Arab J Geosci
DOI 10.1007/s12517-011-0405-5

ORIGINAL PAPER

Assessment of several flood estimation methodologies in Makkah metropolitan area, Saudi Arabia

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Received: 26 February 2011 / Accepted: 18 September 2011

Abstract Estimation of floods in a hydrological basin is essential for efficient flood management and development planning. Several approaches have been proposed to estimate flood peak discharge based on topographic and morphometric characteristics of ungauged hydrological basins. Two global approaches, namely the rational and the curve number methods, along with four national regression models have been compared over Makkah metropolitan area, Saudi Arabia. The curve number methodology has been taken as the basis of comparison due to its precision and wide utilization. Results show that the rational method produces differences equal to 44% in terms of peak discharges. Moreover, the best national regression model gives difference in the order of 18% with respect to the curve number results. Other national models give results very far away from those of the curve number (up to 95%), which can be considered as measures for their awful accuracy. Hence, the curve number is recommended as an optimum methodology for flood estimation, in Makkah city, in case of availability of geological, metrological, land use, and topographic datasets. Otherwise, a specific national regression model (Al-Subai) may be utilized in a simple way.

Keywords Flood assessment · Rainfall–runoff models · Ungauged catchments · Saudi Arabia

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Introduction

Hazards of flash floods are vital in terms of human lives loss and economical damages. Flash floods affect local residents in a dangerous way particularly in developing countries, and flood hazard maps should be available and updated (Hagen and Lu 2011). Economically speaking, floods produce significant financial loss so that a flood assessment model should include the estimation of economic damages (Hsu et al. 2011). Utilization of recent technologies, such as the geographic information systems (GIS) and remote sensing (RS), in developing flood hazard maps is gaining increasing attention in the last couple of decades (e.g., Forkuo 2011; Mouri et al. 2011; Parker et al. 2011; Dang et al. 2011; and Soussa et al. 2010). A reliable estimation of floods in a hydrological basin is crucial for efficient flood management and surface water resources planning. On a national level, a precise flood assessment is considered as an important demand in Makkah metropolitan area, Kingdom of Saudi Arabia (KSA) due to the unexpected nature of rainfall that often produces hazardous flash floods. It is worth mentioning that the southwest part of KSA contains almost 60% of the volume of wadi flow, particularly in the terrain situated between the Red Sea coast and the adjacent mountains (Nouh 2006). Extensive flood estimation studies have been carried out in KSA in the last few years chiefly with the utilization of GIS and RS techniques (e.g., Dawod et al. 2011; Dawod and Koshak 2011; Al Saud 2010; and Metwaly et al. 2010).

It is economically costly and physically difficult to gauge all streams in a region, particularly in a large country such as KSA (Şen and Al-Suba'l 2002). For ungauged hydrological catchments, where measured flood discharge data records are missing, the flood estimation becomes more complicated. Countless approaches have been proposed globally trying to estimate flood peak discharge quantities based on topographic and morphometric characteristics of hydrological regions. Such approaches may be grouped into three categories: simple, medium, and complex models (Mihalik 2007). Simple hydrological models can produce estimates of flood peak discharge, and other hydrological quantities, fast and with little amount of required data. Rational and regression can be classified as simple models. Ordinary and other regression models have been utilized in hydrological modeling all over the world (e.g., Ishak et al. 2011; Liu et al. 2011; Subyani 2011; and Meddi et al. 2010). Medium hydrological models, e.g., the curve number approach, utilize more parameters in modeling the rainfall–runoff relationship. Complex models, e.g., the Soil and Water Assessment Tool, are able to identify the causes of problems rather than producing a simple description of overall conditions.

The rainfall–runoff relationship plays a fundamental role in many aspects of watershed management such as the determination of the available and sustainable water resources, the design of flood operations and protective measures, and drought management (Sen 2008b). On a national scale, some regression models have been developed to perform that task. For example, Şen and Al-Suba'l (2002) and Al-Subai (1992) have developed empirical formulas to model the precipitation–runoff relationship in the southwest region of KSA. However, understanding the nature and limitations of those estimation models is necessary before utilizing any specific method. This paper aims to present and justify some global and national models for estimating flood discharge in Makkah metropolitan area.

Flood estimation models

Simple flood estimation methods usually employ empirical relationships between rainfall and runoff that allow estimation of design discharges on ungauged watersheds by the development of parameters describing the watershed. Moreover, other models are presented in case of availability of measured discharge datasets such as ordinary regression, Bayesian regression, artificial neural networks, fuzzy logic, and genetic algorithms (e.g., Tayfur and Singh 2010; Kim and Lee 2010; Singh et al. 2010).

On a national level, some regression models have been developed in Saudi Arabia in order to compute flood discharge. Other methods have presented non-computational different approaches to accomplish this task, such as utilizing hydrographs (e.g., Sen 2008a) and geostatistical method (e.g., Subyani and Al-Dakheel 2009). However, only the computational methods are considered herein, and they are briefed in the next sections. It is a matter of reality that the accuracy of the input data in flood modeling seriously influences the precision of the estimated quantities (Moel and Aerts 2011).

General flood estimation models

There are countless hydrologic flood estimation methodologies that have been proposed in the last decades. In this paper, only two approaches are considered, namely the rational method and the U.S. National Resources Conservation Services (NRCS) method.

The rational method was first introduced in 1889. Although it is often considered simplistic, it still is appropriate for estimating peak discharges for small drainage areas of up to about 200 acres (80 ha) in which no significant flood storage appears. A main assumption in this method is that the rainfall is assumed uniform over the area of interest, which is a valid assumption for small areas (US TDoT 2009). The metric form of the rational method reads:

$$Q_{\mathrm{p}} = C\, I\, A/360 \tag{1}$$

where,

- Q_{p} is the peak discharge (cubic meters per second)
- I is the rainfall intensity for the design storm (millimeters per hour)
- A is the drainage area (square kilometer), and
- C is a dimensionless runoff coefficient assumed to be a function of the cover of the watershed and often the frequency of the flood being estimated. Tables which provide values of this constant are provided in several hydraulic literatures (e.g., US DoT 2002).

It worth mentioning that Sen (2008b) reported that the estimation of the C value is difficult and is the major source of uncertainty in many water resources projects. This coefficient must account for all the significant factors affecting the peak flow to average rainfall intensity, not restricted to area and response time.

The NRCS, formerly known as the Soil Conservation Service (SCS), utilizes geological information to assign a unique curve number (CN) coefficient value for each area that will be further used to estimate the surface runoff depth and the peak discharge magnitude. The NRCS method is quite utilized in engineering design and flood management

Table 1 Coefficient discharge values of modified Talbot formula (after Quraishi and Al-Hassoun 1996)

Constant	Value	Usage
C_1	0.30	Mountainous areas
	0.20	Semi-mountainous areas
	0.10	Low land areas
C_2	0.50	$S>15\%$
	0.40	$10<S<15\%$
	0.30	$5<S<10\%$
	0.25	$2<S<5\%$
	0.20	$1<S<2\%$
	0.15	$0.5<S<1\%$
	0.10	$S<0.5\%$
C_3	0.30	$W=L$
	0.20	W=0.4 L
	0.10	W=0.2 L

S slope, *W* width, and *L* length of the drainage area

projects in several countries (e.g., Al-Jabari et al. 2009; Adebayo et al. 2009; Elaji 2010; Xianzhao and Jiazhu 2008; and Gul et al. 2009), and particularly in USA (e.g., US ACE 2004; US DoT 2002). The basic formulas of the NRCS approach are (e.g., US NRCS 1986):

$$Q = (P - 0.2S)^2/(P + 0.8S) \tag{2}$$

where,

Q=depth of direct runoff (millimeter)
P=depth of precipitation for a specific return period (millimeter)
S=maximum potential retention (millimeter):

$$S = 25.4((1,000/\mathrm{CN}) - 10) \tag{3}$$

where CN is the curve number. Tables which provide values of CN are presented in several hydraulic literatures (e.g., Sen 2008b, pp. 165).

$$\mathrm{qp} = \mathrm{qu}\,A\,Q \tag{4}$$

where,

qp=peak discharge (cubic meters per second)
A=drainage area (square kilometer)
Q=depth of runoff (millimeter)
qu=unit peak discharge (cubic meters per second per kilometer per millimeter) that can be interpolated from specific charts (e.g., US NRCS 1986) or computed from corresponding tables (e.g., US DoT 2002, pp. 5–28).

The time of concentration constitutes an important factor in flood assessment studies since it is the time required by runoff to travel from the most distant point to the basin's outlet point. There are several formulas to compute the concentration time; one of them is the NRCS equation which is given as:

$$\mathrm{tc} = 1.67\left[L^{0.8}(S+1)^{0.7}\right]/\left[1,900 \times \mathrm{SL}^{0.5}\right] \tag{5}$$

where L is the basin length (expressed in units of meters), tc is the concentration time (minutes), and SL is the average watershed land slope in percentage.

National flood regression models

Al-Subai (1992) has determined, from actual field measurements in the southwest part of KSA, that average peak discharge can be estimated for the Arabian Peninsula as the power relation of classic regression technique as (Sen 2008b, Eq. 4.33, pp. 135):

$$Q_\mathrm{p} = 43\,A^{0:522} \tag{6}$$

where Q_p is the average discharge (cubic meters per second) of a given Area A (square kilometer).

The mean annual flood discharge for the wadi being considered has to be known in order to use the method, and empirical methods can also be applied to estimate this from catchment properties. Nouh 1987 has presented a regression formula based on data from 26 gauging stations in the southwest part of KSA:

$$\mathrm{MAF} = 0.365\,A^{0.83}\mathrm{ELEV}^{0.47} \tag{7}$$

where:

MAF is the mean annual flood peak discharge (cubic meters per second)
A is the catchment area (square kilometer), and
ELEV is the mean catchment elevation (meter).

It is worth to mention that another slightly different regression formula has been developed by Nouh (2006) similar to Eq. 7, but the geographic area includes the southwest KSA and Yemen.

Farquharson et al. (1992) also developed general relationships, which only depend on catchment area, for eight separate world regions using catchment area only, as follows:

$$\mathrm{MAF} = \text{constant } A \text{ exponent} \tag{8}$$

Table 2 Design storm frequency factor of modified Talbot formula (after Quraishi and Al-Hassoun 1996)

Frequency in years	F_f
5	0.60
10	0.80
25	1.00
50	1.20
100	1.40

In Saudi Arabia and Yemen, the developed formula is (Steenbergen 2010):

$$\mathrm{MAF} = 0.991\,A^{0.701} \tag{9}$$

Quraishi and Al-Hassoun (1996) reported a method called modified Talbot that is used in the Saudi Ministry of Communication on a national level. The basic modified Talbot formula is:

$$Q_p = K\,C\,A^n R_f F_f \tag{10}$$

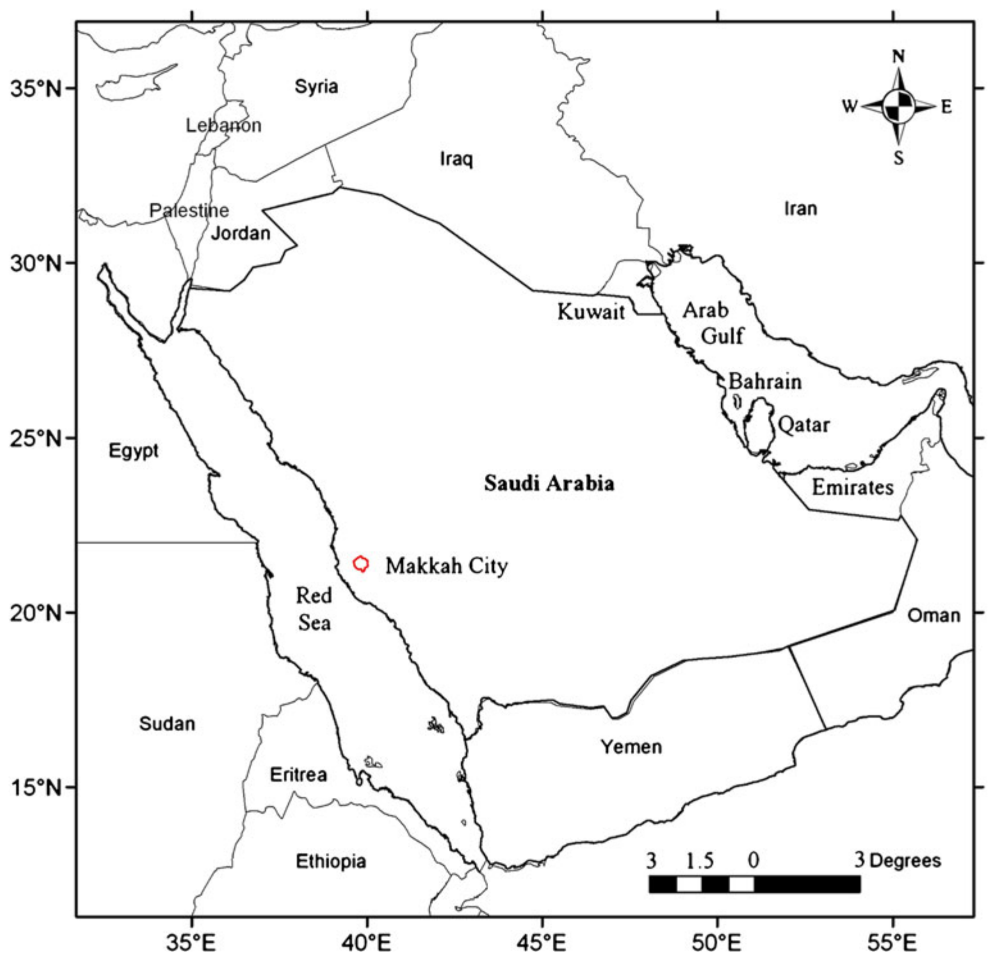
where,

- K is a constant which has values of 0.557, 3.561, and 10.166 for medium, large, and regional watersheds, respectively. The catchment area categories are: medium for size 400–1,258 ha, large for size 1,258–35,944 ha, and regional for size more than 35,944 ha
- A is the drainage area in hectares
- N is an exponent which depends on the size of the drainage area, and has values of 0.75, 0.50, and 0.40 for medium, large, and regional watersheds, respectively.
- C is a coefficient of discharge which was suggested to be the summation of C_1, C_2, C_3, where C_1 is the coefficient of terrain condition, C_2 is the coefficient of slope of drainage area, and C_3 is the coefficient of shape of drainage area. Table 1 shows the values of these constants.
- R_f is a rainfall factor suggested to be 1.5 for medium watersheds and 1.4 for both large and regional watersheds.
- F_f is a frequency factor which depends on the desired storm frequency, and is shown in Table 2.

Study area and available data

Makkah city is located in the southwest part of KSA, about 80 km east of the Red Sea (Fig. 1). It extends from 39° 35′ E to 40° 02′ E and from 21° 09′ N to 21° 37′ N. The area of the metropolitan region (the study area) equals 1,593 km^2 approximately. The topography of Makkah is complex in nature, and several mountainous areas exist inside its metropolitan area. Winter is considered as the main rainy season in Saudi Arabia. The annual rain over Makkah city, for a period extending from 1966–2009, varies from 3.8 to 318.5 mm, with an average of rainfall

Fig. 1 Study area



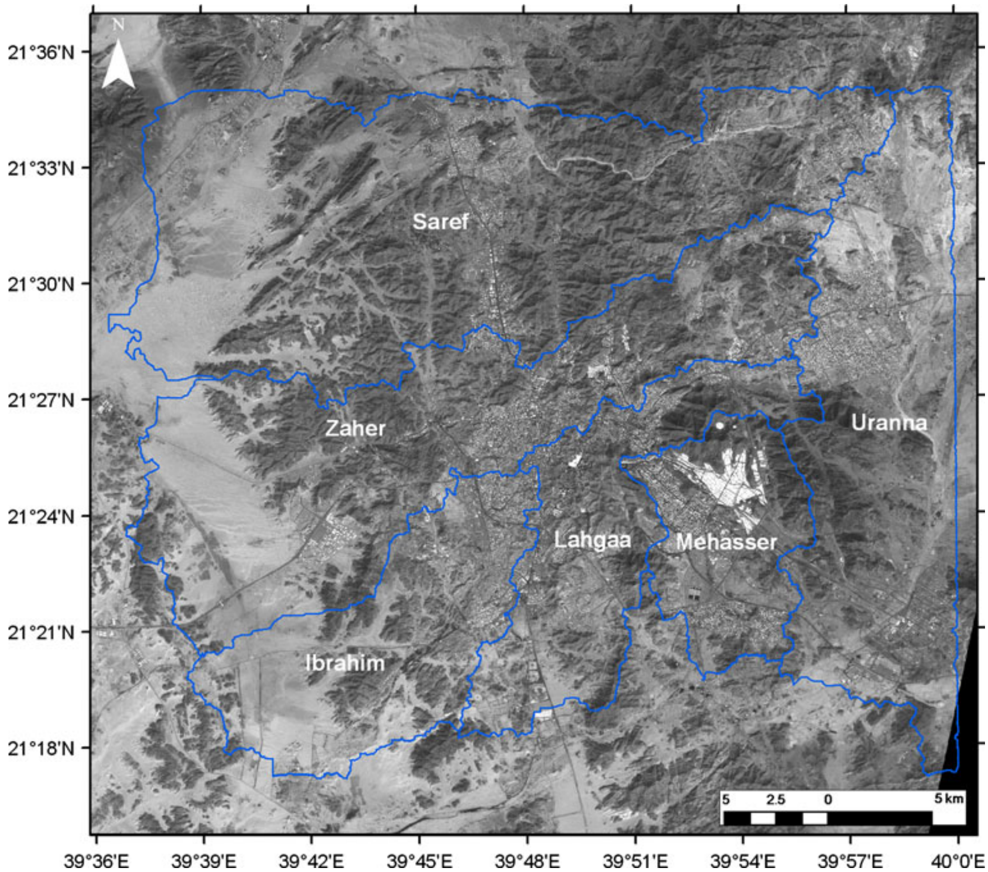


Fig. 2 The main basins in Makkah metropolitan area

equal to 101.2 mm (Mirza et al. 2011a). Due to the complexity of Makkah's topography, flash floods occur periodically with significant variations in magnitude. The rain intensity in a single extreme storm may exceed the annual rain average in that year.

Several datasets have been collected for the cause of flood assessment. The main data piece is a digital elevation model (DEM) for the study area. The acquired DEM produced by the by King Abdulaziz City of Sciences and Technology had a spatial resolution of 5 m. A window covering Makkah metropolitan area has been provided through the Center of Research Excellence in Hajj and Umrah, Umm Al-Qura University. Mirza et al. (2011b) confirm that that national DEM is three times more accurate than published global DEMs. The other collected datasets include digital geological, soil, and land use maps of the study area. The Arc GIS software has been utilized to delineate the main catchments in Makkah based on the available DEM (Dawod et al. 2011). Six main basins are identified whose area ranges from 74.3 to 360.6 km^2, and lengths of their main streams vary from 16.50 to 48.55 km (Fig. 2). Table 3 presents statistics of some hydrological parameters of these catchments. A comprehensive GIS-based morphometric analysis of these basins has been carried out (Koshak and Dawod 2011).

Table 3 Statistics of morphometric quantities

Item	C1	C2	C3	C4	C5	C6
Basin area (km^2)	252.7	122.3	74.3	109.9	360.6	200.2
Basin premier (km)	134.6	69.13	50.23	89.09	134.76	102.03
Length of main stream (km)	42.48	23.64	16.50	29.70	48.55	38.13
Relief ratio (m/km)	12.6	14.1	40.4	25.9	13.0	18.7

C1 Zaher wadi, *C2* Ibrahim wadi, *C3* Mehasser wadi, *C4* Lahgaa wadi, *C5* Sareef wadi, *C6* Uranna wadi

Table 4 NRCS flood results (for a 10-year return period)

Item	C1	C2	C3	C4	C5	C6
Time of concentration (h)	6.00	4.00	1.98	3.24	2.51	4.60
CN	84	84	93	89	84	83
Runoff depth (mm)	71.5	71.5	94.2	83.7	71.5	69.2
Peak discharge (m^3/s)	733	501	689	620	2,116	705

Table 5 Rational flood results (for a 10-year return period)

Item	C1	C2	C3	C4	C5	C6
Peak discharge (m^3/s)	642	311	189	279	916	508
Difference to NRCS-based peak discharge (m^3/s)	91	190	500	341	1,200	196
Difference percentage to NRCS-based peak discharge	12%	38%	73%	55%	57%	28%
Difference mean percentage	44%					

Table 7 Nouh's model flood results

Item	C1	C2	C3	C4	C5	C6
Mean catchment elevation (ELEV in m)	278	225	460	324	289	395
Peak discharge (m^3/s)	507	251	207	273	694	493
Difference to NRCS-based peak discharge (m^3/s)	226	250	481	347	1,422	212
Difference percentage to NRCS-based peak discharge	31%	50%	70%	56%	67%	30%
Difference mean percentage	51%					

Accomplished results

The recent extensive utilization of the NRCS method on a global basis (e.g., Reshma et al. 2010; Ebrahimian et al. 2009; Soussa et al. 2010) has led the authors of the current paper to believe that it may be considered as an optimum tool for estimating flood discharge for ungauged hydrological basins. Consequently, this method is considered as a base of comparison to the other investigated hydrological methods. The NRCS method has been performed for the available data of Makkah metropolitan area to compute the peak discharge value for the six basins. The return period has been chosen, herein, as 10 years, for which the rainfall intensity has been estimated, by applying the Log Pearson III statistical analysis, as 114.3 mm/h. Similar results have been reported for Makkah city (MPWH 2001). Based on the geological, soil, and land use characteristics, the curve number (CN) has been estimated for the study area catchments. Table 4 presents the results of the NRCS method.

Secondly, the rational method has been performed using appropriate values of the runoff coefficients C (Eq. 1). The *C* coefficient ranges from 0.05 to 0.95 based on land use, soil, and geology of the concerned regions. A detailed classification of these values can be found in several flood analysis literature (e.g., US ACE 1994, pp. 11–2). In the current research, the *C* value has been taken as 0.8 since the majority of the Makkah metropolitan area constitutes paved-street residential areas. Then, the achieved results have been compared to those of the NRCS method. Table 5 presents the accomplished results. It can be noticed that the overall agreement between the NRCS and rational methods is 45% only. That is expected due to the assumption behind the rational method, which is the equal distribution of rainfall over all the catchment areas. As mentioned earlier, the rational method is valid only for small basins with about 1 km^2 in area.

Thirdly, the national regression models have been carried out to compute peak discharge quantities in Makkah metropolitan area. Al-Subai's model (Eq. 6) is computed for the six hydrological catchments and then compared to the NRCS results (Table 6). It can be noticed that the overall differences agreement with the NRCS method reaches 18%, which means that this model produces 82% of the NRCS-based peak discharges in the study area. Recall that this model has been developed for the southwest region of KSA, where the study area is located.

Next, the Nouh's formula (Eq. 7) has been utilized in the same manner (Table 7). The mean catchment elevation has been obtained from the DEM using the Arc GIS software. It can be noticed that the overall differences agreement with the NRCS method reaches 51%, which means that this model produces 49% of the NRCS-based peak discharges in the study area. It should be considered that the results of this model are in a mean scene as stated in Eq. 7.

Next, Farquharson's model (Eq. 9) has been performed and, as usual, was compared to the NRCS results (Table 8). It can be seen that the general differences agreement with the NRCS method reaches 95%, which means that this model produces only 5% of the NRCS-based peak discharges in the study area. Such extraordinary results are due to the fact that this model covers a huge geographic

Table 6 Al-Subai's model flood results (for a 10-year return period)

Item	C1	C2	C3	C4	C5	C6
Peak discharge (m^3/s)	772	529	408	500	929	684
Difference to NRCS-based peak discharge (m^3/s)	−39	−27	281	120	1,176	21
Difference percentage to NRCS-based peak discharge	−5%	−5%	41%	19%	56%	3%
Difference mean percentage	18%					

Table 8 Farquharson's model flood results

Item	C1	C2	C3	C4	C5	C6
Peak discharge (m^3/s)	48	29	20	27	61	41
Difference to NRCS-based peak discharge (m^3/s)	685	472	668	593	2,055	664
Difference percentage to NRCS-based peak discharge	93%	94%	97%	96%	97%	94%
Difference mean percentage	95%					

Table 9 Modified Talbot's model flood results

Item	C1	C2	C3	C4	C5	C6
Peak discharge (m^3/s)	444	309	309	334	606	395
Difference to NRCS-based peak discharge (m^3/s)	289	192	379	285	1,510	310
Difference percentage to NRCS-based peak discharge	39%	38%	55%	46%	71%	44%
Difference mean percentage	49%					

area (Saudi Arabia and Yemen) utilizing only 26 gauge stations in its development, which in turns makes it impractical in nature.

Lastly, the modified Talbot model (Eq. 10) has been carried out and again compared to the NRCS results (Table 9). It can be noticed that the general differences agreement with the NRCS method reaches 49%, which means that this model produces only 51% of the NRCS-based peak discharges in the study area. Similar results have been reported by Quraishi and Al-Hassoun (1996).

As a conclusion, Table 10 presents a brief comparison of all the test models. Clearly, it can be concluded that Al-Subai's regression model is the closer method to the NRCS approach. On the other hand, it is obvious that Farquharson's regression model produces results very far from those of the NRCS hydrologic methodology.

Conclusions

Rainfall–runoff modeling plays a vital role in several watershed management phases, particularly for the determination of the available and sustainable water resources and for flood management. The southwest part of KSA contains almost 60% of the volume of wadi flow, and hence, precise flood assessment is important in planning and development. There are a lot of flood modeling approaches at hand, and their simplicity and accuracy are significantly different. This study has examined two global flood modeling approaches, namely the rational and SCS methodologies.

Table 10 Summary of all flood estimation models

Model	Percent of produced discharge as compared to the NRCS method (%)
NRCS	NA
Rational	56
Al-Subai	82
Nouh	49
Farquharson	5
Talbot	51

On a national levels, some regression models have been developed in Saudi Arabia in order to compute flood discharge. Other methods have presented non-computational different approaches to accomplish this task, such as utilizing hydrographs and geostatistical method. Four regression models have been also justified in the current research to compute flood discharge in Makkah metropolitan area based on the available precise datasets. The curve number methodology has been taken as the basis of comparison due to its precision and wide utilization in engineering and environmental projects in several countries. The accomplished results show that the rational method produces differences equal to 44% in terms of peak discharges. That is expected due to the assumption behind the rational method, which is the equal distribution of rainfall over all the catchment areas. Previous hydrological studies recommended this approach only for estimating peak discharges in small drainage areas of up to about 200 acres (80 ha).

Regarding the national flood regression models, it has been found that Al-Subai, Nouh, Farquharson, and the modified Talbot methods provide peak discharge values that equal 82%, 49%, 5%, and 51%, respectively, with respect to the curve number results. These differences may be attributed to the fact that the accuracy of the input data in flood modeling greatly affects the precision of the computed output. Furthermore, it can be obviously realized that the catchment C3 (Mehasser wadi) produced almost the biggest difference in the utilized national regression models. That can be attributed to the fact that these models depend only upon the catchment area and its mean elevation, and ignore all other topographic and morphometric characteristics of the basin. Mehasser wadi, even though it is the smallest wadi in terms of area, has specific natural properties that make it the most dangerous basin in Makkah city. For example, its terrain slope (relief ratio in Table 3) is the maximum one in this area that extensively increases the hazards of flash floods. That is an important conclusion since this basin covers the holy shrines (Mina and Muzdalifa), in which millions of Muslims are gathered for few days during the pilgrim (Hajj) seasons.

It is concluded that Al-Subai's model is the most precise national hydrological model in Makkah area. This is due to the fact that this model has been developed based on actual precise field measurements in the southwest part of KSA. The other national empirical function aimed to estimate annual flood peak discharge in a mean sense. However, in case of availability of topographic, metrological, land use, and geological datasets, the curve number method should be considered as the optimum flood modeling approach.

Acknowledgments The authors would like to acknowledge the financial support offered by the Center of Research Excellence in Hajj and Umrah (Hajjcore), Umm Al-Qura University, Makkah, Saudi Arabia.

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