



Flash flood prediction in Southwest Saudi Arabia using GIS technique and surface water models

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Received: 13 June 2023 / Accepted: 25 January 2024 / Published online: 29 February 2024
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Abstract

A flash flood is one of the hazardous phenomena, especially in dry regions. In Saudi Arabia, Jazan Province experiences data scarcity especially historical hydrological data and a lack of studies related to flash flood analysis and the rainfall and runoff interrelationship. Thus, this research aims to study the rainfall-runoff inter-relation, predict flash floods, and to map the risk areas in Jazan Province by the geological, geomorphological, and hydrogeological characteristics along with digital elevation model (DEM), watershed modeling system (WMS) and HEC-HMS models. Jazan Province encompasses 25 drainage basins, receiving a considerable amount of rainfall (ranging from 100 to 500 mm) (August, October–November, March) which intermittently cause strong and destructive flash floods. The DEM was used for delineating the catchment (drainage basins) parameters. Physiographic parameters of the catchments have been analyzed for mapping the hazard degree of the flash flood strength. Further, basins with high hazard degrees of flash floods were selected to assess rainfall-runoff inter-relation using the HEC-HMS models, GIS, and morphometric parameters. Forty %, 8%, 52% of the study area are high, medium, and low hazard degrees of flash floods, respectively. The groundwater recharge in the study area was calculated through the integration of satellite image analysis, SWAT and GIS techniques and it ranges from 0.002 mm/km²/year to 8 mm/km²/year with an average of 2.5 mm/km²/year. Rainfall-runoff inter-relation of study basins, assessed based on the integration of WMS and HEC-HMS models, indicates that the resulting runoff volume ranges from 18.5 × 10⁶ m³ to 473.1 × 10⁶ m³ at a recurrence period of 5 and 100 years at rainfall events of 65 mm and 116.8 mm, respectively.

Keywords Flash floods · Hydrographs · HEC-HMS, watershed modeling system (WMS) · Jazan · Saudi Arabia

Introduction

Flash flood is the utmost hazardous natural phenomenon in the world, especially in arid regions which lead to major loss of life and assets (Arnous and Green 2011). In arid regions,

the majority of flash floods occur in a sporadic pattern due to the extensive amount of rainfall with high intensity.

Estimation of the surface runoff resulting from rainfall events is of great importance, especially for water resources management and sustainability, including the design of the

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various hydraulic infrastructures, operation, and management of reservoirs. Field measurements of single or continuous storms are usually important for estimating the amount of surface runoff. Although the field measurements of the rainfall storms and the corresponding flash floods are necessary to study the rainfall-runoff interrelationship, in dry regions, in situ monitoring of hydrologic data rarely happens. Therefore, in those regions the estimations of the rainfall-runoff relationships depending upon the physiographic characteristics of the drainage basin, soil formation, and land use are essential.

According to Saleh (1989), there are additional variables such as evaporation and infiltration rates that depict the soil condition and hydrologic characteristics of the catchment that influence flash flood hazards. Zbigniew et al. (2014) concluded that geology, geomorphology, and climate are predominantly controlling factors influencing the hazard degree of flash floods. Drainage basin characteristics and hydrologic behavior depending upon the analysis of the morphometric parameters have been done by many authors (Horton 1945; Strahler 1964; Gardiner 1990; Zenger and Smith 2003; Bajabaa et al. 2014; Basahi et al. 2016).

Flash flood evaluation depends on a detailed study of the hydrology and hydrogeology of the watershed with the integration between remote sensing, GIS applications, and hydrologic modeling codes. Masoud (2015), El Osta and Masoud (2015), Youssef et al., (2020), Elfeki et al. (2017) and El Osta et al. (2021) reported that the integration between morphometric parameters, remote sensing, and hydrologic models are significant techniques for estimating and mapping the flash flood hazard in arid regions. According to Abuzied et al. (2016), GIS is considered as a main tool to evaluate, control and integrate the effective parameters which lead to flash floods with sufficient accuracy and proficiency. Dawod et al. (2012) reported that the zonation of flash flood-prone basins is based on the classification levels corresponding to the significance and influence of each factor.

The problem in the Jazan province as well as in the arid and semi-arid regions is that flash floods frequently occur and there are no studies about the rainfall and runoff relationship and flash flood risk maps. The climate is represented as the essential among the parameters which influence the water resources and hydrogeological performance of the different catchments. Almazroui et al. (2009) reported that the Kingdom of Saudi Arabia (KSA) is climatically characterized by notable different climatic change features, because of a wide range of variations in spatial and temporal temperature.

In the drainage basins of the southwestern region of KSA, flash floods frequently occur, which often lead to damage to agricultural lands, property, and facilities, especially those located near the main streams of the basins.

In the Jazan province, floods are characterized by high speed, intensity (a short period), and frequency compared with those occurring in other regions of KSA, due to the climatic factors and the steep slope of the basins in the Asir mountainous range. Although the government has established dams and protection tools, such torrential flash floods still cause major problems for the residents. Studying the characteristics of these floods and predicting their quantities and frequency, is very important to design and develop appropriate strategies to mitigate the harmful effects of floods.

The research question in this study, is it possible to apply sustainable development in Jazan by managing flash floods and groundwater recharge based on hydro-geomorphological analysis with scarce data? If not, then what are the other suitable methodologies to do sustainable catchment development in Jazan?

In light of the scarcity of data, an effective approach is proposed to study the relationship between hydrologic behavior of the catchment and its morphometric parameters. So, the main goal of the study is to apply a sustainable development to water resources through drawing attention to flash flood and groundwater recharge based on hydro-geo-morphometric analysis and creation of specific thematic maps of the study catchments.

Flash floods hazardous zonation is very vital for drainage basin management and sustainable development of water resources. The precipitation storms and the corresponding surface runoff records are the necessary hydrological fundamentals for flash flood zonation of the drainage basins. Since Jazan Province suffers from a shortage of such data, so, the flash floods evaluation and mapping are reliant upon the topographical and geomorphic aspects of the drainage basin (Şen et al. 2012).

The objective of this research is to assess and evaluate the hazards of flash floods in the drainage basins of the Jazan Province depending upon the analysis of the physiographic parameters integrated with GIS, remote sensing, and hydrologic models. In addition, synthetic hydrograph analysis (SH) will be used to determine the peak discharge, time of concentration, time to peak, and runoff volume in different events of rainfall with different recurrence times in the study area. SH has been used increasingly by hydrologists and geomorphologists to represent the flood behavior of ungauged catchments. Generally, a catchment's unique characteristic have more influence on the shape of a unit hydrograph resulting from the effective rainfall of a specified duration. This is why most SUHs are applied as an alternative to a UH by relating the physical characteristics of a catchment to the UH model parameters. The resulting discharge ordinates constructed with the SUH for a catchment are then considered a multiplier function used for converting storms of any magnitude in the catchment.

This research can highlight the influence of the geological and topographical characteristics and the distribution of rainfall on the occurrence of flash floods in the study area and its impact on the hydrological response of the ungauged basins, by offering a methodical approach for analyzing rainfall data and developing a hydrologic model in such ungauged basins.

Study area

Location

Jazan Province (study area) includes 25 basins which are located in Jazan Province. Jazan coastal basin existed in the southwestern part of Saudi Arabia which is flowing toward the Red Sea Coast. It is covering an area of about 22454 km² (Fig. 1). The watersheds are characterized by deep and long, dendritic patterns of hydrographic basins which reflect the topography variation of the study area.

Geomorphology and geology

The study area comprises three different geomorphologic sections, displaying different hydrological features (Al-Turki 1995) as the following:

1. The coastal plain with a width ranging between 20 and 100 km is shielded by alluvial deposits which have good possibilities for groundwater recharge to form a potential water-bearing formation (Abu-Alainine 1979; Al-Sharif 1977).
2. The sloped areas (foothills) cover the area from the coastal plain to the mountain range with width ranges from 62 to 155 km and an elevation of 420 m above mean sea level (Fig. 2a). These areas are moderately sloping and are shielded with boulders, rocks, and depressions that are mostly occupied with Wadi deposits and characterized by good groundwater recharge. Most of the stream networks of the study basins originated in the Mountainous area of Asir Province crossing the hilly areas to the Red Sea.
3. The Asir Mountain series extends east of the hills from north to south, parallel to the Coast with a high elevation of more than 3000 m (Fig. 2a). These mountain series are intersected by profound Wadis, flowing towards the

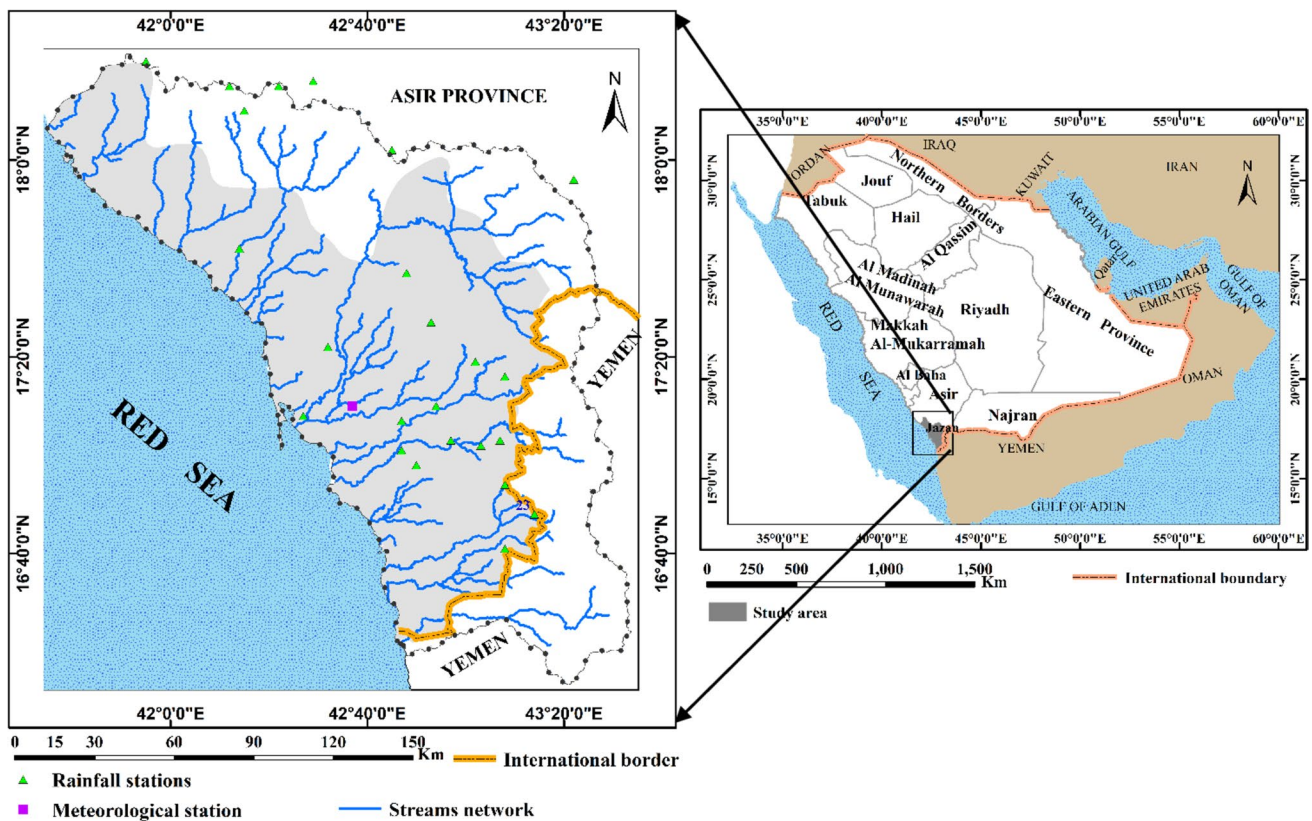


Fig. 1 Location of Jazan province

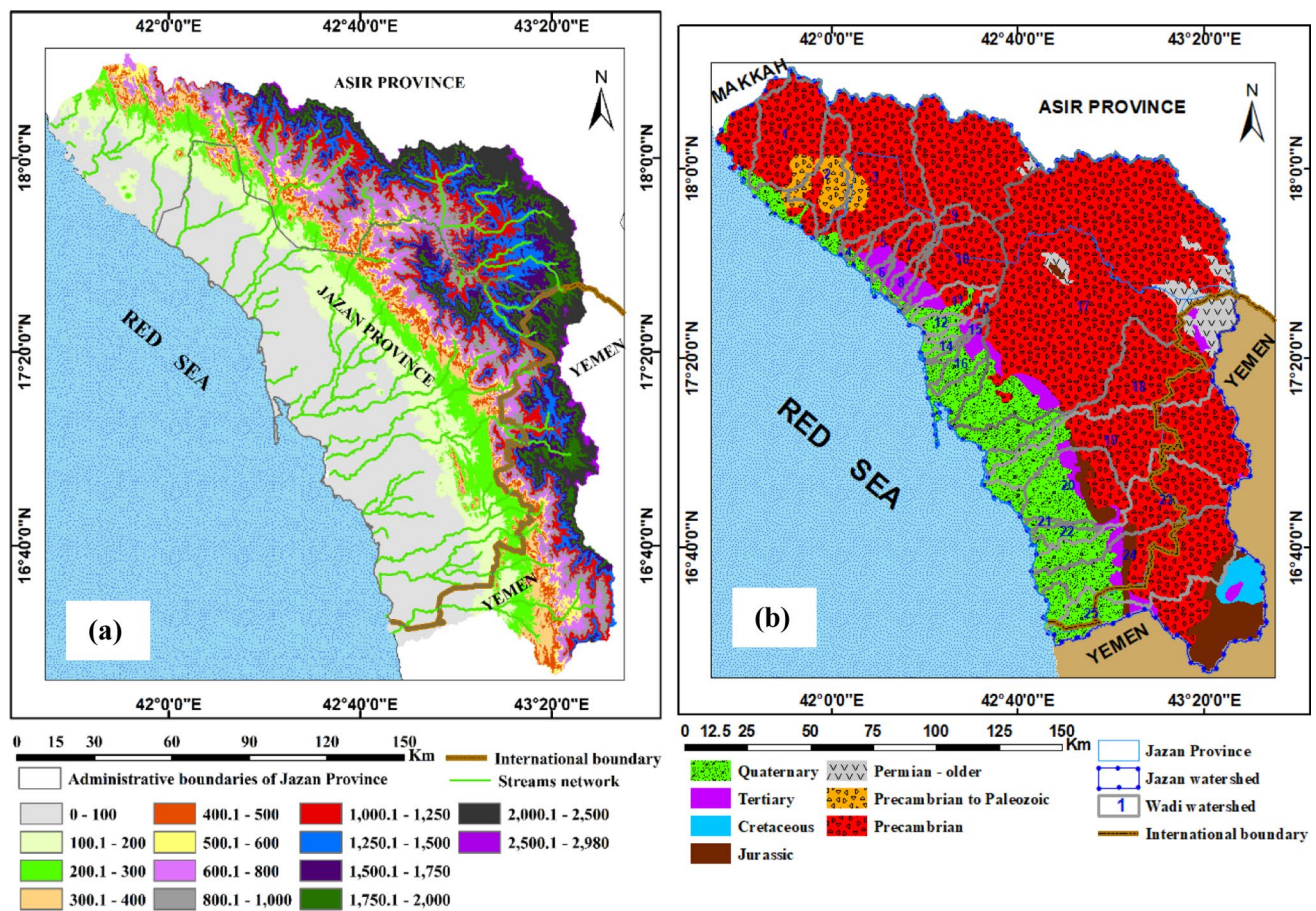


Fig. 2 Digital elevation model (DEM) (a), geological map (quadrangles 16F, 17E, 17F, 18 E and 18 F, Prinz 1985) (b)

Red Sea, where the major Wadis are located in Jazan province.

Geologically, the KSA could be separated into two structural sections as the following

- Western section (Arabian Shield) considers a portion of the Precambrian Era and is mainly exposed except for some areas shielded by Tertiary volcanic rocks.
- Eastern section (Arabian Shelf) comprises sedimentary rocks covering the Arabian tectonic plate.

Most of the Jazan Province is located in the Arabian Shield as shown in Fig. 2b. Its development happened in the Oligocene. The Proterozoic rocks (Precambrian) are exposed along the northeastern edge of the Red Sea Coast (Fig. 2b). sediments of the Palaeozoic and Mesozoic are covering the Basement (Fig. 2b), but were partly, conserved in down-faulted beds.

Jazan Province is a part of the Tihama Asir front which is characterized by a flat coast and is cracked by the gentle elevation (52 m) of the Jazan salt dome (intrusion). The

coastal portion of Jazan Province is composed of sabkha which is called (the sabkha zone) with a width of up to several kilometres. Underground comprises multi-layers of silt, clay sediments, and evaporation products with higher salt formations due to the elevated groundwater level as well as the high evaporation rate. The sabkha zone is formed during the flooding duration which is caused by high rainfall intensity. Tertiary formations occur underneath the coastal plain and are outcropping in the foothills.

Alluvial deposits occur in the Wadi beds and extend to cover many portions of the coastal plain. The alluvial deposits have a thickness of up to 12 m. The Jazan coastal plain is located in a geological depression covering the area from the Red Sea to the base of the Asir mountain series. (Abu-Alaulae 1983).

From a hydrological point of view, the main aquifer in the study area is unconfined Quaternary aquifer which considers the main aquifer and is recharging direct from rainfall and flash flood events. This aquifer is composed mainly of gravels, coarse sand, fine sand with intercalations of silt and clay.

Meteorological characteristics

Jazan Province is characterized by tropical to sub-tropical dry zone climate (Köppen–Geiger climate classification, 1936 and Glenn 1954). Meteorological parameters i.e. air temperatures, relative humidity, and evaporation were collected for one station for 42 years (1965–2007) as shown in Fig. 1. The air temperature shows a wide range of seasonal and spatial variations, with an average of 36 °C in July and 26 °C in January, respectively (Fig. 3a). Spatial variations are brought on by elevation, with an average annual temperature of 25 °C, at Abu Arish and 15 °C at Abha in the Asir Mountainous series. The Asir Mountain region has the lowest mean annual temperature, whereas the coastal regions have the greatest mean annual temperature (Al Turki, 1995). Due to the arid climate, the evaporation rate is often high throughout the KSA, except for Asir and Jazan. Figure 3a, shows that the mean evaporation varies between 5.90 mm/day in Winter and 13.00 mm/day in Summer. Average relative humidity varies between 56% in July and 70% in January (Fig. 3a).

Rainfall details

Sporadic rainfall with high intensity in arid regions usually causes flash floods, which are recorded in Jeddah, Riyadh, and other places in Saudi Arabia in the last decades. Climate change may alter the intensity, length, and form of rainfall in the future (e.g., Mahmoodi et al. 2021). The southwest area of KSA receives the greatest quantity of rainfall compared with the other areas due to its higher elevation (mountainous terrain) within the subtropical climatic condition. Rainfall intensities in Jazan province are mainly controlled by geographic landscapes, space from the origin of moistened clouds, air temperature, and pressure (Subyani 1999). Sen (2002 and 2008) reported that flash floods flow in many Wadis of southwest Saudi Arabia, during high-intensity storms. These wadis are most vulnerable to floods, whereas only Wadi Baysh provides a vast cultivable area, which could be used for any agricultural developments. Data from 10 rainfall stations were inventoried over a period of 53 years (1966–2018), the annual mean of rainfall ranges from 120 mm towards the Red Sea and on the leeward of the mountains to the east to 380 mm (Fig. 3b). Figure 3b, illustrates the spatial variations of precipitation where the rainfall increases in the basins of Baysh, Damad, and Jazan (high intensity of contours).

Materials and methods

Rainfall analysis

Rainfall distribution analysis in this research is carried out based on the following:

- Collecting daily rainfall data
- Frequency analysis of maximum daily rainfall events,
- Fitting the actual data using the common probability distribution functions.
- Selection of the outstanding probability distribution function depending on the Root Mean Square Error (RMSE) measure,
- Applied spatial analysis technique to illustrate the isohyetal lines of the study catchments at different recurrence times.

Table 1 displays that the best distributions depending on the minimum RMSE are different from one station to another. Stations of have 2-parameters log normal represent well the distributions of rainfall in SA 104 and SA 126 stations while for the stations A 103 and SA 108, 3-parameters log normal distributions, for the stations of SA 102, A 104 and A 118, Pearson type III distributions, and for the stations of SA 107, SA 125 and SA 136, log Pearson type III achieve better outcomes (Table 2). Equation 1 provides an explanation of the mapping (zonation) of forecasting rainfall distribution, as reported by Viessman et al. (1977).

$$P(x_0, y_0) = \sum_{i=1}^m w_i P_i$$

$$w_i = \frac{1/X_i^2}{\sum_{i=1}^m 1/X_i^2} \quad (1)$$

$$X_i^2 = (x_i - x_0)^2 + (y_i - y_0)^2$$

where $P(x_0, y_0)$ is the estimated rainfall at coordinates (x_0, y_0) , P_i is the rainfall at the i th station, w_i is the weight of i th station, and $x_i = (x_i, y_i)$ is the coordinates of the station.

The best-fit distributions have been applied to show the spatial variation of rainfall at different return periods (5 years, 10 years, 25 years, 50 years, and 100 years) in the Jazan Basin (Fig. 4).

Spatially analysis shows that the middle and southern portions of Jazan Province have a great possibility for flood hazards due to the predictable rainfall quantities which are higher than those of other areas. Thus, protection schemes must be cautiously planned for these Wadis to avoid and mitigate the expected flood hazards.

Morphometric parameter analysis

Flash flood hazard mapping of the un-gauged catchments depends on the analysis of the morphometric parameters. Morphometric analyses were done via demarcation of the drainage networks based upon DEM with 30 m resolution, GIS techniques, and topographical sheets (scale 1: 250,000). The stream networks are ordered and the morphometric

Table 1 RMSE of the rainfall stations in Jazan Province

Distribution Type	Stations										
	18 A103	19 A104	28 A118	503 SA102	505 SA104	508 SA107	509 SA108	524 SA125	525 SA126	531 SA136	
Normal	7.52	3.76	6.59	2.61	6.36	5.74	6.67	3.88	11.38	5.70	
2-Parameter log normal	5.04	2.77	5.45	5.31	4.78	2.95	4.54	2.80	7.71	3.48	
3-Parameter log normal	4.90	2.40	5.28	2.57	4.90	3.11	4.28	2.51	7.72	3.68	
Pearson Type III	4.95	2.25	5.10	2.56	4.95	2.65	4.41	2.33	8.57	3.33	
Log Pearson Type III	4.98	3.72	14.03	3.02	12.28	2.37	4.39	1.98	7.79	2.86	
Gumbel Type I	5.37	2.28	5.17	3.88	5.04	3.40	4.60	2.23	8.52	3.35	

Where the bold represents the smallest error distribution of RMSE

elements are measured, assessed, and analyzed, based on Brocklehurst and Whipple (2002); Chorley et al. (1957); Elfeki et al. (2017); Faniran (1968); Gregory and Walling (1973); Haggett 1965; Horton (1932 and 1945); Majure and Soenksen (1991); Masoud (2015, 2016); Melton (1957); Miller (1953); Mueller (1968); Schumm (1956); Strahler (1952, 1953 and 1964).

Hydrological model

The SWAT model is applied to simulate hydrological processes (Arnold et al. 1998) by creating several sub-basins from the main basin where each sub-basin involves Hydrological Response Units (HRUs). ASTER 30 m resolution DEM, Soil and Land Use/Land Cover data for the study area were acquired from USGS Earth Explorer, FAO, and ESRI, respectively. World soil map was produced by FAO and UNESCO during 1980 at a scaling measurement of 1: 5,000,000. The Land Use/Land Cover map is produced by Impact Observatory Microsoft, and Esri using Sentinel-2 L2A imagery and gives access to individual 10-m resolutions, for each year from 2017 to 2021. Each layer of these maps is produced from Impact Observatory’s land classification model. Land Use/Land Cover (2021) has been used in this study. Ten Wadis under high risk of flash flood were selected to model the surface runoff resulting from the rainfall events of 5-, 10-, 25-, 50- and 100-year recurrence time duration. The proposed dams were selected at the main channel depending on the digital elevation model, integrating GIS, remote sensing techniques and hydrological models to simulate streamflow in the un-gauged catchments. Two hydrologic models are used; Watershed Modeling System (WMS 10.2) and Hydrologic Modeling System (HEC-HMS 4.02).

WMS can achieve tasks such as automatic catchment delineation, GIS overlay calculations, geometric parameter calculations; storm drain analysis, and hydrograph generation. Hydrologic modeling system (HEC-HMS), is planned for rainfall-runoff modeling of dendritic catchment systems. The Hydrologic Modeling System (HMS) is a versatile software used to simulate precipitation-runoff processes in watershed systems. It can address various hydrological problems and applies to different geographic areas. HMS produces hydrographs for analyzing water availability, urban drainage, flood forecasting, and more. The program has a user-friendly interface, an integrated database, and supports multiple platforms. Data storage is handled by the HEC-DSS system. HEC-HMS allows choosing between several infiltration losses and unit hydrograph parameterizations (U.S. Army Corps of Engineers, 2000). The SCS-CN method is employed to calculate the extra rainfall. For the rainfall distributions over the storm interval, the SCS type

Table 2 Rainfall (mm) forecasting of best distribution in different return periods (year)

Station	Probabilities	0.80	0.90	0.96	0.98	0.99
	Return periods (year)	5	10	25	50	100
18 A 103		45.1	53.0	61.6	67.3	72.4
19 A 104		65.3	77.0	91.7	102.7	113.7
28 A 118		61.4	74.8	91.0	102.7	113.9
503 SA 102		39.2	48.6	59.9	67.7	75.0
505 SA 104		63.6	80.8	104.4	123.2	143.0
508 SA 107		60.9	73.8	90.5	103.2	116.1
509 SA 108		48.3	59.1	73.7	85.1	96.9
524 SA 125		45.8	55.6	67.5	76.0	84.3
525 SA 126		66.1	79.4	95.5	106.9	117.9
535 SA 136		54.5	65.0	78.8	89.6	100.6

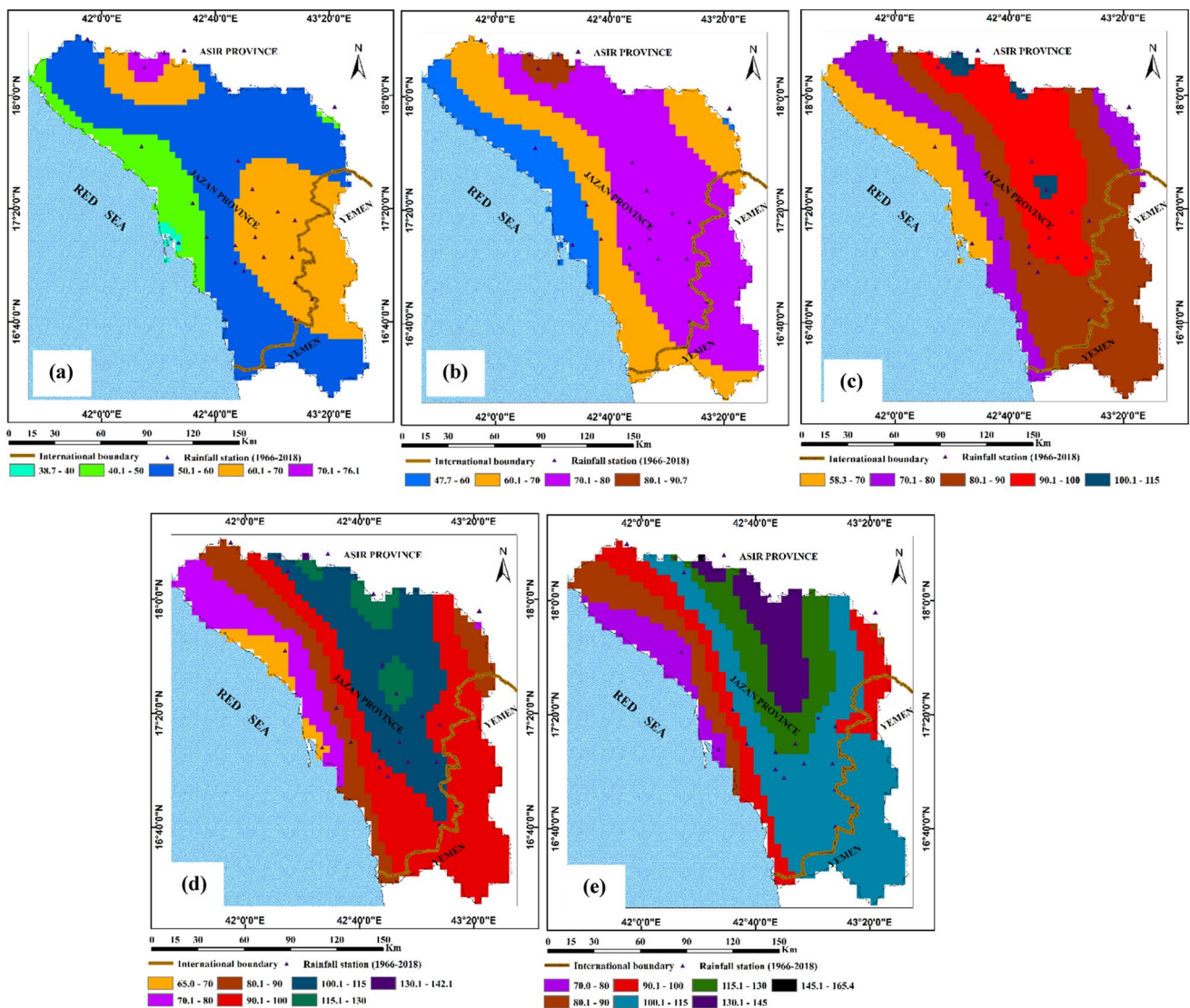


Fig. 4 Zonation maps of the rainfall distribution for different return periods based on the best distributions ((5 years (a), 10 years (b), 25 years (c), 50 years (d), and 100 years (e))

II hyetograph is applied which is frequently implemented in dry Provinces.

Groundwater recharge assessment

Groundwater recharge assessment is the main parameter for the sustainable development of groundwater resources especially in dry areas which are characterized by the scarcity of hydrological measurements, mainly the groundwater recharge element. So, this research represents a challenge to assess the groundwater recharge based on the interlink between the satellite image analysis, SWAT and GIS techniques. The methodology, input and output parameters for the groundwater recharge assessment are presented in Fig. 5.

Results and discussions

Basin characteristics

Structural lineaments

The lineaments are highly scattered within the basin (Fig. 6) which have an impact on the groundwater recharge of shallow aquifers.

Lineaments frequency (F') of the structural lineaments is well known as the total number of lineaments per unit of the area as shown in Eq. 2.

$$F' = \sum N/A(\text{km}^{-2}) \tag{2}$$

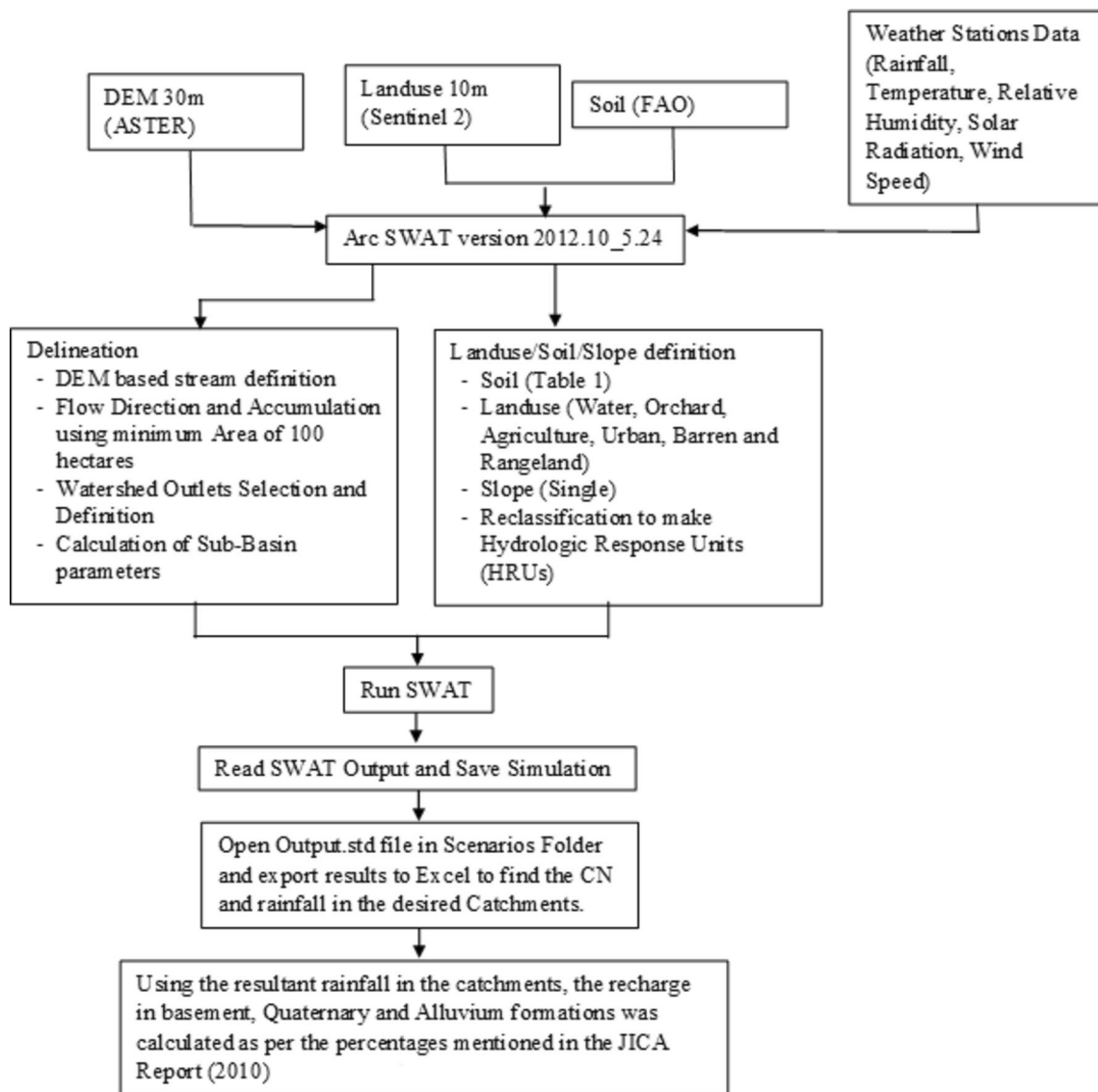


Fig. 5 Groundwater recharge assessment chart

where ($\sum N$) is the total number of the lineaments and (A) is the area of the investigated basin in a square kilometre. The study area shows great variations in lineaments frequency values reflecting the impact of the lithological types as shown in supplementary Table ST1. The basins have a frequency range between 0 km^{-2} and 0.1 km^{-2} with a mean value of 0.03 km^{-2} (Table ST1).

Lineaments density (D').

Lineaments density has a direct bearing on the permeability of the rocks. D' is recognized as the summation of lengths of structural lineaments per unit area (Eq. 3).

$$D' = \sum L/A(\text{km}^{-1}) \quad (3)$$

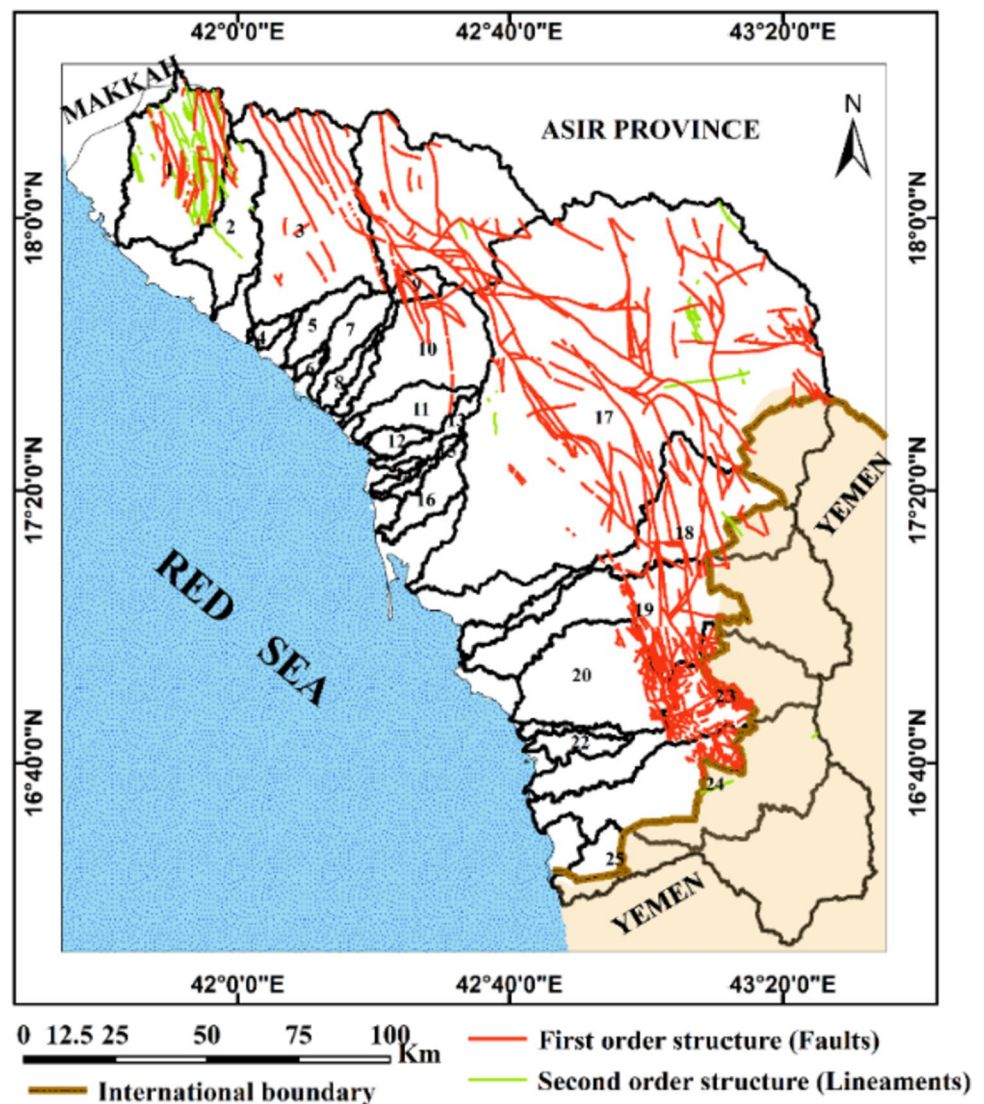
where $\sum L$ is the total length of the structural lineaments in km and (A) is the area of the study basins in km^2 . The study basins have a density range between 0 km^{-1} and 0.53 km^{-1} with a mean value of 0.2 km^{-1} (Table ST1). Variation of the

frequency and density values of the catchments is because of the dissimilarity of lithology.

Physiographic (morphometric) parameters of the studied catchments

Flash flood hazardous evaluation for the un-gauged catchments depends on the analysis of the physiographic parameters (Tables ST2 & 3). Morphometric features examinations of the studied catchments are principally dependent on the physiographic parameters. Morphometric analyses were done by outlining the drainage network using DEM with 30 m resolution, topographic sheets (scale 1: 250,000), and GIS tools. By applying the Strahler method (1964), the stream networks are ordered and the physiographic parameters are measured and assessed. Morphometric characteristics of the study catchments can be categorized into four categories as follows:

Fig. 6 lineaments map of Jazan Province, (quadrangles 16F, 17E, 17F, 18 E and 18 F, Prinz, 1986)



Drainage network features.

Stream order (u) Stream orders of the current catchments have been created using DEM for each Wadi Tables ST2 & 3. Stream orders of the study catchments range from 4 to 8 (Table 3).

Stream number (Nu) Stream numbers were measured and counted for each order using GIS and tabulated in Table 3. The lowest order has the highest number.

Stream length (Lu) Lengths of the stream networks have been assessed according to the rules recommended by Horton (1945). The total stream lengths of current catchments range from 90.8 to 13,704 km (Table 3).

The stream length expresses the inter-relationships among the climatic aspects, vegetation cover, and the resistivity of rocks and soils to weathering. In case of situation similarity, impermeable rock formations produce long stream lengths, subsequently, greater drainage densities are noticed compared to the porous rock formations. This means the arid and semi-arid areas display greater drainage density compared with the humid areas which have identical geology due to the scarcity of floods and shrubbery in the arid areas.

Bifurcation ratio (Rb) and weighted mean bifurcation ratio (WMRb) Rb ratio is an index of topography (elevation) and lineaments (Horton 1945) and varies depending upon the geological and lithological aspects of the catchment (Strahler 1964). The Rb is a dimensionless parameter, ranging from 3.0 to 5.0. Catchments of low Rb values are characterized by small structural geology (Nag 1998). Catchments of high Rb value indicate the high influence of structure on the drainage pattern while the catchments of low Rb values have less effect by geological structure. The study catchments show a restricted variation in Rb and (WMRb) due to the rock formation characteristics. Table 3 shows that Rb and WMRb are characterized by values bigger than 3 due to great elevated, structural, and elongated catchments (Table 3).

Main channel length (MC) MC considers the length of the extended main channel starting from the outlet of the catchment to the upstream of the watershed. Length of MC is computed by ArcGIS 10.5 software. MC length of the study catchments ranges between 1.4 km and 151 km (Table 3). The widespread differences in the MC lengths of the considered catchments are due to the dissimilarity of the geology.

Main channel index (MCi) MCi is the indication of sinuosity characteristics that reflect the deviancy of the chief valley from its geometric pathway (Mueller 1968). MCi of the study catchments ranges between 1.07 and 1.82 (Table 3). The basins with high MCi have higher groundwater-surface water interactions while the basins with low MCi have a high potentiality of surface runoff accumulation.

Sinuosity (Si) The sinuosity is concerned with the pattern of the basin channel (Gregory and Walling 1973). Catchments of short Si values have a great potential for flash

floods, while catchments of long Si values have good potential for groundwater-surface water exchange. Si of the study catchments ranges between 0.1 and 1.34 (Table 3).

Rho coefficient (ρ) Rho is the primary factor determining the interrelationship of the drainage density and the morphological development of a particular catchment. It simplifies the estimation of the water volume of the catchment tributaries (Horton 1945). Catchments with a low value of Rho have low water storage capacity, while catchments with large Rho values can accumulate more volume of surface runoff. Rho values of this research catchments have a widespread dissimilarity and range between 0.27 and 0.98 (Table 3). It is clear that the results of Rho of the study catchments reveal higher water storage through flood events.

Basin geometry characteristics.

Catchment area (A) Areas of the current catchments were calculated by ArcGIS 10.5. According to Horton (1945), the study catchments can be categorized based on the size into three categories; small basins of area less than 50 Km², basins of medium size which ranges from 50 to 100 Km² and basins of large size which are more than 100 Km² (Table 3). Basins of large areas are collecting more surface runoff than small areas.

The basin length (LB) LB expresses the travelling time of surface runoff, particularly the flash floods crossing the catchment. LB of the current catchments ranges between 11.7 km and 130 km (Table 3).

The basin perimeter (Pr) Basin perimeters of the current catchments have an extensive range of dissimilarity and range between 50.8 km and 509 km (Table 3).

Basin width (W) W of the current catchments was calculated based on Horton 1932, and it ranges between 2.3 km and 56.2 km (Table 3). Catchment of small basin width value is characterized by elongated shape and high potentiality for replenishment of the water-bearing formation than the others of great values.

Circularity ratio (Rc) Rc is affected by the stream lengths and frequencies of, structural geology, land uses, land covers, climate, relief and slope of the catchment (Miller 1953). The assessed values of Rc, following Strahler (1964) and Miller (1953) have wide variations and ranges between 0.06 and 0.54 (Table 3). Basins of Rc value less than 0.5 have an elongated shape, whereas basins of greater than 0.5 values, tend to have a circularity shape and are characterized by strong to medium potentiality of surface runoff.

Elongation ratio (Re) Schumm (1956) explained the Re as the proportion between the circle diameter which owns the identical area, and the maximum length of the catchment. The differences in the elongated shapes of the current catchments are due to the impact of geological and structural aspects. Re is essential to understand hydrological behavior and to estimate flood hazards. Re indicates that the catchments of great values of Re, are characterized by more

Table 3 Measured and calculated physiographic features and hazard degree for the watersheds in Jazan Province

Morphometric Parameters			Region								
			Jazan province								
			*Number of Wadi								
			1	2	3	4	5	6	7	8	9
Drainage Network	1	(U)	7.000	7.000	8.000	5.000	6.000	5.000	7.000	5.000	5.000
	2	(N_u)	3664.000	1863.000	5577.000	188.000	722.000	125.000	5845.000	358.000	651.000
	3	(L_u)	2291.100	1223.900	3393.600	128.800	509.100	98.700	3417.200	246.400	423.200
	4	(Rb)	3.850	3.510	3.490	3.750	3.820	3.320	4.100	4.130	4.800
	5	(WMRb)	4.560	4.630	4.540	4.980	4.990	4.330	4.560	4.590	4.580
	6	(MC)	22.600	18.700	8.600	1.400	4.400	2.200	72.200	8.800	56.100
	7	(MCi)	1.820	1.190	1.190	1.170	1.100	1.160	1.340	1.170	1.300
	8	(Si)	0.460	0.380	0.140	0.120	0.140	0.170	0.880	0.330	1.150
	9	(ρ)	0.510	0.530	0.510	0.870	0.650	0.730	0.450	0.480	0.360
Basin Geometry	10	(A)	984.500	504.800	1493.000	50.600	199.800	40.800	1698.600	95.200	183.000
	11	(LB)	49.500	49.300	63.000	11.700	32.000	13.000	82.000	26.500	49.000
	12	(Pr)	232.400	149.400	332.300	54.300	124.200	50.800	285.000	103.600	193.400
	13	(W)	19.900	10.240	23.700	4.320	6.240	3.140	20.720	3.590	3.730
	14	(Rc)	0.230	0.280	0.170	0.220	0.160	0.200	0.260	0.110	0.060
	15	(Re)	0.720	0.510	0.690	0.690	0.500	0.560	0.570	0.420	0.310
	16	(Rt)	15.770	12.470	16.780	3.460	5.810	2.460	20.510	3.460	3.370
	17	(FFR)	0.400	0.210	0.380	0.370	0.200	0.240	0.250	0.140	0.080
	18	(Sv) or (Sf)	2.490	4.820	2.660	2.710	5.130	4.140	3.960	7.380	13.120
	19	(Ish)	0.510	0.260	0.480	0.470	0.250	0.310	0.320	0.170	0.100
	20	(S_H)	2.100	1.880	2.430	2.150	2.480	2.240	1.950	3.000	4.030
	21	(Fr)	0.097	0.125	0.026	0.026	0.035	0.043	0.253	0.085	0.290
	22	(Ls)	1.950	3.780	2.090	2.120	4.020	3.250	3.110	5.790	10.300
Morphometric Parameters			Region								
			Jazan province								
			*Number of Wadi								
			1	2	3	4	5	6	7	8	9
Drainage texture	23	(F)	3.720	3.690	3.740	3.720	3.610	3.060	3.440	3.760	3.560
	24	(D)	2.330	2.430	2.270	2.550	2.550	2.420	2.010	2.590	2.310
	25	(Di)	1.600	1.520	1.640	1.460	1.420	1.270	1.710	1.450	1.540
	26	(Lo)	0.215	0.206	0.220	0.196	0.196	0.210	0.250	0.190	0.216
	27	(FN)	8.660	8.950	8.490	9.460	9.210	7.410	6.920	9.730	8.230
	28	(Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic
	29	H_{max}	1371.000	1007.000	2007.000	50.000	298.000	42.000	2962.000	161.000	982.000
Relief Characterizes	30	H_{min}	0.000	2.000	0.000	0.000	0.000	0.000	2.000	0.000	0.000
	31	(Rf)	1371.000	1005.000	2007.000	50.000	298.000	42.000	2960.000	161.000	982.000
	32	(E)	950.000	550.000	1550.000	30.000	150.000	25.000	1550.000	80.000	480.000
	33	(Hm)	253.300	147.400	385.000	13.300	62.000	14.000	1045.000	31.000	240.000
	34	(Rr)	0.028	0.020	0.032	0.004	0.009	0.003	0.036	0.006	0.020
	35	(SI %)	0.056	0.0390	0.240	0.029	0.045	0.015	0.029	0.012	0.011
	36	(Sm)	8.30°	4.90°	10.60°	1.30°	1.90°	1.03°	18.00°	1.40°	6.50°
	37	(Rn)	3.1900	2.440	4.560	0.130	0.760	0.100	5.960	0.420	2.270
	38	BFD	41.7° SW	13.0° SW	36.7° SW	47.2° SW	56.5° SW	49.2° SW	38.4° SW	46.9° SW	45.0° SW
	39	(HI)	0.180	0.150	0.190	0.270	0.210	0.330	0.350	0.190	0.240
Summation of Hazard degree			28.37	24.63	32.83	20.60	20.38	18.65	27.55	20.77	21.01
<i>Hazard degree</i>			<i>4.00</i>	<i>3.00</i>	<i>5.00</i>	<i>2.00</i>	<i>2.00</i>	<i>1.00</i>	<i>4.00</i>	<i>2.00</i>	<i>2.00</i>

Table 3 (continued)

Morphometric Parameters			Region								
			Jazan province								
			*Number of Wadi								
			10	11	12	13	14	15	16	17	18
Drainage Network	1	(Q)	6.000	6.000	5.000	5.000	5.000	5.000	6.000	8.000	7.000
	2	(N_b)	2752.000	1012.000	329.000	503.000	139.000	262.000	869.000	20208.000	4169.000
	3	(L_b)	1720.400	654.000	225.100	321.900	90.800	169.700	573.000	13704.000	2421.600
	4	(Rb)	4.720	3.880	4.080	4.530	3.550	4.130	3.8300	4.100	3.920
	5	(WMRb)	4.480	4.450	4.790	4.650	5.340	4.830	4.340	4.490	4.420
	6	(MC)	48.400	18.000	4.200	27.700	1.500	10.400	18.400	151.000	109.400
	7	(MCi)	1.310	1.300	1.200	1.320	1.070	1.300	1.300	1.610	1.370
	8	(Si)	1.000	0.500	0.240	0.760	0.100	0.370	0.590	1.160	1.200
	9	(ρ)	0.400	0.480	0.700	0.370	0.980	0.430	0.490	0.570	0.460
Basin Geometry	10	(A)	737.800	260.500	89.200	128.300	35.700	68.300	225.300	7308.4000	1156.200
	11	(LB)	48.500	36.000	17.200	36.500	15.500	28.000	31.000	130.000	91.000
	12	(Pr)	147.300	103.700	74.800	99.700	63.200	120.400	163.800	485.000	432.200
	13	(W)	15.210	7.240	5.190	3.520	2.300	2.440	7.270	56.220	12.710
	14	(Rc)	0.430	0.300	0.200	0.160	0.110	0.060	0.110	0.390	0.080
	15	(Re)	0.630	0.510	0.620	0.350	0.440	0.330	0.550	0.740	0.420
	16	(Rt)	18.680	9.760	4.400	5.040	2.200	2.180	5.310	41.670	9.650
	17	(FFR)	0.313	0.200	0.300	0.100	0.150	0.090	0.230	0.430	0.140
	18	(Sv) or (Sf)	3.190	4.980	3.320	10.380	6.730	11.480	4.270	2.310	7.160
	19	(Ish)	0.400	0.260	0.380	0.120	0.190	0.110	0.300	0.550	0.180
	20	(S_H)	1.530	1.810	2.240	2.480	2.990	4.110	3.080	1.600	3.590
	21	(Fr)	0.329	0.174	0.056	0.278	0.024	0.086	0.112	0.311	0.253
	22	(Ls)	2.500	3.910	2.600	8.150	5.280	9.000	3.350	1.820	5.620
Morphometric Parameters			Region								
			Jazan province								
			*Number of Wadi								
			10	11	12	13	14	15	16	17	18
Drainage texture	23	(F)	3.730	3.890	3.690	3.920	3.890	3.840	3.860	2.770	3.610
	24	(D)	2.330	2.510	2.520	2.510	2.540	2.480	2.540	1.880	2.090
	25	(Di)	1.600	1.550	1.460	1.560	1.530	1.540	1.520	1.480	1.720
	26	(Lo)	0.214	0.200	0.200	0.200	0.197	0.200	0.197	0.267	0.240
	27	(FN)	8.700	9.750	9.310	9.840	9.900	9.530	9.810	5.190	7.550
Relief Character-izes	28	(Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic
	29	H_{max}	1415.000	202.000	88.000	204.000	60.000	125.000	144.000	2980.000	2724.000
	30	H_{min}	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000
	31	(Rf)	1415.000	202.000	88.000	204.000	60.000	125.000	143.000	2980.000	2724.000
	32	(E)	590.000	135.000	60.000	150.000	40.000	75.000	70.000	1785.000	1280.000
	33	(Hm)	217.000	70.000	28.000	87.000	20.000	46.000	42.000	1043.000	804.000
	34	(Rr)	0.029	0.006	0.005	0.006	0.004	0.004	0.005	0.023	0.030
	35	(SI %)	0.016	0.010	0.019	0.007	0.036	0.010	0.005	0.016	0.016
	36	(Sm)	6.40°	2.10°	1.90°	2.30°	1.90°	1.80°	1.60°	15.20°	15.50°
	37	(Rn)	3.300	0.510	0.220	0.510	0.150	0.310	0.360	5.590	5.710
	38	BFD	46.00° SW	70.50° SW	73.00° SW	63.40° SW	61.90° SW	58.40° SW	47.80° SW	58.70° SW	53.90° SW
	39	(HI)	0.150	0.350	0.320	0.430	0.33	0.370	0.290	0.350	0.30
Summation of Hazard degree			27.70	22.65	20.64	20.48	17.93	18.61	22.64	29.41	25.76

Table 3 (continued)

Morphometric Parameters		Region								
		Jazan province								
		*Number of Wadi								
		10	11	12	13	14	15	16	17	18
<i>Hazard degree</i>		4.00	2.00	2.00	2.00	1.00	1.00	2.00	4.00	3.00

Morphometric Parameters		Region							
		Jazan province							
		*Number of Wadi							
		19	20	21	22	23	24	25	
Drainage Network	1	(ω)	7.000	7.000	4.000	6.000	7.000	7.000	7.000
	2	(N_u)	6922.000	3542.000	253.000	538.000	4005.000	5760.000	5541.000
	3	(L_u)	4110.700	2334.400	165.400	354.200	2419.100	3614.400	3348.200
	4	(Rb)	4.190	3.930	6.540	3.630	3.870	4.130	4.200
	5	(WMRb)	4.350	4.500	4.910	4.540	4.510	4.520	4.450
	6	(MC)	102.000	7.100	37.600	8.200	66.800	39.400	54.400
	7	(MCi)	1.430	1.290	1.500	1.370	1.390	1.410	1.320
	8	(Si)	1.030	0.180	1.340	0.300	0.860	0.500	0.650
	9	(ρ)	0.420	0.690	0.270	0.520	0.440	0.460	0.440
Basin Geometry	10	(A)	1867.000	941.600	70.500	142.000	1071.100	1580.400	1521.100
	11	(LB)	99.000	40.500	28.000	27.000	77.500	78.500	84.000
	12	(Pr)	509.400	148.400	126.000	133.300	252.000	383.800	449.000
	13	(W)	18.860	23.250	2.520	5.260	13.820	20.130	18.110
	14	(Rc)	0.090	0.540	0.060	0.100	0.210	0.140	0.100
	15	(Re)	0.490	0.860	0.340	0.500	0.480	0.570	0.520
	16	(Rt)	13.590	23.870	2.010	4.040	15.900	15.000	12.340
	17	(FFR)	0.190	0.570	0.090	0.200	0.180	0.260	0.220
	18	(Sv) or (Sf)	5.250	1.740	11.120	5.130	5.610	3.900	4.640
	19	(Ish)	0.240	0.730	0.110	0.250	0.230	0.330	0.270
	20	(S_H)	3.330	1.370	4.230	3.160	2.170	2.720	3.250
	21	(Fr)	0.200	0.048	0.298	0.062	0.265	0.103	0.121
	22	(Ls)	4.120	1.370	8.730	4.030	4.400	3.060	3.640

Morphometric Parameters		Region							
		Jazan province							
		*Number of Wadi							
		19	20	21	22	23	24	25	
Drainage texture	23	(F)	3.710	3.760	3.590	3.790	3.740	3.650	3.640
	24	(D)	2.200	2.480	2.350	2.490	2.260	2.290	2.200
	25	(Di)	1.680	1.520	1.530	1.520	1.660	1.590	1.660
	26	(Lo)	0.230	0.202	0.213	0.200	0.220	0.219	0.227
	27	(FN)	8.160	9.330	8.420	9.450	8.450	8.340	8.01
	28	(Dp)	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic	Dendritic

Table 3 (continued)

Morphometric Parameters			Region						
			Jazan province						
			*Number of Wadi						
			19	20	21	22	23	24	25
Relief Characterizes	29	H_{max}	2872.000	718.000	81.000	86.000	2738.000	2656.000	2275.000
	30	H_{min}	0.000	0.000	0.000	0.000	0.000	1.000	0.000
	31	(Rf)	2872.000	718.000	81.000	86.000	2738.000	2655.000	2275.000
	32	(E)	1730.000	110.000	50.000	50.000	1090.000	1188.000	880.000
	33	(Hm)	886.000	85.300	31.000	33.000	574.000	386.000	549.000
	34	(Rr)	0.029	0.018	0.003	0.003	0.035	0.034	0.027
	35	(SI %)	0.023	0.021	0.002	0.008	0.022	0.040	0.022
	36	(Sm)	11.70°	3.20°	1.70°	1.90°	10.80°	8.20°	10.60°
	37	(Rn)	6.320	1.780	0.190	0.220	6.180	6.070	5.010
	38	BFD	76.40° SW	64.40° SW	86.20° NW	77.20° SW	54.10° SW	81.40° SW	83.90° SW
39	(HI)	0.310	0.120	0.380	0.380	0.210	0.150	0.240	
Summation of Hazard degree			28.56	29.07	16.34	20.55	28.72	29.47	26.69
<i>Hazard degree</i>			<i>4.00</i>	<i>5.00</i>	<i>1.00</i>	<i>2.00</i>	<i>4.00</i>	<i>4.00</i>	<i>4.00</i>

*Number of Wadi

1 Khiyam, 2 Nahab, 3 Rim, 4 Al Qa', 5 Al Aslab, 6 Qa' Itwad, 7 Itwad, 8 Ramlan, 9 Erg Minshibah

*Number of Wadi

10 Bayd, 11 Samrah, 12 Bi'r Ukrash, 13 SIRR, 14 Bi'r Wafiyah, 15 Misliyah, 16 Bi'r al Sha'afah, 17 Baysh, 18 Damad

*Number of Wadi

19 Jazan, 20 Wadi Al Khurnah, 21 Al Madaya, 22 Al ahad al Musariyah, 23 Khulab, 24 Liyah, 25 Harad

potentiality of infiltration rate and less accumulation of surface runoff. Values of Re normally vary from 0.6 to 1.0 according to the variations in climate, relief, and geology. Re-values close to 1.0 represent the catchment of exact weak relief, but values in the range of 0.6 to 0.8 are characterized by great relief and sharp slopes (Strahler 1964). Re of the study catchments ranges from 0.31 to 0.86 (Table 3).

Texture ratio (Rt) According to the formula that was assumed by Horton (1945), the current catchments have Rt range between 2.0 km^{-1} and 41.67 km^{-1} (Table 3). Rt of the catchments is classified into three classes (Smith 1958); coarse ($< 6.4 \text{ km}^{-1}$), intermediate (6.4 km^{-1} – 16 km^{-1}), and fine ($> 16 \text{ km}^{-1}$). Schumm, (1965) reported that the Rt is a significant parameter that is based on the lithological characteristics, infiltration rate, and elevation features of the catchment. The extending differentiations of the Rt are due to the difference in the lithology and structural geology. A low value of Rt refers that the catchment is characterized by a great potentiality for recharging the groundwater aquifer, but the catchments of a large Rt value, which consist of solid rocks and don't have enough capacity for water penetration, have a good possibility for surface runoff accumulations (Pareta and Pareta, 2011a).

Form factor ratio (FFR) FFR considers the mathematical key which is responsible for the form of the catchment

(Horton 1932; Pareta and Pareta, 2011b) and it ranges between 0.1 and 0.8. Table 3, displays that the values of FFR have to extend variations, ranging between 0.08 and 0.57. Catchments of low FFR value are characterized by elongated shapes and have a small runoff peak (Gupta 1999). Catchments with high FFR values have a high runoff peak.

The inverse shape form (Sf) Sf is an indicator of the length and area of the basin (Horton 1932). The resulting assessed values of Sf show high variation and range from 1.74 to 13.12 (Table 3). Catchments of great values are described by elongated basin length and have a great possibility for groundwater recharge. However, the catchments of smaller value are characterized by short basin lengths and high potentiality for surface runoff accumulations.

Basin shape index (Ish) Ish was calculated based on (Haggett 1965) and it ranges from 0.1 to 0.73 (Table 3). Catchments of great Ish value are described by longitudinal shape and great potentiality of groundwater recharge. But, the catchments of small values have a circular shape and great potentiality for surface runoff accumulations.

Compactness ratio (SH) Compactness ratio is the relation between the circle which has the identical area of the current catchment (Horton 1945). Catchment of a low SH value is characterized by a high potentiality of flood risk, due to the

short time of concentration. Results of SH values have wide variations and are ranging from 1.37 to 4.23 (Table 3).

Fitness ratio (Fr) The Fr is considered as the proportion of the mainly valley length and the catchment perimeter. The values of the fitness ratio of the current catchments have a wide variation and vary from 0.02 to 0.33 (Table 3). Basins of greater values of Fr indicate that they are described by the elongated shape of great possibility for groundwater recharge in the catchment than in the other catchments.

Lemniscate shape (Ls) The lemniscate is considered an indicator of the shape and slope of the catchment (Chorley, 1957). Elongated catchments have Ls ranging from 0.50 to 1.80. Catchments of spherical shape have Ls lesser than 0.50, and the elongated catchments have Ls greater than 2 (Lykoudiet al. 2004). The calculated lemniscate values of the current catchments have an extended variant and range from 1.37 to 10.3 (Table 3). Catchments of small Ls values are described by being highly prone to erosion hazards because these catchments are close to being a circular shape with a short time of concentration and have high potentiality for surface runoff accumulations.

Drainage texture.

Stream frequency (F) Horton 1945, summarized that the stream frequency is controlled by lithology. The hilly and structural catchments are characterized by greater stream frequencies and drainage densities but the catchments of alluvial deposits and sediments have small values. Stream frequencies of the current catchments have limited variation close to medium and high values and range from 2.77 to 3.92 (Table 3). The narrow range of difference is due to the similarity in lithological features, rainfall, elevation, infiltration capacity, and resistance to erosion.

Drainage density (D) The resulting drainage density values show a restricted difference and range between 1.88 and 2.59 (Table 3). Catchments with a high value of drainage density reflect that these catchments were subjected to a high-intensity rainfall that resulted in a runoff, but the catchments of a small drainage density value indicate an erosional-resist fissured solid rocks (Basement) and the majority portion of the rainfall was infiltrated to replenish the water-bearing formation.

Drainage intensity (Di) Di is well known as the proportion between the stream frequency and the drainage density (Faniran 1968). The resulting values of Di of the study catchments have narrow variation and range between 1.27 and 1.72 (Table 3). Catchments of low Di value indicate that the stream frequency and drainage density have a weak impact on the hydrologic behavior.

Length of overland flow (Lo) Lo is well known as the length of the watercourse flows over the terrain beforehand it accumulated in a particular tributary (Horton 1945). Catchments with low Lo values are characterized by a faster

concentration of surface runoff than the others with high Lo values. Lo has a narrow variation and is from 0.19 km to 0.27 km (Table 3).

Infiltration number (FN) FN of the catchment is considered as the drainage density multiplied by stream frequency (Faniran 1968). FN is considered an important indicator for the infiltration characteristics of the catchment. Watersheds with high infiltration numbers are characterized by low infiltration rates and high potentiality of groundwater recharge. The resulting FN values for the catchments of Jazan Province range from 5.19 to 9.9 (Table 3).

Drainage pattern (Dp) The drainage patterns of the catchment are an essential factor to identify the erosional phase and show the impact of gradient, lithology, and structure (Howard 1967; Pareta and Pareta, 2011b). Dendritic patterns are the most common style in the Jazan Basins. Catchments of dendritic drainage patterns reflect a textural similarity and influence of the structural geology.

Relief characteristics.

Relief Elevation of the basin is the main controlling element for reliable evaluation of flood hazards, as it affects the direction of the surface runoff as well as the velocity, and geometry of the flood inundation. The study catchments are characterized by wide variation in reliefs and ranging between 42 and 2980 m AMSL (Table 3). Study catchments could be grouped based on the relief into three groups as follows:

Low relief group which has relief ranges from 0 to 100 m AMSL; **Medium relief group** which has relief ranges from 100 to 500 m AMSL and **High relief group** which is characterised by relief more than 500 m AMSL (Table 3).

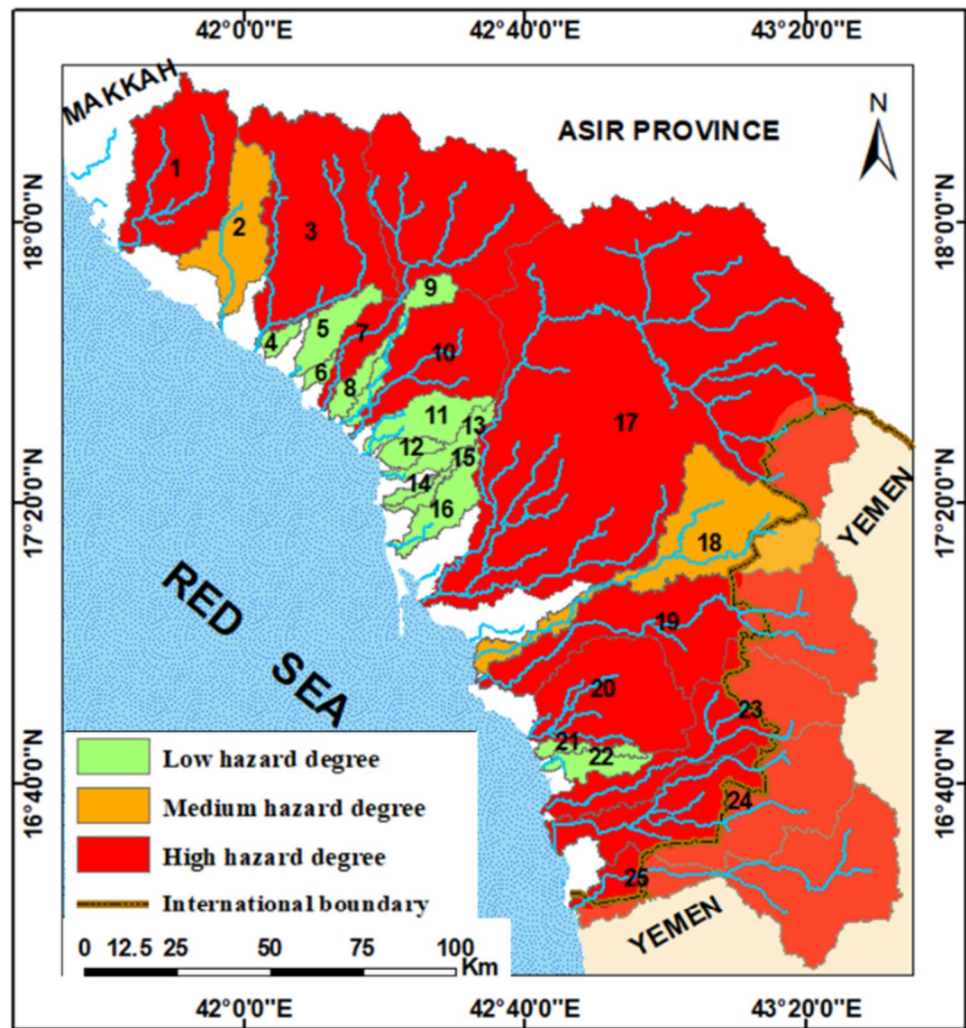
Internal relief (E) The internal relief (E) is the difference in point elevations (m) at 85% and 10% of the main valley length from its entrance (Strahler 1952). It ranges from 25 m AMSL to 1785 m (ASL) as tabulated in Table 3.

Mean elevation (Hm) It is calculated from DEM of 30 m resolution using ArcGIS 10.5 and ranges from about 14 m AMSL to about 1045 (Table 3).

Relief ratio (Rr) Rr expresses the hydrologic behavior due to the inter-relation of the relief and the catchment length (Schumm 1956). Catchments with great Rr values are described by great elevation and steep slopes with a great possibility of flash flood accumulations, but the others with low Rr values are characterized by low relief with gentle slopes which permit considerable possibilities for groundwater recharge. The calculated Rr values of the study basins range from about 0.003 to about 0.04 (Table 3).

The slope index (SI%) It is considered an indicator of the stream gradient and it is important to assess the runoff volume. The study catchments are described by wide variations of slope and range from 0.002 to 0.24 (Table 3). Catchments of low slope index values have more groundwater recharge

Fig. 7 Potential of flash flood hazard degree of Jazan watershed



potentiality, while the catchments of high slope index values have a great potential for flash flood hazard.

Mean basin slope (S_m) Slope considers the major parameter of the catchment which is controlling the hydrologic behavior. Slope maps of the study catchments have been generated based on the Surface Analyst Tools in ArcGIS 10.5. The resulting average slopes of the current catchments have wide variations and range from 1.03° to 18° (Table 3). This variation between the mean slope values is because of the inhomogeneity of the topographic conditions. Usually, the catchment slope controls the shape of the hydrograph via the time to peak concentration.

Ruggedness number (R_n) R_n , is the dimensionless parameter that is equal to the drainage density multiplied by the relief (Melton 1957). Catchments of high R_n values are characterised by high relief which is mountainous areas. This means that the catchments of high R_n values have a great potential for the high degree of flood risk. Calculated R_n

values of the catchments of Jazan Province have wide variations and range from 0.1 to 6.3 (Table 3).

Basin flow direction (BFD) The catchment flow direction has been generated using ArcGIS 10.5 tools. Calculated main flow directions of the current catchments are confirmed with the main channel direction which flows towards the Red Sea (Table 3).

Hypsometric integral (HI) According to Bishop et al. (2002), HI, is an important parameter to interpret the erosion processes of the catchments that happened throughout geological time. HI represents the area underneath the hypsometric curve and it ranges between 0 and 1 (Hurtez et al. 1999). According to Brocklehurst and Whipple (2002), as shown in Table 3, the resulting HI values of the current catchments range from 0.12 to 0.43.

Singh et al. (2008) classified the catchments into three classes; catchments with (HI) values greater than 0.6 are called young, while catchments with (HI) values smaller

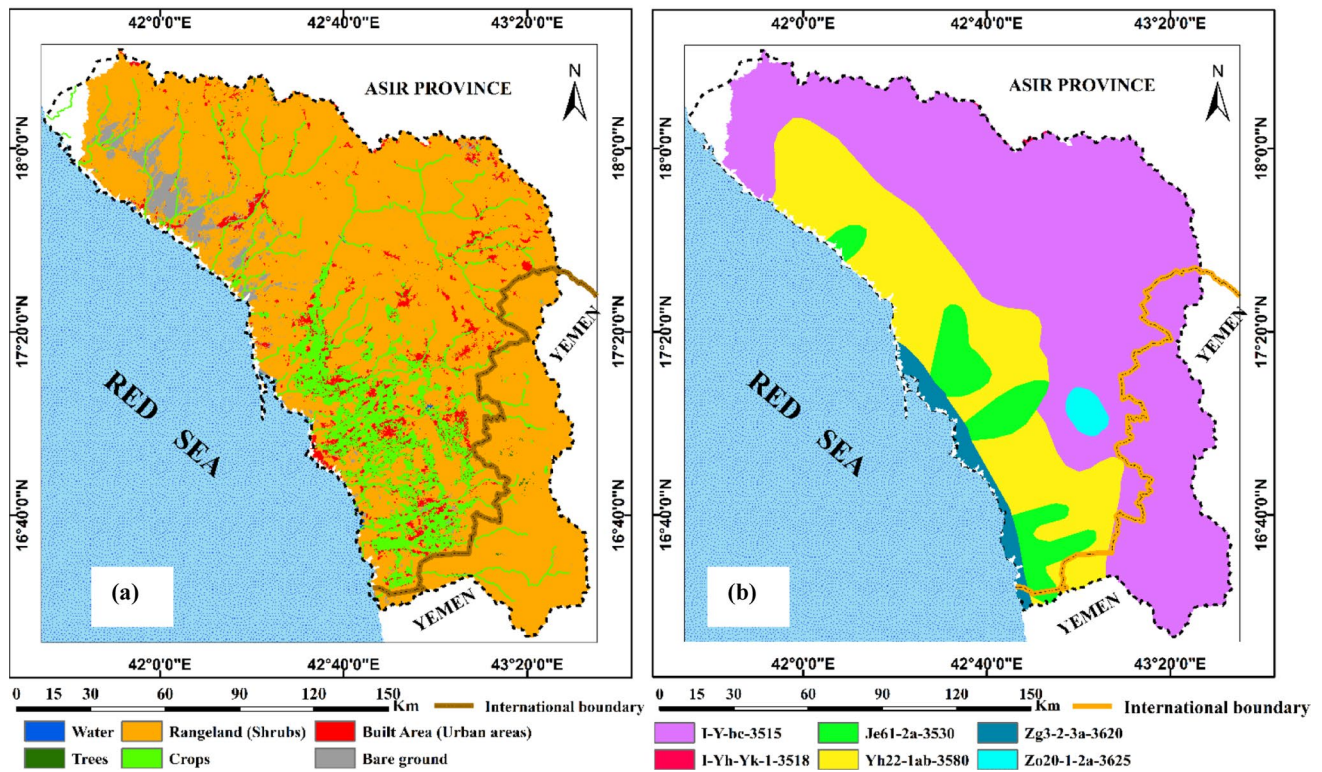


Fig. 8 Land use (a) and soil (b) maps

Table 4 The dominant soil types in the Jazan Basin

Soil code	Explanation
I-Y-bc-3515	Loamy texture soil with the dominance of silt (39%) and sand (38%) with low conductivity
I-Yh-Yk-1-3518	Loamy texture soil with the dominance of sand (48%) and silt (31%) with low conductivity
Je61-2a-3530	Loamy texture soil with the dominance of sand (41%) and silt (39%) with high conductivity
Zg3-2-3a-3620	Clay texture soil with the dominance of clay (52%) with very low conductivity
Zo20-1-2a-3625	Sandy-Loam texture soil with the dominance of sand (58%) with low conductivity
Yh22-1ab-3580	Sandy-Loam texture soil with the dominance of sand (58%) with low conductivity

than 0.3 are named old or Monadnock. But, the matured phase catchments have (HI) values ranging from 0.3 to 0.6.

Catchments of Jazan Province were classified into two groups as follows:

Mature Wadis; which have HI values and are ranging from 0.3 to 0.6 (Table 3).

Old Wadis; which have HI values less than 0.3 (Table 3).

Flash flood hazardous appraisal

Flash flood hazardous degree appraisal set up on nine morphometric parameters that have direct or indirect controls upon surface water accumulation. These nine parameters are; (A), (D), (F), (Ish), (SI), (Rr), (Rn), (Rt), and (WMRb).

The mathematical behavior of all selected morphometric parameters shows a positive proportional relationship with the hazard degree excluding the (WMRb) which displays a negative relationship. Flash flood hazard degrees range from 1 to 5 for all parameters. Flash flood hazard degree has been evaluated for the study catchments according to the next scheme:

- Minimum and maximum value of specific morphometric elements for the current catchments was specified.
- Hazard degree of the flash flood for the selected morphometric elements which are positioned between the actual minimum and maximum values were calculated based on the experimental Eqs. (4 and 5), which assume a linear

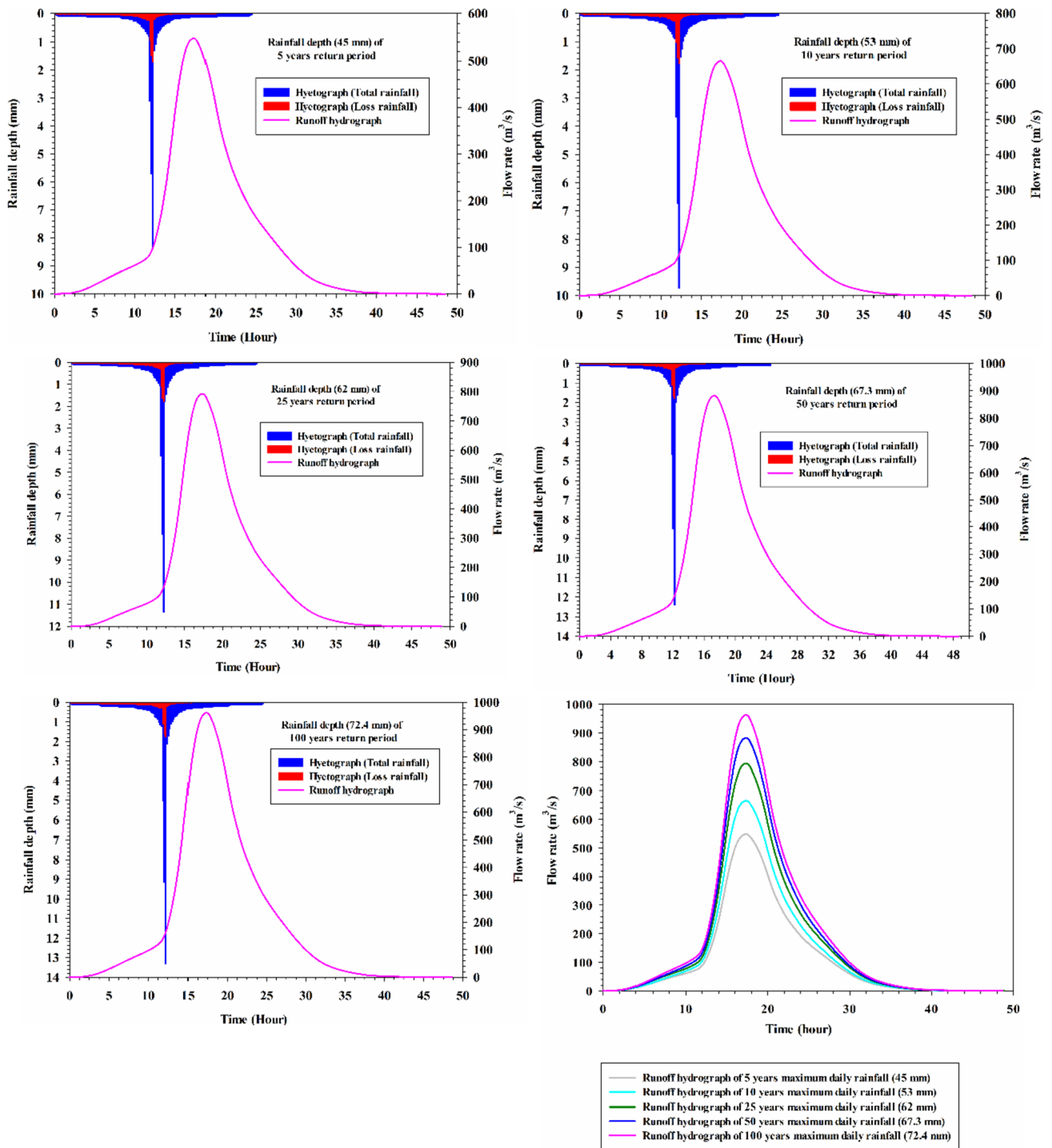


Fig. 9 Representative hydrographs of Wdai Baydh basin at different return periods (5,10, 25, 50 and 100) years as a represented example of the output hydrographs of the study Province

relationship between samples and intermediary values of hazard degree (Davis 1975):

$$\text{Hazard degree} = \frac{4(X - X_{\min})}{(X_{\max} - X_{\min})} + 1 \tag{4}$$

Table 5 Summary of the hydrograph elements

Basin Name	Return period (Year)	The model condition under SCS method						
		Rainfall (mm)	Total area (Km ²)	Modeled area (Km ²)	CN	Peake of discharge Qp (m ³ /s)	Time to Peak (minutes)	Outflow Volume (MCM)
Wadi Khiyam basin	5	53.10	984.50	854.38	87.00	950.4	1035.00	35.50
	10	63.80				1178.7		44.00
	25	78.00				1488.3		54.80
	50	89.10				1740.9		64.50
	100	100.40				1997.1		74.00
Wadi Rim basin	5	77.00	1493.00	1459.10	86.10	2098.9	1150.00	91.80
	10	86.40				2412.4		106.10
	25	96.40				2735.7		120.00
	50	102.80				2936.0		128.00
	100	108.60				3131.4		137.30
Wadi Itwad basin	5	65.80	1698.60	1474.40	86.10	2674.3	960.00	78.30
	10	85.30				3625.4		105.90
	25	113.10				4994.8		145.00
	50	136.00				6133.9		177.90
	100	160.70				7374		213.50
Wadi Baydh basin	5	45.10	737.80	580.50	84.77	548.2	1040.00	19.80
	10	53.0				665.1		23.60
	25	61.60				793.4		28.10
	50	67.30				882.5		31.20
	100	72.40				962.3		34.20
Wadi Baysh Basin	5	59.20	7308.40	4746.69	84.41	4467.3	1220.00	220.60
	10	72.50				5676.1		279.30
	25	89.80				7257.4		353.80
	50	103.00				8518		414.90
	100	116.60				9752.7		473.10
Wadi Jazan Basin	5	63.60	1867.00	1413.50	85.00	2092.5	1020.00	71.00
	10	76.50				2598.8		87.20
	25	92.70				3261		109.10
	50	104.80				3757.6		125.60
	100	116.80				4244.7		141.20
Wadi Khurmah Basin	5	65.00	941.60	352.30	86.30	488.7	1070.00	18.50
	10	81.20				632.3		23.80
	25	101.80				819.4		30.70
	50	117.00				959.4		35.80
	100	132.10				1097		40.90
Basin Name	Return period (Year)	The model condition under SCS method						
		Rainfall (mm)	Total area (Km ²)	Modeled area (Km ²)	CN	Peake of discharge Qp(m ³ /s)	Time to Peak (minutes)	Outflow Volume (MCM)
Wadi Khulab Basin	5	59.30	1071.10	782.70	84.60	1278.80	950.00	36.20
	10	64.60				1413.90		39.70
	25	69.50				1540.80		43.00
	50	72.30				1615.70		45.40
	100	74.50				1680.20		47.30

Table 5 (continued)

Basin Name	Return period (Year)	The model condition under SCS method						
		Rainfall (mm)	Total area (Km ²)	Modeled area (Km ²)	CN	Peake of discharge Qp(m ³ /s)	Time to Peak (minutes)	Outflow Volume (MCM)
Wadi Liyah Basin	5	60.30	1580.40	1416.10	83.30	1482.20	1150.00	65.20
	10	72.80				1859.70		81.70
	25	88.60				2347.70		102.30
	50	100.30				2712.00		118.00
	100	112.00				3082.90		134.10
Wadi Harad Basin	5	60.30	1521.10	1160.30	84.20	1566.40	1030.00	54.10
	10	72.80				1964.60		67.70
	25	88.60				2477.80		84.70
	50	100.30				2861.20		97.70
	100	112.00				3248.70		111.00

Equation 5 (Davis 1975) deals with WMRb, which displays a negative relationship as the next:

$$\text{Hazard degree} = \frac{4(X - X_{\max})}{(X_{\min} - X_{\max})} + 1 \tag{5}$$

where X: morphometric elements to be calculated for each catchment hazard degree, X_{min} and X_{max} are the minimum and maximum values of the morphometric elements of all catchments.

The summations of the hazardous degree for every catchment represent the flood hazard degree of that catchment (Table 3 and Fig. 7). The values range from 16.34 to 32.8 (Table 3 and Fig. 7).

Hydrological modeling

Analysis of land use and cover (LUC) and curve numbers (CNs) assessment

Flash flood (Runoff) is well known as the extra rainfall after deducting primarily and additionally abstractions (Evaporations and infiltrations) from the rainfall event. Evaporation and evapotranspiration parameters depend on the climate conditions and land use of the catchments. The infiltration process and potential maximum retention rely on the soil features (textures, compactions, structures, and moisture contents) and surface features (topography, LUC, and land treatments).

Soil Conservation Services (SCS, 1972, 1985, and 1986) of the USA (now, called Natural Resources Conservation Service, NRCS), established formulas to assess the catchment surface runoff depending on the aforementioned

factors. These equations are interconnected with runoff depth, precipitation, potential maximum retention, and curve number (CN), where the CN is considered as a hydrological parameter and indicator of the land use and soil type as follows:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \tag{6}$$

where Q, P, and S are runoff quantity, rainfall depth and potential maximum retention depth, respectively.

Assessment of potential maximum retention based on a hydrologic factor called curve number (CN) according to the coming formula:

$$S = (25400/CN) - 254 \tag{7}$$

where CN is the curve number.

According to the SCS of the USA, soils of the USA are grouped into 4 hydrologic groups and allocated a letter for each group as A, B, C, and D. Each group could be recognized with particular hydrologic features. All the details about the characteristics of the soil groups are in SCS, 1972, 1985, and 1986.

From land use and soil analysis (Fig. 8 and Table 4), it is found that almost 85% of the Jazan watershed is rock outcrops and bare soil according to Sat image analysis of Sentinel-2 of 10 m resolution (Fig. 8).

Calibration and validation of the model

Comparisons between the modeled and observed runoff storm hydrographs were measured by Japan International Cooperation Agency, JICA (2010) to test and validate the prediction of the unit hydrograph method developed against the observed data. Hydrograph parameters used in the

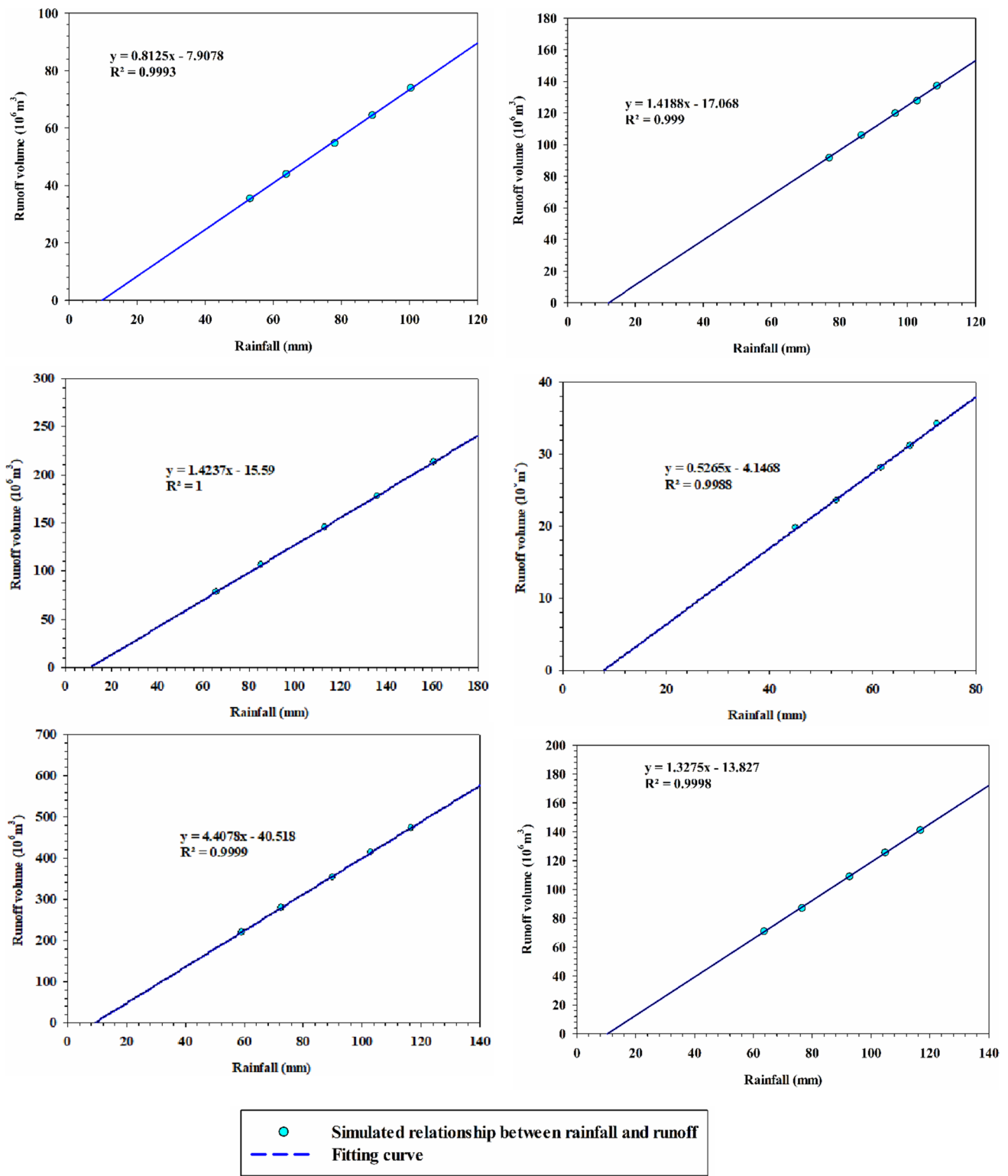


Fig. 10 Rainfall-runoff relationships for each basin in return periods 5, 10, 25, 50, and 10 years (Basins 1–6)

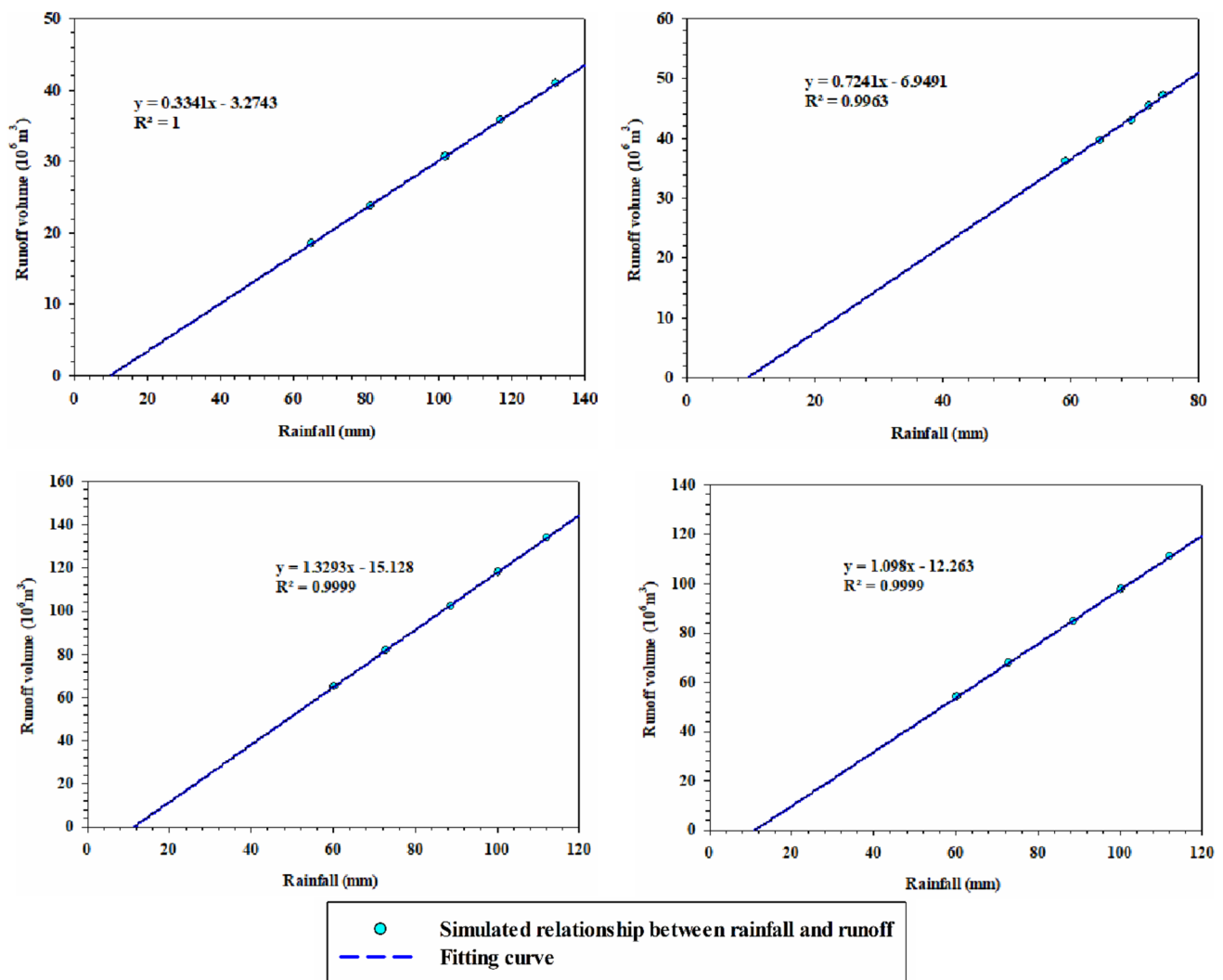


Fig. 11 Rainfall-runoff relationships for each basin in return periods 5, 10, 25, 50, and 100 years (Basins 7–10)

comparison are the peak discharge, time to peak, base time, lag time, time of concentration and runoff volume.

Rainfall-runoff modeling

Ten Wadis under high risk of flash flood were selected to model the surface runoff resulting from the rainfall events of 5-, 10-, 25-, 50- and 100-year recurrence time duration (Fig. 9). The proposed dams were selected at the main channel depending on the digital elevation model, integrating GIS, remote sensing techniques and hydrological models to simulate streamflow in the un-gauged catchments. Two hydrologic models are used: watershed modeling system (WMS 10.2) and hydrologic modeling system (HEC-HMS 4.02).

WMS can achieve tasks such as automatic catchment delineation, GIS overlay calculations, geometric parameter calculations: storm drain analysis, and hydrograph generation. Hydrologic modeling system (HEC-HMS) is planned for rainfall-runoff modeling of dendritic catchment systems. The hydrologic modeling system (HMS) is a versatile software used to simulate precipitation-runoff processes in watershed systems. It can address various hydrological problems and applies to different geographic areas. HMS produces hydrographs for analyzing water availability, urban drainage, flood forecasting, and more. The program has a user-friendly interface, an integrated database, and supports multiple platforms. Data storage is handled by the HEC-DSS system. HEC-HMS allows choosing between several infiltration losses and unit

Table 6 detailed groundwater recharge from the mean annual rainfall over the upstream portion

Drainage Basin No	Average Annual rainfall (mm) in Basement	Evapotranspiration (mm)	Effective rainfall (mm)	Total Recharge on Basement (mm) (30%)	Basement area(Km ²)	Recharge on Basement per unit area (mm/km ²)	Remaining Evapotranspiration which flows in streams (mm)	Recharge in Alluvium from remaining Evapotranspiration (mm)	ET in Alluvium of remaining Evapotranspiration (mm)	Sea (mm) of remaining Evapotranspiration	Runoff to the streams to be recharged (km ²)	Area of streams to be recharged (km ²)	Recharge on Alluvium per unit area (mm/km ²)
1	240.40	213.96	26.44	7.93	900.61	0.009	18.511	13.180	1.78	3.55	-	-	-
2	292.24	260.09	32.15	9.64	114.97	0.084	22.502	16.022	2.16	4.32	7.26	7.26	2.207
3	358.11	318.72	39.39	11.82	911.98	0.013	27.574	19.633	2.65	5.29	9.35	9.35	2.101
5	371.03	330.22	40.81	12.24	0.96	12.745	28.569	20.341	2.74	5.49	-	-	-
7	312.94	278.52	34.42	10.33	1479.95	0.007	24.096	17.157	2.31	4.63	5.34	5.34	3.214
9	299.20	266.29	32.91	9.87	89.77	0.110	23.038	16.403	2.21	4.42	4.43	4.43	3.700
10	270.70	240.92	29.78	8.93	364.76	0.024	20.844	14.841	2.00	4.00	6.94	6.94	2.140
11	192.80	171.59	21.21	6.36	3.92	1.623	14.846	10.570	1.43	2.85	-	-	-
13	192.80	171.59	21.21	6.36	2.91	2.185	14.846	10.570	1.43	2.85	-	-	-
17	305.17	271.60	33.57	10.07	5924.61	0.002	23.498	16.731	2.26	4.51	18.16	18.16	0.921
18	455.41	405.31	50.10	15.03	998.40	0.015	35.067	24.967	3.37	6.73	5.74	5.74	4.349
19	348.68	310.33	38.35	11.51	1529.08	0.008	26.848	19.116	2.58	5.15	7.87	7.87	2.429
20	264.59	235.49	29.10	8.73	222.48	0.039	20.373	14.506	1.96	3.91	5.30	5.30	2.737
23	298.92	266.04	32.88	9.86	604.63	0.016	23.017	16.388	2.21	4.42	8.30	8.30	1.975
24	261.50	232.74	28.77	8.63	913.70	0.009	20.136	14.336	1.93	3.87	10.65	10.65	1.346
25	261.50	232.74	28.77	8.63	1160.42	0.007	20.136	14.336	1.93	3.87	5.00	5.00	2.870
Average	295.37	262.88	32.49	9.75	15,223.16	1.06	23.93	16.19	2.18	4.37	94.33	94.33	2.50

Table 7 detailed groundwater recharge from the mean annual rainfall over the downstream portion

Drainage Basin No	Average Annual rainfall (mm) in Quaternary	Evapotran- spiration (mm)	Effective rainfall (mm)	Recharge on Quater- nary from Effective rainfall (mm)	Area of Quaternary to be recharged (km ²)	Recharge on Quaternary per unit area (mm/km ²)
1	254.72	226.70	28.02	4.20	69.47	0.0605
2	352.35	313.59	38.76	5.81	381.90	0.0152
3	371.00	330.19	40.81	6.12	571.11	0.0107
4	371.00	330.19	40.81	6.12	49.26	0.1243
5	301.46	268.30	33.16	4.97	198.5	0.0251
6	135.57	120.66	14.91	2.24	40.26	0.0556
7	239.96	213.56	26.40	3.96	211.28	0.0187
8	143.16	127.41	15.75	2.36	94.35	0.0250
9	167.05	148.67	18.38	2.76	88.16	0.0313
10	166.87	148.51	18.36	2.75	364.85	0.0075
11	135.57	120.66	14.91	2.24	255.5	0.0088
12	135.57	120.66	14.91	2.24	88.76	0.0252
13	135.57	120.66	14.91	2.24	124.31	0.0180
14	135.57	120.66	14.91	2.24	33.48	0.0668
15	135.57	120.66	14.91	2.24	68.07	0.0329
16	116.93	104.07	12.86	1.93	224.9	0.0086
17	182.23	162.18	20.05	3.01	1351.9	0.0022
18	156.55	139.33	17.22	2.58	149.6	0.0173
19	161.36	143.61	17.75	2.66	328.9	0.0081
20	182.87	162.75	20.12	3.02	713.22	0.0042
21	183.30	163.14	20.16	3.02	68.48	0.0442
22	196.14	174.56	21.58	3.24	141.26	0.0229
23	253.70	225.79	27.91	4.19	454.03	0.0092
24	260.53	231.87	28.66	4.30	654.22	0.0066
25	261.52	232.75	28.77	4.32	353.33	0.0122
Average	205.44	182.85	22.60	3.39	7079.1	0.03

hydrograph parameterizations (U.S. Army Corps of Engineers, 2000). The SCS-CN method is employed to calculate the extra rainfall. For the rainfall distributions over the storm interval, the SCS type II hyetograph is applied which is frequently implemented in dry Provinces. Table 5 and Fig. 9, show an example of the hyetographs of the measured rainfall and the corresponding modeled flood hydrograph elements at various recurrence time durations (5, 10, 25, 50 and 100 years) for each basin.

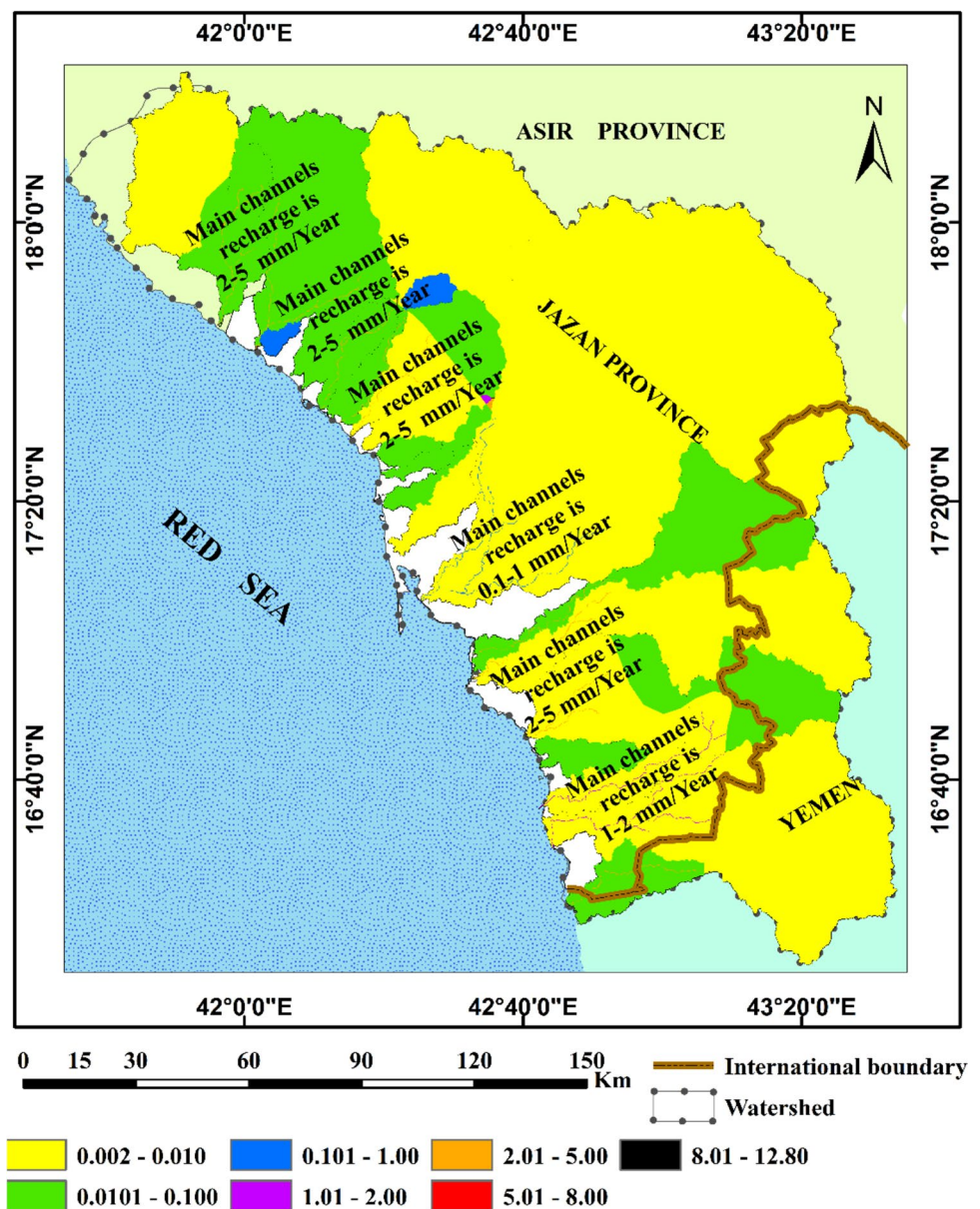
Figure 9 explains the rainfall-runoff relationship of the Wadi Baydh (for example), which shows the hyetograph for each event and the corresponding hydrograph parameters. All the inputs and outputs of the hydrographs generation are tabulated in Table 5. Figures 10 and 11 show the relationships between the rainfall and runoff for the catchments of Jazan Province. The relationships are characterized by a linear relation with excellent correlation coefficients close to the unity as shown in Figs. 10 and 11.

Groundwater recharge assessment

Groundwater recharge assessment is the main parameter for the sustainable development of groundwater resources especially in dry areas which are characterized by the scarcity of hydrological measurements, mainly the groundwater recharge element. So, this research represents a challenge to assess the groundwater recharge based on the interlink between the satellite image analysis, SWAT and GIS techniques.

Catchments of Jazan Province are covering an area is about 22,397 Km² which is distributed into the 15,224 Km² of the mountainous area (Basement) and 7173 Km² of the Wadi plain (Quaternary). From the historical rainfall measurements (1966–2018), and the SWAT model the average annual precipitation in the mountainous area (upstream portion) is 295 mm while in the downstream portion is about 205 mm. The average annual precipitation on the upstream portion could be classified into two parts as evapotranspiration losses is about 89% (265.5 mm) and

Fig. 12 Groundwater recharge assessment



effective rainfall is equal to 11% (32.5 mm). About 30% (9.75 mm) of the effective rainfall on the upstream portion is going to recharge the groundwater aquifer through the basement fracture and the rest 70% (22.75 mm) is going as surface runoff in the main valleys of the drainage basins in the direction of the downstream portion.

The mean annual rainfall on the downstream portion (Quaternary) could be classified into two parts as evapotranspiration losses is about 90% (182.9 mm) and effective rainfall is equal to 10% (22.6 mm). The effective rainfall in the downstream portion (rainfall excess or surface runoff) will divide into about 90% (19.2 mm) as evapotranspiration losses and 10% (3.4 mm) as recharge in the main channels in the drainage basins. The results of the SWAT recharge model are in agreement with JICA internal report (2010).

The details of the recharge calculation and results are shown in Tables 6, 7 and Fig. 12.

Conclusion and recommendations

Flash flood hazardous degree appraisal, groundwater recharge and rainfall-runoff relationship are very significant for un-gauged watershed management, particularly for water resources sustainability development, mitigation of flood hazards, and drought management. With integrated analyses of the resulting physiographic features for the current catchments, it could be reported that the hydrologic response is controlled by the geomorphology, topography, and the prevailing land cover and soil environments.

This study proved that topographic and geologic features are the main governing elements that control the hydrological response of the catchments, particularly for flash floods and groundwater recharge.

In the absence of the historical measured data, so, this research depended upon the incorporation of the morphometric features of the study watersheds for Jazan Province with GIS technology and hydrologic models for estimating the rainfall and runoff relationship. As the results of measuring and calculating the influencing parameters which are responsible for the hydrologic behavior, so, the study catchments were divided into three groups according to their degree (high, medium and low). Annual groundwater recharge has been calculated, and it represents about 30% and 15% of the effective rainfall over the upstream and downstream portions, respectively.

Application of WMS, HEC-HMS models generated some hydrographs of the study Wadis with a volume of runoff ranges from $18.5 \times 10^6 \text{ m}^3$ to $473.1 \times 10^6 \text{ m}^3$ at a return period of 5 and 100 years at rainfall events of 65 mm and 116.8 mm, respectively. The relationships between the rainfall and runoff for the study catchments exhibit linear relations with excellent correlation coefficients close to the unity.

Retarding dams should be constructed in the main channel of high order to permit the groundwater recharge of the shallow unconfined Quaternary aquifer.

Detailed hydrological study for each Wadi and its sub-basins should be done, to create a comprehensive and coordinated planning for the optimal use of surface water resources and estimations of the groundwater recharge with different methods to determine the appropriate value for each drainage basin.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13201-024-02117-2>.

Acknowledgements The authors extend their appreciation to the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project number (70).

Funding This project was funded by the Deputyship for Research & Innovation, Ministry of Education in Saudi Arabia through project number (70).

Data availability All data are provided as tables and figures in this article.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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