JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 19 2011

RAINFALL-RUNOFF MODELING IN THE AL-MADINAH AREA OF WESTERN SAUDI ARABIA

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The Al-Madinah area, which is located in the western region of Saudi Arabia, is characterized by extremely arid conditions. This area is also subject to flash flooding that occurs immediately after heavy, short rainstorms, resulting in loss of life, infrastructure, and property. This valuable and important area requires the development of sustainable structures that can withstand such flooding. In this study, a runoff model adapted from the US Soil Conservation Service was built for the catchments of five selected ungauged dry wadis in the Al-Madinah area. Data from 16 rain gauges that have been recording the annual maximum daily rainfall for over 30 years were analyzed and used to derive the Gumbel extreme value distribution for 25-yr, 50-yr and 100-yr return periods. Hydrographs for different return periods were drawn using the results from this analysis along with the morphometric parameters of the wadi catchments. Regional maps of maximum probable precipitation and probable maximum flood were also produced for the study area. These results will be helpful when decisions are made regarding the planning, management, operation, and maintenance of flood mitigation measures in this important area.

INTRODUCTION

Flash flooding is a major phenomenon that results in heavy losses in infrastructure, property, and life. This is particularly prevalent in arid regions where residents living in the floodplain and inundation areas are unaware of the consequences of flooding due to long periods of aridity. The frequency and magnitude of disastrous floods has increased due to climate changes. However, one benefit of flooding could be to use the rainwater as a resource to fulfill the water demand in these extremely arid regions.

In addition to the uncertainty of flood occurrences with regards to time and area, the behavior of flooding is complex, depending on interactions between the geological, morphological, and hydrological characteristics of the basin. Human impact and interaction also affect flood behavior (Flerchinger et al., 2000; Nouh, 2006). Therefore, it is important and essential to know the rainfall and runoff relation to get the peak discharges for catchments flow from the peak rainfall for the design of the structures. The peak discharges in different return periods can be obtained from the design storm hydrographs developed from unit hydrographs. Models from the Soil Conservation Service (SCS, 1985) are used to assess the hydrologic response in gauged and ungauged catchments in arid areas (Littlewood, 2002; Kokkonen, 2003; Salami, 2009). Relationships between hydrograph characteristics (e.g., time to peak, duration, and volume) and basin parameters (e.g., area, slope, drainage density, and relief) in arid areas are commonly used to model runoff (Nouh, 1990; Gaith and Sultan 2002; Masoud, 2009). In addition, statistical analysis of extreme runoff and rainfall phenomena has played an important role in engineering water resources and management. Regional rainfall and flood frequency analysis are used in areas with a sparse data network and short-range records, which are especially common in arid regions (Katz et al., 2002; Islam and Kumar, 2003, Tingsanchali and Karim, 2005, Subyani, 2009). The Geographic Information System and remote sensing techniques are also useful tools that integrate geomorphology and hydrology with land use and land cover to help identify areas that are prone to runoff and flood hazards (Ologunorisa and Abawua , 2005; Subyani et al., 2009; Masoud, 2009).

Al-Madinah area located in western Saudi Arabia experiences average to extremely dry conditions. Rainfall patterns and runoff in this area are characterized by extremely high temporal and spatial variability. Unfortunately, accurate and continuous hydrometeorological data are limited or incomplete. Acquiring runoff measurements and continuous extensive spatial and temporal rainfall data is difficult, making runoff less predictable and rainfall-runoff processes more difficult to analyze and model (ªen, 2008; Masoud, 2009; Subyani and Al-Modayan, 2010).

In this study, SCS models were used to predict the hydrologic response of five ungauged dry wadis in Al-Madinah area, namely Mastorah, Marij, Safra, Fara'a, and Alaqiq. The maximum annual daily rainfall of 16 rainfall stations was evaluated and derived using the Gumbel extreme value distribution (EV1) probability density function in different return periods. A Digital Elevation Model was also used to calculate the morphometric parameters of the wadis. With this data, hydrographs for different return periods were drawn. Regional maps of maximum probable precipitation (PMP) and probable maximum flood (PMF) were also produced for this study area.

GEOLOGIC AND GEOGRAPHIC SETTING

The study area, which is approximately 14,000 km^2, is located in the western province of Saudi Arabia, bounded between latitude 23° and 25° N and longitude 37° and 40° E. Geologically, Al-Madinah area is part of the mid-western Precambrian Arabian Shield, which is bounded on the west by the Red Sea rift and on the east by the Paleozoic and younger sedimentary rocks. Many parts of the Shield are overlaid by lava plateaus (i.e., harrats) and sediments from the Tertiary and Quaternary Ages. In general, the rocks in the Arabian Shield are divided into two major categories, layered and plutonic. According to Brown et al. (1989), the layered rocks of the Arabian Shield are comprised of metavolvanic and metasedimentary rock (Figure 1). The plutonic rocks of the Arabian Shield are divided into two major suites, namely the older diorite suite and the younger syn- and post-tectonic granitic suite.

Quaternary and Tertiary basaltic lava (i.e., harrats) are scattered and widespread in the study area. These lava fields form plateaus and are known as Al Harrah, or harrats. One of the largest basalt lava flow fields in the Arabian Shield area is Harrat Rahat, which encompasses a large portion of the study area and forms the eastern boundary of most wadi basins in the area (Fig. 1). Quaternary deposits cover extensive areas, principally on the coastal plain, but also in the large inland drainage basins of wadis. The deposits found in the area include, reef limestone, alluvial-fan, talus, wadi alluvium, aeolian sand, and sabkhah.

Geographically, flat and wide valley floors with relatively small channels confined by steep escarpments are typical for this region. These watersheds (i.e., wadis) drain the plain in the west after traversing the Precambrian basement complex and basalt flows constituting the upland area in the east (Al-Sayari and Zötl, 1978; Brown et al., 1989).

The drainage pattern formed by these basins reflects previous geologic events that occurred in the Arabian Peninsula. The Tertiary uplift of mountainous areas in the Arabian Shield affects drainage shape and direction. Extensive lava flows from Harrat Rahat (i.e., plateau basalt) also changed the morphometric characteristics of the catchments (Saudi Geological Survey, 2007, Subyani et al., 2010).

The altitude of the study area ranges from the level of the Red Sea in the west to more than 2000 m in the mountainous area in the east. The study area is predominately arid with hot summer and cooler winter seasons. The mean temperature ranges from 24°C to 40°C in the summer and from 15°C to 25°C in the winter. Rainfall is sporadic, characterized by moderate to high variations in space and time. The rainy season, which is from October to April, produces mean annual rainfall of 40 mm in the coastal plain to around 100 mm in the mountainous areas (Sen, 1983; Subyani et al., 2009).

Many of the major cities and villages are situated along or at the mouth of these wadis, which are ephemeral water courses. These wadis constitute a major source of water for domestic and agricultural use in addition to the supply of desalinated sea water. Flash flooding along these wadis caused severe loss of life and property. The selected five major wadis in Al-Madinah area, except Wadi Alaqiq, lay along the Red Sea coastal area and are all confluent with the Red Sea (Figure 1). These wadis were selected because of their location near the most developed and populated areas, as well as their propensity for flash flooding.

MATERIALS AND METHODS

Digital Elevation Model (DEM) and morphometric parameters

The SRTM3 DEM with 3-arc second grid spacing was used to represent the topography of the study area. The Watershed Modeling System (WMS, v.8.0), and Global Mapper (v.10) were used to establish a spatial database for the wadis located in the study area. These systems provided most

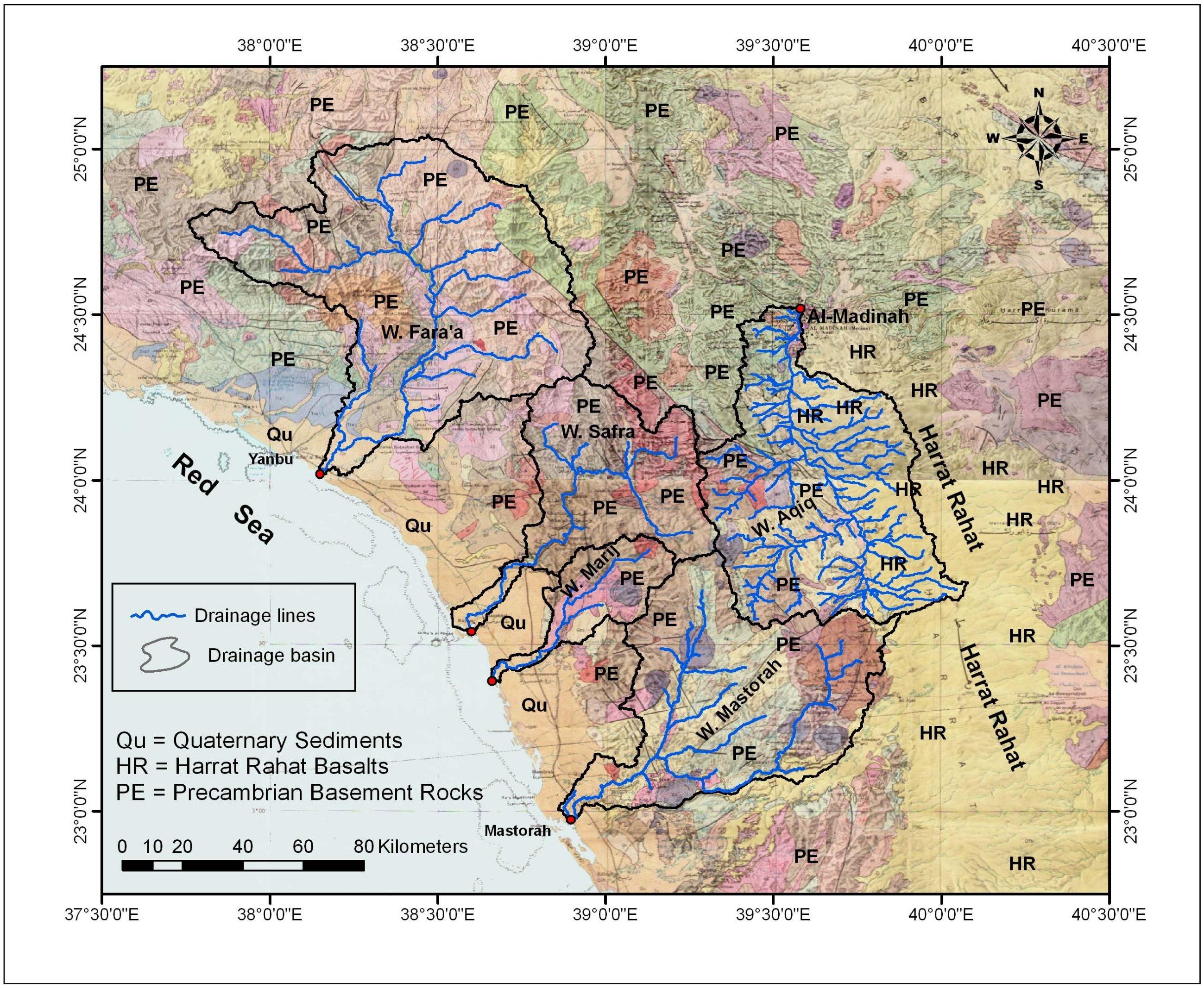

Figure 1. Geology of the study area.

of the morphometric parameters of the basins studied and their stream attributes (Strahler, 1952; Ally et al., 1980). The morphometric variables that were determined by the DEMs were: watershed area, perimeter, total channel length, main channel slope, maximum stream length (L), centroid stream distance (L_c), mean basin elevation, and basin length. In addition, watershed parameters such as circularity, sinuosity factor, drainage density, relief ratio, elongation, and stream order were also obtained (Gregory and Walling, 1973; Maidment, 1993, Bardossy and Schmidt, 2002; Subyani et al., 2010).

Rainfall frequency curves

In arid regions and ungauged basins for runoff estimation, the only information available for flood risk analysis is rainfall frequency. Statistical methods were used to assess the annual maximum daily rainfall series. Data were collected from 16 stations located in and around wadi basins (Ministry of Water and Electricity, 2009) for up to 40 years. In this study, we applied Gumbel's extreme value distribution (EV1), which is one of the most widely used analytical tools for evaluating extreme values and therefore the most suitable for estimating one-day maximum rainfall (Hershfield, 1961, Gupta, 1970; Islam and Kumar, 2003; Subyani, 2009).

This method calculates extreme values in hydrological and meteorological studies to predict such factors as flood peak, maximum rainfall, and maximum wind speed. According to Gumbel's

EVI, a flood is defined as the largest rainfall during a 365-day period and the annual series of flood flows constitutes a series of flow values. This probability density function (pdf) is given by:

$$p = 1 - e^{-e^{-y}} \tag{1}$$

where p is the probability of a given flow of equal or greater quantity, and y is the reduced variate as a function of probability from ready tables (Subramanya, 1994). In addition,

$$x = \bar{x} + k\sigma_x \tag{2}$$

where $\bar{x}$ is the mean of the data series, and σ_x is its standard deviation, k = 0.7797y - 0.45.

To prevent loss of life and property damage, the Probable Maximum Precipitation (PMP) is considered when designing major architectural structures such as dams and bridges. Therefore, the statistical analysis of PMP for a specific return period can be estimated as:

$$PMP = \bar{p} + k_T\sigma_x \tag{3}$$

where $\bar{p}$ is the mean annual maximum rainfall, σ_x is the series standard deviation, and k_T is a frequency factor that depends on the distribution type and number of recorded years (or return periods). The latter variable can be estimated from published ready tables (Subramanya 1994; Wanielista et al., 1997).

The Probable Maximum Flood (PMF) is defined as the maximum water flow in a drainage area that would be expected from a PMP event. The PMF is also useful when designing major structures. Calculation of the PMF begins by obtaining an estimate of the PMP. Not all catchment areas with the same PMP possess the same magnitude of PMF because different areas vary in their morphometric characteristics, including the slope, drainage density, shape, size, vegetation, and geology. All of these factors affect runoff patterns and floodwater discharge in a catchment area. In general, a basin discharge is a function of climatic and watershed characteristics (Cech 2005). In arid regions, such as the area investigated in this study, runoff gauging records and measurements are unavailable. As a result, several methods have been developed to estimate the flood volume with PMFs for different return periods and discharges.

Hydrographs

One of the most important factors in groundwater recharge studies is to define the hydraulic response of the wadi basin. This includes peak discharge, lag time, base time, and time concentration, which is called a hydrograph. A listing of flow rate data versus time, a hydrograph, is one of the more useful concepts in hydrology and storm water management. The Soil Conservation Services (SCS, 1985) method was used to design a hydrograph for small humid catchments and was adopted recently for use with ungauged arid areas. For ungauged catchments, the unit hydrograph can be generated by relating the shape of the unit hydrograph to catchment parameters such as basin length, centroid distance, area, and curve number, and then relating these parameters to hydrograph characteristics such as lag time, peak discharge, base time, and time concentration (Nouh, 1990; El-Hames and Richards, 1994; Sorman and Abdulrazzak, 1996; Masoud, 2009). The SCS method is based on a simple storm relationship between the actual runoff (Q), rainfall (P), and potential maximum retention (S). Once the runoff begins and $S \geq F$, where F is the actual retention after runoff,

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \text{ and } F = P-Q$$

I_a= initial abstraction, I_a= 0.2S (4)

The SCS method requires the curve number, *CN*, (0<*CN*<100), for estimating the potential maximum retention *S* as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{5}$$

The curve number (*CN*) depends on such characteristics as the soil texture, antecedent moisture, land use, vegetation, and slope. In the study area, rainfall events are rare and the soil would have been dry before any storm event. Land use type and hydrologic condition were classified as Desert Landscaping and Desert Shrub (e.g., poor coverage, <30% ground cover), respectively (Gheith and Sultan, 2002). Three main soil types exist in the study area, Quaternary wadi deposits, Tertiary and Quaternary lava plateaus, and igneous and metamorphic rocks as shown in Figure 1. Because all basins in the study area contain these three soil types, the areal weighted average of the curve numbers is given by:

$$CCN = \frac{\sum CN_i A_i}{\sum A_i} \tag{6}$$

where *CCN* is the composite curve number, CN_i is the curve number of subregion *i*, and A_i is the area of subregion *i*. The storm runoff or hydrograph was estimated from rainfall and the curve number.

Given the absence of flood records, the synthetic Unit Hydrograph approach (SCS, 1985) was calculated. The UH can be given as (Masoud, 2009):

$$q_u = \frac{CA}{T_{lag}} \tag{7}$$

where q_u is the unit peak discharge ($m^3/s/km^2/mm$) of runoff, *A* is the catchment area in km^2, *C* is the peak factor (ranged from 0.258 in steep areas to 0.129 in flat areas), and T_{lag} is the lag time to peak in hours. This lag time was dependent on the catchment properties, as signified by:

$$T_{lag} = 24n\left(\frac{LL_{ca}}{\sqrt{S}}\right)^{0.38} \tag{8}$$

where *L* is the length of the longest water course in miles, L_{ca} is the length along the longest water course to the sub-basin centroid in miles, *S* is the overall slope of the longest water course, and *n* is the Manning coefficient. Roughness values ranged between 0.015 and 0.05 in the natural desert landscape. Finally, flood hydrographs of the catchments for different return periods of annual maximum daily rainfall were quantified as.

$$q_p = q_u AQ \tag{9}$$

where Q is the depth of the direct runoff.

RESULTS AND DISCUSSION

Delineation of catchment within the study area is shown in Figure 2. Morphometric characteristics of the main catchments and their channel networks in the five studied catchments were extracted using DEM (Table 1). Our data revealed that basin areas range from less than 1000 km^2 to more than 7000 km^2, and that their drainage patterns are generally dendritic. The drainage density ranged from 0.75 to 1.46 km^{-1}, implying a permeable landscape with moderate runoff potential. The slope of the basins ranges from 0.1 to 0.22, suggesting that floods are of low to medium risk. In addition, the relief ratio ranged from 0.01 to 0.027, indicating that the host rocks are more resistant to physical geological processes. Finally, stream orders ranged from 4 to 6 orders, which indicated that the basin in moderate potential of runoff.

Our prediction of daily maximum rainfall of the surrounding stations using the EV1 probability density function (pdf) for different return periods is summarized in Table 2. Isoheytal maps of probable maximum precipitation for different return periods were also generated (Figures 3 to 5). These data illustrate that rainfall storms are inconsistent in this area due to its topography, which

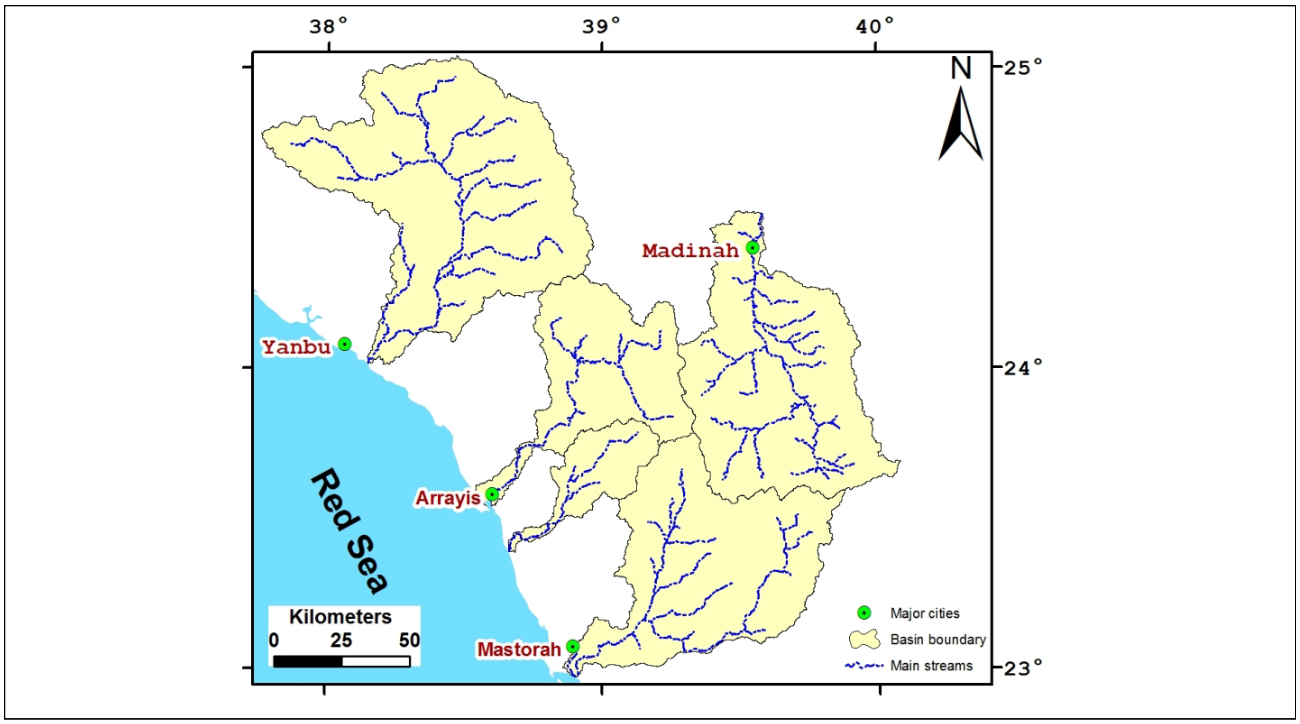

Figure 2. Drainage map of the study area.

Table 1. Morphometric characteristics of the main basins in Al-Madinah area.

Parameter	Unit	Basin				
		W. Mastorah	W. Marij	W. Safra	W. Fara'a	W. Alaqiq
Area (km)	km	4745	981	2850	7030	5138
Perimeter	km	568	271	496	692	545
Total Str. Length	km	6937	741	4109	10096	5570
Max. Str. Leng, L	km	163	89	155	197	122
Slope		0.153	0.144	0.223	0.213	0.098
Cent. St. Dist., L_c	km	84	63	105	100	74.7
Basin Length	km	122	70	100	118	109
Drainage Density		1.46	0.75	1.44	1.45	1.08
Relief	km	2.12	1.86	2.31	2.26	1.1
Relief Ratio	m/m	0.017	0.027	0.023	0.019	0.01
Stream Orders		5	4	5	6	5

Table 2. Prediction (mm) for Gumbel pdf for selected return periods (in years) based on 24-hr duration data.

Station ID	Site	Probability Return Period (yr)	0.995 200	0.99 100	0.98 50	0.96 25	0.9 10	0.8 5
J109	Faqair		97.7	88.0	78.2	68.4	55.1	44.6
J110	Malbanah		108.9	97.4	85.8	74.2	58.5	46.0
J111	Mastorah		84.1	74.8	65.5	56.1	43.4	33.3
J112	Umm Albirak		77.5	69.6	61.7	53.7	43.0	34.4
J117	Bader		86.4	76.9	67.5	57.9	45.0	34.8
J118	Mosijid		121.6	107.9	94.3	80.5	61.9	47.2
J133	Umm Dayan		103.4	92.4	81.4	70.4	55.4	43.6
J140	Rabigh		80.5	71.5	62.6	53.5	41.3	31.6
W109	Sowayq		72.5	64.5	56.4	48.2	37.2	28.5
M001	Madinah		97.0	86.4	75.7	65.0	50.5	39.0
M101	Ise		76.7	68.4	60.1	51.8	40.5	31.6
M103	Bir Mashi		63.2	57.1	50.9	44.6	36.2	29.5
M108	Meleileh		80.5	71.9	63.3	54.7	43.0	33.8
M110	Suwayriqiyah		89.7	80.9	72.1	63.1	51.1	41.6
M112	Buwayr		58.4	52.0	45.6	39.2	30.5	23.7
W106	Umm Lajj		102.5	91.1	79.8	68.3	52.8	40.6

is normal for an arid region. The PMP estimates for a 25-year return period indicated that mountain stations received rainfall of more than 70 mm (Figure 3). The PMP estimates for a 50-year return period revealed an increase in rainfall from the southeast to the northwest (i.e., from 50 to 80 mm.) (Figure 4). However, over a 100-year return period, the annual maximum daily rainstorm increased in the mountainous and middle parts of the study area (i.e., from 60 to 100 mm.) (Figure 5). The annual maximum daily rainfall values increased equivalently with increasing return periods, demonstrating that the chosen model is accurate and that rain storm events covering the area vary slightly. These figures will be very helpful when planning different structural designs.

Table 3 shows that the composite curve number (*CCN*) ranges from 83 with high runoff flow with dominant wadi bed coverage to 95 with hard rock cover and larger runoff flow. The calculated

Table 3. Unit Hydrograph, hydrograph characteristics of the basins.

		Basin				
		W. Mastorah	W. Marij	W. Safra	W. Fara'a	W. Alaqiq
CCN		87	83	89	91	85
Max. Ret., S (mm)		37.95	52.02	31.39	25.12	44.82
T_{lag} (h)		29.4	21.2	29.2	31.7	27.4
UH Peak (m^3/s)		27.4	7.8	16.6	37.9	31.8
Rainfall 25-Y		60	60	70	55	60
Rainfall 50-Y		70	70	85	60	65
Rainfall 100-Y		85	80	90	70	75
25- y Storm Hydrogr.	Peak (m^3/s)	832	188	708	1262	864
	Runoff (mm)	30.4	24.2	42.7	33.3	27.17
	Volume ($m^3 x 10^6$)	144	23.7	121.8	233.8	139.6
50- y Storm Hydrogr.	Peak (m^3/s)	1063	243	934	1413	989
	Runoff (mm)	38.8	31.2	56.27	37.7	31.1
	Volume ($m^3 x 10^6$)	184	31.2	160.6	265.2	159.8
100- y Storm Hydrogr.	Peak (m^3/s)	1422	310	1010	1773	1250
	Runoff (m m)	51.9	39.8	60.9	46.8	39.3
	Volume ($m^3 x 10^6$)	246	39	173	329.4	202
I_a		7.6	10.44	6.3	5.0	9.0

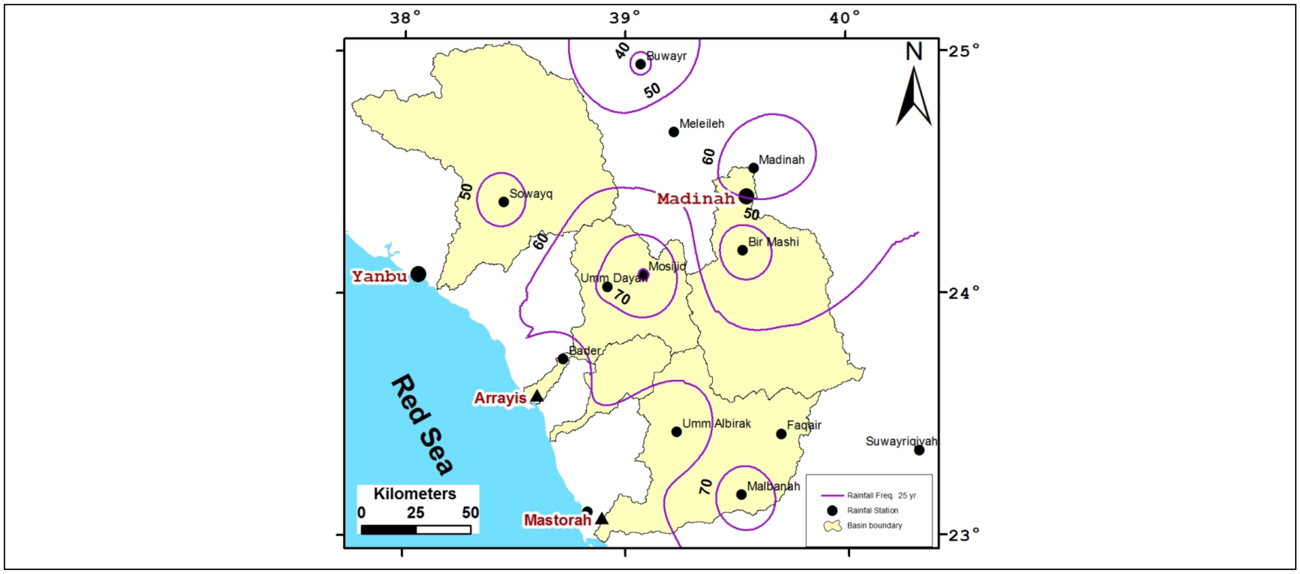

Figure 3. PMP of 25-years return period.

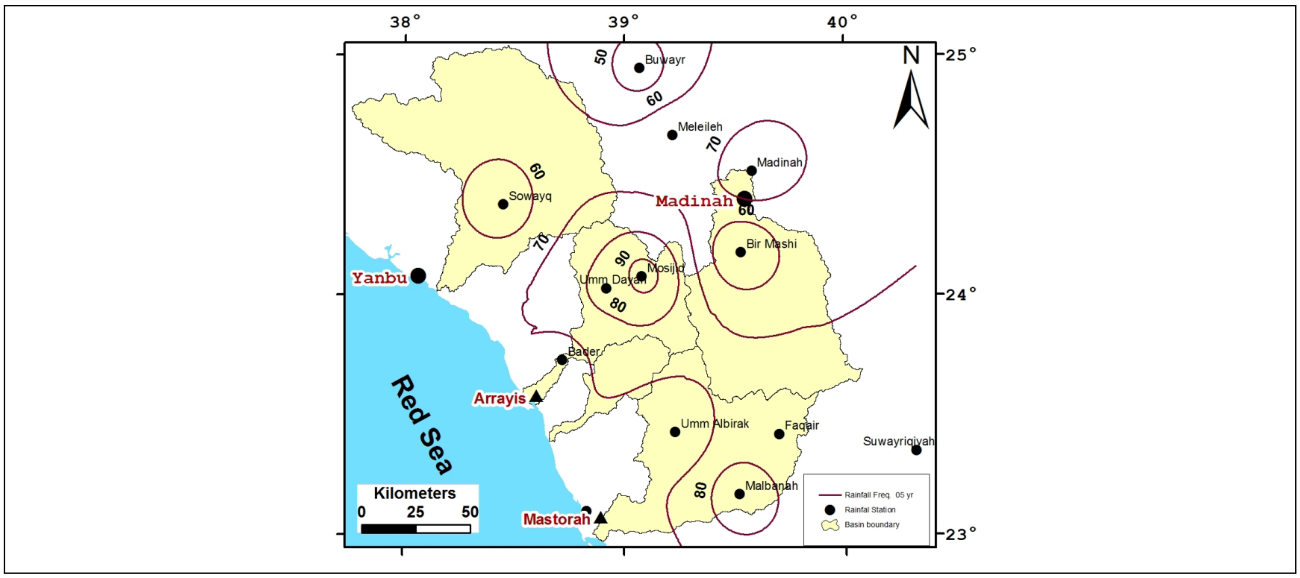

Figure 4. PMP of 50-years return period.

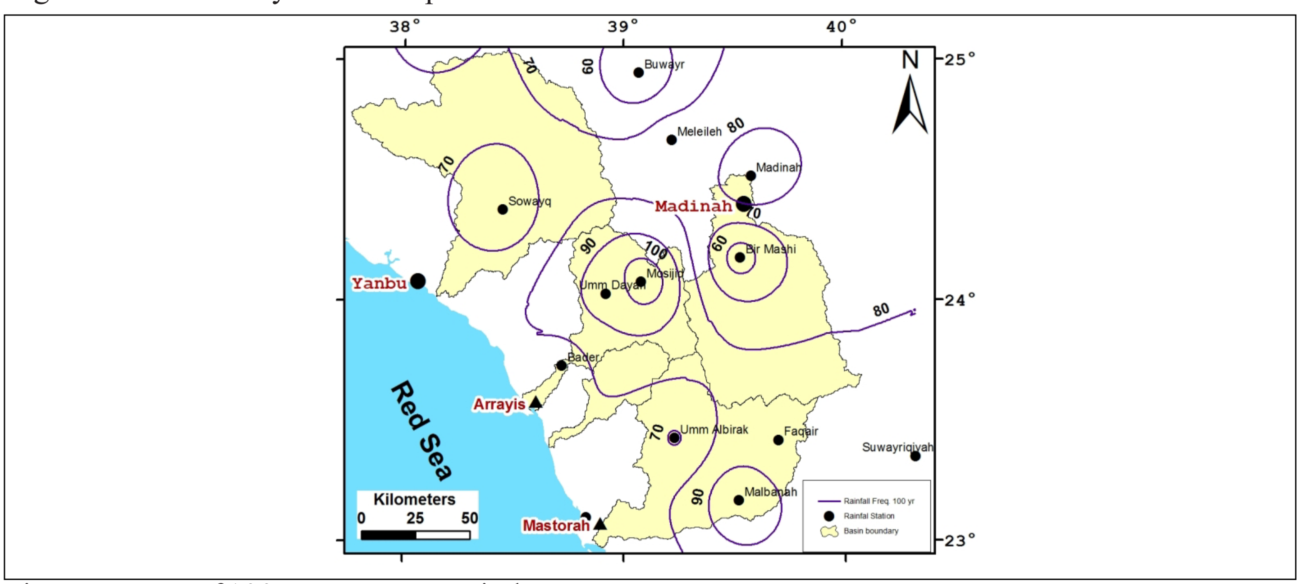

Figure 5. PMP of 100-years return period.

values for the SCS dimensionless unit hydrographs are shown in Figure 6 and Table 3. Generated storm hydrographs for return periods of 25, 50 and 100 years are shown in Figures 7, 8 and 9. The shape of the unit hydrographs for all basins was not symmetrical, showing a steep rise and slight decrease in falling limbs. Using Equation 8 above, the lag time of peak discharge of the basins was calculated as ranging between 21.2 h for W. Marij to 31.7 h for W. Fara'a depending on the morphometric parameters of the basin, potential maximum retention, and the composite curve number. Peak discharge of the basins ranged from 7.8 to 37.9 ($m^3/s/km^2/mm$). Finally, according to the contribution of lower curve number (i.e., *CCN*= 85) and effects on the huge basin area, W. Fara'a possesses the highest peak amongst all the wadis studied.

This study also showed that the direct runoff ranged from 35% to 65% of the total rainfall (Table 3). This is due mostly to topography, high values of curve numbers, and the use of predicted maximum daily rainfall results.

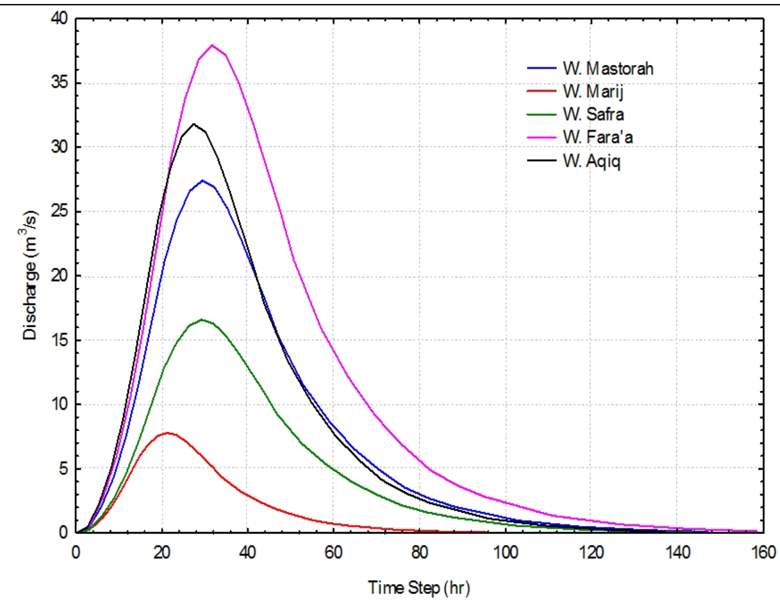

Figure 6. Unit hydrographs for studied wadis.

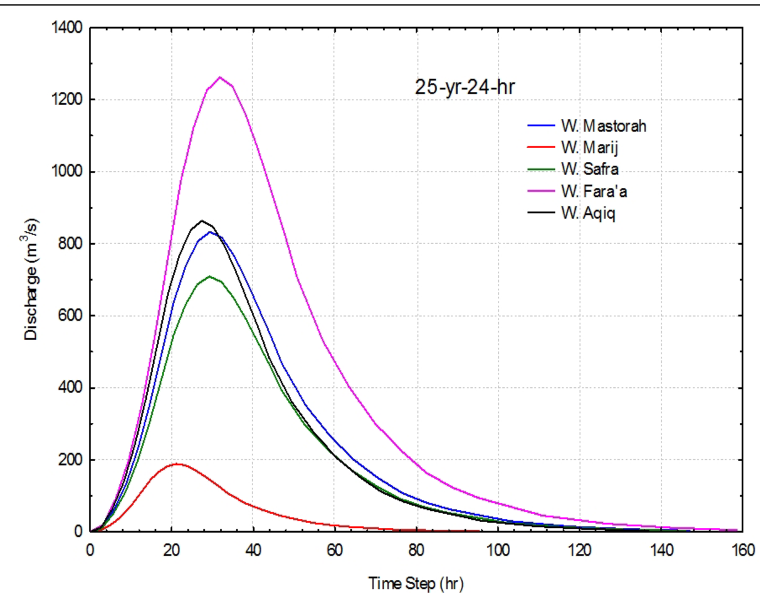

Figure 7. Generated storm hydrographs for 25-yr return period.

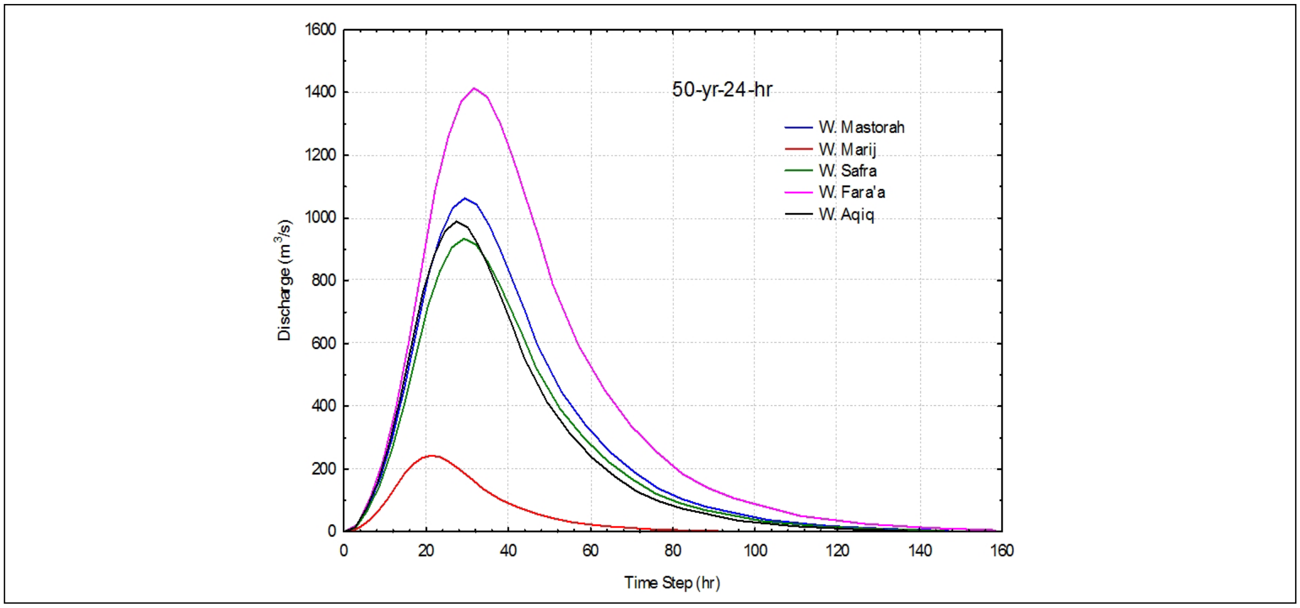

Figure 8. Generated storm hydrographs for 50-yr return period.

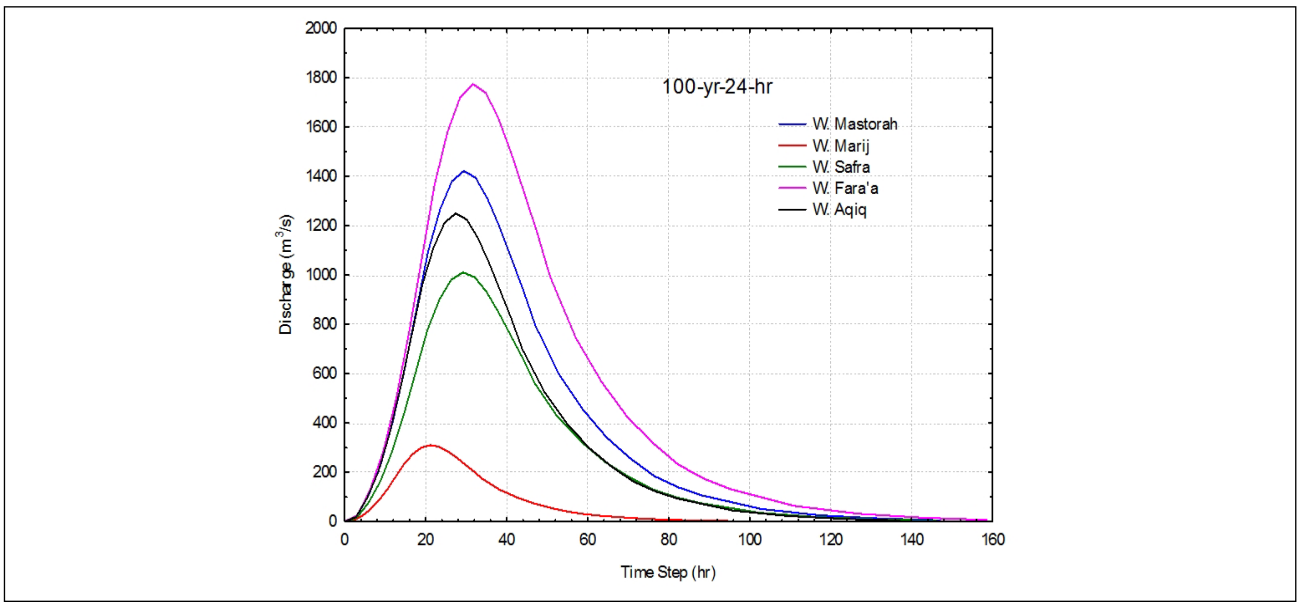

Figure 9. Generated storm hydrographs for 100-yr return period.

CONCLUSION

Floods can occur at any time, but weather patterns have a strong influence on when and where they happen. Unfortunately, in arid regions, where suitable and continuous hydrometeorological data are limited or incomplete, floods result in loss of life, infrastructure, and property due to long-term aridity, increased urbanization, and coastal development. The methodology used by the Soil Conservation Services was adopted in this study to investigate five ungauged dry wadis in Al-Madinah area. The annual maximum daily rainfall was obtained and modeled for these wadis and quantified as storm hydrographs, peak discharge, and runoff volume for different return periods. The results indicate that high flooding may occur in the area. Flood-control systems, such as dams and levees, could be built on major streams to store rainwater runoff and reduce downstream flooding, as well as increase the rate of groundwater recharge in these shallow dry wadis during floods. Thus, the results from this study can expand our understanding of the hydrological and morphometric processes that affect flood behavior in arid regions.

ACKNOWLEDGMENTS

This paper was reviewed by Professor Zekai Sen of the Technical University of Istanbul, Turkey, and by Dr. Abdulrahman Al-Dakheel of the Department of Geology at King Saud University, Saudi Arabia.

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