

FLOOD ANALYSIS AND MITIGATION FOR PETRA AREA IN JORDAN

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ABSTRACT: Petra is located in the southwest region of Jordan about 200 km south of Amman, between the Dead Sea and the Gulf of Aqaba. Petra was carved in sandstone canyons by the Nabatean over 2,000 years ago. Today the city is a major tourist attraction, its monuments being considered the jewels of Jordan. Floods pose a serious threat to the tourist activities in Petra as well as to the monuments themselves. In this paper, a flood analysis model developed and calibrated for the Petra catchment is described. Using the model, flood flows and volumes are estimated for storm events of various return periods. To alleviate the impact of floods on tourism in Petra, several flood mitigation measures are proposed. The impact of these measures on flood peakflow and volume is evaluated. These include afforestation, terracing, construction of check and storage dams, and various combinations of these measures. The flood simulation model predicts that the measures can reduce flood peakflows and volumes by up to 70%.

INTRODUCTION

The Petra region is located in the southwest of Jordan, between the Dead Sea and the Gulf of Aqaba. It lies in the Sherah Mountains overseeing Wadi Araba in the Jordan Rift Valley, at latitude of 30° 20' North and longitude of 35° 27' East and at an average elevation of 950 m above mean sea level. It lies in an arid zone about 100 km north of the Gulf of Aqaba and 200 km south of Amman.

Petra, which is a greek word for rock, is a major tourism attraction for both its beauty and its silent aura. The colorful red-hued sandstones of the rocks have dubbed it the "rose rock city." All the monuments of Petra are concentrated in the lowest part of the drainage area where many water courses (wadis) meet. The main wadi is Wadi Musa (River of Moses), after which the town adjacent to Petra took its name. Most of these monuments were built and carved by the Nabatean Arabs over 2,000 years ago in sandstone canyons that are protected by limited and very narrow accesses, like gorges. The main access gorge, a narrow passage bound by high cliffs, is called the Siq. In most places this Siq is only a few meters wide and more than 60 m high. Its has an average bed slope of about 5%. When a heavy-rainfall storm occurs several kilometers upstream it may still be hot and dry in the downstream area. As a flood wave progresses, both the Siq and several monuments of Petra may be inundated without what is considered adequate warning. To control such floods, the Nabateans constructed a dam at the entrance of the Siq and a tunnel to divert flood waters away from the Siq. Fig. 1 shows the general layout of the Petra catchment area.

Historical records and other events concerning flash floods threatening Petra have shown that flood protection and mitigation measures are urgently needed to protect tourists and the existing monuments. These measures should be implemented only after a detailed hydrological analysis and assessment. With careful consideration for the unique nature of Petra, alternative measures should be evaluated to assure that they will not negatively affect the monuments.

As documented in most of the available studies (e.g., Electricite de France, EDF 1995), the flood that occurred in 1963

was an extreme event, probably with a 100-year return period. During this extreme event, the intense and sudden rainfall caused flood water to flow from all wadis into the main wadi upstream of the Siq. The flood carried a huge sediment load of loose silt and sand 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 instead of being diverted through the tunnel of Wadi Al-Mudhlim. Eyewitnesses stated that the flood water depth was about 10 m in some areas of the Siq passage. Despite the great emergency efforts by different authorities in Jordan, it was impossible to rescue all the tourists trapped in the Siq—twenty lost their lives in that flood.

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 tourists. Although the flood water did not enter the Siq, traces of high water within Wadi Al-Matahah (to which the diversion tunnel of Wadi Al-Mudhlim discharges) indicated that the water level reached an elevation of more than 12 m above the wadi bed. Flood flow made crossing the wadi within the archaeological area very difficult. The monument of "Qasr El-Bint" at a site downstream of the Siq was also flooded. 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. The relevant authorities are doing their best to mitigate flood risks in the Siq.

CLIMATE AND RAINFALL

The Petra region belongs to the Mediterranean climatic zone. The average annual precipitation is around 200 mm. Most rainfall is concentrated between October and April and is mainly of orographic origin.

A meteorological station located in the Wadi Musa area was installed in 1984, and is operated by the Meteorological Department of Jordan (MDJ). Seasonal mean temperatures at Petra vary from 6°C in January to 22°C in July. The maximum temperature in summer may reach 39°C, while the minimum temperature in winter is slightly below 0°C. Dominant winds in the area are from west and southwest. The average daily evaporation is about 6.8 mm. The reported highest evaporation rate is 9.8 mm/day in June, while the lowest rate is 3.6 mm/day in December. At the Wadi Musa area, the annual average sunshine duration is 8.6 h/day ranging from 11.6 h in summer to 5.6 h in winter. The annual average relative humidity is 49.9%, ranging from 62% in winter to 45% in summer (MDJ 1995).

There are three rainfall gauging stations in the Wadi Musa watershed. These stations, designated DG1, DG2, and DG3, are operated by the Water Authority of Jordan (WAJ). Annual total rainfall records are available for these stations since 1937,

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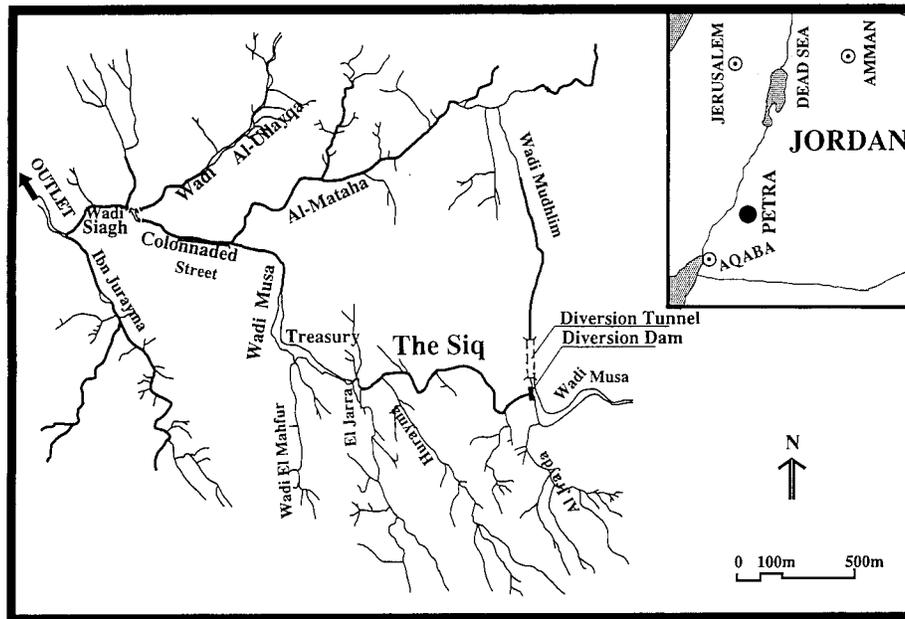


FIG. 1. General Layout of Petra Watershed in Jordan

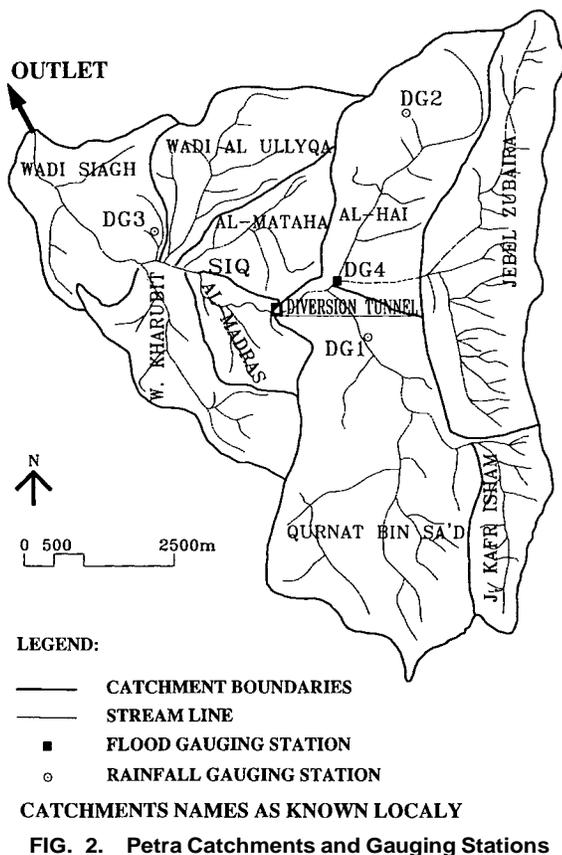


FIG. 2. Petra Catchments and Gauging Stations

and daily total rainfall records are available since 1980. Locations of these meteorological stations are shown in Fig. 2.

DESCRIPTION OF CATCHMENTS

The overall Petra catchment has an area of about 50 km². This catchment, which is upstream of Wadi Siagh before its confluence with Wadi Seg El-Ghurah, can be divided into nine subcatchments, as shown in Fig. 2. It was observed during a site visit to the project area that the spatial distributions of rocks and soil cover among the subcatchment areas are quite similar. Two main lithological units were identified. The

Ajloun formation, which consists of marl-limestone alternation outcrops in the northern side of the line between Wadi Baida and Taybeh, and Wadi Musa. This formation forms a dendritic drainage pattern in the soils of the upstream tributary areas. In the downstream areas, Kurnub, Disi, and Umm Ishrin sandstone formations have barren outcrops.

Marl and limestone alternations could be characterized as among the more permeable materials due to the shallow topsoil cover and open fracture system in the limestone. However, barren sandstone cliffs seem to be relatively less permeable, allowing more surface water to flow along creeks and wadis.

The physical characteristics of each of the nine subcatchments in the Petra catchment are described below.

1. **Jebel Zubaira Catchment:** The area of the catchment is about 1390 ha, and the difference in elevation is 320 m over a distance of 6 km. The upper part of the catchment, which forms about 70% of the catchment area, is located at the Cretacian limestone plateau, with some soil cover and sparse vegetation. The lower catchment is dominated by Paleozoic sandstone with no soil cover and no vegetation.
2. **Kafr Is-ham Catchment:** The catchment area is about 430 ha, and the difference in elevation is 200 m over a distance of 3.5 km. It is dominated by the high Cretacian limestone plateau, with some soil cover and sparse vegetal cover.
3. **Al-Hai Catchment:** The catchment area is about 1075 ha, and the difference in elevation is about 560 m over a distance of 6.25 km. The upper part of the catchment, which forms about 60% of the catchment area, is dominated by the limestone plateau, with some soil cover and sparse vegetation. The lower catchment is dominated by a sandstone with no vegetal cover.
4. **Qurnat Bin Sa'd Catchment:** The area of the catchment is about 2110 ha, and the difference in elevation is about 540 m over a distance of 8.75 km. The upper part of the catchment, which forms 65% of the catchment area, is dominated by limestone, with a soil cover and sparse vegetation. The lower catchment is dominated by a steep sandstone with no vegetal cover.
5. **Al-Mataha Catchment:** The area of the catchment is about 420 ha, and the difference in elevation is about

260 m over a distance of 3 km. The catchment is dominated by sandstone with shallow soil cover in some parts and wide areas lacking any soil cover. In this catchment, Wadi Al-Mudhlim tunnel diverts flood water from entering the Siq. An old Nabatean dam was constructed near the Siq entrance to prevent flood water from entering the Siq and to divert water through Wadi Al-Mudhlim tunnel to this catchment.

6. Al-Madras Catchment: The area of the catchment is about 390 ha, and the difference in elevation is about 200 m over a distance of 3 km. This catchment is dominated by sandstone, with no significant soil cover.
7. Wadi Al-Ulyqa Catchment: The area of the catchment is about 700 ha, and the difference in elevation is about 500 m over a distance of 5.5 km. This catchment is dominated by a sandstone lithology, rocky and very steep, with no soil and vegetal cover.
8. Wadi Kharubit Ibn Joraimah Catchment: The area of the catchment is about 690 ha, and the difference in elevation is 500 m over a distance of 5 km. The catchment is dominated by a sandstone, with no soil and vegetal cover.
9. Wadi Siagh Catchment: The area of this catchment is about 780 ha, and the difference in elevation is 500 m over a distance of 4.25 km. The catchment is dominated by a sandstone, with no soil cover and very poor vegetal cover.

FLOOD ANALYSIS

The *time of concentration* (T_c) of each catchment is defined as the travel time in minutes for a drop of water to travel from the hydraulically most distant point of the watershed to the gauging point downstream (Chow et al. 1988). It is estimated using the United States Soil Conservation Service (now called the Natural Resources Conservation Service) method with a proper adjustment factor for each catchment (SCS 1986). The *lag time*, which is the time interval between the midpoint of excess rainfall to the time of peak discharge of the flood hydrograph, is estimated to be 0.6 of T_c according to the SCS method. The SCS method is chosen in this analysis because data is scarce, the method is convenient to use, and the goal of the preliminary assessment does not involve the design of hydraulic structures that could be a danger to life and property. Additional data from monitoring of the catchment would be required for design purposes.

For each catchment a runoff curve number (CN) was selected, based on the SCS method (SCS 1986), taking into consideration the catchment characteristics, which include antecedent moisture conditions, type of soils, initial abstraction of rainfall, slope and length of the longest channel, watershed

TABLE 1. Summary of Catchments Characteristics for Petra Watershed

Catchment number ^a (1)	Catchment name (2)	Area (km ²) (3)	Average slope (%) (4)	Weighted CN (5)	Lag time (h) (6)
A1	Kafr Isham	4.30	5.7	80	0.76
A2	Qurnat Bin Sa'd	21.11	6.2	81	1.50
A3	Al Hai	10.75	9.0	81	1.00
A4	Jebel Zubaira	13.90	5.3	75	1.19
A5	Al Madras	3.90	6.7	91	0.66
A6	Al Mataha	4.20	8.7	91	0.60
A7	Wadi Kharubit	6.90	10.0	91	0.96
A8	Wadi Al Ulyqa	7.05	9.1	91	1.02
A9	Wadi Siagh	7.90	11.8	91	0.67

^aCatchment numbers as used in Fig. 3.

boundaries, urbanization, and land cover (Ponce and Hawkins 1996).

Table 1 summarizes the characteristics of these nine catchments in the study area. This includes the area, weighted average CN value, the average slope and the lag time.

The Watershed Modeling System (WMS), developed by the Brigham Young University (WMS 1996), is used for hydrologic analysis. This system is based on the HEC-1 flood hydrograph package (HEC-1 1985) developed by the U.S. Army Corps of Engineers/Hydrologic Engineering Center. For example, WMS provides a featured-object interface that can be used to derive and delineate watershed parameters based on digital elevation data.

Model

The HEC-1 model is a widely used, hydrologic, event-based simulation model that has been refined over subsequent years. It is designed to simulate the surface runoff hydrograph resulting from a rainfall storm event by representing the basin as an interconnected system of components. Each component models an aspect of the rainfall-runoff process within a sub-basin. Components may include sub-basin runoff, stream channel, and a reservoir. The characteristics of each component are described by a set of parameters representing its physical process (Bedient and Huber 1992).

Model Setup and Available Data Watershed

The Petra area is divided into nine subcatchments, as discussed earlier. The interconnectivity between these catchments is schematically shown in Fig. 3. The squares represent the land surface runoff components, the circles represent the stream confluences, and the arrowheads represent the stream routing components.

Basin data, output control, precipitation data, abstraction method, unit hydrograph method, and general job control HEC-1 cards are input for each sub-basin for specific watershed and storm characteristics.

Noncontinuous daily rainfall data for this watershed is available from Water Authority of Jordan (WAJ) for parts of the

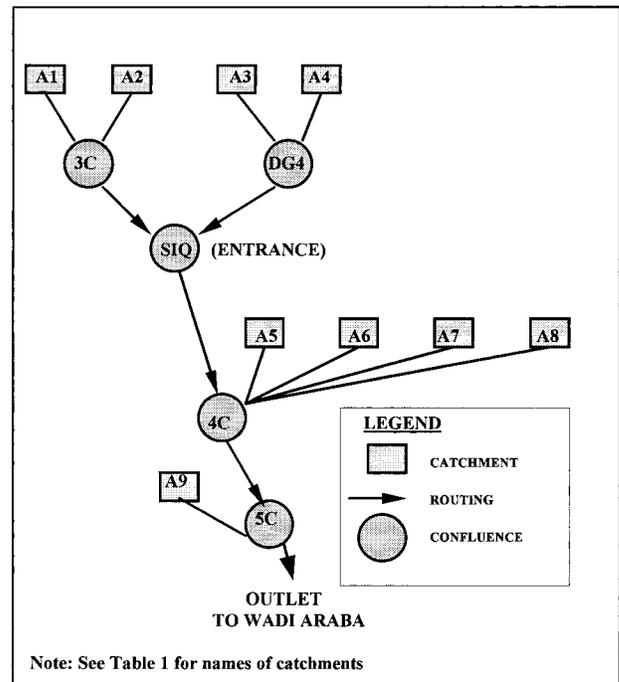


FIG. 3. Schematic Diagram of Flood Model for Petra Watershed

TABLE 2. Available Daily Rainfall Records with Corresponding Flood Flows at DG4 Station (Used for Calibration of Model)

Date (dd/mm/yr) (1)	Daily rainfall (mm) (2)	Peakflow (m ³ /s) (3)	Flood volume (m ³ × 10 ³) (4)
25/11/68	21.0	1.79	5.3
10/03/70	46.1	2.18	4.0
14/01/74	22.6	0.41	4.3

Note: Source: Water Authority Jordan.

period 1980 up to 1995 for the stations DG1, DG2, and DG3 at Wadi Musa. Additional short duration rainfall data for Wadi Musa Station that correspond to the recorded flood events were also provided by the WAJ. Peakflow data is available for a limited number of storm events during the period of record at the flood-recording station DG4. Short-duration rainfall records required for flood modeling on this watershed are available only for the three flood events that occur in the years 1968, 1970, and 1974 (Table 2). The data available for model calibration consists mainly of these three storm records and their corresponding peak flood flows at Wadi Musa gauging station DG4. Unfortunately, no further information is available on the characteristics of these events other than rainfall depths, peakflow values, and average flood volume.

Model Calibration Based on Available Records

The lack of accurate rainfall-runoff data is a major constraint on model calibration and validation. Luckily, the rainfall-runoff model can be calibrated for catchments upstream of the Wadi Musa gauging station near the Wadi Musa Culvert. The area covered by calibration includes the Jebel Zubaira and Al-Hai catchments. The model calibration procedure involves changing the watershed CN values in order to produce simulated floods that can fit reasonably the observed floods.

According to the geological assessment of the catchment areas, two main soil categories can be clearly identified. A curve number (CN) was assigned to each category. The first category consists of limestone with a relatively thin soil cover and sparse vegetation. For this category, the hydrological soil group "C" was chosen. Thus, for mountain brush mixture with poor conditions the curve number (CN) was estimated to be 75. The second category consists of sandstone with no soil cover. The hydrological soil group "D" was chosen, which indicates a hard surface with a very slow infiltration rate. The corresponding curve number was estimated to be 91.

Antecedent moisture condition (AMC) is another parameter to affect the choice of the CN value. Based on the rainfall records and the distribution of the rainfall patterns, the average antecedent moisture condition AMC-II was adopted for the first and third storms. For the second storm, a dry antecedent moisture condition (AMC-I) was selected. The weighted CN value for the catchments upstream from DG4 was estimated to be 78 for the AMC-II, and 60 for AMC-I (Chow et al. 1988).

Table 3 shows the result of the model calibration for the catchment upstream Wadi Musa gauging station DG4 for the storm records available. The calibration process shows that the

peakflow simulation for the storm on March 10, 1970 is reasonable. It is less accurate for the other two storms, which represent a relatively lower peakflow. Thus, the rainfall-runoff process calibration may not be adequate based on these low-flood events.

From the comparison of the simulated flow volume with the observed flow volumes measured by the WAJ, it can be seen that the simulated flood volumes were not closely comparable with the observed volumes for the first and second storms. The comparison was reasonable for the third storm, which represents the lowest-flood event in the available records. The observed flow volumes indicate a slight difference between the volume of the second flood, which represents the highest peak, and the volume of the third flood with the lowest peak. This raises questions about the accuracy of the observed flow-volume measurements, and the use of the model.

Calibration involves uncertainties in estimating various components of the simulation process, including the reliability and accuracy of the rainfall and flood records themselves. Available records correspond to storms of small return periods; it would have been desirable to have records for larger storms.

FLOOD FORECASTING AND PREDICTION

The HEC-1 model was used, after calibration, to estimate the peak flow and flood volume for different return periods ranging from 2 to 200 years, for two stations, namely, the Wadi Musa gauging station and at the Siq entrance. The Intensity-Duration-Frequency (IDF) curves developed for Wadi Musa meteorological station by the WAJ (WAJ open files) were used to estimate the 24-hour design storm for each return period. Table 4 shows the values of the peak discharge and total volume for different return periods at Wadi Musa gauging station DG4 and at the Siq entrance.

A recent study by the EDF for Petra (EDF 1995) evaluated the design flood at the Siq entrance for different return periods. Although the method used by the EDF to evaluate the design flood is different from the HEC-1 method, the results from the two methods were comparable closely in terms of the peak flow and its total flood volume, with differences within 10%.

Sensitivity Analysis

The main uncertain parameter that affects the results of the simulation process is the CN value (Ponce and Hawkins 1996). Selection of this value depends on judgment about the watershed's physical characteristics as well as its antecedent moisture conditions. A sensitivity analysis was performed to assess the effect of changing the SCS-CN values on the peak flow values. Table 5 shows the variation in peak discharge at the Siq entrance for different curve numbers and different return periods. It can be seen that the flood peak is most sensitive for less severe, more frequent flood events.

Flood-Warning System

Petra is a very significant tourist attraction throughout the entire year. In fact, tourists' statistics showed that winter season visitors are greater in number than summertime visitors.

TABLE 3. Results of Model Calibration Upstream Wadi Musa Gauging Station DG4 (Upstream Catchment Area = 24.65 km²)

Storm date (dd/mm/yr) (1)	Total rainfall (mm) (2)	Weighed curve number (3)	Observed Q _{peak} (m ³ /s) (4)	Simulated Q _{peak} (m ³ /s) (5)	Observed volume (m ³ × 10 ³) (6)	Simulated volume (m ³ × 10 ³) (7)
25/11/68	21.0	78	1.79	1.15	5.3	16
10/03/70	46.1	60	2.18	2.16	4.0	25
14/01/74	15.7	78	0.41	0.29	4.3	4

TABLE 4. Flood Discharge and Volumes at Gauging Station DG4 (Upstream Catchment Area = 24.65 km²) and Siq Entrance (Upstream Catchment Area = 50.06 km²) for 24-Hour Storm with Different Return Periods

Return period (years) (1)	Rainfall (P) (mm) (2)	Peakflow at DG4 (m ³ /s) (3)	Volume at DG4 (m ³ × 10 ³) (4)	Peakflow at Siq (m ³ /s) (5)	Volume at Siq (m ³ × 10 ³) (6)
2	33.6	5.22	101	9.87	204
5	50.4	20.38	297	36.77	604
10	60.0	32.40	438	58.58	889
25	74.4	53.17	675	96.53	1,370
50	86.4	72.20	890	131.44	1,808
100	96.0	88.21	1,071	160.90	2,176
200	105.6	104.78	1,259	191.40	2,557

TABLE 5. Sensitivity Analysis of Peakflow to CN at Siq Entrance

CN (1)	Q _{2Year} ^a (m ³ /s) (2)	Q _{5Year} (m ³ /s) (3)	Q _{10Year} (m ³ /s) (4)	Q _{25Year} (m ³ /s) (5)	Q _{50Year} (m ³ /s) (6)	Q _{100Year} (m ³ /s) (7)	Q _{200Year} (m ³ /s) (8)
77	8.24	33.19	53.59	90.11	124.05	152.85	182.77
78	9.87	36.77	58.58	96.53	131.44	160.90	191.40
79	11.69	40.89	63.83	103.15	138.99	169.09	200.16
80	13.69	45.28	69.32	109.98	146.72	177.42	209.02
81	15.90	49.94	75.07	117.01	154.61	185.89	218.00

^aQ_{nYear} is peakflow for n-year return period.

Flash flooding poses a serious risk to tourism during the rainy season (November–March) because of the climatic, topographic, and hydrologic conditions of the area, especially the Siq. In fact, the Siq and most of the other main monuments in Petra are under equal risk of flooding because they are located in the lowest spot in the watershed. Unfortunately, lives were reported lost during the 1963 flood in Petra where flood stage was about 10 m in the narrow gorge of the Siq itself. The main threat is from flood water entering the Siq, which will trap anybody within. During a flood, escape to high ground near the Siq banks is difficult because of steep and high banks around the Siq and the other monuments.

A flood-warning system to detect flash floods is very essential. However, the efficiency of such a system depends on the early warning time it allows. This advance notice is a critical factor in mobilizing the evacuation and rescue activities. Unfortunately, the hydrologic and hydraulic conditions in the region do not allow for more than one hour of early flood-warning time once a flood is observed in the upstream side of the catchment area. This is because channels are quite steep and water will discharge from all wadis to the Siq within one hour. One hour would not be adequate warning, because the access to the Siq is limited, even by air. This fact necessitates investigation of all possible flood mitigation alternatives for the floodplain and for the whole watershed. Due to the historical significance of the site, no major structures can be proposed at or near the main monuments of Petra. At a few sites it would be acceptable to construct small crossing culverts and minor wadi training structures or channel adjustment.

FLOOD MITIGATION MEASURES AND MANAGEMENT SCHEMES

In this paper, most of our focus is on mitigation measures in the upstream side of the catchment areas, which are physically distant from the monuments' site. Four possible watershed management scenarios or measures were hydrologically analyzed to estimate their effectiveness in reducing floods in critical sites in Petra like the Siq entrance. The four scenarios are

- Afforestation of selected parts of the watershed
- Contour terracing and construction of check dams with afforestation
- Construction of storage/detention dams
- Combination of storage/detention dams and afforestation

Most of these measures were originally used by the ancient Nabateans of Petra. They had a unique water detention and watershed management and conservation measures in the whole watershed. Their system was well-maintained and integrated into their life style and agricultural practices. Our aim is to restore parts of the old Nabatean hydraulic system where possible. Our approach is careful to avoid intrusion on the aesthetics of the historical setting of Petra.

First Scenario: Afforestation

Afforestation could be undertaken at selected areas in the two upstream watersheds of Jebel Zubaira and Qurnat Bin Sa'd. The afforestation scheme would cover an area of 1,000 ha (500 ha in Jebel Zubaira and 500 ha in Qurnat Bin Sa'd).

The analysis investigates good afforestation practices according to the definition of the SCS (1986). The good afforestation conditions are applicable when the total vegetated area is greater than 75% of the arable land in the catchment. The afforestation conditions affect the infiltration-runoff process in the catchment, as reflected hydrologically by the CN value. Accordingly, the weighted average CN values for Jebel Zubaira is 63 and for Qurnat Bin Sa'd it is 72. The flood peakflow and volume are evaluated at the bridge culvert near the entrance of the Siq. This analysis covers storm events with return periods of 2, 5, 10, 25, 50, 100, and 200 years. The results of this analysis are shown in Table 6. The afforestation reduced the flood peakflow by 27–50%. Similar reduction in the range of 24–50% was noted for flood volumes. The afforestation impact is more pronounced for more frequent floods (e.g., return period less than 25 years).

Details and plans of afforestation schemes, including the vegetation and tree cover that best fit the area, as well as their socio-economic aspects, need to be addressed in other studies with the help of the Ministry of Agriculture and other concerned agencies. Good examples of soil conservation and afforestation projects in Jordan are the Highland Development Project and the Zarqa River Basin Development Project. Both projects encourage local farmers to undertake soil conservation, afforestation (mainly with olive trees), and water harvesting. This approach can be immediately implemented in the Petra watershed.

Second Scenario: Terracing, Check Dams, and Afforestation

Terracing and constructing of check dams involve construction of dry-stone walls and gabions, which follow the contour

TABLE 6. Impact of Scenario I: Afforestation Only

Return period (years) (1)	Existing Conditions		Scenario I	
	Peakflow (m ³ /s) (2)	Volume (1,000 m ³) (3)	Peakflow (m ³ /s) (4)	Volume (1,000 m ³) (5)
2	14	245	7	122
5	47	673	26	410
10	71	972	43	634
25	113	1,471	74	1,027
50	150	1,922	104	1,397
100	182	2,300	131	1,714
200	215	2,690	158	2,048

lines and intercept overland flow lines. Check dams are gabion structures that are constructed a few meters high across the course of the wadi. Terracing activities are usually accompanied with afforestation schemes. Terracing and check dams have three-fold interconnected effects, namely:

1. Increasing the time of concentration (T_c) for the subbasin. This will decrease the sensitivity of the watershed to short duration high intensity storms, making it less vulnerable to more frequent flood events. The value of T_c depends on the spacing, configuration, and height of terracing. From a practical point of view, compared to existing T_c , it was found that T_c values (and thus lag time values) can be increased by about 30% for the terraced catchments. The increased T_c results from the effect of terracing, which increases the length of flow lines and decreases the slopes of overland and channel flow paths.
2. Decreasing values of the Curve Number (CN) for afforested terraced catchments. Values of CN are reduced by land conservation practices such as terraced catchments. Terracing allows for greater infiltration and abstraction during a storm event. Available literature suggests that conservation measures would reduce the CN value by 5–10%. However, in the present analysis it was considered that a reduction in CN value of 5% is a reasonable estimate for all terraced catchments upstream from the Siq entrance.
3. Providing additional shallow storage, which in turn increases the T_c . Storage provided by terraces and check dams may attenuate the hydrograph and delay the time to peak. The effect of terracing and check dam storage is already considered in the reduced values for CN and increased values for T_c . Therefore, the storage effect of check dams and terracing was not considered as an additional potential benefit.

Table 7 shows that a reduction of 50–80% in the flood peakflow can be achieved by this measure, with the maximum reduction occurring during more frequent events (e.g., return periods less than 10 years). A similar reduction would be achieved in the flood volumes. The time to peak increases slightly from 13.5 h for existing conditions to about 14.25 h with afforestation, terracing, and check dams measures.

Third Scenario: Storage/Detention Dams

Storing flood water in reservoirs and detention basins behind dams is another alternative for flood mitigation and control. The topography of the catchments seems to allow the construction of these reservoirs. Based on available topographic maps, a number of locations are possible sites for these dams and reservoirs. However, a detailed field survey to check the exact location, storage volume, and outlet type of these

TABLE 7. Impact of Scenario II: Afforestation and Terracing with Check Dams

Time Return period (years) (1)	Existing Conditions		Scenario II	
	Peakflow (m ³ /s) (2)	Volume (1,000 m ³) (3)	Peakflow (m ³ /s) (4)	Volume (1,000 m ³) (5)
2	14	245	3	68
5	47	673	14	286
10	71	972	25	471
25	113	1,471	46	809
50	150	1,922	68	1,137
100	182	2,300	87	1,423
200	215	2,690	107	1,727

dams would be required to confirm the feasibility and costs. Approximate elevation-storage volume data were obtained from the available topographic maps. As these dams are flood control structures, their outlets can be designed similar to those of regular detention basins.

Reservoir storage systems were estimated to consist of seven storage dams, constructed in various parts of the catchment, with a total capacity of 214,000 m³. The analysis covers the seven return periods suggested earlier. Table 8 demonstrates that, for the 214,000 m³ storage, the peakflow reduction ranges from 15–45% depending on the frequency of the storm events. The storage effect is more pronounced for less frequent floods (e.g., return periods greater than 50 years). The effect of this scenario on flood volume should be negligible; any effect on flood volume can be attributed to additional infiltration due to the increased detention time.

Fourth Scenario: Combined Effect of Storage Dams and Afforestation

The combined effect of storage dams and afforestation was evaluated according to the schemes outlined in 1 and 3 above. Table 9 shows that the combined impact of afforestation and storage provides the greatest reduction in flood peaks and volumes, but the additional improvement is not large compared to the other alternatives. The relative effects are almost the same for all flood frequencies.

ANALYSIS OF RESULTS AND DISCUSSION

The analysis of the above results focused on evaluating the relative percentage change in the peakflow, time to peak, and flood volumes for storm events of return periods of 2, 5, 10, 25, 50, 100, and 200 years. Improvements are referenced to existing conditions (do-nothing option). The station at the entrance of the Siq was selected because it is a very critical point for tourism activities.

Figs. 4 and 5 represent the relative effectiveness of each of the four measures by comparing them with existing conditions

TABLE 8. Impact of Scenario III: Dam Storage Only

Time Return period (years) (1)	Existing Conditions		Scenario III	
	Peakflow (m ³ /s) (2)	Volume (1,000 m ³) (3)	Peakflow (m ³ /s) (4)	Volume (1,000 m ³) (5)
2	14	245	12	197
5	47	673	30	595
10	71	972	43	885
25	113	1,471	64	1,365
50	150	1,922	83	1,803
100	182	2,300	100	2,166
200	215	2,690	116	2,532

TABLE 9. Impact of Scenario IV: Afforestation and Dam Storage

Time Return period (years) (1)	Existing Conditions		Scenario IV	
	Peakflow (m ³ /s) (2)	Volume (1,000 m ³) (3)	Peakflow (m ³ /s) (4)	Volume (1,000 m ³) (5)
2	14	245	6	111
5	47	673	18	394
10	71	972	27	614
25	113	1,471	42	1,010
50	150	1,922	57	1,394
100	182	2,300	71	1,706
200	215	2,690	86	2,033

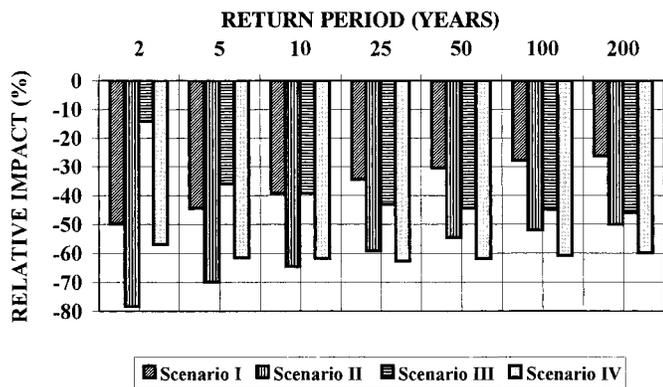


FIG. 4. Relative Impact of Different Flood Mitigation Scenarios on Peakflow near Siq Entrance

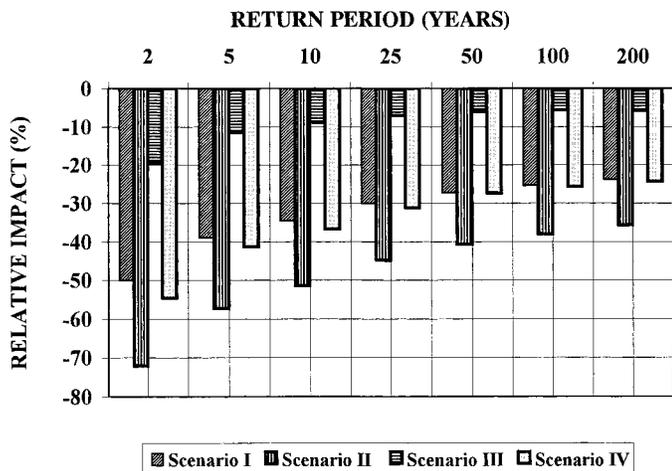


FIG. 5. Relative Impact of Different Flood Mitigation Scenarios on Flood Volume near Siq Entrance

(do-nothing option) for the ratios of peak flow and flood volume at the entrance of the Siq. Fig. 4 shows the relative impact on peakflow. From this figure, it can be seen that afforestation and terracing as well as afforestation and dam storage are the most effective measures for all return periods. Terracing/check dams and afforestation are slightly superior to afforestation and storage action for more frequent (small) events (e.g., return period less than 10 years). The reservoir storage option starts to be slightly more effective than terracing for less frequent (larger) events. Fig. 5 shows the relative impact on flood volumes for the four flood-mitigation scenarios. It can be seen that afforestation and terracing as well as afforestation and storage are the most effective volume control measures for all return periods.

A comprehensive evaluation of each alternative would consider economical, social, legal, and environmental aspects. From a flood-mitigation perspective, terracing and afforestation provide a more than 60% reduction in the flood peakflow, and about 40% reduction in the flood volume at the Siq entrance for moderate events (e.g., return period around 25 years). On the other hand, the terracing/check dams are usually necessary to provide suitable land for afforestation. Terracing/check dams can be used for water harvesting to sustain small amounts of water needed for afforestation. This was the ancient Nabatean practice for desert agriculture. Furthermore, the effect of terracing/check dams on the environment will be less pronounced compared with construction of dams. Terraces/check dams can be constructed by local people without any sophisticated engineering design, contrary to the storage option where skilled technicians and complete engineering designs are needed for the construction of dams. The dam storage option also would be more costly, compared with the terracing/

check dam option. The risk involved in the construction of dams option is usually higher, in the case of dam break, than the risk posed by the terracing/check dams failure. Among the major advantages of reservoir storage is the use of stored water for different purposes (domestic and irrigation use). However, the volumes stored are relatively small, with a seasonal storage volume of about 2–3 million m³. This is quite small relative to the needs, and much of the stored volume can be lost by evaporation during dry hot seasons.

CONCLUSIONS AND RECOMMENDATIONS

Based on the above flood analysis and discussion, the following conclusions and recommendations can be stated.

1. The storage of actual rainfall and flood measurements is a major constraint on model calibration and reliability. Unfortunately, the available records are very limited. Only three flood records could be used for model calibration. Moreover, the highest of these flood events has a return period probably less than two years. Although the calibration resulted in generally accepted parameter levels, the uncertainty related to the data has to be borne in mind when considering the reliability of the simulation results.
2. To support future studies, an adequate rainfall-runoff monitoring system covering critical points in the watershed should be installed. This monitoring system should be able to record short-duration rainfall-runoff events.
3. Flood-recording stations should be installed and rehabilitated at the three major points in the watershed. The first is near Wadi Musa Culvert DG4 (which is not in operation now). The second is at the entrance of the Siq near the diversion channel of Wadi Al-Mudhlim tunnel. The third is upstream of Wadi Siagh (near the museum entrance).
4. Flooding poses a serious risk to lives and property in the Siq area under present conditions—immediate actions should be taken to mitigate the flood risk at these areas. Structural measures that intrude on the integrity and the aesthetics of the historical setting of Petra are not encouraged. However, restoration of some watershed management practices used by the ancient Nabateans of Petra are more attractive and better suited.
5. Afforestation only, of 1000 ha in both Jebel Zubaira and Qurnat Bin Sa'd subbasins, provides about 30–50% reduction in flood peakflow. However, it has a limited impact on flood volume (about 20%) for most storm events.
6. Afforestation, combined with terracing and check dams in the watershed upstream from the Siq entrance, produced about 50–80% reduction in the flood peakflow, and about 40–70% reduction in flood volumes for most storm events. This alternative is the recommended one for immediate implementation.
7. Afforestation combined with dam storage of 214,000 m³ produced about 60% reduction in the flood peakflow, and about 30–50% reduction in flood volumes for most storm events. This scenario would require a chain of seven dams over major wadis in the watershed upstream of the Siq entrance.
8. Terracing with check dams measure would be more suitable and less expensive than dam storage, and more desirable from the socio-economic, environmental, and risk perspectives. However, a further detailed evaluation of these two options must consider all relevant parameters, including social, economical, environmental, risk, etc.

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