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Flash Flood Assessment for Wadi Mousa City-Jordan*

Abstract

This paper aims to assess risks due to potential Flash Floods hazards in Wadi Mousa and to determine the magnitude of flows for flash flood hazards and construct Floodplain Zone maps for the selected flood return periods of 25, 50, 75 and 100 years. Wadi Mousa is considered an ephemeral wadi with intermittent flash flood of flows that can exceed the 298 m^3/s threshold. Its floods, however, do not flow every year. Nevertheless, at certain years the extent of flood can be huge. The surface drainage may be broadly divided into sub-catchments according to drainage namely; Wadi Als-Sader, Wadi Jelwakh with Wadi Khaleel, Wadi Al-Maghir. Wadi Zarraba is the confluence of the three sub- catchments. The study covers an area of 53.3 km^2 and comprises a high semi -arid infrequent flash floods generated by heavy rainstorm over the catchment and flows to Wadi Araba. Average annual rainfall of Wadi Mousa was calculated of 178 mm, and average annual evapotranspiration is 1300 mm per year. The runoff analysis indicates that only rainfall events exceeding 22 mm within the 24 hour period would generate runoff.

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Keywords: Flash Flood; Flood plain; Catchment; Rainfall

1. Introduction

Flood Risk analysis provides a rational basis for flood management decision-making at a national scale and locally. National-scale flood risk assessment can provide consistent information to support the development of flood management policy, allocation of resources and monitoring of the performance of flood mitigation activities, (Hall, J. W., et al. 2003). Wadi Mousa has a notorious history of extreme floods that had caused serve damage to the installations located in its floodway and considerable distances downstream.

As documented in most of the available studies (e.g., Electricite de France, EDF 1995), the flood that occurred in April, 1963 was an extreme event, probably with a 100-year return period (Al-Weshah, R. and F. El-Khoury, 1999).

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During this extreme event, the intense and sudden rainfall caused flood water to flow from all wadis into Wadi Mousa outlet. The flood carried a huge sediment load which blocked most of the hydraulic structures in the wadi. The dam at the entrance of the Siq was filled with sediment; consequently, flood water overtopped the dam and entered the Siq. Despite the great emergency efforts, twenty French tourists lost their lives (Al-Weshah, R. and F. El-Khoury, 1999).

In 1991 another flood, one probably of a 50-year or so return period, washed away two culverts upstream of the Siq and caused a serious problem for visitors and tourists. Although the flood water did not enter the Siq, traces of high water within Wadi Al-Matahah indicated that the water level reached an elevation of more than 12 m above the wadi bed. Other recent major floods in Petra occurred in January, 1995 and November, 1996. During these events, the Siq entrance area was flooded and tourists had to be rescued. In more recent times, many deaths have recorded in the same area (Al-Weshah, R. and F. El-Khoury, 1999). Therefore; floods and flash floods have historically caused a major threat to the Wadi Mousa City. Due to this, hydrologists ranked it as the wadi with the highest risk/damage in Jordan. Geomorphologic investigation in the wadi bed can easily prove that. Wadi Mousa is considered an ephemeral wadi with intermittent flash floods of flows that can exceed the 298 m3/s threshold. Its floods, however, do not flow every year (historical data for Wadi Mousa shows that 4 water year out of 22 was zero flow). Nevertheless, at certain years the extent of flood can be huge (2.42m3/sec daily discharge in January 1964). Its floods may be hydraulically categorized as a hybrid of debris and turbid flows.

Nomenclature

Mcm	Million Cubic Meters	**Cfs**	Cubic feet per second
IDF Curve	Intensity Duration Frequency Curve	**Q**	Discharge
$\overline{X}$	The mean value of the samples	$\overline{Y_n}$	The reduced mean
K	The frequency factor	T_c	Time of concentration (Hours)
σ_{n-1}	The standard deviation of samples variable	T_p	Time of the peak (hours)
P	Storm rainfall (mm)	**A**	Area in square mile
I_a	Initial abstraction	S_n	The reduced standard deviation
Y_{Tr}	The reduced variate		

1.1. Study Area

Study area covers an area of 53.3 km^2 and comprises a high semi -arid infrequent flash floods generated by heavy rainstorm over the catchment and flows to Wadi Araba. The catchment area is considered small by Jordan standard and the total watershed area amounts around 80 km^2 of which only 53.3 km^2 is effectively contributing to the floods upstream of Wadi Mousa city as shown in figure(1:a).

2. Methodology and Approach

Ten locations of the flood flow were determined to detect the drainage boundary of the watershed, figure (1:b). A properly flood risk protection requires a well-designed drainage system, therefore; depending on the extent and magnitude of flood; it is decided to conduct an integrated computerized hydraulic open channel model to determine the flood water level and discharge at every tributary of the critical reach rather than estimating the discharge magnitude and water level depth at sign locations. This requires a determination of the quantity of runoff reaching the drainage structures and an accurate analysis of water flow through the structures in order to properly size them. HAESTED (FLOW MASTER) Software's was customized to estimate the results.

Data from various sources were collected in order to have a representative and homogenous information about the catchment of the study. Unfortunately, no data regarding the instantaneously of flood runoff flow is available for Wadi Mousa. For this purpose, all the available information in terms of meteorological rainfall, topographical maps and flood flow records were used in the conjunction with the best available tools to estimate the surface runoff. The raw data which has been created by the Ministry of Water and Irrigation were collected and revised. Other sources of data were collected from "GTZ und Agrar, and Hydrotechnik", 1977, in cooperation with Natural Resources Authority, who prepared a National Water Master plan for Jordan study. Hydrological parameters related to most of the basins in the country were estimated and calculated. The average annual rainfall over catchments is 225 mm and runoff coefficient of 1.2%, with average annual flood flow of 0.24 mcm (JMD, 2012). And from data analysing for flood flow the average runoff of Wadi Mousa at culvert of 0.63 mcm per year with the mean annual rainfall over sub-catchment of 35.47 mcm. Hence, given the catchment area of 21.4 km^2, the mean runoff coefficient is calculated. The collected raw data are subjected and treated by different approaches and statistical techniques to determine the important factors in the examination of the quality.

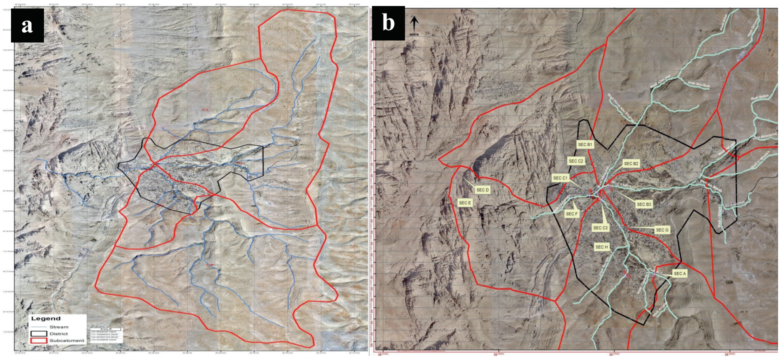

Figure 1: (a)Wadi Mousa watershed and Sub-Catchment area
(b)Location of the selected cross sections

3. Drainage area

The surface drainage of the study area may be broadly divided into three sub-catchment according to drainage namely; the biggest tributary is Wadi Als-Sader sub-catchment, the second is Wadi Jelwakh with Wadi Khaleel sub-catchment and the third is Wadi Al Moghare sub-catchment. Wadi Zarraba is the confluence of the three sub-catchments and represent about 53.3 km^2. All tributaries of Wadi Mousa is ephemeral except Wadi Als-Sader, a small amount of water from Als-Sader spring can be seen in the Wadi course all the year Figure(2:a).

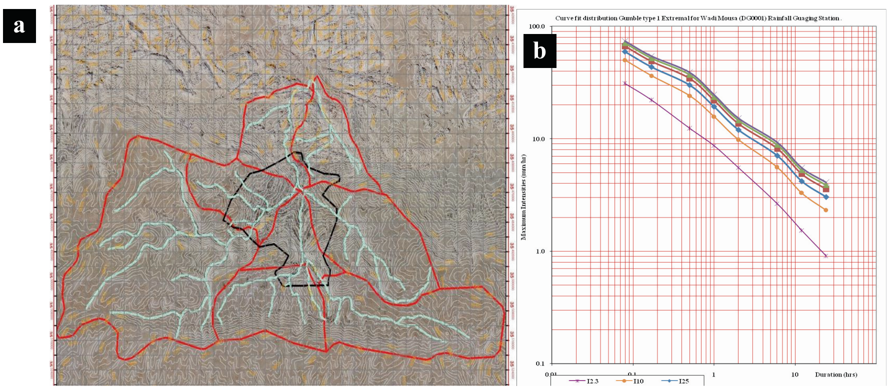

Figure 2: (a) Wadi Mousa sub-catchments and drainage system. (b) IDF curves for Wadi Mousa

4. The Unit Hydrograph

The unit hydrograph theory, which is based on the property of proportionality and the principle of superposition used in this study to determine the peak discharge and its magnitude values. The results obtained by applying these applications (average runoff is 0.63 mcm per year, average rainfall is 35.47 mcm, average runoff coefficient is 2.3%) are acceptable for hydrological simulation purposes.

For each individual storm, the effective rainfall is calculated by applying the constant loss rate method. Therefore, the effective rainfall could be taken as input parameters to calculate the unit hydrograph by applying the matrix inversion method. The effective rainfall should be calculated preliminary to calculate the runoff discharge. To calculate the effective rainfall, the Intensity- Duration- Frequency Curve, (IDF Curve) was created as shown in Figure (2:b).

Using the annual duration series is common in the probabilistic approach of analysis due to the presence of a theoretical basis for extrapolating annual series beyond the range of observation and the return periods, (Tr), of 25, 50,75 and 100 years. The data is analysed to establish the best fit for the sequences of random variables. So the 100-year line would represent rainfall events that have a probability of occurring once every 100 years. The event, which is expected to occur on an average once every N- year or XTr which can be computed by using Gumbel distribution of extreme (1958) given by equation (1):

$$X_{Tr} = \overline{X} + K^{\sigma_{n-1}} \tag{1}$$

Where; X_{Tr}: The magnitude of event reached or exceeded on average once in *Tr* years, $\overline{X}$: The mean value of the samples, K: The frequency factor, σ_{n-1}: The standard deviation of the variable of the samples.

The K is a function of the reoccurrence interval (return period), Tr, is given by Gumbel, (1958). In this approach using extreme value distribution, therefore, the maximum annual floods for the generalized data from the rainfall storms are assumed to be distributed in accordance with the distribution of extreme values. The K values are calculated by using equation (2) as given by Gumbel (1958):

$$K = \frac{Y_{Tr} - \overline{Y_n}}{S_n} \tag{2}$$

Where; $\overline{Y_n}$: the reduced mean, S_n : the reduced standard deviation, Y_{Tr}: the reduced variate.

The (Y_{Tr}) parameter related to the return period is calculated by equation (3) given by Gumbel (1958) as follows:

$$Y_{Tr} = -\left[\ln\left(\ln\frac{T_r}{T_r - 1}\right)\right] \tag{3}$$

After calculating values of (Y_{Tr}) and use to calculate the (K) values of ($\overline{Y_n}$) and (S_n) for the selected return periods and then substituted in the extreme equation to compute the (Y_{Tr}). The short rainfall duration for the computation of (Y_{Tr}) has been transformed into the corresponding intensities (mm/hr), Table (1).

Table 1: Results of rainfall intensities calculation for selected return period

Return period in Year	0.33	0.5	1	2	6	12	24
25	50.07	36.37	24.16	15.76	9.83	5.60	3.31
50	59.63	43.54	30.08	19.33	12.00	7.08	4.20
75	66.72	48.86	34.47	21.98	13.61	8.19	4.86
100	70.84	51.96	37.02	23.52	14.55	8.83	5.25

Rainfall intensity can be calculated using equation (4).

$$I = a \times Tb \quad (4)$$

Where; I : The intensity of rainfall in mm/hr, T : The duration in hours (1, 2, 3...), a, b : coefficients for the IDF equation of rain gauging station

By applying the equation (4) and use the best fit line, the regression equations were obtained, Station coefficients for the IDF equation (a and b) are determined for each site for the selected years return period. The rainfall increment was calculated. The intensity of the rainfall is obtained by apply this equation.

5. Estimation Of Peak Discharge

Characteristics of the watershed area directly affect the hydrologic analysis. Basic features of the watershed basin include size, shape, slope, land use, soil type, storage, and orientation. The size of the watershed basin is the most important characteristic affecting the determination of the total runoff. The shape of the watershed primarily affects the rate of water flow to the main channel. Peak flows may be reduced by the effective storage of drainage water. The geometric characteristics for each sub –catchment were identified to be used to calculate the time of concentration, time to base and other parameters that will be used later on in Unit Hydrographs.

High relief and slope of wadi bed were calculated for each sub-catchment in feet (then it is converted to meters) from map for all sub-catchment. Area in square miles (then converted to square kilometres) were determined. The information obtained from this calculation was used to estimate the peak of runoff for each of the sub-catchment in this study.

6. Hydrological Model Construction

Hydrological Model was constructed to determine the flood risk according to the runoff in the main tributaries of Wadi Mousa. The following procedure was adopted to construct a hydrological model for Wadi Mousa watershed.

To estimate peak discharge by using the Hydrologic Model for Wadi Mousa watershed, the sub- catchment parameters were determined based on the available Drainage Elevation Map (DEM), calculated and stored in the sub-catchment tribute Table (2).

Table 2: Hydrologic characteristics of the selected cross section in the study area.

	Hydraulic Length (L)	Hydraulic Length (L)	Elevation difference (H)	Average Slope	Drainage Area (A)	Drainage Area (A)
	km	mile	Feet	%	km^2	$(mile)^2$
Wadi JelwakhSec-B2	9.78	6.1	20993	3.4	18.9	7.30
Wadi Als-Sader sec -A	9.3	5.7	1968	4.0	26	10.04
Wadi Als-Sader sec- G at C3 cross section) at Culvert	9.3	5.7	1968	4.0	26	10.04
Wadi Al Magher Sec-B3	6.95	4.3	1706	4.9	8.4	3.24
Wadi Khalil Sec- B1	7.0	4.3	2099	4.9	27.3	10.5
Wadi Khalil Sec- C1	7.0	4.3	2099	4.9	27.3	10.5
Wadi Zarraba inlet Cross Sec -C2	7.0	4.3	2099	3.5	53.3	20.6
Wadi Zarraba outlet Sec -F	7.0	4.3	2099	3.5	53.3	20.6

To determine how the runoff is distributed over time, a time-dependent factor must be introduced. The time concentration, (Tc), which is the time required for the most remote drop of water to reach the outlet of the watershed were calculated using Kirpich's Formula given by equation (5). The (Tc) mainly depends on the length and elevation difference between the highest and the lowest point of the flow path.

$$T_c = \left(\frac{11.9 \times L^3}{H} \right)^{0.385} \tag{5}$$

Where; T_c: Time of concentration (Hours), L: Hydraulic length (mile), H: elevation difference (feet)

The time of peak (T_p) is calculated by the given equation (6)

$$T_p = \frac{D}{2} + 0.6 \times T_c \tag{6}$$

Where; T_p : Time of the peak (Hours), D : Duration equal 1 hour

Peak discharge can be calculated from equation (7)

$$Q_p = \frac{484 \times A}{T_p} \tag{7}$$

Where; 484: constant value, Q_p: Peak discharge of the unit hydrograph (cfs) , A : area in square mile

According to the hydrological parameters of the watersheds it can be concluded that the estimated values of the peak discharge in the outlet of Wadi Mousa catchment could be reached 297 m^3/sec which is the peak discharge for wadi cross section B2, A, B3, and B1

7. Rainfall-Runoff Model Approach

There are two basic components to modelling flash flood scenarios. The first component is to convert rainfall into run-off and the second is to determine how that run-off will route to the catchment outlet. The SCS-curve number (CN: 0-100) method is used to establish the initial soil moisture condition and the infiltration characteristics. In this study, CN of 70 was chosen where the standard SCS curve number method is based on the following relationship between rainfall depth, p, and runoff depth, Q:

$$I_a = 0.2 \times \left(\frac{1000}{CN} - 10 \right) \times 25.4 \quad \text{in (mm)} \tag{8}$$

Where; I_a : Initial abstraction (I_a : 0.2S)

The initial abstraction (the losses due to infiltration and storage into depressions) has been calculated for the selected year return periods of 25, 50, 75 and 100 by using equation (8). The excess rainfalls that will flow into sub-catchments were calculated by using equation (9).

$$Q = \frac{(P - 0.2S)^2}{(p + 0.8S)} \quad \text{for } P>0.2S\text{; otherwise } Q=0 \tag{9}$$

Where; Q: the surface runoff (mm), P: storm rainfall (mm), S: the soil retention (mm)

The potential retention (S) and the initial loss (I_a) were computed and the results of the calculation were of 109 mm and 22 mm respectively. These values were used in the Hydrological model for Wadi Mousa watershed.

8. Calculations Of Flood Hydrographs and Discharge

The intensity of rainfall was obtained from the Wadi Mousa Autographic rain gauging station IDF curve for the selected year return periods: 25years, 50 years, 75 years and 100 years.

Computation of the flood discharge using the effective rainfall of 25, 50, 75 and 100 year return periods for Wadi Mousa sub-catchments were performed. The total discharge values in MCM that obtained from the calculation of 1.02,1.18, 1.91 and 2.52 MCM for the selected year return periods of 25, 50, 75 and 100 years respectively were used as input in FLOWMASTER software to calculate the water level at the selected sites.

9. Flash Flood Hazard Scenarios

Heasted Model (FLOWMASTER Model) was identifying model to be used for the calculations the water level of the antecedent floods in the selected wadi courses. The flow regime in the 100-year flood in Wadi Mousa is supercritical type, where the normal water surface elevation is lower than the critical water elevation. It means that any major obstacle in the wadi channels will result in hydraulic jumps increasing the depth of flow to subcritical levels with a potential to reach depths of about 2 to 4 meters further risking the road. At supercritical regime, the depths ranged from a minimum of 2 meters to a maximum of about 4.65 meters of critical depth. The 100-year flood velocities have extremely high values of 12.3 m/s and the flood values as calculated in this study can reach of 298 m^3/sec at Wadi Mousa outlet.

10. Runoff Frequency Analysis

It is attempting in this section to evaluate the frequency and magnitude of the flood flow at the selected sites. The approach that used the daily series of the flood magnitude occurred in each water year is very common approach in hydrological studies.

The runoff analysis indicates that only rainfall events exceeding 22 mm within the 24 hour period would be generate runoff. All the rainy days that have values over the calculated threshold value of 22 mm which was calculated previously were used in this section. The series values that obtained from flood magnitude are ranked in the order of descending magnitude. The reoccurrence time period T_r of a given event is the average number of days within which the event is expected to be equal or exceed, Chow (1964). There are several methods to determine the T_r, the most common method used is given by Weibull's equation (1939) as:

$$T_r = \frac{(n+1)}{m} \tag{10}$$

Where; T_r : is the return period of n-year event, n : is the number of years of record, m : is the rank of the item on the series and m is being one for the largest.

11. Discussion, Conclusions And Recommendations

Hydraulic cross sections for the selected sites accompanied with the analyses of long-term rainfall data and flood flow discharge measurements showed that Wadi Mousa sub-catchments have experienced several floods. The analysis and computation of the flood hydraulic properties reveal that parts of the watercourse will be submersed in the 25, 50, 75 and 100-year of flood return periods and the surrounded area may be exposed to excessive flood velocities, putting the neighbour land at high risk.

Little correlation between the measured and the estimated runoff was found due to the non-homogeneity between the rainfall records and the flow records. Calculated runoff coefficients based on measured flood reveal low runoff coefficient compared with the rainfall only of 2.3 %. This could be due to the limited number of storms that are greater than the initial abstraction, the nature of Wadi Mousa watershed.

According to results obtained from unit hydrograph calculation, the Floodplain Zone in the main water paths were determined with the aid of ArcGIS software. Floodplains are geographical areas within which the likelihood of flooding is in a particular range. There are four types or levels of floodplains were defined for the purposes of this study as follows:

- 25 year Floodplain Zone where the probability of flooding from the wadi is highest (greater than 4% or 1 in 25 years), as can be seen in Figure (3a). Two Geo- units are considered as high probability of flooding. Geo-Unit 474 and 226 the first land used is commercial and the second is residential development. Most types of development would be considered inappropriate in this zone. Development in this zone should be avoided.

- 50 year Floodplain Zone Moderate probability of flooding (greater than 2% or 1 in 50 years) as can be seen in Figure (3b). Three Geo- units are considered as high probability of flooding. Geo-Unit 226, 273 and 474 the first land used is commercial and the second is residential development. Highly vulnerable development, such as hotels, buildings, markets, would generally be considered inappropriate in this zone.

- 75 year Floodplain Zone low -Moderate probability of flooding (greater than 1.5% or 1 in 75 years) as can be seen in Figure (3c). Six Geo- units are considered as high probability of flooding. Geo-Unit 247, 325, 397as well as the unit mentioned in 50 year Floodplain Zone. The land used for these units are commercial, agriculture, tourist and tourist investment respectively.

- 100 year Floodplain Zone (1% or 1 in 100 years). Low probability of flooding as can be seen in Figure (3d). Seven Geo- units are considered as high probability of flooding. Geo-Unit, and, 438, 473, 474, 485 as well as the units that mentioned in 75 year Floodplain Zone. Land used for these units are commercial, agriculture, tourist and tourist investment respectively. Development in this zone is appropriate from a flood risk perspective.

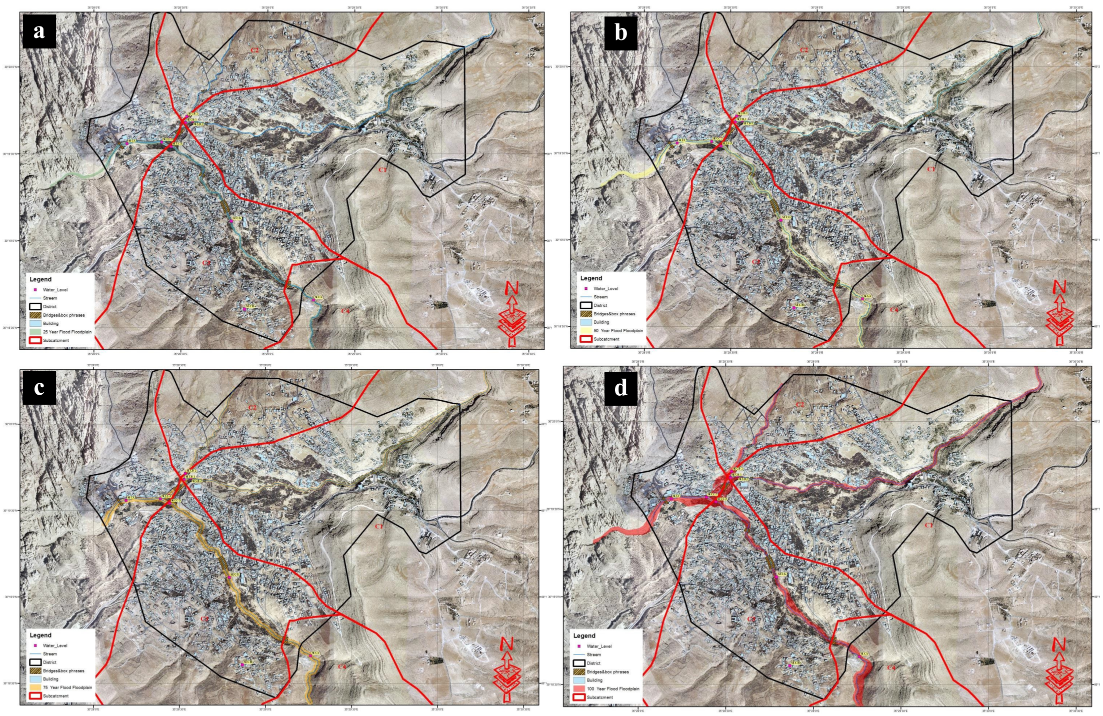

Figure 3: Floodplain Zone of Wadi Mousa watershed (a) 25 year (b) 50 year (c) 75 year (d) 100 year

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