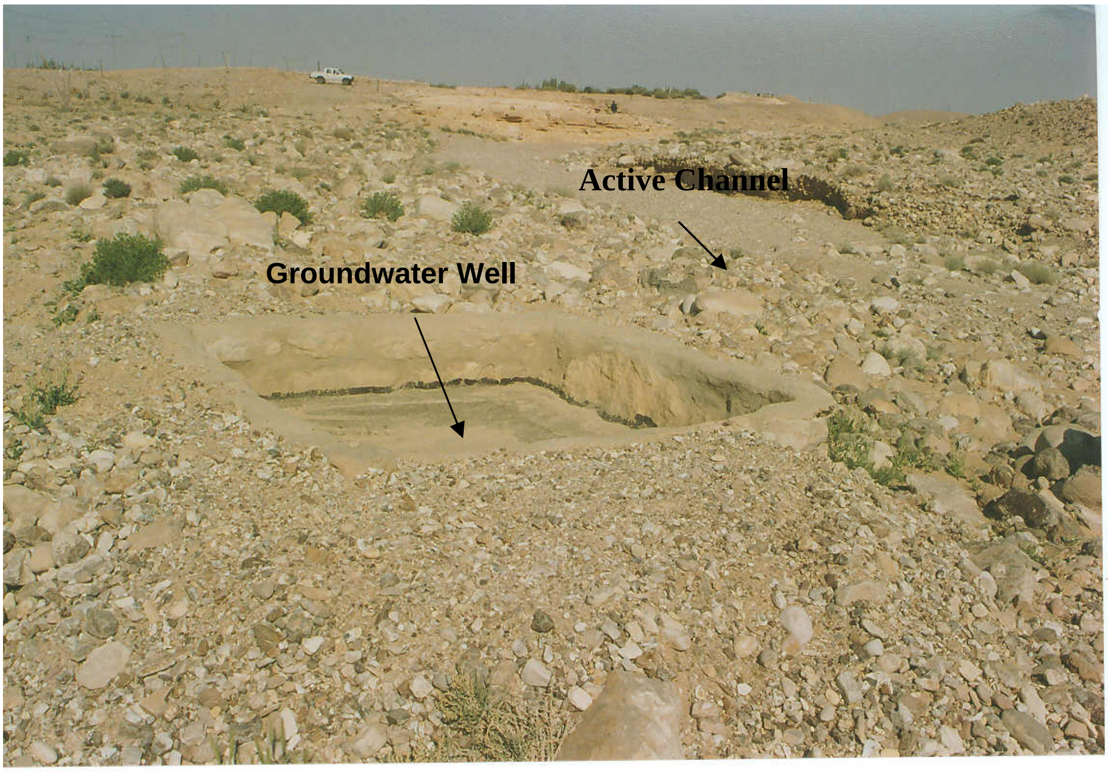

Figure 3: Photograph showing the main channel of Wadi Ouhadah with hand-dug groundwater well in the left bank of the channel, the view is looking downstream

A study on the major floods (floods with recurrence interval > 5 years) in southern Israel, showed that 52 major floods occurred during the period from 1965-1994 (Kahana et al., 2002, 2004). Out of the 52 floods, 37 were associated with two synoptic types. The RST is the most frequent type and accounted for 20 floods, while the Syrian low was the second frequent type and accounted for 17 floods. An example of the sea-level pressure chart for the RST that influences the southern parts of Jordan and Israel is shown in (Figure 2). However, some Red Sea–influenced storms may occur in the winter time (Ziv et al., 2005). Also, the significant storm which resulted in large amounts of rain in southern Jordan and Israel on the 17th of January 2010 was influenced by the RST (personal observation).

RESULTS

Precipitation Analysis

Table 1: Basic statistical analysis of annual rainfall (mm) for Wadi Ouhadah subcatchment during the period from 1963 to 2006

	Ras Ennaqab	Sadaqa	Qurain	Rajif	Ma'an
Average	131. 4	117. 9	145. 7	159. 9	40
Median	120	109. 5	143	152	32. 2
Max.	314	254	345	374	107. 7
Min.	16. 4	15	34	46	12. 2
St. dev.	78. 7	59. 7	66. 7	68. 5	25. 5

Five daily rain gauge stations were situated in or near the Wadi Ouhadah subcatchment; four in the headwater and one downstream at Ma'an (Figure 1). The average annual rainfall at these stations is 132, 146, 118, 160 and 45 mm for Ras Ennaqab, Qurain, Sadaqa, Rajif and Ma'an, respectively. The available overlapped record of operation for the water stations is from 1963 to 2006 except for Ma'an station from 1970-2006. Based on personal observations, the records for these stations must be considered dubious because of the poor maintenance at remote locations. However, in some years, data are missing in some stations and in other years, daily data were accumulated over several days. Therefore, the analysis of daily rainfall data will not be accurate and may indicate misleading results.

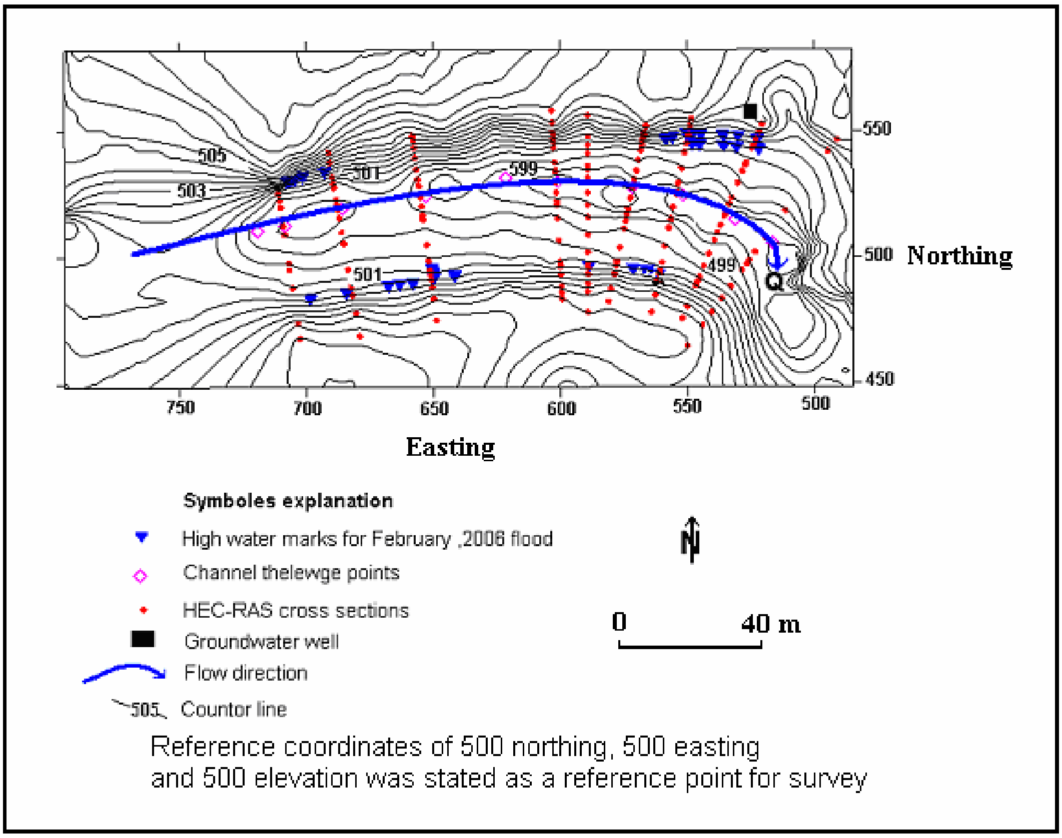

Figure 4: High-resolution topographic map of Wadi Ouhadah used for flood model estimation showing cross-section locations, high water marks and flow direction

Basic statistical analysis of the annual precipitation at the headwater stations is presented in Table 1. The average annual rainfall for the headwater was calculated using Thiessen polygon method (Figure 1) and is estimated to be about 140mm. Correlation between headwater stations shows weak correlation (R<0.25) between Ras Ennaqab and other stations. Positive linear correlation exists between Sadaqa and Qurain (R=0. 66) and positive correlation between Sadaqa and Rajif (R=0. 60). Additionally, positive correlation between Rajif and Qurain (R=0. 75) is found.

The Event of February 2-3, 2006

On February 2-3, 2006, a cold upper trough developed over the east Mediterranean Sea. At the surface, the Red Sea trough developed and extended north to the Mediterranean Sea region. This configuration, termed RST-N (Bar-Lavy et al., 1977), resulted in convective storms over the southern and eastern parts of Jordan (Figure 2). As a result, a low extension over western Jordan was developed. Cold air was injected into the region through the upper trough, and a subtropical jet stream penetrated and brought humid tropical air to the area. This combination of adverted cold air and tropical moisture produced extreme instability and resulted in thunderstorms in the area. Rainfall amounts that were recorded in the stations during the thunderstorm (Table 2) are not compatible with the magnitude of the flood that was caused by this event. This may reflect the convective cell pattern of the rain-bearing cloud.

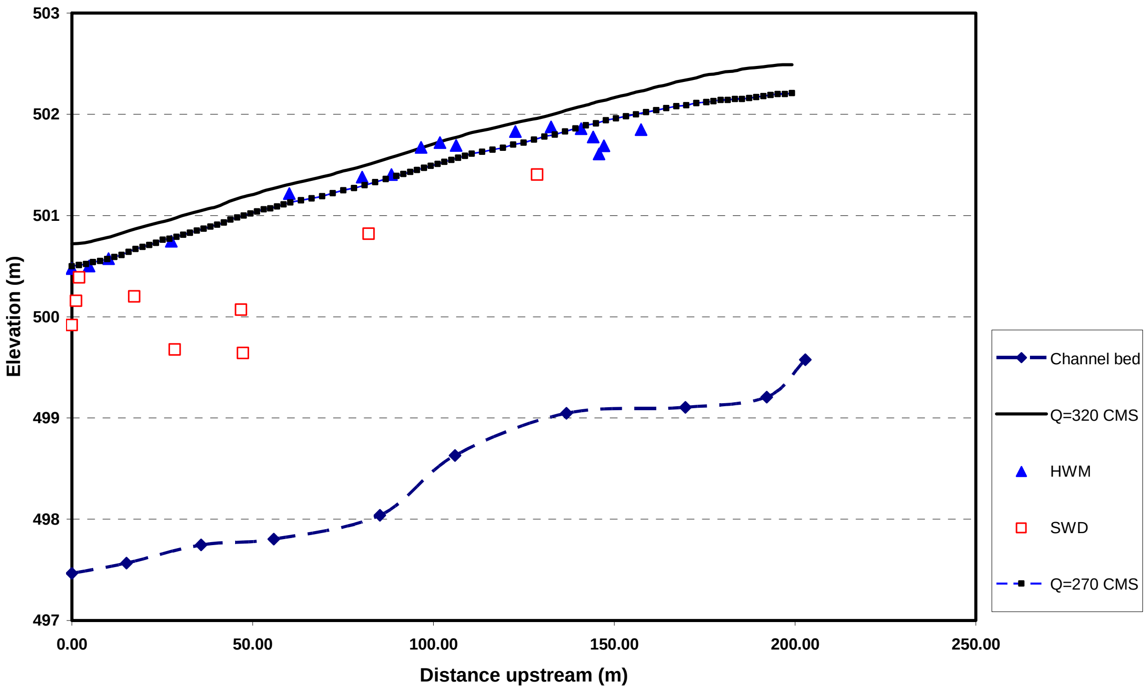

Figure 5: Paleoflood discharge estimates based on the high-watermarks of the February 2006 in Wadi Ouhadah subcatchment. Water-surface profiles were calculated using the HEC-RAS 4 open channel-flow model

Paleohydrology and Flood Study Sites

A detailed survey of Wadi Ouhadah and its tributaries was conducted for evidence of recent floods and paleofloods. Slack-Water-Deposits (SWDs) were found in several locations along the lower reach of Wadi Ouhadah, especially on the confluence of small tributaries with the main channel, also SWDs were recorded on small caves along bedrock walls on the main channel. A 200m reach of the lower part of Wadi Ouhadah main channel was chosen for flood discharge estimation (Figure 3). At this site, the channel has a stable cross section with bedrock wall on some parts of the channel sides. Additionally, it shows SWD and discontinuous line of paleosatge indicators mainly consisting of flood debris of straw, wood remnants and sheep feces. Along this reach, the flow was confined for about 200 m, then the channel abruptly expanded to an increased width of approximately 50 m. SWDs and flood debris were found trapped on bedrock terraces and between boulders on channel sides.

Table 2: Rainfall amounts at Wadi Ouhadah during the February 2-3, 2006 flood event

Rain gauge	Rainfall amounts (mm)
Ras Ennaqab	6
Qurain	14
Sadaqa	12
Rajif	4
Ma'an	9.8

Hydraulic Modeling of Paleoflood Site

A detailed survey of cross-sections, topographic control points, SWDs and high watermarks (HWM) was conducted using a total station instrument. These data were used to produce a high-resolution topographic map (Figure 4). Nine cross-sections were selected for the model of SWDs, high-water marks along the lower reach of Wadi Ouhadah. Using excel sheets, channel cross sections were projected to the slope of end points. The HWM and SWD were projected to the slope of the thalweg points of the reach.

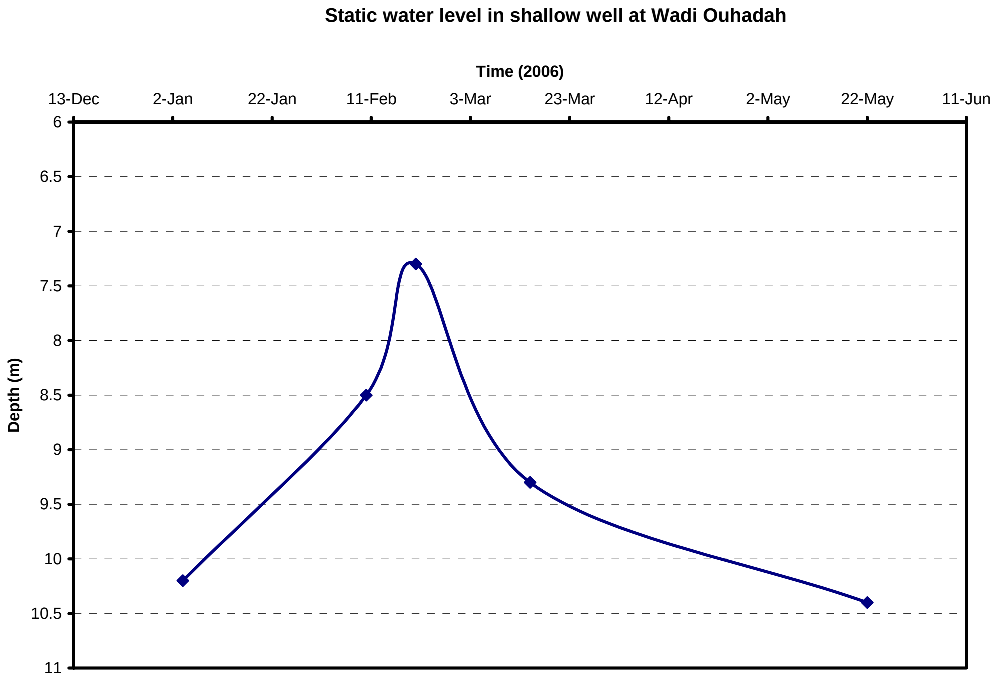

Figure 6: Depth from surface to water level at the shallow well in the lower reach of Wadi Ouhadah

Water surface profiles were estimated using HEC-RAS 4. 0 to best fit the SWDs and high watermarks. The channel bed material ranges from coarse sand to large boulders (Figure 3). Corresponding roughness coefficient values (Manning's n) were selected between 0.035 and 0.05 based on channel characteristics (Chow, 1959). The results indicate that the continuous high watermarks' line along the modeled reach which is believed to belong to the flood event of February 2006 has an estimated peak discharge range from 270 to 320 m^3s^{-1} (Figure 5).

FLOODS AND GROUNDWATER RECHARGE TO SHALLOW AQUIFERS IN THE BASIN

A shallow aquifer is found in the lower reach of Wadi Ouhadah within the Rijam formation which is considered the upper most carbonate aquifer in Jordan. The water table in this aquifer west of Ma'an ranges from 6m to 18m. Many hand-dug wells have been constructed in the area and mostly used for irrigation.

Bearing in mind that transmission losses are high in ephemeral streams, and in an attempt to demonstrate the influence of floodwaters on the recharge of the shallow aquifer, the water table was monitored during the winter of 2006 at the groundwater well dug on the left bank of the modeled channel reach (Figure 3). The total depth of the well depth is 12 meters. Before the first winter storm, the water level (static water level) on December 2005 was 10.2m. One week after the flood event of February 2-3, 2006, the water level rose to 8.5m. On February 20, the water level rose to 7.3m. This was after another rainfall event on February 13-15, 2006. In March 2006, the water level declined to 9.3m and in May 2006, the water table dropped to 10.4m (Figure 6).

DISCUSSION

Floods in arid and semiarid regions are considered the only hydrologic process that generates large volumes of water for surface storage and groundwater recharge into the aquifers (Greenbaum et al., 2009). Therefore, understanding how these floods and their causative precipitation events developed is important. Rainfall events with high intensity in southern Jordan are most likely to result from the influence of Red Sea Trough (RST). RST rainfall events are generated by instability conditions and result in convective rainstorm cells with variable intensity lasting for small durations. During the rainfall event of February 2-3, 2010, for example, the amount of rainfall that was recorded in the study area was low and did not reflect the magnitude of the flood (320m^3/s) caused by this event.

Orographic effect of Asharah Mountains on precipitation in the headwater of Wadi Ouhadah subcatchment is very significant, where it increases the average annual precipitation in the headwater to about 140mm and decreases it eastward to less than 50 mm at Ma'an.

The large surface area of the headwater which represents about 56% of the total surface of the Wadi Ouhadah subcatchment is exposed to a relatively higher orographic rainfall (annual average=140mm). Moreover, the rocky, steep gradient and the low vegetation density in the headwater lead to high runoff coefficients, in addition to the mushroom-shape of the subcatchment that provides a large surface area at the headwater which is elongated south-north and the general orientation of the subcatchment from west to east. This makes the subcatchment fall in the track of both the RST depressions from the south and the frontal depressions from the west.

Since stream gauges were not available in the basin, paleohydrologic techniques (using SWDs and PSIs) in combination with a gradually varied flow model (HEC-RAS 4) were used to estimate the magnitude of recent floods in the basin. The most recent flood in the basin occurred on February 2-3, 2006 and left well-preserved debris lines on the channel sides. The peak discharge of the February 2-3, 2006 flood was estimated using the gradually varied flow model (HEC-RAS 4) to range approximately from 270- 320 m^3/s.

Following the flood event of February 2-3, 2006, the groundwater level at shallow Rijam aquifer in the lower reach of the wadi rose by1.7m, reflecting the rapid recharge caused by the flood events.

As the topography of the subcatchment at Wadi Ouhadah area becomes more flat and the main channel confluences with other channels of adjacent subcatchments near Ma'an city, the hazard of flooding becomes great in Ma'an.

CONCLUSIONS

Surface runoff and flood generation are highly controlled by climatic conditions that affect rainfall intensity and distribution. Flood events in southern Jordan are mainly controlled by the influence of the Red Sea trough and to a less extent by the south deepening Mediterranean fronts. The climatic conditions, geology, geomorphology and geometry of the Wadi Ouhadah subcatchment greatly promote flood generation and pose a very high risk of flooding to Ma'an city. The flood event of February 2-3, 2006 was caused by the influence of RST. Slackwater deposits and paleostage indicator technique incorporated with gradually varied flow model (HEC-RAS) were used to estimate the peak discharge of the February 2006 flood, which was found to be in the range of 270 to 320 m^3/s.

Flood water is contributing to rapid recharge to the shallow aquifer along the lower reach of Wadi Ouhadah subcatchment. However, flood water of Wadi Ouhadah represents a high risk for Ma'an city, therefore flood control on Wadi Ouhadah upstream of Ma'an city is highly necessary.

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