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Interfacing the geographic information system, remote sensing, and the soil conservation service–curve number method to estimate curve number and runoff volume in the Asir region of Saudi Arabia

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Abstract Runoff coefficients are widely used as a diagnostic variable of runoff generation in process studies and as an important input parameter in hydrologic design. Many regions of Saudi Arabia do not have sufficient historical records and the detailed runoff information needed for physically based distribution models. The US Department of Agriculture, Natural Resources Conservation Service Curve Number (USDA-NRCS-CN) method was used in this study for determining the curve number and runoff depth for Asir region, Saudi Arabia. Runoff curve number was determined based on the factors of hydrologic soil group, land use and land cover, and slope gradient in the Asir region of Saudi Arabia using the geographic information system (GIS). The region was not subjected before for any previous studies concerning runoff generation or rainwater harvesting by using GIS and remote sensing. ArcGIS 9.3 and the global positioning system were used to develop the soil map on the basis of samples collected during a field survey. Soil textures were identified and used to build a map of the hydrological soil groups. Unsupervised and supervised classification of Landsat images was used to generate land use and land cover maps. The land cover distribution in the study area revealed that the largest class in the area, barren and sparsely vegetated land, occupied 62,832.38 km^2 of the study area (more than 80 % of the total area), followed by shrubland (15,212.66 km^2), cropland and pasture (52.34 km^2), mixed shrubland/grassland (40.89 km^2),

and grassland (12.27 km^2). Built-up land occupied only 11.45 km^2. The slope map for the Asir region was generated from a 15-m digital elevation model. The GIS technique was used to develop the CN for the region based on the Soil Conservation Service method. The annual runoff depth was derived from the annual rainfall and CN per pixel using the raster calculator tool in ArcGIS. The rainfall distribution in the study area showed the wise identification of suitable sites for rainwater harvesting, as most of the constructed dams were located in the areas with higher rainfall. The analysis also revealed that the annual runoff for the study area ranged from 27 to 69 % of the total rainfall, with variation as low as 80 to 300 mm/year. This is the highest amount of runoff that can be generated in Saudi Arabia. The runoff volume was calculated for the entire region using the previously developed runoff depth map and basin areas. The results showed that the runoff volume (M3) in the Asir region varied from as low as 237,000 m^3 to a maximum of 2,140,000 m^3; this result revealed a significant yearly amount of runoff that can be harvested for any use. Moreover, the calculated runoff depth in the area agreed with the actual dam capacities for the existing dams in the Asir region. This approach can be applied in other regions in Saudi Arabia for rainwater harvesting and groundwater recharge.

Introduction

Saudi Arabia is one of the hottest and driest subtropical desert countries in the world. With an average of 112 mm of precipitation per year, much of the country falls within the standard definition of a desert, which is an area with less than 250 mm

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of precipitation per year, compared with the global average of 800 mm. The amount of rainwater in Saudi Arabia is estimated at 158.47 billion m^3 per year (Mahmoud et al. 2014a). More than 90 % of this precipitation is converted to runoff, a problem that is compounded by the lack of rainwater harvesting practices. The exploitation of subsurface water from deep aquifers also depletes resources that have taken decades or centuries to accumulate and upon which the current annual rainfall has no immediate effect. In this severely arid zone, the lack of water resources and the limited access to them are aggravated during droughts. It is therefore important that adequate supplies of water are developed to sustain human life. The harvesting of rainwater, which has been practiced in many countries of the world to sustain water resources, could be one of these indispensable supplies, in conjunction with techniques for the efficient use of water.

The main problem facing the country is the scarcity of water in the absence of perennial surface water sources (Mahmoud et al. 2014a) such as lakes and rivers. This absence is accompanied by the increasing need for water associated with the increasing population. The study of runoff harvesting is gaining significant importance in the development of water resources and agricultural development schemes in Saudi Arabia. This valuable effort will enhance the availability of water and the productivity of the land in the severely arid regions of Saudi Arabia.

The runoff coefficient can be defined either as the ratio of the total runoff depth to the total rainfall depth or as the ratio of the peak rate of runoff to the rainfall intensity (Wanielista and Yousef 1993). At the time of the rainfall that produces the runoff, the coefficient varies with the topography, land use, vegetation, soil type, and moisture content of the soil. The rational runoff coefficient is strongly dependent on land use and, to a lesser extent, on watershed slope, as suggested by ASCE (1992). The generation of runoff plays an important role in the environment for any nation. There are several approaches to estimate ungauged basin runoff, including the soil conservation service (SCS) curve number (CN) model and the geomorphological instantaneous unit hydrograph (GIUH). Among these methods, the SCS (now called the Natural Resources Conservation Service) method is widely used because of its simplicity. It combines watershed parameters and climatic factors into a single entity called the CN.

The SCS runoff curve number method has been the focus of much discussion in agriculture, hydrologic literature and is widely used in continuous modeling schemes (Hawkins 1975, 1978, 1981, 1993; Rallison 1980; Bales and Betson 1981; Mishra et al. 2004, 2005). The main reason behind the method being adopted by most hydrologists lies in its simplicity and applicability to watersheds with minimum hydrologic information, viz., soil type, land use and treatment, surface condition, and antecedent moisture condition. Many investigators have critically reviewed this method to clarify its conceptual and empirical basis (Rallison and Miller 1981; Bondelid et al. 1982a, b; Hjelmfelt 1991; Ponce and Hawkins 1996; Yu 1998; Mishra and Singh 1999; McCuen 2002, 2003). The method has been used successfully in ungauged rural watersheds and has evolved well beyond its original objective to be adopted for surface runoff prediction in urbanized and forested watersheds (USDA 1986). In addition, it has been integrated into many hydrologic, erosion, and water-quality models such as CREAMS (Knisel 1980), SWRRB (Williams et al. 1985; Arnold et al. 1990), AGNPS (Young et al. 1987a, b), EPIC (Sharpley and Williams 1990), PERFECT (Littleboy et al. 1992), and WEPP (Risse et al. 1994; Nearing et al. 1996).

The use of geographic information systems (GISs) and remote sensing to facilitate the estimation of runoff from watershed and agricultural fields has gained increasing attention in recent years. Many researchers (Pandey and Sahu 2002; Nayak and Jaiswal 2003; Zhan and Huang 2004; Gandini and Usunoff 2004) have used the geographic information system (GIS) technique to estimate runoff CN values throughout the world. Most of the previous work on adapting remote sensing to hydrologic modeling has involved the Natural Resources Conservation Service (NRCS) runoff curve number (CN) model (US Department of Agriculture 1972). This involvement used remote sensing data as a substitute for land cover maps, which had been obtained by conventional means (Jackson et al. 1977; Bondelid et al. 1982a, b; Mahmoud 2014). Still and Shih (1984, 1985, 1991) used Landsat data to develop a basin-wide runoff index and successfully demonstrated how remotely sensed data can be used to track the changes in runoff that occur in a basin due to land use change. In Saudi Arabia, Mahmoud et al. (2014b) pointed out that land use/land cover is an important parameter input of the SCS-CN model. Nayak and Jaiswal (2003) found a good correlation between the measured and estimated runoff depths using the GIS and CN techniques. They concluded that GIS is an efficient tool for the preparation of most input data. Savabi and Stott (1994) proved that this porous media can store significant amounts of liquid water. Rutter et al. (1971) and later Scopel et al. (1998) showed that a mulch partly intercepts the rain and cuts down the quantity of water reaching the soil. Gilley and Kottwitz (1994) observed an increase in soil retention capacity due to the modification of soil microtopography by mulch elements. In addition, mulch elements act as a succession of barriers that block runoff and increase roughness (Weltz et al. 1992).

The CN method (SCS 1972), also known as the hydrologic soil cover complex method, is a versatile and widely used procedure for the estimation of runoff. In this method, the runoff-producing capability is expressed as a numeric value between 0 and 1. In the past 30 years, the SCS method has been used by a few researchers because it gives consistently usable results for runoff estimation (Rao et al. 1996; Sharma et al. 2001; Chandrmohan and Durbude 2001; Sharma and
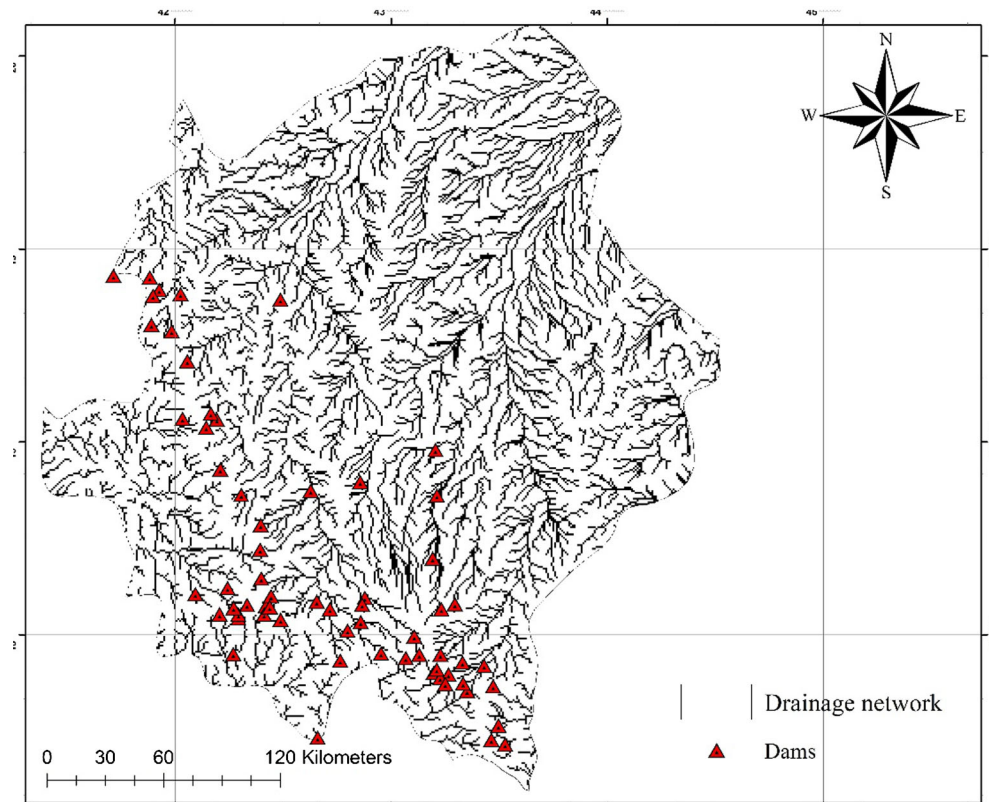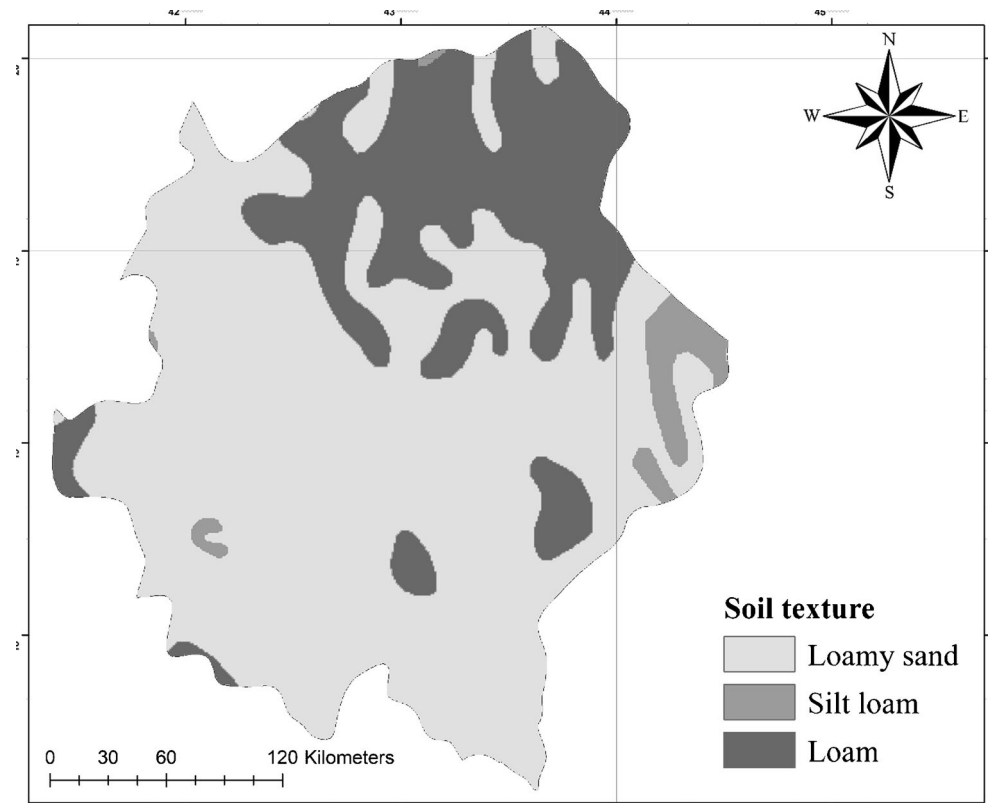
Fig. 1 Study area

Fig. 2 Soil texture map for the study area

Kumar 2002). The SCS method with initial abstraction consideration is given below.

The SCS-CN method estimates the total area runoff depth Q (mm) for a storm by the SCS runoff equation:

$$Q = \frac{(P_e)^2}{(P_e + S_e)} \tag{1}$$

where P_e (mm) is the depth of the effective rainfall after runoff begins and S_e (mm) is the depth of the effective available storage (mm), i.e., the spatially averaged available volume of retention in the watershed when runoff begins. We use the term effective and the subscript "e" to identify parameter values that refer to the period after runoff starts. Although S_e in Eq. 1 is typically written simply as S, this term is clearly defined for the time

when the runoff begins as opposed to that when the rainfall begins; thus, we refer to it as S_e. At the beginning of a storm event, an initial abstraction, I_a (mm), of rainfall is retained by the watershed before the runoff generation begins. Effective rainfall P_e and storage S_e are thus (USDA-SCS 1972):

$$P_e = P–I_a, \tag{2a}$$
$$S_e = S–I_a, \tag{2b}$$

where P (mm) is the total rainfall for the storm event and S (mm) is the available storage at the onset of rainfall. In the traditional SCS-CN method, I_a is estimated as an empirically derived fraction of available storage:

$$I_a = 0.2 \, S_e. \tag{3}$$

Table 1 Hydrological soil groups and major soil types of the Asir region

| Hydrological soil group	Description	Distribution
Group A	Loamy sand or sandy loam types of soils. They have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well-drained to excessively drained sands or gravels and have a high rate of water transmission.	65 %
Group B	Silt loam has a moderate infiltration rate when thoroughly wetted and consists chiefly of moderately deep to deep, moderately well-drained to well-drained soils with moderately fine to moderately coarse textures.	35 %
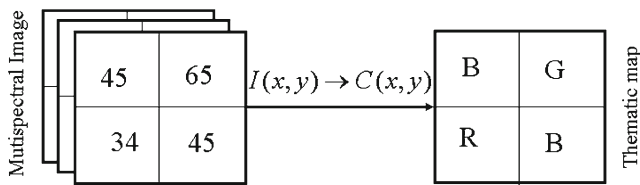
Fig. 3 An illustration of the purpose of classification: inferring from a multispectral image to a thematic map

The effective available storage S_e depends on the moisture status of the watershed and can vary between a maximum $S_{e,max}$ (mm) when the watershed is dry, e.g., during the summer, and a minimum $S_{e,min}$ (mm) when the watershed is wet, usually during the early spring. The $S_{e,max}$ and $S_{e,min}$ limits have been estimated to vary around an average watershed moisture condition with the corresponding $S_{e,avg}$ (mm) based on an empirical analysis of the rainfall-runoff data for experimental watersheds:

$$S_{e,max} = 2.381 S_{e,avg}, \tag{4}$$

$$S_{e,min} = 0.4348 S_{e,avg}. \tag{5}$$

$S_{e,avg}$ is determined via table-derived CN values for average watershed moisture conditions (CN_{II}) and a standard relationship between S_e and CN_{II}.

$$S_{e,avg} = 254 \left(\frac{100}{CN_{II}} - 1 \right), \tag{6}$$

where C is the potential runoff coefficient for a surface slope S (%) and Co is the potential runoff coefficient for a near-zero slope. In addition, S (%) is a slope constant for different combinations of land use and soil type. The objective of this study is to develop a CN map for the Asir region using GIS for the estimation of the runoff depth and the effect of the slope on the CN values and the generation of runoff.

Methodology and data analysis

Study area and data collection

The Asir region (Fig. 1; latitude 19° N and longitude 43° E) is situated on a high plateau that receives more rainfall than the
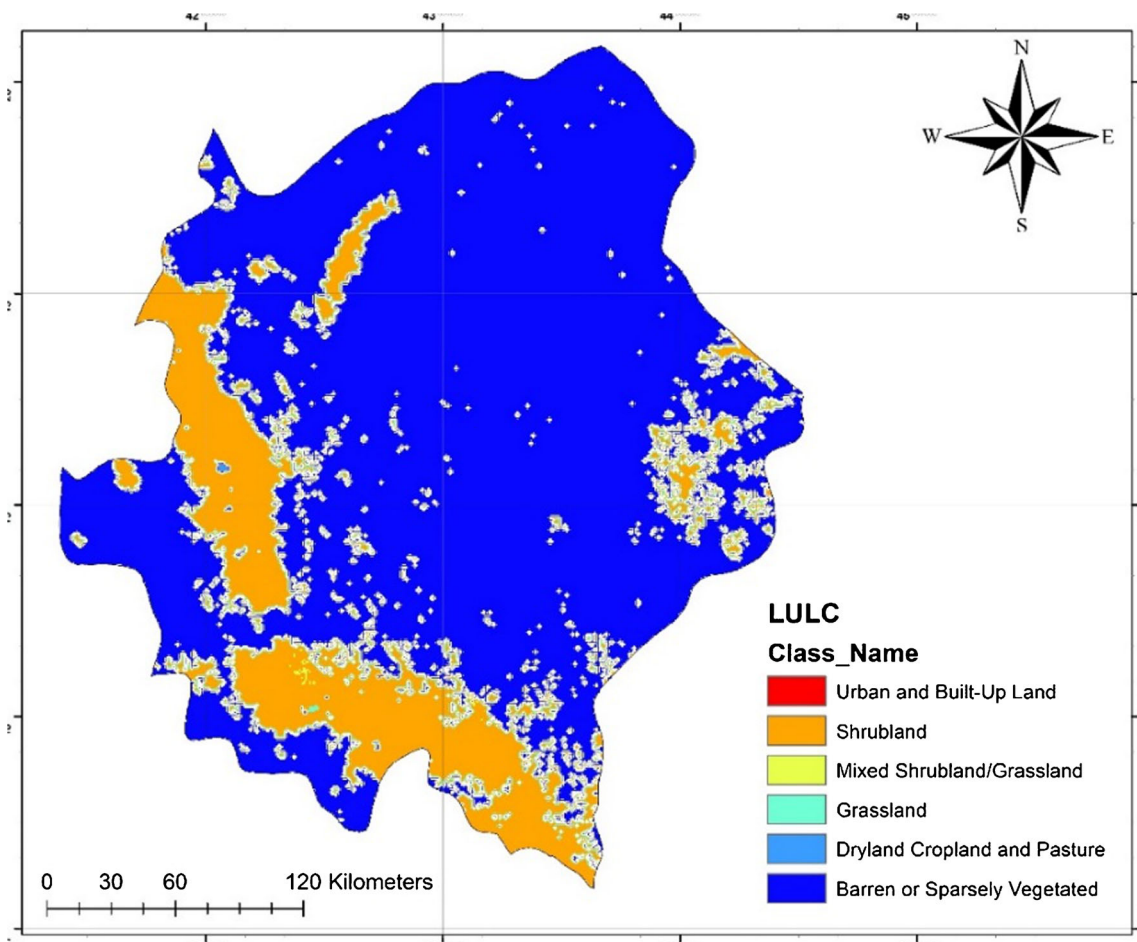

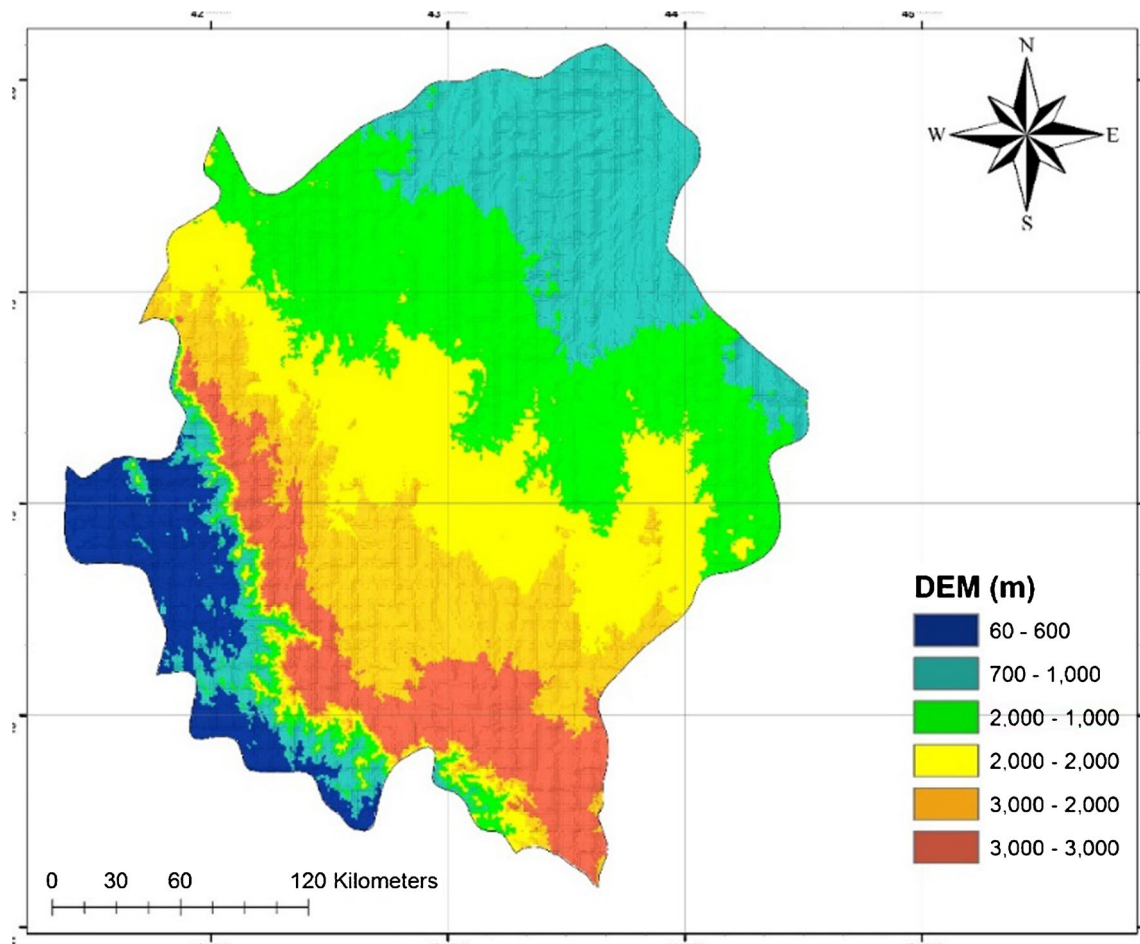Fig. 4 Land cover map for the study area

Fig. 5 DEM for the study area (KACST 2011)

rest of Saudi Arabia and contains the country's highest peaks, which rise to almost 3000 m at Jebel Sawdah near Abha; the Asir region occupies an area of 78,162 km^2. Although the data are exceedingly sparse and unreliable, the average annual rainfall in the highlands probably ranges from 300 to 500 mm (12 to 20 in) falling mostly in two rainy seasons; the chief rainy season occurs in March and April, with some rain falling in the summer. The dramatic increase in elevation in the Asir Mountains influences the amount and geographical distribution of rainfall in the region. The eastern side of the escarpment receives less annual rainfall than the western side because the latter steeply increases and enhances the air circulation of the westerly and northwesterly winds that carry moisture from the Red Sea (Alyamani and Sen 1993; Abdullah and Al-Mazroui 1998; Subyani 1999; Hutjes et al. 2005; Subyani and Al-Dakheel 2009; Al-Ahmadi and Al-Ahmadi 2014). The temperatures are very extreme; the diurnal temperature ranges in the highlands are the greatest in the world. It is common for afternoon temperatures to exceed 30 °C (85 °F), yet the mornings can be extremely frosty and fog can cut visibility to near zero. As a result, there is much more natural vegetation in Asir

than in any other part of Saudi Arabia, with sheltered areas even containing areas of dense coniferous forest, although the more-exposed ridges are still very dry.

The materials and software used in the implementation of this study included the family raster software of ArcGIS (MAP family, Erdas) and remote sensing data. The data collection for the study area included a soil texture map, digital elevation model (DEM), ground truth points for land cover generation, remote sensing data for the Asir region, Landsat satellite images (from 2000), and global positioning system (GPS) ground truth points.

Soil texture

The soil map was developed for the study area using GPS data with the support of soil experts to identify the soil textures at the site. The GPS points for soil texture covering the entire area during the field survey were imported into ArcGIS to develop a soil texture map for the Asir region (Fig. 2). The soil map was classified into three soil textures: loam, loam sand, and silt loam. Loamy soil has a moderate infiltration rate
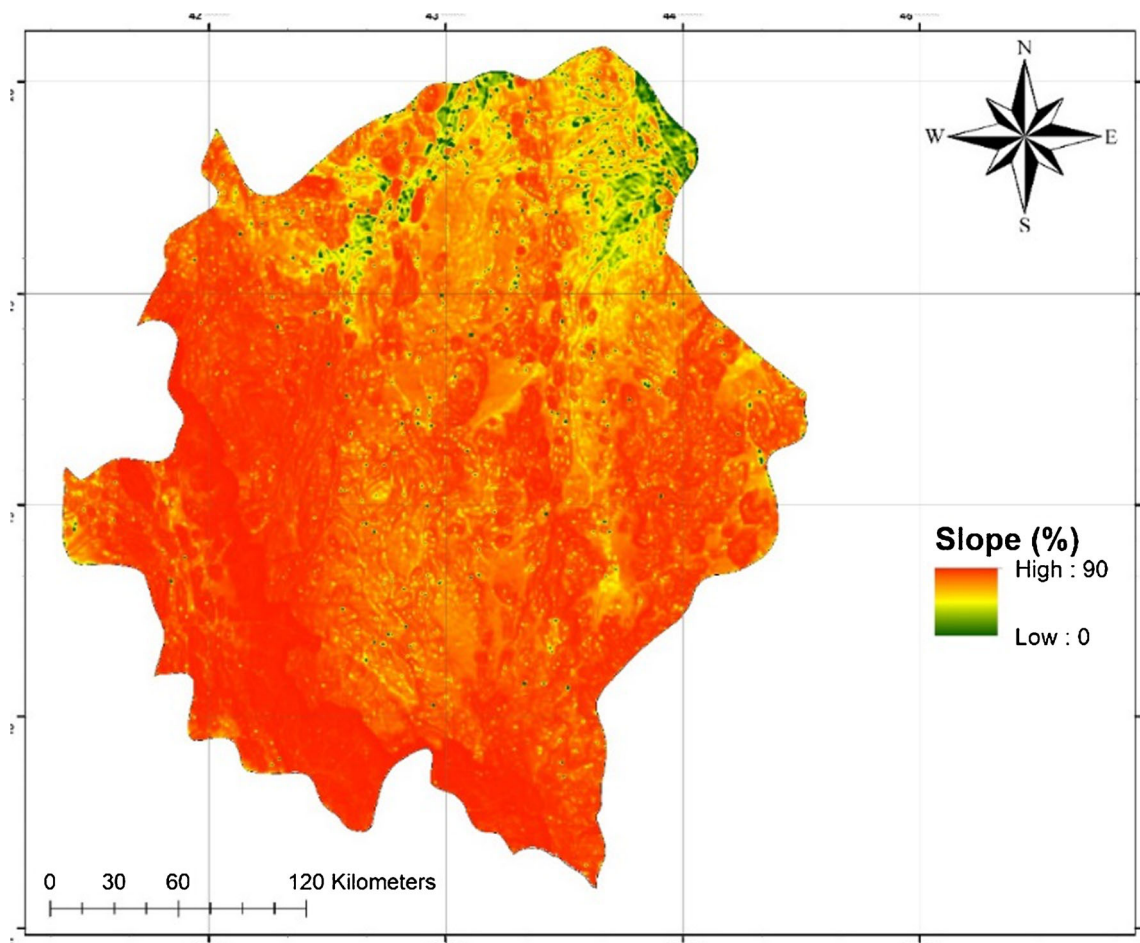
Fig. 6 Slope map for the study area

when thoroughly wetted and is classified as having mainly or moderately deep infiltration and moderately drained to well-drained soils with moderately fine to moderately coarse textures. The boundaries of different soil textures were digitized in ARC/INFO and polygons representing various soil classes were assigned different colors for recognition. The hydrologic soil groups, i.e., A, B, C, and D, were considered for the classification of soils in the study area (Table 1). The soils of group A had low runoff potential and a high infiltration rate, and the soils of group B had a moderate infiltration rate and

were moderately well drained to well drained. The soils of group C had moderately fine to moderately coarse textures and a moderate rate of water transmission, and the soils of group D had slow infiltration and high runoff potential.

Land cover

Landsat 5/7 TM/ETM images were obtained in 2010 from the King Abdellaziz City for Science and Technology (KACST). The ground resolution for these images was 15 m. Landsat TM records data in seven bandwidths, which are broken down into portions of the visible, infrared, and thermal infrared regions of the electromagnetic spectrum. From these various bandwidths, a great deal of information about the land cover can be displayed and analyzed (Fig. 3). The final approach involved the use of several different band ratios and different techniques of supervised and unsupervised classification.

Unsupervised and supervised classification of the image was performed using ArcGIS 9.3 and the ground validation points collected during field surveys covering the entire area. The results revealed six main classes: barren or sparsely

Table 2 Distribution of land cover in the study area

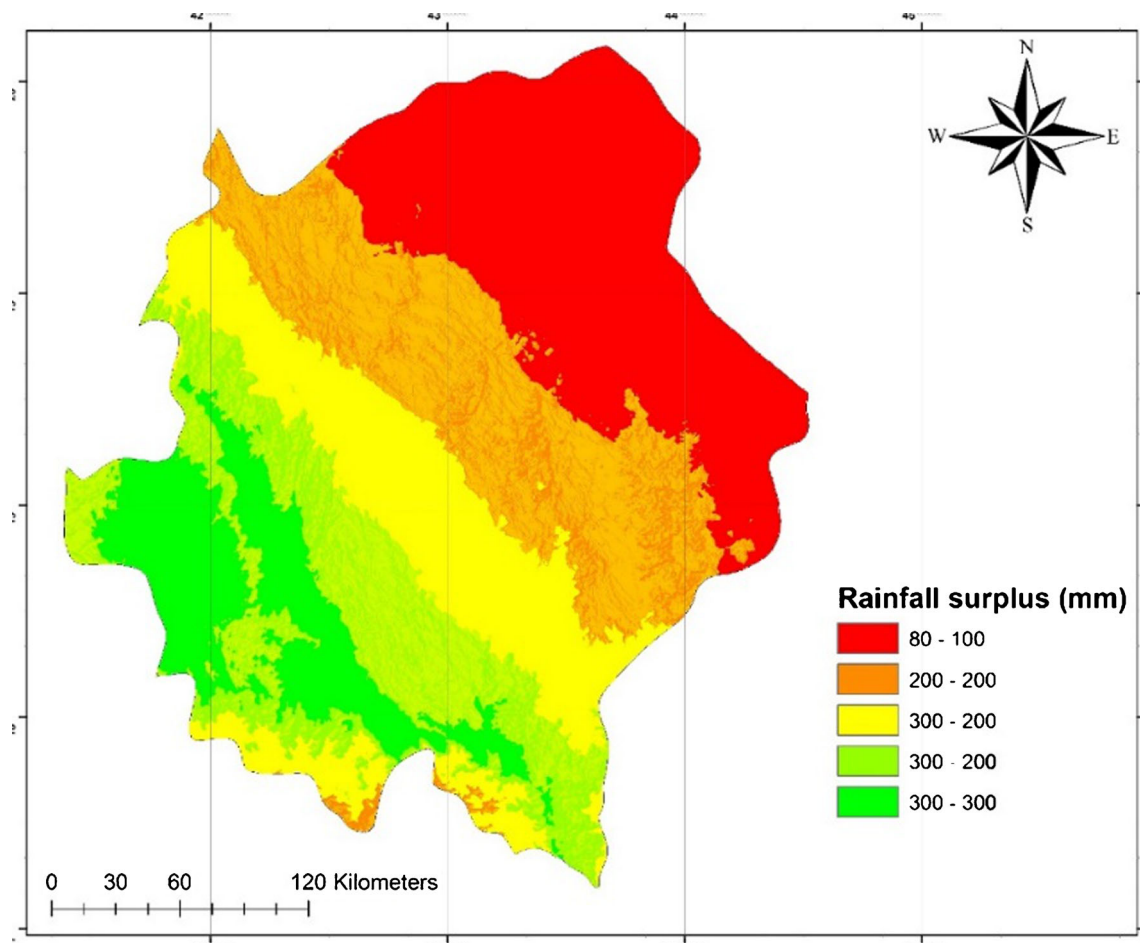| Class	Area (km^2)
Barren or sparsely vegetated	62,832.4
Dry land cropland and pasture	52.34
Grassland	12.27
Mixed shrubland/grassland	40.89
Shrubland	15,212.7
Urban and built-up land	11.45

Fig. 7 Annual rainfall in the Asir region

vegetated, dry cropland and pasture, grassland, mixed shrubland/grassland, shrubland, and urban and built-up land. The resulting classified land cover map for the study area is shown in Fig. 4.

There is much more natural vegetation in the Asir region than in any other part of Saudi Arabia. Even the sheltered areas contain areas of dense coniferous forest, although the more-exposed ridges are still very dry. Asir is home to many farmers who chiefly grow wheat and fruit crops, although irrigation has greatly expanded production in modern times.

Digital elevation model

A DEM is a digital representation of ground surface topography or terrain. A DEM can be represented as a raster or as an irregular triangular network. DEMs are commonly constructed with the use of remote sensing techniques; however, they may also be built from land surveys. In this study, a 15-m DEM was obtained from KACST (Fig. 5). The fill sink function was used to fill the sinks in a grid. The DEM was used

later to generate the slope map for the study, as shown in Fig. 6.

Annual rainfall

To determine the area-weighted rainfall for each station within the study area using the Theissen polygon method, straight lines were plotted to connect each station with several of the nearest stations, forming a series of triangles. Perpendicular bisectors were erected on each of these lines and extended to intersect with other bisectors, thus forming a series of irregular polygons. An estimation for each station polygon was then done by counting the grid squares (points) for the polygons formed by the bisecting lines and multiplying them by the cosine of the latitude, because at a higher latitude, each grid corresponds to a smaller area. The area of each station was calculated by summing the grids in that particular polygon. The station weights were calculated by dividing the station area by the total study area. The sum of all of the station weights thus was 1. Similar procedures were adopted for the calculation of station weights for the whole polygons. The
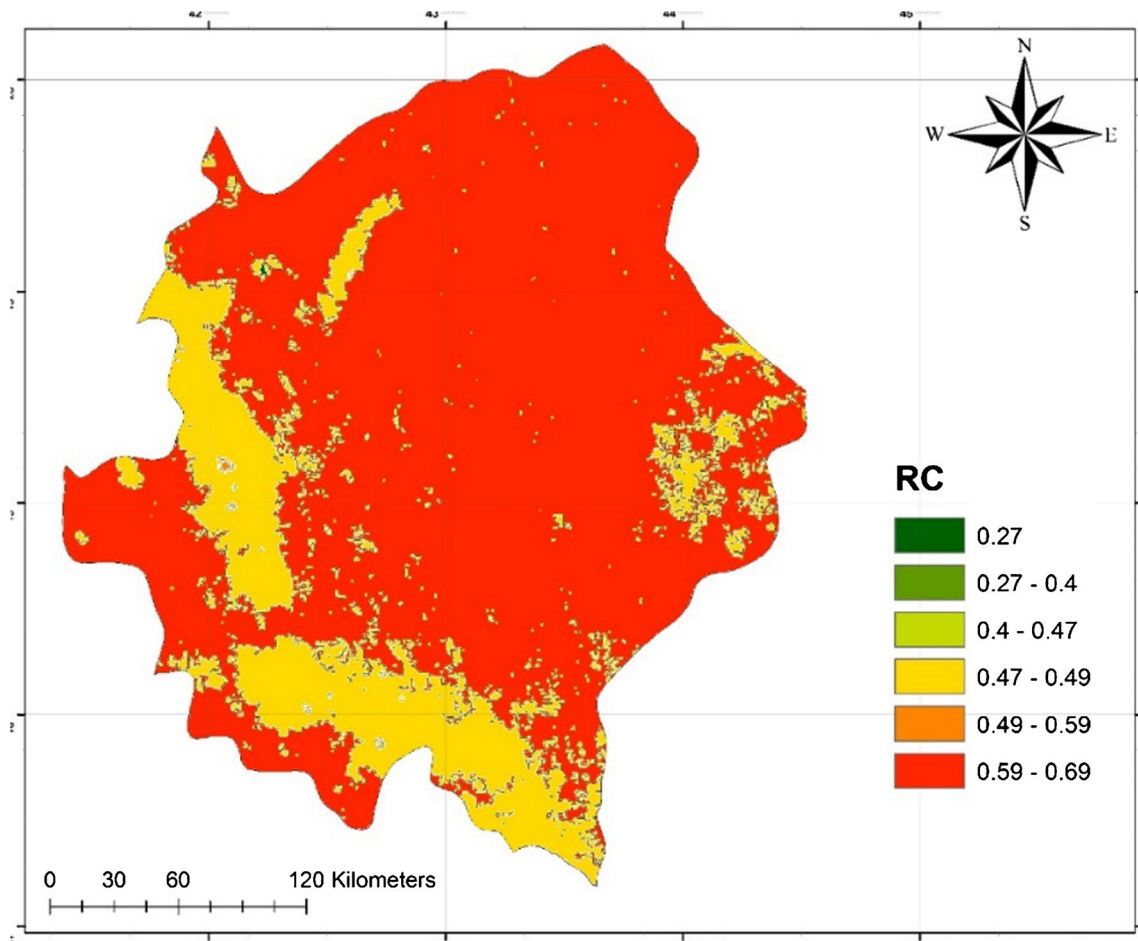
Fig. 8 CN for the Asir region

Results and discussion

area-weighted rainfall for each station was determined by multiplying its area factor and the rainfall amount recorded at the station.

The US Department of Agriculture, Natural Resources Conservation Service Curve Number (USDA-NRCS-CN) method was used in this study for determining the curve number and runoff depth. Runoff curve number was determined based on the factors of hydrologic soil group, land use and land cover, and slope gradient. Land cover mapping for the study area was performed with unsupervised and supervised classification techniques. The land cover distribution in the study area (Table 2) revealed that barren and sparsely vegetated land was the largest class, occupying 62,832.38 km^2 (more than 80 % of the total area), followed by shrubland (15,212.66 km^2), cropland and pasture (52.34 km^2), mixed shrubland/grassland (40.89 km^2), and grassland (12.27 km^2). Built-up land occupied only 11.45 km^2. Mixed shrubland/grassland areas tend to produce more runoff than non-shrubland/grassland area as found in this study.

The annual rainfall in the study area (Fig. 7) shows that the mean annual rainfall of the Asir region is 198 mm, whereas the mean area-weighted rainfall series developed by this study was 150 mm per year. The slight difference between the mean values of the two series was due to the consideration of some stations located in high mountain regions. The variation of rainfall in the study area, as shown in Fig. 7, varied from 80 to 300 mm per year toward the north and southwestern portions. There is a significant effect of ground elevation on the mean annual rainfall in Asir region. Where, the largest amount of mean annual rainfall occurs during spring, when rainfall displays a significant relationship with topographic factors. Moreover, this finding agrees with Al-Ahmadi and Al-Ahmadi (2014).

To create the CN map, the hydrologic soil group and land use maps were developed in ArcGIS. The hydrologic soil grouped on the soil theme and the land use were selected for intersection. After intersection, a map with new polygons
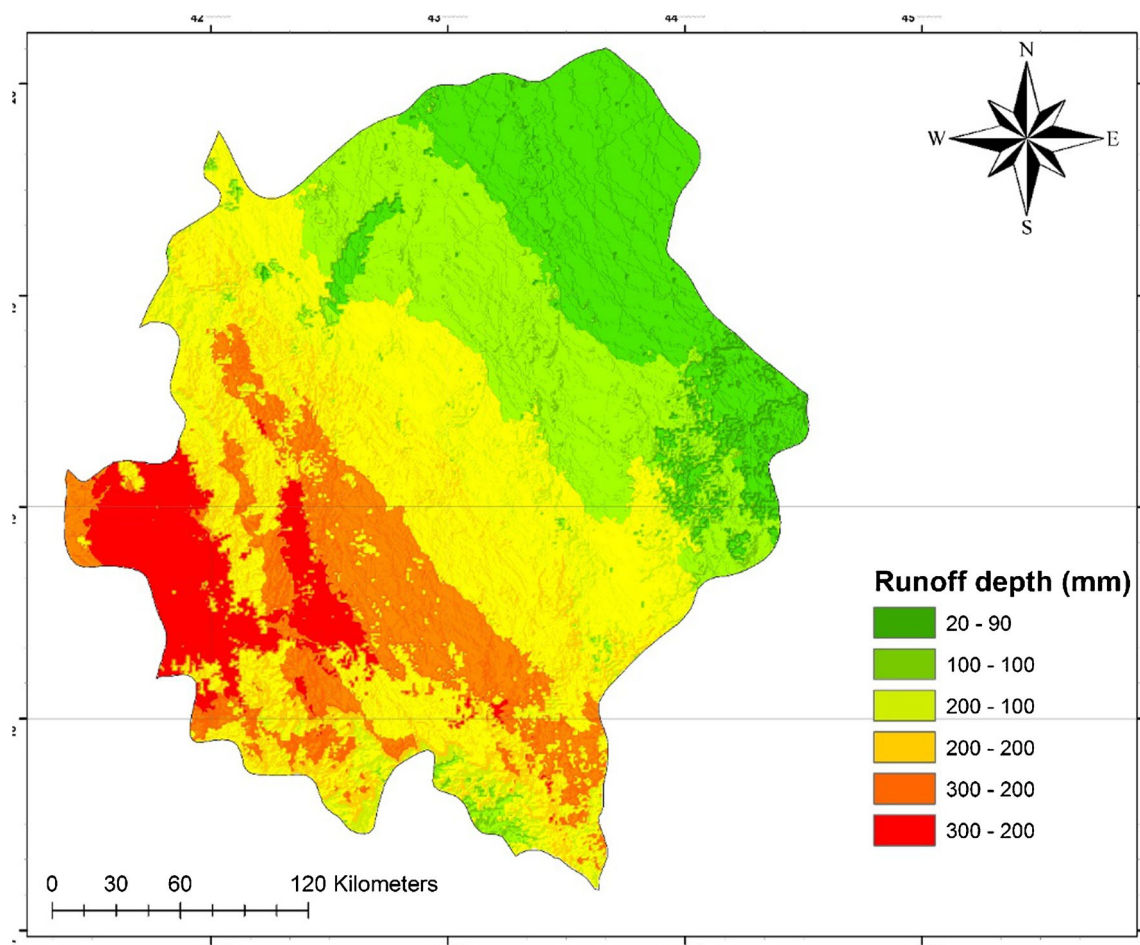
Fig. 9 Annual runoff depth

representing the merged soil hydrologic group and land use (soil-land map) was generated. The appropriate CN value for each polygon of the soil-land map was assigned on the basis of the approach developed by Mahmoud et al. (2014b). The CN for the Asir region varied from 0.27 to 0.69, as shown in Fig. 8.

The estimated runoff depths were used to generate runoff depths for all annual rainfall. In hydrology, the CN is used to determine how much rainfall infiltrates into the soil or an aquifer and how much rainfall becomes surface runoff. A high CN means a high degree of runoff and a low degree of infiltration (urban areas), whereas a low CN means a low degree of runoff and a high degree of infiltration (dry soil). The CN is a function of land use and the hydrologic soil group. The SCS-CN method is the most common method for the prediction of storm runoff volume. Many watershed models such as AGNPS (Young et al. 1987a, b; Arnold et al. 1996) and WMS (http://www.ems-i. com/WMS/WMS_Overview/wms_overview.html) use this method to determine runoff. Sediment and nutrient transport are then calculated on the basis of the runoff. Some applications of this method with watershed models in Kansas have been reported (Bhuyan et al. 2002).

The annual runoff depth (Fig. 8) was derived for this study as opposed to the event CN for annual rainfall, because establishment of the runoff amount available for agricultural production by this method takes into account rainfall events that do not significantly contribute to any runoff. The annual runoff depth was derived from the annual rainfall surplus and CN per pixel using the raster calculator tool in ArcGIS, which gave an indication of the percentage rainfall that was transformed to runoff. In addition, the results confirm the findings obtained by Merz et al. (2006) that the spatial distribution of runoff coefficients is highly correlated with mean annual precipitation but little correlated with soil type and land use.

The spatial distributions of the modeled annual runoff depth in millimeters are shown in Fig. 9. A variation from as low as 20 mm into a maximum of 300 mm was observed due to the divergence in the topography and climate of the study area. The greatest rainfall was observed in the mountainous area. Where the steep western slopes (windward side) receive more rainfall than the gentle eastern slopes (leeward side): this may be due to the Asir Mountains forcing moist air masses carried by the westerly and northwest winds to rise and cool
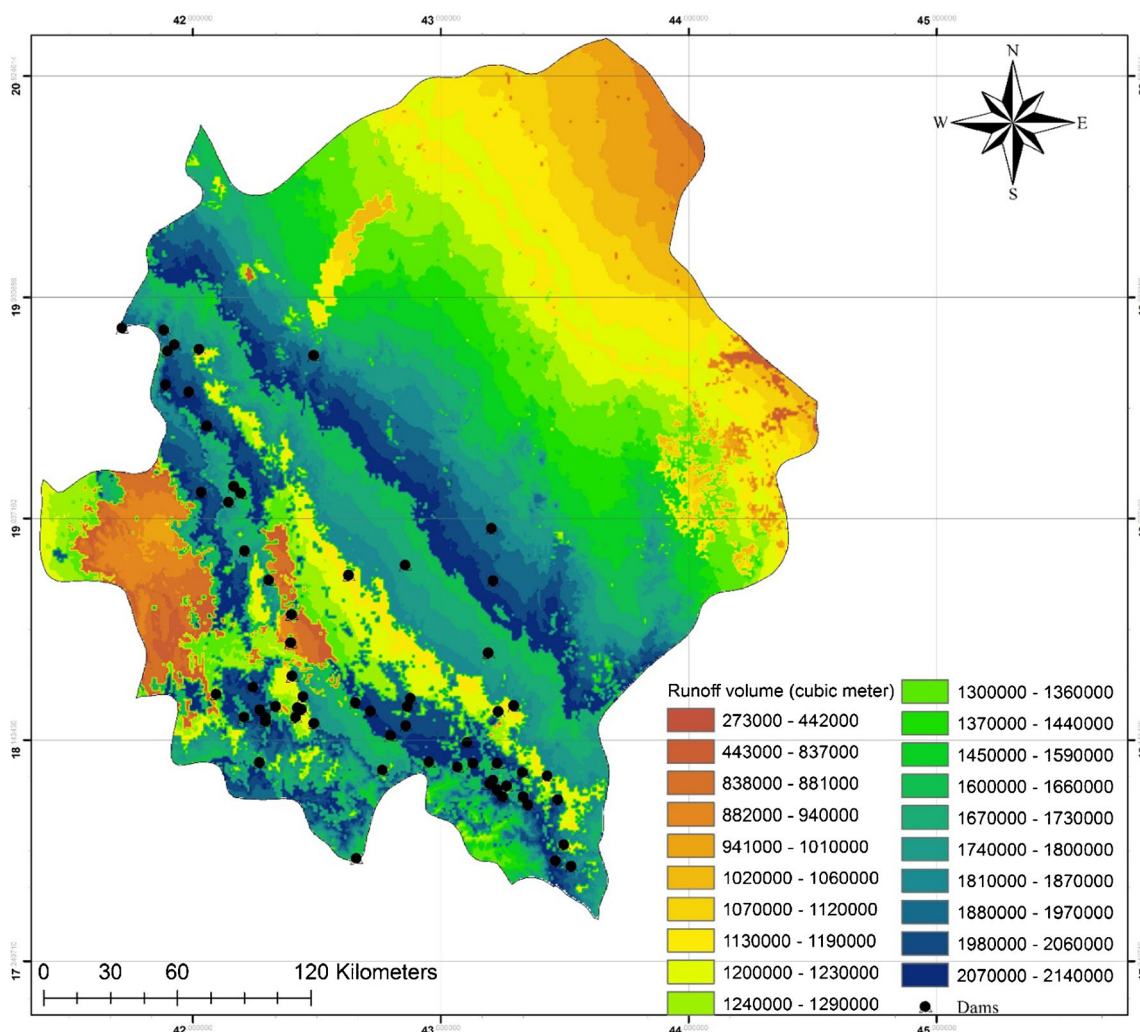
Fig. 10 Runoff volume (m³) in the Asir region with locations of dams

before they descend and warm on the leeward side (Al-Ahmadi and Al-Ahmadi 2014).

As noted during the field survey, the mountainous area is exposed to the formation of clouds and fog, which often occurs in winter due to air masses coming from the Red Sea. The mountainous area also has the greatest runoff depth due to its soil type, land cover conditions, and steep slope. The CN, which is the ratio of the modeled runoff depth to the annual rainfall, showed wide variation over the study area, ranging from 0.27 to 0.69 (69 %).

Due to the limited water resources and increases in the potentially cultivated area in the Asir region and other agricultural regions in Saudi Arabia, it is necessary to develop an alternative, supplementary water source for potable and agricultural uses. The harvest of rainwater runoff is one of the most important ways to make each drop of water count; it is worth the effort to collect rainwater. In addition to its application in water resources planning, groundwater is crucial in Saudi Arabia due to the shortage of high-quality subsurface

water and the increasing need for water for domestic, agricultural, and industrial uses. It has become crucial not only to target potential groundwater zones but also to monitor and conserve this important resource. In addition to targeting potential groundwater zones, it is also important to identify suitable sites for artificial recharge. When the natural recharge rate cannot meet the demand for water, the balance is disturbed. Calls have therefore been made throughout the country for artificial recharge.

The field survey identified 65 dams in the study areas. These dams vary in their capacity and in the purpose of their constriction. Some are used for groundwater recharge, but most are used for rainwater harvesting and agriculture purposes. The runoff volume was calculated for the entire region using the previously developed runoff depth map and basin areas. The results showed that the runoff volume (m³) in the Asir region varied from as low as 237,000 m³ to a maximum of 2,140,000 m³, a significant amount of runoff that can be harvested yearly for any use. The calculated runoff depth of

the area agreed with the actual dam capacities for the existing dams in the Asir region. Ninety percent of these dams lie in the areas with the highest rainfall and in the areas with the maximum runoff volume, as seen in Fig. 10. Consequently, the risk of flash flood occurrence in areas having a high curve number is very high due to the high potential to transform most of the rainfall into surface runoff.

The analysis of rainfall runoff modeling in the area shows that the Asir region has the highest rainfall in Saudi Arabia. In addition, a huge amount of runoff depth and volume is generated in the area due to its topography on a high plateau. More dams can be constructed in areas with large runoff volumes to allow the benefits of these conditions to be gained. Rainfall plays an important role in the water balance in the Asir region as its only source of surface water. During the past 20 years, rainfall has increased the groundwater budget through groundwater recharge, which has allowed farmers to increase the size of their farms and increase the variety of crops grown in the region.

The results of this work will assist planners in the management of rainwater in similar arid regions. A feasibility study will be conducted for various techniques used in harvesting rainwater to identify site-specific mechanisms that augment groundwater recharge from catchment areas, such as the construction of small dams, bounds, soil pits, recharge wells, and tanks, targeting partial or whole regions of Saudi Arabia as a pilot study. Capturing rainwater runoff may increase water availability and reduce water demand.

Conclusions

Runoff coefficients are widely used as a diagnostic variable of runoff generation in process studies and as an important input parameter in hydrologic design. Many regions of Saudi Arabia and of developing countries do not have sufficient historical records and the detailed runoff information needed for physically based distribution models. In these cases, this study can provide a better solution for flood management programs. The results of the spatial distributions of the modeled annual runoff depth show a variation in annual rainfall from as low as 20 mm to a maximum of 300 mm due to the varied topography and climate in the study area, where the greatest rainfall is observed in the mountainous area. As noticed during the field survey, the mountainous area is exposed to the formation of clouds and fog, which often happens in winter due to air masses coming from the Red Sea.

The great spatial variability in the mean runoff coefficient, which ranges from 0.27 to 0.69, is relatively well-explained by the mean annual precipitation. The runoff coefficients tend to increase with the mean annual precipitation. The significance of this relationship means that the mean annual precipitation influences the distribution of runoff coefficients not

only through the characteristics of the flood-generating storm events but also by controlling the variability of the initial conditions and, in longer time scales, likely by controlling the geomorphological structure of catchments through the processes of soil formation and erosion. The mountainous area also has the largest runoff depth due to its soil type, land cover conditions, and steep slope. The CN, which is the ratio of the modeled runoff depth to the annual rainfall, shows wide variation over the study area, ranging from 0.27 to 0.69 (69 %).

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