Arab J Geosci (2016) 9:387
DOI 10.1007/s12517-016-2410-1

ORIGINAL PAPER

Assessment of a water-harvesting site in Riyadh Region of Kingdom of Saudi Arabia using hydrological analysis

Hesham Fouli[1,2] · **Abdulaziz S. AL-Turbak**[1,2] · **Bashar Bashir**[1,2] ·
Oumar A. Loni[1,3]

Received: 16 July 2015 / Accepted: 26 February 2016

Abstract A potential ungauged water-harvesting site was chosen in the central Riyadh Region of Saudi Arabia. A hydrological study was carried out on the catchment area from which runoff water will be diverted to the chosen site. Rainfall depth records from three neighboring rain gauges were used. Runoff volumes and peak discharges for the 2-, 5-, and 10-year storms were estimated using three methods, namely, (a) Soil Conservation Service (SCS) Dimensionless Unit Hydrograph (DUH) method assuming Gumbel distribution for rainfall depth analysis, (b) HEC-HMS modeling, and (c) the modified Talbot formula. The results show that the modified Talbot formula yields an order of magnitude higher peak discharge values for all return periods. The SCS-DUH method and HEC-HMS modeling provide comparable estimates for the peak discharges and runoff volumes. The peak discharges obtained through the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model for the 2-, 5-, and 10-year storms are 0.17, 0.83, and 1.34 times than those obtained by the SCS-DUH, respectively. The HEC-HMS runoff volume estimates are 0.18, 0.85, and 1.36 times than those estimated by the SCS-DUH for the 2-, 5-, and 10-year storms, respectively.

Keywords Water harvesting · Arid regions · Riyadh Region · Hydrologic analyses

Introduction

The Kingdom of Saudi Arabia (KSA), which has an area of about 2.25 million km^2, is located within the arid and semi-arid climate region of southwest Asia. The aridity of the climate leads to a low average annual rainfall, which is estimated to be about 100 mm (Climate Atlas of Saudi Arabia 1988). Due to the lack of surface water streams and low rainfall, there is an urgent need to manage the available water resources using different techniques including water harvesting.

Rainwater and runoff harvesting has been an important topic that is emphasized by many researchers, professionals, and decision makers. Although it may sound more important for arid regions, rainwater and runoff harvesting has been equally important and practiced in humid climates as well. Oweis et al. (2012) discuss extensively rainwater harvesting for agriculture in the dry areas. They demonstrate how to design, build, and maintain water-harvesting systems tailored to local needs. Different water-harvesting techniques are reported by researchers in literature. For example, Adhikari et al. (2013) evaluated the effect of percolation tanks and check dams on groundwater recharge and water quality in semi-arid regions of India. Wu et al. (2009) investigated collecting brooklet water in a series of ponds and rainwater in underground tanks, to increase agricultural productivity in some semi-arid parts of southwest China. Several rainwater and runoff harvesting studies utilized remote sensing techniques for selecting potential water-harvesting locations. For example, Al-Adamat (2008) used geographic information systems (GIS) for siting water-harvesting ponds in the Basalt Aquifer, Jordan. Hadadin et al. (2012) used GIS and digital elevation

✉ Hesham Fouli
hfouli@ksu.edu.sa

[1] Chair of Prince Sultan Bin Abdulaziz International Prize for Water, Prince Sultan Institute for Environmental, Water and Desert Research, King Saud University, P.O. Box 2454, Riyadh 11451, Saudi Arabia

[2] Department of Civil Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

[3] King Abdulaziz City for Science and Technology (KACST), P.O. Box 6086, Riyadh 11442, Saudi Arabia

model (DEM) to identify potential water-harvesting sites in the northeast Badia of Jordan. More recently, Bashir et al. (2015) used GIS and DEM to identify potential water-harvesting sites in Riyadh Region of KSA; the site selected in this study is in fact one of those recommended in their work.

A preliminary step before selecting potential water-harvesting sites is the hydrologic temporal and spatial analyses of precipitation. Brockwell and Davis (2002) and Machiwal and Jha (2012) provide important tools for detecting and analyzing historical changes in climatic systems, as well as theory and practical applications relevant to hydrologic time series. Many studies analyzed rainfall for water-harvesting purposes. For example, Zerizghy et al. (2012) characterized rainfall events based on parameters of significance for in-field runoff. They used two algorithms of event identification that enabled systematic grouping of rainfall parameters, which included duration, rainfall event amount, and intensity.

Within KSA, a number of studies were previously carried out to study precipitation in the kingdom, particularly in the southwest region that receives the highest rainfall amounts. For example, Al-Turbak and Quraishi (1986) did a study on floods using regional frequency analysis for selected basins in south and southwest regions of KSA. Wheater et al. (1991a) formulated a stochastic multivariate spatial-temporal model for rainfall distribution within five basins in Southwest Saudi Arabia based on hourly rain data. Wheater et al. (1991b) evaluated long-term performance of rain gauges using regional analysis. Alazba (2004) developed contour maps for hydrologic and climatic parameters in KSA. AlHassoun (2011) developed empirical formula to estimate design rainfall intensity for Riyadh Region of KSA based on intensity-duration-frequency (IDF) curves generated from 32-year rainfall record. He used three extreme-value frequency analysis methods: Gumbel, log Pearson type III, and log normal. Elsebaie (2011) developed IDF equations for two regions in KSA: Najran and the central and eastern provinces using Gumbel and log Pearson type III. Al-Shareef et al. (2013) compared between different methods, including HEC-HMS, the probabilistic rational method (PRM), the modified Talbot method and regional flood frequency analysis, in estimating peak discharges at different return periods for the Wadi Marwani basin in Jeddah, Western Saudi Arabia.

More recently, Mahmoud and Alazba (2014) constructed a suitability map for potential rainwater-harvesting sites in some arid regions of KSA using GIS, remote sensing (RS) data, and field survey. Mahmoud et al. (2014) used the same procedure to identify ground water recharge in Jazan Region of KSA. All these studies relied on either extreme value analysis using classical approaches or more recent different approaches, such as GIS and RS. It is to be noted here that King Fahd Project for Rainwater and Floodwater Harvesting and Storage was carried out by Prince Sultan Institute for Environmental, Water and Desert Research (Al-Shaikh 2004). The project aimed at increasing water resources in KSA, especially for rural settings, and mitigating hazards of flash floods. The project was pioneer in harvesting runoff water and included the application of artificial ponds, recharge wells, and check dams at some locations in the central region of the province of Riyadh.

The main objective of this paper is to evaluate and assess the runoff harvesting potential for one of the sites within Riyadh Region using different approaches. Among the criteria to be considered in selecting the sites are nearness to existing rural communities and being sufficiently large in area, such that the estimated runoff to be harvested provides adequate water for neighboring communities. Too large site area in arid regions is probably not of much benefit, since rainfall rarely covers the full watershed area. In addition, if rainfall occurs at the upper end of the watershed, the runoff may not reach the outlet where the water-harvesting pond is typically constructed. Hydrologic analyses for estimating the harvested water potential as runoff at the selected site are implemented. This starts with analysis of rainfall data to determine the maximum 24-h rainfall for the area using Gumbel method as a statistical approach. Estimation of frequency floods with return periods ranging from 2 to 10 years, which is typical for water-harvesting projects, using (a) the Soil Conservation Service (SCS) Dimensionless Unit Hydrograph (DUH) method, (b) HEC-HMS modeling, and (c) the modified Talbot empirical approach, is performed. Both peak discharges and flood volumes are estimated; the latter, particularly of the 2- and 5-year floods, will be used for designing and constructing suitable harvested runoff storage facilities. Comparison and discussion of the results from the three methods are provided, as well.

Description of the study area

The study area is located in the central part of Saudi Arabia; it is close to the town of Alrain which is part of the Riyadh Region. Alrain is located about 120 km southwest of Riyadh City and about 70 km from AL-Muzahimiyah Governorate. The study area can be accessed by the Riyadh–Makkah AlMukramah Highway; it is located between the longitudes 45° 40′ 15.1″ and 45° 52′ 53.2″ E and the latitudes 23° 51′ 21.5″ and 24° 18′ 0.3″ N (Fig. 1). Generally, the study area is characterized by having mild slope and is geometrically irregular. It is surrounded by some low hills, from which most of the tributaries originate. These characteristics have been identified through interpretation of old and recent satellite images, topographic maps generated through DEM, and field visits. The project site is considered to be virgin land. There are no industrial or commercial facilities in the area and no urban development. The elevations of study area range from 620 to 750 m above mean sea level (Fig. 2).

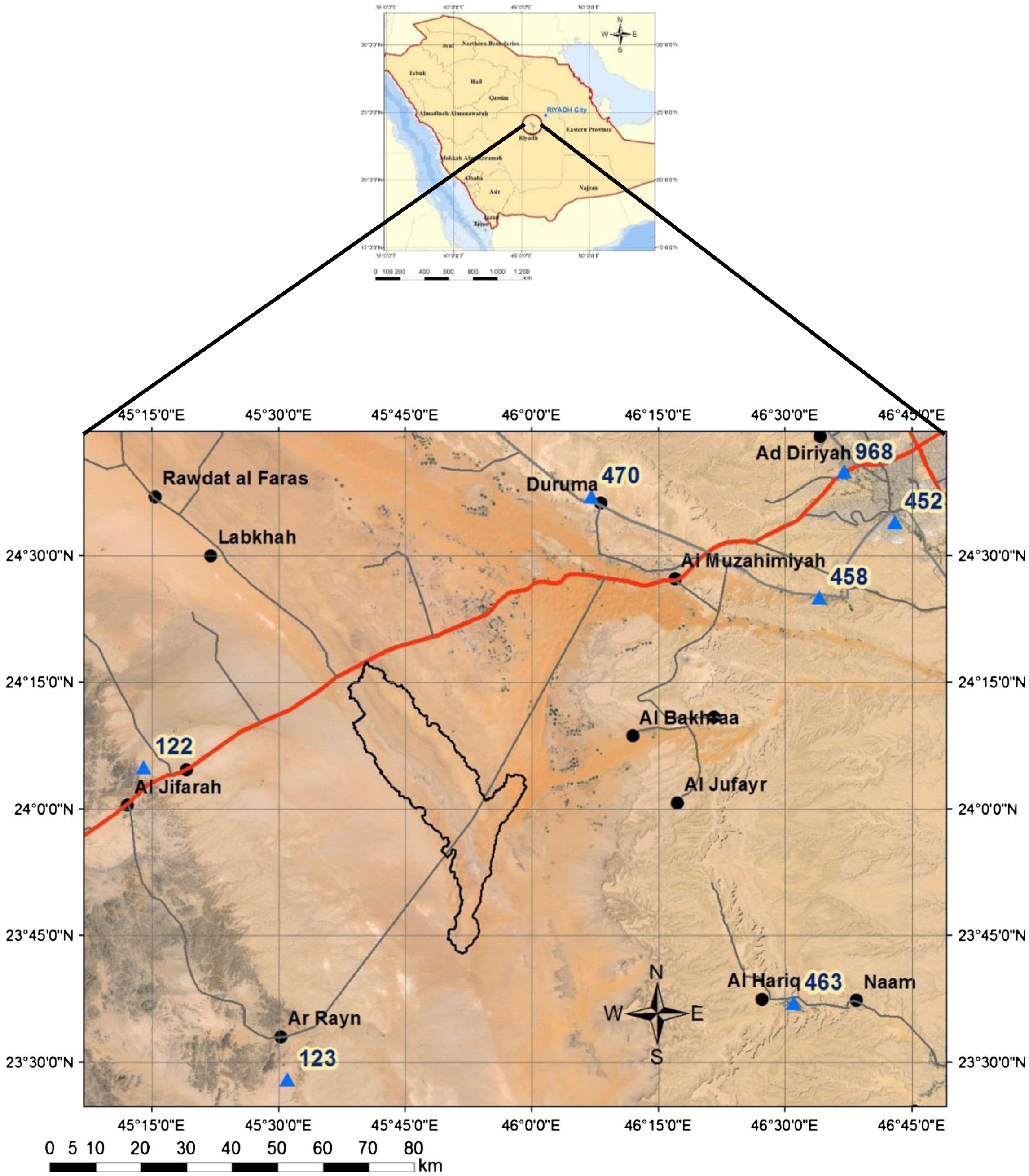


Fig. 1 Location of the study area: the *top map* is of the Kingdom of Saudi Arabia and the *bottom* is a zoomed-in view of the selected site. Locations of the surrounding communities (*black circle*) and rain stations (*blue up-pointing triangle*) are overplotted

Data and methods

To identify the meteorological parameters, the study area was mapped in relation to the closest three rain stations in the surrounding area that have adequately long record length; these have IDs 122, 123, and 463, as shown in Fig. 1. Daily rainfall data from these three stations were used in this study; the data were obtained from the Ministry of Water and Electricity (MOWE). Table 1 shows the IDs, name, and available data record length, as well as the average rainfall depth of the 24-h annual rainfall depth maxima (D_{avg}) for each of these three stations. Figure 3 presents the time series of the total annual precipitation at rain gauge 463 from 1964 to 2013 as a sample. A very strong temporal variability of the data is quite obvious. Also, it is seen that there is slowly increasing linear trend that reflects the non-stationary characteristic of the rainfall data at that site.

Three different methods, namely, (a) the Dimensionless Unit Hydrograph SCS method, (b) HEC-HMS modeling, and (c) the modified Talbot empirical approach were used to estimate the peak discharges and flood volumes; these are described in the following subsections. The choice of these

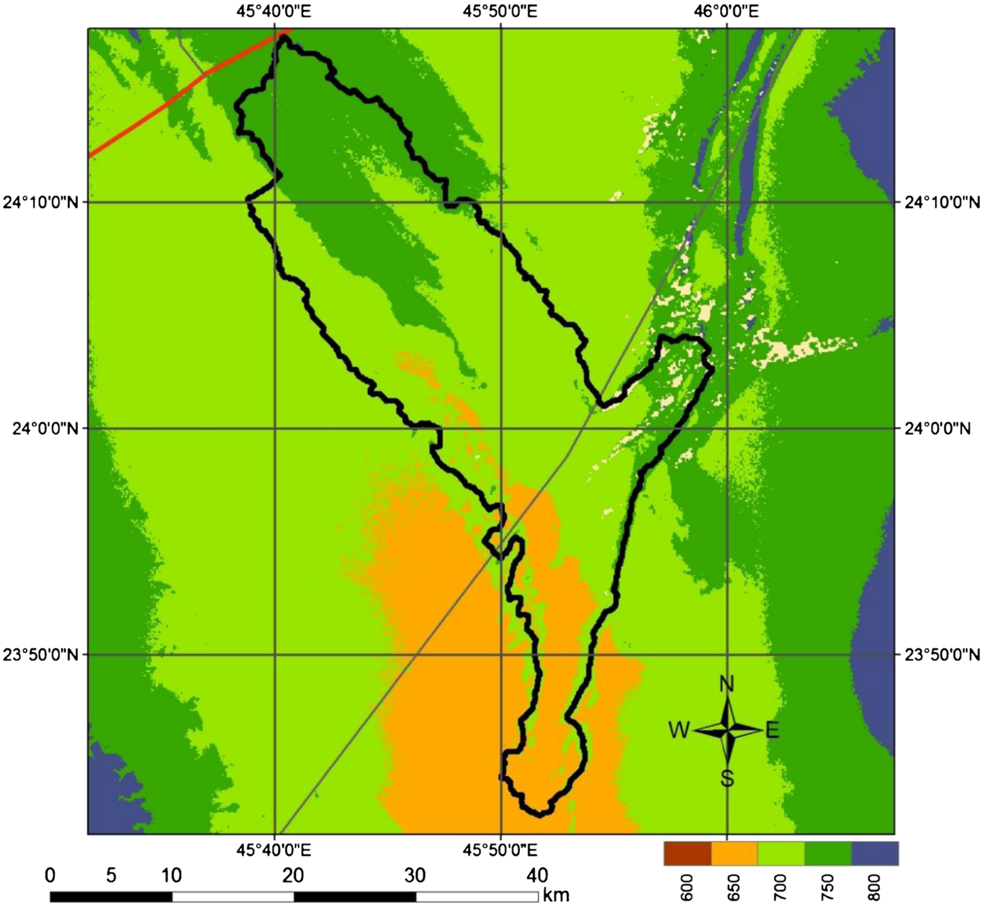


Fig. 2 Digital elevation model of the study area and its surroundings. The *color bar* represents the elevations above mean sea level in meters

methods is justified, since all three of them are based on extreme value analysis that matches the nature of arid and semi-arid regions. The number of rainy days in a year in Riyadh Region where our site is located is on average 16; this is about only 4 % of the days in a year (Tekeli et al. 2015).

SCS-DUH method

Analysis of rainfall data to determine the maximum 24-h rainfall for the area using Gumbel method as a statistical approach is used. The approach as described in Wilson (1990) is as follows:

Table 1 ID numbers, name, available record lengths, and D_{avg} for the selected stations

Rain station ID	Name	Available record length up to 2014 (years)	Average rainfall depth for maximum 24 h; D_{avg} (mm)
122	Al-Quwayiyah	41	18.77
123	Ar Rayn	43	23.58
463	Al-Hairq	48	21.22

$$D_T = D_{AVG} + \sigma(0.78y - 0.45) \quad (1)$$

where:

D_T	Rain depth for return period T
D_{AVG}	Average rainfall depth for maximum 24 h
σ	Standard deviation (see Eq. 2)
y	Reduced variate (see Eq. 3)

$$\sigma = \sqrt{\left(\frac{n}{n-1}\left(\frac{\sum D^2}{n} - D^2_{AVG}\right)\right)} \quad (2)$$

where:

n Number of years of record

$$y = -\ln\left(-\ln\left(1 - \frac{1}{T}\right)\right) \quad (3)$$

where:

T Year of return period

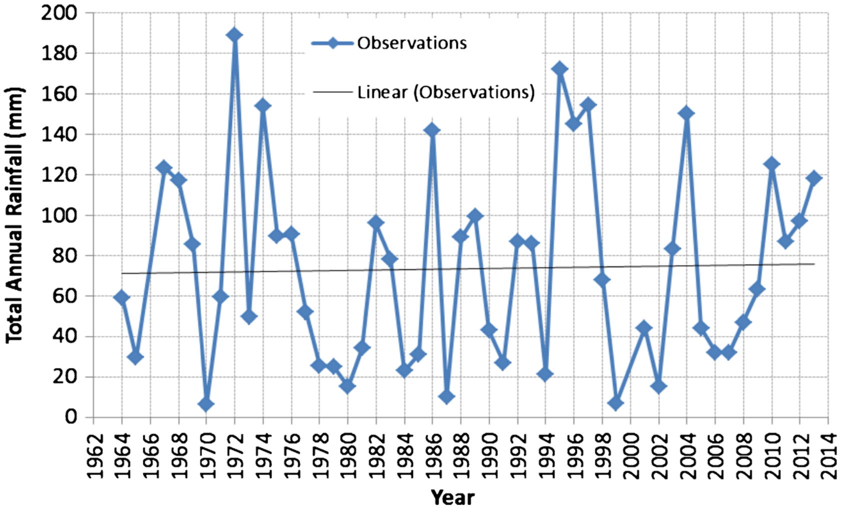


Fig. 3 The total annual rainfall depth at rain gauge 463

The D_T for each return period is found by taking the average of the results for the three stations.

The calculation of peak discharge for different return periods is done using the following steps:First, the time of concentration, t_c, is calculated using Kirpich's equation (Wilson 1990) as follows:

$$t_c = 0.0195 \frac{L^{0.77}}{S^{0.385}} \quad (4)$$

where:

t_c Time of concentration (min)
L Longest channel flow length (m)
S The dimensionless main channel slope (m/m)

Second, the time to peak, t_p, is calculated using the following equation:

$$t_p = (t_c + 0.133\, t_c)/1.7 \quad (5)$$

where t_p is in hours.

Finally, the peak discharge, Q_p, for different return periods, is calculated using the following equation:

$$Q_p = 0.208\, A\, Q/t_p \quad (6)$$

where:

Q_p Peak discharge (m^3/s)
A Area (km^2)
Q Excess rainfall (mm) for different return period floods
t_p Time to peak (h)

The excess rainfall is estimated by applying suitable runoff coefficient, C, or curve number, C_N, both of which depend on the land use and the soil hydrologic group. Volumes of runoff from the study area can then be calculated by multiplying excess rainfall with catchment area.

HEC-HMS modeling

The Hydrologic Modeling System HEC-HMS is a product of the Hydrologic Engineering Center of the U.S. Army Corps of Engineers (http://www.hec.usace.army.mil/software/hec-hms/). It is designed to simulate the complete hydrologic processes of watershed systems. The program includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing. HEC-HMS also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting. The program features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools.

The program allows selecting from a variety of precipitation meteorology models, loss methods and transform methods.

Modified Talbot empirical approach

The modified Talbot method has been in use by the Ministry of Transportation (MoT) to estimate the peak discharges for designing road crossings. The method classifies the watersheds into three categories based on their areas as follows (Murrow 1971):

1. Medium watersheds = 400–1258 ha
2. Large watersheds = 1258–35,944 ha
3. Regional watersheds = 35,944 ha and larger

The basic equation for peak discharge of the modified Talbot formula is in the form:

$$Q = \mathrm{KCA}^n R_f F_f \quad (7)$$

where:

Q	The peak discharge in m^3/s
K	A constant having values of 0.558, 3.561, and 10.166 for medium, large, and regional watersheds, respectively
C	A coefficient of discharge which was suggested to be the summation of C_1, C_2, and 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 as given in Table 2, where S is the slope and W and L are the width and length of the drainage area, respectively)
A	The drainage area in hectares
n	An exponent, which depends on the size of the drainage area having values of 0.75, 0.50, and 0.40 for medium, large, and regional watersheds, respectively
R_f	A rainfall factor which was suggested to be 1.5 for medium watershed and 1.4 for both large and regional watersheds
F_f	A frequency factor depending on the desired storm frequency and are provided in Table 3

Results and discussion

Rainfall analysis

The study area lies generally within the climatic zone of Riyadh Region, which is characterized by drought, generally high temperatures, scarcity of rain, and the lack of vegetation cover for most of the year. Rainfall usually occurs during winter.

The maximum 24-h rainfall depths, as well as the average rainfall depth for maximum 24 h, D_{avg}, were obtained for the previously reported three stations in Table 1 for all years of records. The results are shown in Table 4. These values represent the maximum 24-h rainfall depths for the study area for different return periods.

Table 2 Values of C_1, C_2, and C_3 used in modified Talbot formula

C1	0.30	Mountainous
	0.20	Semi-mountainous
	0.10	Low land
C2	0.50	$S > 15\ \%$
	0.40	$10\ \% < S < 15\ \%$
	0.03	$5\ \% < S < 10\ \%$
	0.25	$2\ \% < S < 5\ \%$
	0.20	$1\ \% < S < 2\ \%$
	0.15	$0.5\ \% < S < 1\ \%$
	0.10	$S < 0.5\ \%$
C3	0.30	$W = L$
	0.20	$W = 0.4\ L$
	0.10	$W = 0.2\ L$

Table 3 Design storm frequency factor F_f

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

Estimation of peak discharges and runoff volumes using the SCS-DUH method

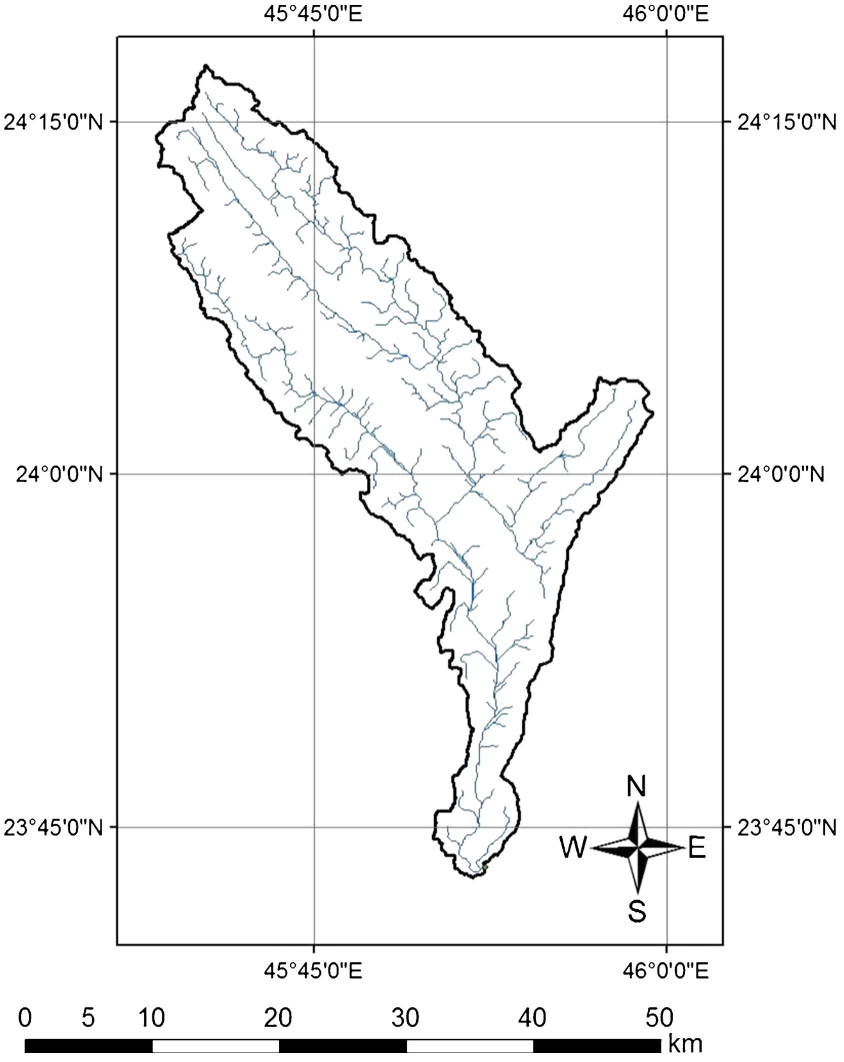
From the analysis of the satellite images and DEM data, it was found that the study area is 660 km^2 and the longest flow path, L, is 86,912 m with an average slope, S, of 0.0012. The wadi details within the catchment area are shown in Fig. 4.

Using Eqs. 4 and 5, the time of concentration, t_c, and the time to peak, t_p, for the study area were calculated and found to be $t_c = 1650.60$ min or 27.51 h and $t_p = 18.33$ h. Using this value of t_c and the longest channel flow length, L, of 86,912 m, the average travel speed of the flood waves in the main channel was estimated and found to be 0.88 m/s, which is quite reasonable in natural channels within such area. The runoff coefficient, C, depends on many factors including land surface and geological features, storm frequency, rainfall intensity, and slope of the area. Figure 5 shows a geological map of the study area. According to the geological characteristics of KSA, there are two major rock units, the igneous and metamorphic rocks, which represent the basement complex and occupy the western part of KSA; they are called the Arabian Shield, while the second unit is comprised of sedimentary rocks, which cover two thirds of the area and are located in the eastern and northern part of KSA. The drainage basin of the study area is part of the continental shelf. The main geological feature of the area, according to Manivit et al. (1985) and the geological field trip, is that the study area is underlain by surficial sediments that relate to the Quaternary Age. These are mainly eolian, alluvium, gravel sheet, inactive gravel sheet, eolian sand, and depression deposits (Qdz, Qty, Qgy, and Qk). They are of sedimentary rocks scattered in and around the study area and are cut by many

Table 4 Estimated maximum 24-h rainfall depth and rainfall excess for the study area

Return period (years)	2	5	10
Maximum 24-h rainfall depth (mm)	16.97	26.79	33.29
Rainfall excess (mm)	1.697	2.679	3.329

Fig. 4 Wadi details within the catchment area for the water harvesting



streams of the so-called JILH formation in middle Triassic Age, which is composed of fine- to medium-grained sandstone, sandy laminated dolomite, sandy oolitic limestone, and gypsiferous green claystone.

Since our study area is undeveloped and according to the previous geological description, the runoff coefficient, *C*, is assumed reasonably to be 0.1 as recommended by Mays (1999) for unimproved areas to vary between 0.1 and 0.3. The value of 0.1 was reasonably favored, since the slope of the watershed is fairly flat. Volumes of runoff for different return periods are then calculated by multiplying the values in Table 4 by the selected runoff coefficient value of 0.1, which result in values of rainfall excess. These values are then multiplied by the area of the catchment to obtain the runoff volumes. The peak discharges for the different return periods were also calculated using Eq. 6 and the values of rainfall excess reported in Table 4. The results of the estimated peak discharges and runoff volumes for the different return periods are shown in Table 5. All these estimates in Table 5 are based on the maxima 24-h rainfall depth records previously presented in Table 4.

HEC-HMS model results

In the HEC-HMS model of the study area, the SCS unit hydrograph transform method was selected to match the first method previously used in estimating the peak discharges, i.e., the SCS Dimensionless Unit Hydrograph method. The model requires determining SCS C_N for infiltration loss calculations. For that, the map of the study area was overlaid on the corresponding soil map obtained from the General Soil Map of the Kingdom of Saudi Arabia (1985). Figure 6 shows the resulting hydrological soil group map of the study area. By comparing both land use and soil characteristics, it was found that 99 % of the area is barren land; the remaining 1 % being roads and built-up land. The hydrologic soil group classification of the barren land is such that 81.25 % of the area corresponds to group B and 18.75 % of the area is group C, for

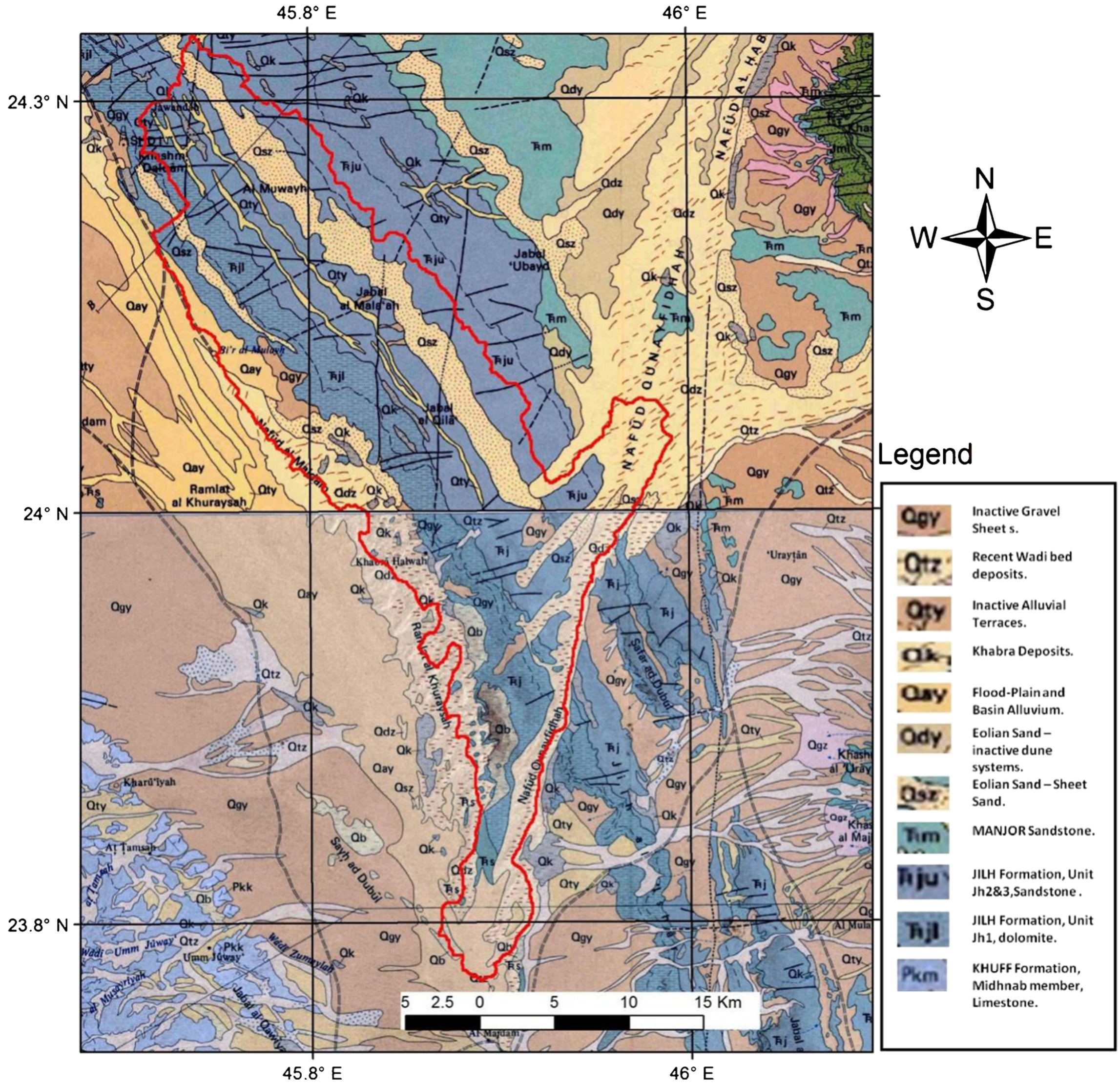


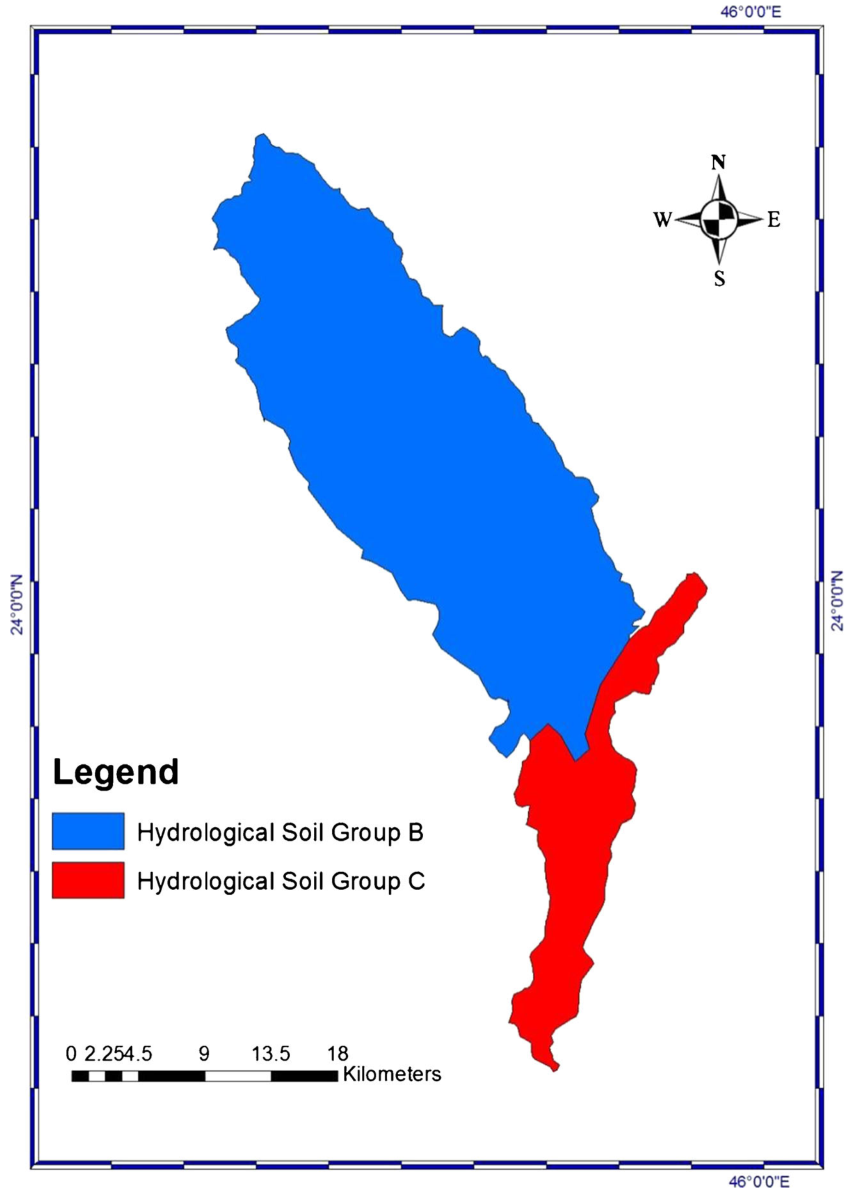
Fig. 5 Geologic map showing the different rock units in the study area

which C_N equals 77 and 85, respectively, assuming desert shrub cover type with poor hydrologic conditions. A composite C_N was computed accordingly and found to be approximately 78.54. The model also requires inputting a lag time, t_{lag}, which represents the time from the center of mass of rainfall excess to the time of peak runoff, t_p. The t_{lag} is typically taken as 0.6 t_c (Wilson 1990); in our case, t_{lag} was estimated at 990.35 min or 16.51 h. Due to lack of detailed records of storm durations, storm duration of 6 h was assumed; this is based on observations and experience of local people who have been living for long years in the area when contacted. Four types of storms according to different climatological and hydrologic conditions are classified in HEC-HMS based on the US climate. These are type 1, type 1A, type 2, and type 3. Types 1 and 1A represent climates similar to the Pacific maritime with wet winters and dry summers, type 3 is typical for the Gulf of Mexico and Atlantic coastal area climate, and type 2 is for the rest of the USA. Type 2

Table 5 Comparison of peak discharge and runoff volume estimates by the different methods for different return periods

Return periods (years)	Peak discharges (m^3/s)			Runoff volume (m^3)	
	SCS-DUH	HEC-HMS	Modified Talbot	SCS-DUH	HEC-HMS
2	12.71	2.1	–	1,120,716	200,000
5	20.07	16.6	224	1,769,238	1,500,700
10	24.94	33.3	298	2,198,505	2,993,200

Fig. 6 Hydrological soil group map of the study area



storm, which matches inland weather conditions, was assumed; this assumption was also made by Al-Shareef et al. (2013). Table 5 presents the model results of peak discharges and corresponding runoff volumes for the different return periods.

Results of modified Talbot method

The area of the selected site is 660 km^2, which amounts to 66, 000 ha; hence, it is considered as regional watershed according to Talbot's classification. Table 5 presents the peak discharge estimates obtained by the modified Talbot method after selecting the appropriate coefficients of Eq. 7 suiting the study area (C1, C2, and C3 were taken as 0.1 each based on the description in Table 2).

Comparison and discussion of results from all three methods

Table 5 presents comparison of the results obtained from all three methods: the modified Talbot is used to estimate only peak discharges and is not applicable for the 2-year return period. It is seen that the modified Talbot formula yields one order of magnitude higher peak discharge values than the other two methods. This may be attributed to the large variation of the *K* value, which depends on the category of the watershed area. There is a significant increase of *K* from 0.558 for medium watersheds to 3.561 for large watersheds and to 10.166 for regional watersheds. Both the SCS-DUH and HEC-HMS provide results that are relatively close for the 5- and 10-year periods, whereas for the 2-year period, the SCS-DUH seems significantly overestimating the peak flows and runoff volumes. One reason for the discrepancy at the 2-year period could be the assumption of constant runoff coefficient, *C*, for the SCS-DUH. *C* should increase with larger return periods and its minimum assumed value of 0.1 for such soil type, and land cover may be higher than its actual estimate. Unfortunately, there are no runoff gauges to verify such estimates. It is to be noted that our results agree with the results of Al-Shareef et al. (2013) in that the modified Talbot method seems significantly overestimating the peak discharges. In their study, they verified the estimated peak discharges against measured flows; they reported the root mean square error values were highest for the modified Talbot method and the regional flood frequency analysis reaching 19.8 and 20.5 %, respectively. In our study, the modified Talbot method yields an order of magnitude higher peak discharges.

Conclusions and recommendations

- Estimation of peak discharges and runoff volumes for the 2-, 5-, and 10-year return periods using three different methods, namely, (a) the SCS-DUH method, (b) HEC-HMS modeling, and (c) the modified Talbot empirical approach, has been performed for one potential ungauged water-harvesting site in the arid Riyadh Region of Saudi Arabia. These relatively short return periods are typically used for planning, designing, and constructing water-harvesting facilities.
- The results show that the SCS-DUH method and HEC-HMS modeling provide comparable estimates for the peak discharges and runoff volumes, especially of the 5-year storm.
- The modified Talbot formula yields an order of magnitude higher peak discharge values for all return periods.
- The peak discharge estimates are important when designing the approach channel from the wadi to the water-harvesting facility, whereas the runoff volume estimates are used to design the water-harvesting facility.
- For the design of water-harvesting facility at the selected location, the chosen volume should not exceed half of that for the 2-year storm. Previous experiences in Riyadh Region indicate that 300,000–400,000 m^3 is the limit capacity of any water-harvesting work. From economic point of view, this limit has been shown to be the optimum (Al-Shaikh 2004).
- Table 5 shows the expected runoff volumes at the outlet of the study area. Whereas the 2-year runoff volume using SCS-DUH method is estimated at 1,120,716 m^3, the corresponding HEC-HMS estimate is only 200,000 m^3. For the 5-year storm, however, the volumes are 1,769,238 and 1,500,700 m^3 respectively. The larger discrepancy at the 2-year storm is due to assuming constant runoff coefficient of 0.1 for all return periods. This was only an average value for this type of land surface; the real runoff coefficient varies with location and return period. For low return period such as the 2-year period, the runoff coefficient for such area may be assumed smaller, especially that the average watershed slope is less than 2°.

Acknowledgments The authors would like to thank the Chair of Prince Sultan Bin Abdulaziz International Prize for Water of Prince Sultan Institute for Environmental, Water and Desert Research at King Saud University for the provided financial and technical support. The authors also thank Dr. Rabie S. Fouli, former World Meteorological Organization (WMO) expert, for his productive discussions and review of the manuscript.

References

Adhikari RN, Singh AK, Math SKN, Raizada A, Mishra PK, Reddy KK (2013) Augmentation of groundwater recharge and water quality improvement by water harvesting structures in the semi-arid Deccan. Curr Sci 104(11):1534–1543

Al-Adamat R (2008) GIS as a decision support system for siting water harvesting ponds in the basalt Aquifer/NE Jordan. J Environ Assess Policy Manag 10(2):189–206

Alazba AA (2004) Contour maps for hydrologic and climatic parameters in Saudi Arabia. American Society of agricultural and biological engineers, paper number 042096, ASAE annual meeting. (doi: 10.13031/2013.16379)

AlHassoun SA (2011) Developing an empirical formulae to estimate rainfall intensity in Riyadh region. J King Saud Univ – Eng Sci 23:81–88

Al-Shaikh A (2004) King Fahd's project for rainwater and runoff harvesting and recharge in Saudi Arabia. Internal Report (in Arabic) at Prince Sultan Research Institute for Environment, Water and Desert, King Saud University, Riyadh, Saudi Arabia

Al-Shareef OH, Ezzeldin M, Gutub S (2013) Comparison of peak discharge estimation methods in northern Jeddah in western Saudi Arabia. J Environ Hydrol 21, Paper 13

Al-Turbak AS, Quraishi AA (1986) Regional flood frequency analysis for some selected basins in Saudi Arabia. In: Proceedings of international symposium on flood frequency and risk analysis, Louisiana State University, Baton Rouge, LA., Volume on Regional Flood Frequency Analysis, 27–34

Bashir B, Fouli H, Al-Turbak A, Loni OA (2015) Using GIS and DEM to identify suitable rainwater harvesting sites in Riyadh Region of Saudi Arabia. Proceedings of the European water resources association 9th world congress - Water resources management in a changing world: challenges and opportunities, 10–13 June, Istanbul, Turkey

Brockwell PJ, Davis RA (2002) Introduction to time series and forecasting, 2nd edn. Springer, New York

Climate Atlas of Saudi Arabia (1988) Publication of Ministry of Agriculture and Water (now Ministry of Water and Electricity) in cooperation with the Saudi Arabian-United States Joint Commission on Economic Cooperation

Elsebaie IH (2011) Rainfall intensity-duration-frequency relationship for some regions in Saudi Arabia. Int J Sustain Water Environ Syst 2(1): 7–16

General Soil Map of the Kingdom of Saudi Arabia (1985) Ministry of Agriculture and Water, Land Management Dept.; [S.I.]: U.S.-Saudi Arabian Joint Commission on Economic Cooperation

Hadadin N, Shawash S, Tarawneh Z, Banihani Q, Hamdi MR (2012) Spatial hydrological analysis for water harvesting potential using

ArcGIS model: the case of the north-eastern desert, Jordan. Water Policy 14:524–538

Machiwal D, Jha MK (2012) Hydrologic time series analysis: theory and practice, Springer, ISBN: 978-94-007-1860-9 (Print); 978-94-007-1861-6 (Online)

Mahmoud SH, Alazba AA (2014) The potential of in situ rainwater harvesting in arid regions: developing a methodology to identify suitable areas using GIS-based decision support system. Arab J Geosci. doi:10.1007/s12517-014-1535-3

Mahmoud SH, Alazba AA, Amin MT (2014) Identification of potential sites for groundwater recharge using a GIS-based decision support system in Jazan region-Saudi Arabia. Water Resour Manag 28:3319–3340

Manivit J, Pellaton C, Vaslet D, Le Nindre Y, Brosse J, Breton J, Fourniguet J (1985) Explanatory notes to the geologic map of the Darma quadrangle, sheet 24 H, Ministry of Petroleum and Mineral Resource, Deputy Ministry for Mineral Resource, Kingdom of Saudi Arabia

Mays LW (1999) Hydraulic design handbook. McGraw-Hill, New York, ISBN: 9780070411524

Murrow W (1971) Drainage report, a report submitted to Ministry of Communications, Riyadh, Saudi Arabia, p. 217

Oweis TY, Prinz D, Hachum AY (2012) Rainwater harvesting for agriculture in the dry areas. CRC Press, Balkema, ISBN: 978-0-415-62114-4

Tekeli AE, Fouli H, Al-Turbak AS (2015) Using TRMM satellite based precipitation products for flood monitoring over Riyadh City in Kingdom of Saudi Arabia. Proceedings of the European Water Resources Association 9th World Congress - Water Resources Management in a Changing World: Challenges and Opportunities, 10–13 June, Istanbul, Turkey

Wheater HS, Butler AP, Stewart EJ, Hamilton GS (1991a) A multivariate spatial-temporal model of rainfall in southwest Saudi Arabia. I. Spatial rainfall characteristics and model formulation. J Hydrol 125:175–199

Wheater HS, Onof C, Butler AP, Hamilton GS (1991b) A multivariate spatial-temporal model of rainfall in southwest Saudi Arabia. II. Regional analysis and long-term performance. J Hydrol 125:201–220

Wilson EM (1990) Engineering hydrology, 4th edn. Palgrave Macmillan, UK, ISBN: 9780333517178

Wu Y, Tang Y, Huang C (2009) Harvesting of rainwater and brooklets water to increase mountain agricultural productivity: a case study from a dry valley of southwestern China. Nat Res Forum 33:39–48

Zerizghy MG, Rensburg LDV, Stigter K (2012) Characterization of rainfall in the Central South African Highveld for application in water harvesting. Irrig Drain 61 (Suppl. 2): 24–33