Journal of Geoscience and Environment Protection, 2023, 11, 30-43
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

SCS-CN and GIS-Based Approach for Estimating Runoff in Western Region of Saudi Arabia

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How to cite this paper: Alataway, A. (2023). SCS-CN and GIS-Based Approach for Estimating Runoff in Western Region of Saudi Arabia. *Journal of Geoscience and Environment Protection, 11,* 30-43.
https://doi.org/10.4236/gep.2023.113003

Received: February 18, 2023
Accepted: March 12, 2023
Published: March 15, 2023

Abstract

Designing reservoir operations, hydraulic structure, and soil erosion management techniques all require an estimation of a potential runoff. Accurate runoff in-formation is typically scarce in Saudi Arabia—a significant challenge for hydrologists. Wadi-Rahjan catchment in Western Saudi Arabia has been taken as a case study to determine the potential runoff estimates. The study integrates the soil conservation service curve number (SCN-CN) technique, remote sensing (RS), and geographical information system (GIS). Critical parameters including the digital elevation model (DEM), land use/land cover (LULC), hydrologic soil groups (HSGs), and rainfall data were also employed. The curve number (CN), which shows the catchment's reaction to a storm was estimated based on LULC and HSG layers. The CN map obtained and rainfall data were employed in the GIS-based SCS-CN model to develop the potential runoff map. Based on the results of calculations, the study area is classified into three HSGs, namely, B, C, D. Averagely, CN for a normal condition is 90 while wet and dry conditions are 97 and 80, respectively. Results obtained from the SCS-CN method's calculations reveal a yearly runoff result that varies from 194 mm to 295 mm. A higher percentage of runoff water (35%) in a runoff range from 289 to 295 mm, followed by 24%, ranged 269 to 288 mm. An interesting rainfall-runoff regression evaluation reveals a good 0.90 correlation. Other watersheds in Saudi Arabia may use this method for planning and development.

Keywords

Runoff, SCS-CN, GIS, Remote Sensing

1. Introduction

For sustainable water resources development and flood risk and drought control, rainfall-runoff modeling has become a necessity. Precipitation and surface runoff are the most important hydrological indicators for assessing and mapping flash floods. In the absence of observed hydrological data in the research area, it is crucial to identify alternate modeling techniques for rainfall-runoff. Another major concern is the runoff loss towards the sea and deserts without fair use and mobilization. Worse, too often, hydrological studies lack records of runoffs from a watershed. The geographical information system (GIS)-based soil conservation service curve number (SCN-CN) method comes in handy to resolve this issue (Geena & Ballukraya, 2011; Shrestha, 2003).

Verifying direct runoff estimates without records has been successful with the SCS-CN method, a method developed by hydrologists at the US Department of Agriculture (Pradhan et al., 2010; Shadeed & Almasri, 2010; USDA, 1972). The SCS-CN technique uses the Curve Number (CN). This CN requires essential measures, converted into numerical values incorporated into the established approach to determining the direct watershed runoff (Taher, 2015). Low CN means low runoff and high infiltration. Conversely, high CN represents high runoff and low infiltration. Land use/land cover, rainfall, and soil data are typical runoff-related watershed characteristics that affect the SCS-CN method (Hawkins et al., 2008; Huang et al., 2006; Shi et al., 2017).

Since the conventional SCS-CN technique is more time-demanding and tedious, combining GIS and SCS-CN technique aids spatial analysis (Shadeed & Almasri, 2010). Several researchers (Gupta & Panigrahy, 2008; Melesse & Shih, 2002; Pradhan et al., 2010) have obtained CN and runoff with the Remote Sensing (RS) and GIS technique. The researchers conclude that these approaches are flexible and popular and promote a faster, reliable, and relatively easier composite CN estimation and runoff for the watershed. Geena and Ballukraya (2011) built CN suitably designed for Indian conditions with GIS and SCN-CN method at Red Hills watershed. They posit that the spatial hydrological measures and temporary factors can be obtained using the GIS and RS tools. Nayak et al. (2012) in the Uri River watershed study reveal that in ungagged regions with inadequate hydrological data, combining SCN-CN and RS results in a more effective and faster runoff estimation. They report a useful link between observed and computed runoff data. Al-Ghobari et al. (2020) simulated surface runoff in Saudi Arabia's western region using the RS and GIS-based SCS-CN model. They reported that SCS-CN, in conjunction with RS and GIS, merited greater consideration in order to improve basin management and conservation. Shadeed and Almasri (2010) compared runoff measured data, and GIS-based SCN-CN predicted runoff, with 85% estimated method accuracy-sufficient for runoff estimation. Ningaraju et al. (2016) preferred the SCN-CN technique for the Haradya Milli watershed in Mandya, Karnataka. They reported a link between runoff estimation and rainfall for 11 years of datasets. Aldoma and Mohamed (2014) estimated rainfall-runoff for Sudanese' Khartoum state with the SCS-CN method and reported that the SCS-CN method may help estimate runoff. Tirkey et al. (2013) developed a runoff estimate for Jharkhand in India, showing that the

SCS-CN method resulted in higher accuracy of runoff estimates. Liu and Li (2008) used the SCS-CN method for runoff estimates during a flooding season from a small watershed in Loess Plateau, China. They found the legitimacy of the SCS-CN technique and its potency in stimulating runoff estimation of small watersheds. For the design of such hydraulic structures, like a small dam and soil erosion management, discharge values from such ungauged catchments are required, necessitating the use of particular analytical approaches to estimate these values. In light of the aforementioned, and given that there are fewer records of surface runoff than of rainfall in Saudi Arabia, this study attempted to estimate runoff using the SCS-CN approach coupled with GIS for the Wadi-Rahjan catchment in Saudi Arabia's western region.

2. Materials and Methods

2.1. Study Area

Wadi-Rahjan catchment of Western Saudi Arabia is the study area (**Figure 1**). Geographically, the catchment is located within latitude ranges of 21˚11'0"N to 21˚20'0"N and longitude of 40˚2'0"E to 40˚12'0"E. The catchment area accounts for about 157 km^2 with 359 to 2021 elevation above mean sea level. Physiographically, Wadi-Rahjan consists of hills, urban masses, and barren areas. The climate is semi-arid with an extensive hot summer season and a short winter characterized by rainfalls. Annually, the average temperature and precipitation are shown in **Figure 2** and **Figure 3**.

2.2. Data and Methodology

Figure 4 shows a flowchart of the methodology used to estimate runoff with the soil conservation service curve number (SCN-CN) method, remote sensing (RS), and geographic information system (GIS). The land use/land cover (LULC), digital

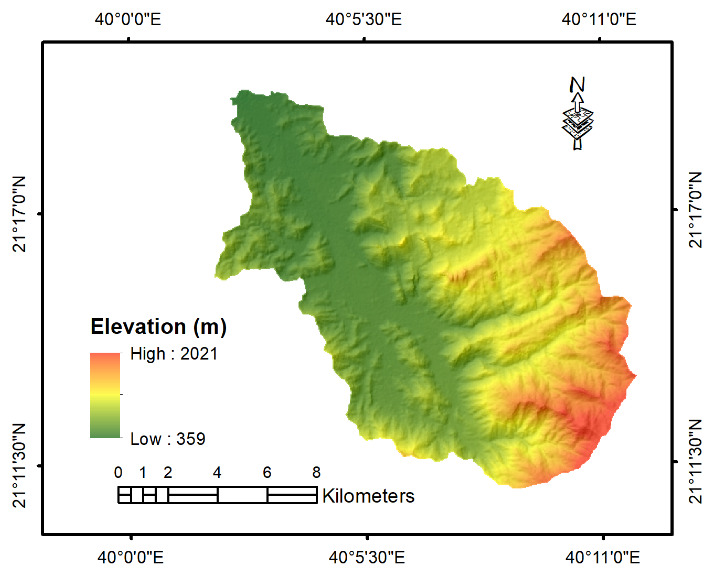

Figure 1. Wadi-Rahjan catchment in the western region of Saudi Arabia.

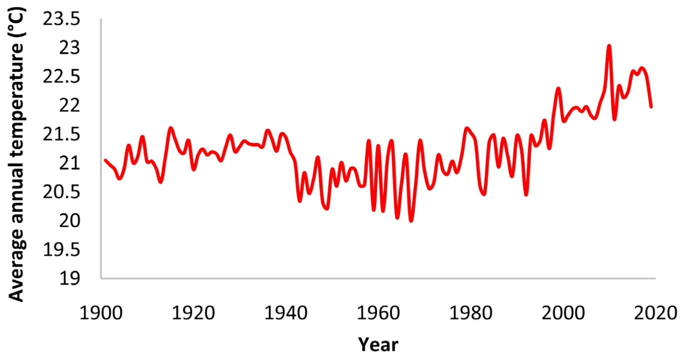

Figure 2. The average annual temperature within the study area.

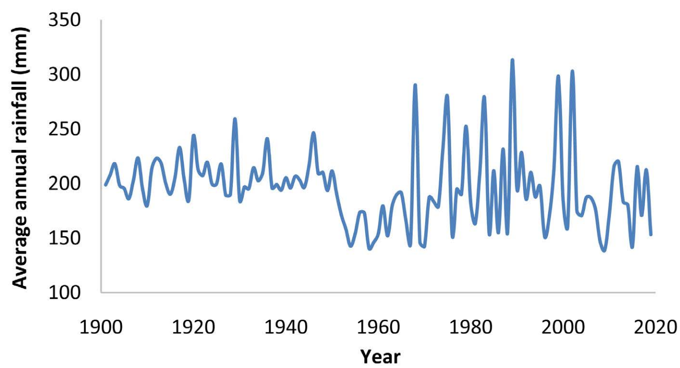

Figure 3. The average annual precipitation within the study area.

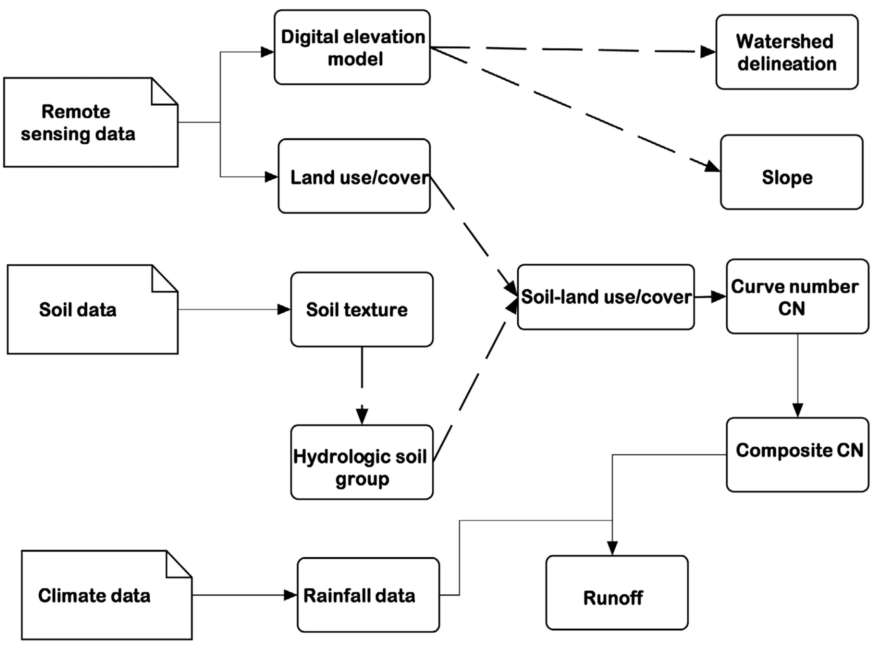

Figure 4. A flow chart demonstrating the process used to calculate runoff.

elevation model (DEM), and soil texture maps were obtained from easily accessible RS data and processed with the ArcGIS 10.3 software. The United States' Geological Survey's Dem data with a 30-m resolution was employed to outline the Wadi-Rahjan area using the ArcGIS 10.3 (Figure 5). It also produced a slope map (Figure 6). The LULC map was developed with the Landsat ETM+ satellite imagery, downloaded from the US Geological Survey's website. The climatic research unit (CRU) supplied the rainfall data with 1900 to 2019 records. The study's soil data was obtained from Saudi's main soil map, ministry of environment, water and agriculture.

2.3. Soil Map

Soil The texture of the soil indicates the percentage of sand, silt, and clay particles within a given area (Saxton et al., 1986). Studying the soil water relation

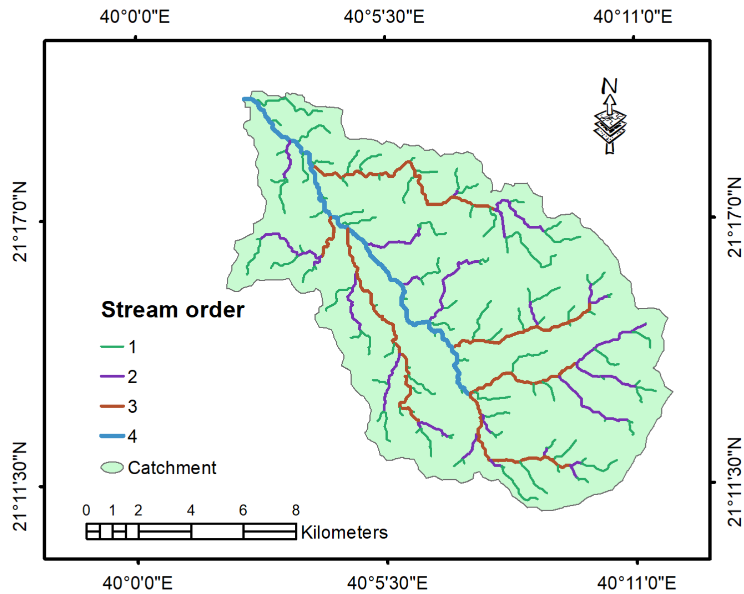

Figure 5. Delineation of Wadi-Rahjan catchment map.

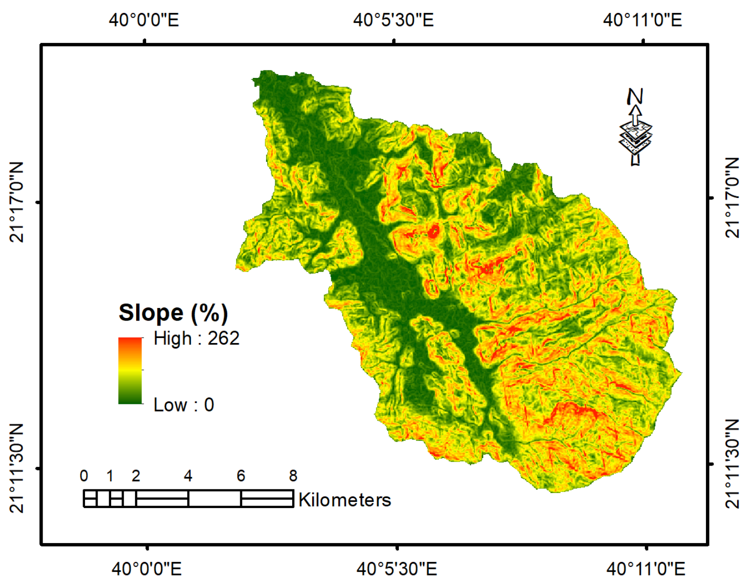

Figure 6. Slope map of the study area.

and soil hydraulic properties is important when attempting to understand the soil-water relationship (Cosby et al., 1984; Saxton et al., 1986). For soil data to be utilized in the SCS-CN model, the natural resource conservation service (NRCS) categorized soils according to their hydrologic soil groups (HSGs) into four separate soil categories: A, B, C, and D, which are respectively graded according to their capacity for infiltrating water and rate of water transmission through the soil (NRCS, 2009) (**Table 1**). HSG-A represents high permeability with low runoff potential. HSG-D, on the other hand, implies a very shallow or high clay content with high runoff potential. HSG-B and HSG-C are intermediate classes (NRCS, 2009; Sekar & Randhir, 2007).

2.4. Land Use/Land Cover

A significant thematic input in the study analysis is LULC. It specifies the current state of land use and pattern (Bhange & Deshmukh, 2018). As LULC shifts rapidly, remote sensing satellite mapping is used widely (Bhange & Deshmukh, 2018). LULC is a frequently used method for estimating the influence of watershed cover on infiltration and runoff, and it includes most types of natural vegetation, terraced bare soil, and rocks (Taher, 2015). The Landsat ETM+ satellite imagery with a resolution of 30 m was used for the investigation. The LULC for the research region was obtained using supervised classification in the ERDAS Imagine program. Further real field land use data were used to support the supervised classification.

2.5. Curve Number Method

The United States' Department of Agriculture's SCS initiated the SCS-CN, specifically for rural areas (Mishra & Singh, 2003; USDA, 1972). The SCS-CN technique is based on the link between rainfall and runoff depth under the curve number (CN) concept. CN helps convert the rainfall frequency distribution into a runoff frequency distribution. The CN has no dimension and is defined as $1 \leq CN \leq 100$. Low CNs denote dry antecedent soil moisture conditions (AMCI), whereas average CNs denote a normal condition (AMCII), and high CNs denote a wet soil condition (AMCIII). Normal condition CN can be changed to wet and dry conditions through the Equation (1) and Equation (2) shown below (Hawkins et al., 1985):

Table 1. The natural resource conservation service classification.

Hydrologic Soil Group	Soil Textures	Runoff Potential	Water Transmission	Infiltration (mm/hr)
A	"Sand, loamy sand or sandy loam"	"Low"	"High rate"	>7.62
B	"Silt loam or loam"	"Moderate"	"Moderate rate"	3.81 - 7.62
C	"Sandy clay loam"	"Moderate"	"Low rate"	1.27 - 3.81
D	"Clay loam, silty clay loam, sandy clay, silty clay, clay"	"High"	"Very low rate"	<1.27

$$\mathrm{CN_I} = \frac{4.2 \times \mathrm{CN_{II}}}{10 - (0.058 \times \mathrm{CN_{II}})} \quad (1)$$

$$\mathrm{CN_{III}} = \frac{23 \times \mathrm{CN_{II}}}{10 + (0.13 \times \mathrm{CN_{II}})} \quad (2)$$

where $\mathrm{CN_I}$ is a CN applied for dry conditions, $\mathrm{CN_{II}}$ is a CN applied for normal conditions, and $\mathrm{CN_{III}}$ is a CN applied for wet conditions. The range of AMC for each class is listed in **Table 2**. The composite CN ($\mathrm{CN_c}$) can be used to estimate direct runoff in a catchment that consists of several soil types and land use using Equation (3) (Hawkins et al., 1985):

$$\mathrm{CN_c} = \sum_{i=1}^{n} \frac{\mathrm{CN}_i \times A_i}{A} \quad (3)$$

where CN_i is the CN value of the sub-region, A_i is the area of the sub-region, and A is the catchment area.

2.6. Direct Runoff Depth

The SCS-CN model developed by the USDA (USDA, 1972) is responsible for many challenges associated with runoff generation, incorporating them under the CN parameter (Soulis & Valiantzas, 2012). CN captures the potentiality of runoff as regards LULC, HSG, and rainfall. Using the SCS-CN technique, the runoff Equation (4) is obtained as follows:

$$Q = \begin{cases} \dfrac{(P - \lambda S)^2}{P + (1-\lambda)S} & P > \lambda S \\ 0 & P \le \lambda S \end{cases} \quad (4)$$

where Q is the direct runoff depth (mm), P is rainfall depth (mm), S is potential maximum retention after runoff begins (mm), and λ is surface runoff abstraction (dimensionless). Many studies on various geographical regions in various nations have shown that the values of λ are between 0.1 and 0.3 (Shrestha, 2003). Studying the West Bank attachment, Shadeed and Almasri (2010) suggested λ = 0.2. Shrestha (2003), in his sensitivity breakdown, uncovered that λ = 0.2 value is appropriate for mountainous agricultural lands, which have comparable features to the study location. Substituting λ = 0.2 in Equation (4), it becomes:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (5)$$

Table 2. AMC classification and the corresponding CN.

AMC	Curve Number	5-Days Antecedent Rainfall (mm)	
		Non-growing season	Growing season
I	$\mathrm{CN_I}$	<12.7	<35.6
II	$\mathrm{CN_{II}}$	12.7 - 27.9	35.6 - 53.3
III	$\mathrm{CN_{III}}$	>27.9	>53.3

When runoff starts, the potential maximum retention (S) is found from Equation (6):

$$S = \frac{25400}{CN} - 254 \tag{6}$$

3. Results and Discussion

3.1. Land Use/Land Cover

The catchment's LULC map was grouped into four categories: agriculture, urban, bare soil, and rocks (**Figure 7**). **Figure 7** shows the catchment area was predominantly rocky, followed by bare soils, urban masses, and agriculture, respectively. Both rocky and bare soils are most dominant, encompassing 62% (98 km^2) and 35% (55 km^2), respectively. Urban masses cover 2% area (about 2.5 km^2) found in the central part of the catchment area. For agricultural areas, they have barely 1% (1.5 km^2) of the catchment area. According to Zhao et al. (2004), a good relationship between vegetation cover and runoff, where a high runoff was traced to deforestation and urbanization. The study featured a similar trend, which established a strong link between rainfall and runoff due to low vegetation cover.

3.2. Soil Map

Wadi-Rahjan has three soil textures, namely, sandy, loam, clay, and sandy clay loam. By soil categories and infiltration rates, the catchment area studied is grouped into three HSGs—Groups B, C, and D (**Figure 8**). HSG-D represents a clay soil region of about 35%, covering 56 km^2. This explains that a larger part of the study area is a good fit for water retention and runoff estimation. With about 25% dominance, the HSG-C has lesser land coverage. The C-class represents a

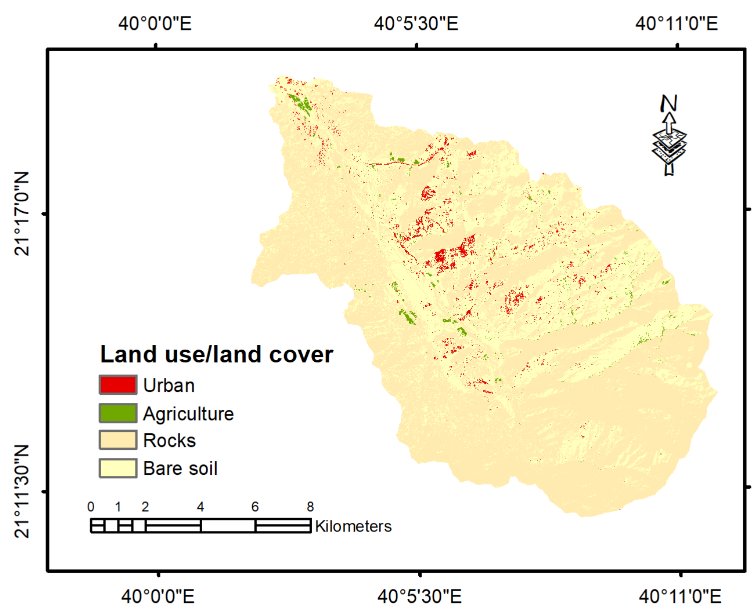

Figure 7. Land use/land cover map of the Wadi-Rahjan catchment.

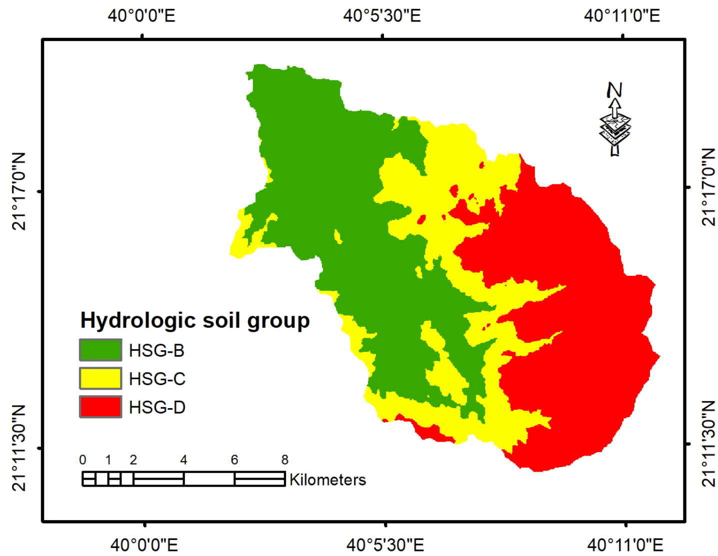

Figure 8. Hydrologic soil group map of the study area.

portion mixed with both clay and loam soils. HSG-B region accounts for about 40%, predominantly loamy soil texture. With the HSG portions, it's worth concluding that soil texture within the study area contributes to significant runoff.

3.3. CN Map

The CN_{II} values related to AMC-II were derived through cross-mapping the HSGs and LULC maps with the ArcGIS 10.3 software (**Figure 9**). The CN values obtained for CN_{I} and CN_{III} linked with AMC-I and AMC-III, respectively, were derived by Equation (1) and Equation (2), as shown in **Figure 10** and **Figure 11**. The 90 to 94 group is considered the highest CN_{II}, covering 59% (93 km^2), where between 74 and 80 CN group accounts for 1 km^2 of the entire study area recording less runoff. The CN category between 80 and 85 represents low-to-moderation runoff potential, covering 2 km^2, whereas the high-moderate runoff (CN class 85 to 90) accounts for 39% (about 61 km^2). These indicators point to the Wadi-Rahjan catchment's potency to record higher runoff for remarkably high CN values. A weighted CN (or CNc) was estimated, dividing the total CN value and related area by the total sub-catchment areas with Equation (3). As a result, the weighted CN_{I}, CN_{II}, and CN_{III} values were 80, 90, and 97, respectively.

3.4. Potential Maximum Retention Map

Potential maximum retention (S) is obtained in the ArcGIS 10.3 software with Equation (6), following the CN map. S value (**Figure 12**) falls between 16 to 89 mm. Within the catchment, the least S values are found in developed areas and rock with typical low retention capacity. Also, bare areas around municipalities had far less retention capacity caused by improper use. Agricultural regions record the largest values with their high retention capacity. Noteworthily, the catchment area is mostly dominated by the S range from 16 to 50 mm.

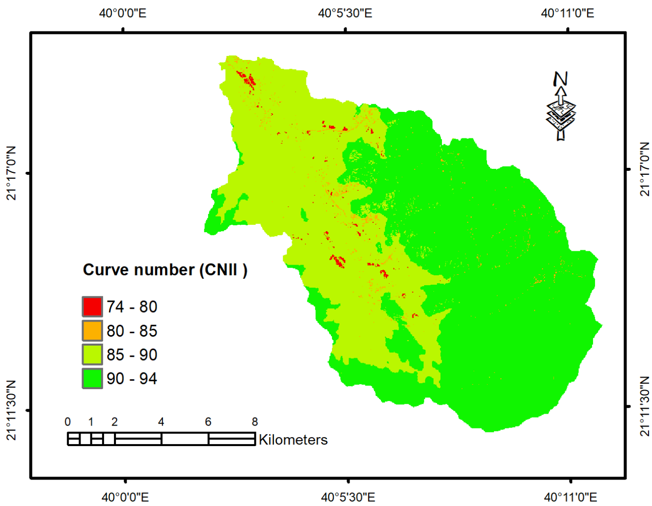

Figure 9. Curve number (CN_{II}) associated with AMC-II map.

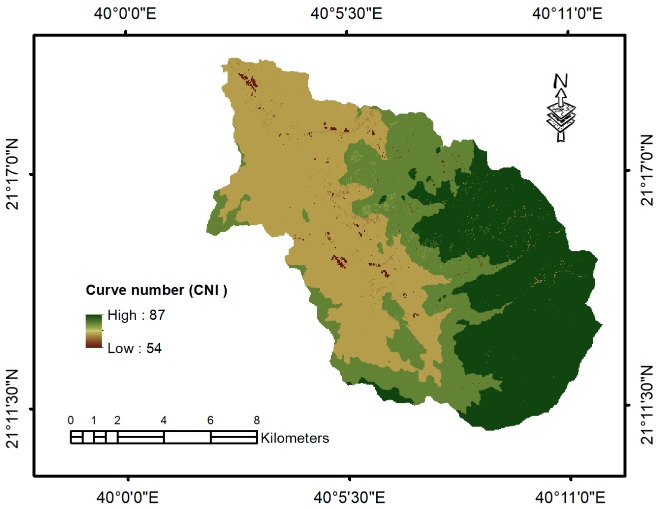

Figure 10. Curve number (CN_{I}) associated with AMC-I map.

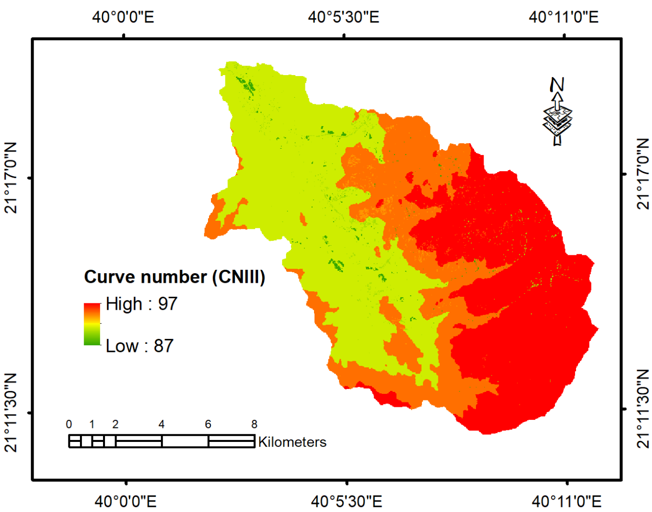

Figure 11. Curve number (CN_{III}) associated with AMC-III map.

3.5. Runoff Map

The primary measures used or direct runoff computation is rainfall and CN. The SCS-CN model was employed in the GIS environment to develop the runoff potential map (Figure 13). The annual runoff ranged from 194 to 295 mm, with the highest percentage of runoff water occurring between 289 and 295 mm (35%) and 24% occurring between 269 and 288 mm. The 194 to 268 mm runoff water range was harvestable around the southern and eastern regions of the catchment. The results corroborated Choi and Ball (2002) assertion that fine-particle-rich soils have a lower infiltration rate than those with larger particles. As a result, outflow can occur more easily on the soils with these characteristics.

3.6. Rainfall-Runoff Analysis

The CN values calculated are tested by pairing the rainfall and runoff data (Figure 14). This rainfall-runoff union is strongly correlated with a correlation

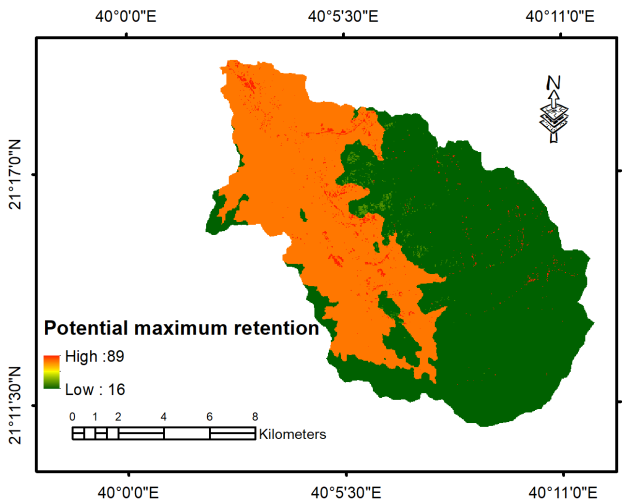

Figure 12. Potential maximum retention of the study area.

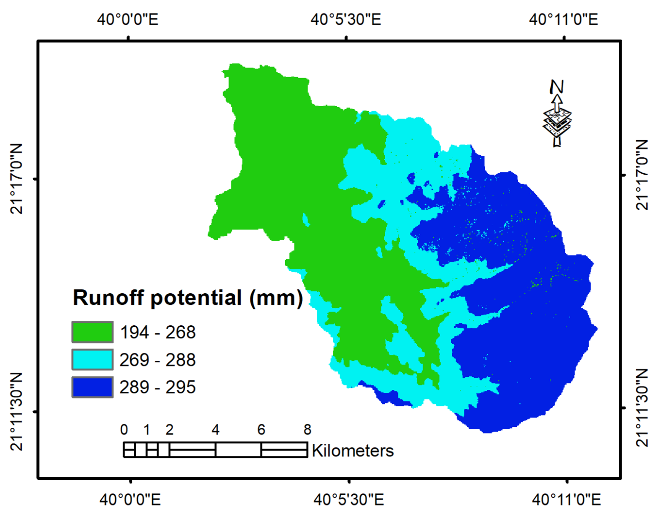

Figure 13. Runoff potential map of the study area.

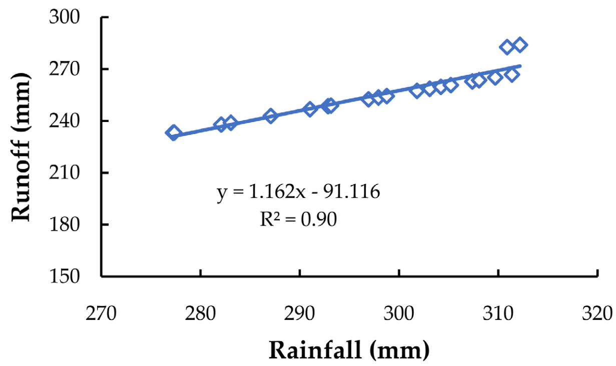

Figure 14. Rainfall-runoff correlation analysis for the study area.

coefficient R^2 valued at 0.90. The SCS-CN model results matched the findings of Peng and You (2006) who found that study areas with a coefficient of runoff greater than 0.5 showed a better simulation effect.

4. Conclusion

An accurate understanding of hydrological behavior of an area is crucial for efficient management of water resources. Since the amount of farmland available per capita has been declining over time, it is essential to develop, use, and manage all water and land resources together. The most fundamental and crucial parameter for developing water management methods is runoff. Wadi-Rahjan catchment, which is located in Saudi Arabia's western region, was used as a case study for the estimation of runoff by the SCN-CN method and GIS technology in the present work. Direct runoff is dependent on precipitation, soil type, soil moisture, drainage density, topography, watershed size and shape, and land cover, among other factors. In a GIS environment, various thematic layers, including Soil, land use, and slope, have been produced. The curve number (CN) has been determined polygonally utilizing a combination of land use, soil, and antecedent soil moisture condition (AMC). The original soil map has been transformed into a Hydrologic Soil Groups map (HSG). The areas of various land cover and soil types have been used as a weighting factor to integrate properties of multiple thematic layers in ArcGIS to find a representative curve number. The yearly runoff depth for this non-gauged catchment area was then determined. The study demonstrates that the SCS-CN model can be considerably used to estimate surface runoff, especially in cases where adequate hydrological information is not available.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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