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Watershed Delineation and Estimation of Groundwater Recharge for Ras Gharib Region, Egypt

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Abstract

The present work tried to estimate the runoff discharge and groundwater recharge volumes for the catchments of Ras Gharib area using the Soil Conservation Service curve number (SCS-curve number) and the water balance methods. The two methods were selected among other methods used by hydrologists due to simplicity and popularity for application in arid and semi-arid areas like Egypt. The watershed delineation and streamlines for Ras Gharib region have been accomplished using ArcMap 10 GIS and the 1-arc second DEM which demonstrated three basins in the study area. The rainfall data points nearby the study area, extracted from the TRMM data, have been used as input for the Log-Pearson III distribution in order to calculate the design storm for different return periods (100, 50, 25, and 10 years). The results of applying the SCS model estimated the runoff depths as 19.86, 8.00, 2.32, and 0.06 mm for the different return periods, respectively. The total surface runoff volumes reached the study area are 34.78, 14.02, 4.07, and 0.11 Mm^3, respectively for the selected return periods, whereas the total groundwater recharge volumes for the selected storm return periods are 58.16, 31.34, 18.14, 3.18 Mm^3, respectively.

Keywords

Rainfall, Surface Runoff, SCS Method, Groundwater Recharge, Ras Gharib, Egypt

1. Introduction

Egypt is facing water scarcity threats due to population growth and water consumption trends. If that continues by the years to come, water supply per capita will drop severely. To make matters worse, rainfall fluctuation, building dams, and climate change are anticipated to increase water scarcity in Egypt which will drive Egypt to severe water stress. With rapid depletion of ground water resources, flood management could provide a potential means for further optimization of water resources. In order to manage and sustain current and future water resources, sound and proper understanding of floods is required for water resources management (Masoud, 2004).

Recharge is defined as the process of adding water into the saturated zone. The total moisture which eventually arrives to the water table is defined as the natural groundwater recharge. The groundwater recharge depends upon many factors including the duration and rate of rainfall, soil type, antecedent moisture, and the water table depth (Kumar, 1993). Due to these factors, estimating the groundwater recharge is deemed to be the most difficult part of all measures in assessing the groundwater resources. In addition, estimates normally are subjected to large errors where no single technique provides adequate results (Kumar, 1977). The used techniques to estimate recharge could be classified as chemical, physical, and modeling techniques depending on the data source, groundwater, surface water, and unsaturated zone (Scanlon et al., 2002). Many methods have been used to estimate the groundwater recharge; the most used methods are the water balance method, groundwater modeling, water table fluctuation, watershed loss measurements, chloride and the environmental isotopes (Gomaa et al., 2016).

The water balance method has been frequently used where it has an advantage over the other methods. It estimates the direct recharge to groundwater by using the available climatic data (Rushton & Ward, 1979). The parameters of the soil water balance method are precipitation, runoff, evapotranspiration, and soil water storage. The direct runoff or precipitation excess Runoff could be estimated using the Soil Conservation Service curve number (SCS-curve number) method which is a function of the ability of soil to infiltrate water, land use, and the soil water conditions at the start of a rainfall storm.

Youssef et al. (2009), Ezz (2017), and Elnazer et al. (2017) studied the hazard effect of flash floods on Ras Gharib city and the nearby areas along the Red Sea Coast of Egypt. However, none of them tried to estimate the runoff discharge and groundwater recharge volumes. For this reason, the present work attempts to estimate the runoff discharge and groundwater recharge volumes using the SCS-curve number and the water balance methods due to popularity and simplicity for application in arid and semi-arid conditions like Ras Gharib area.

2. Site Description

Ras Gharib city is one of the old cities established on the Red Sea Coast in Egypt. The city was founded in early thirties of the last century. It is considered the most important Egyptian city in oil production. The city located in the Egyptian

Eastern Desert directly on the Red Sea Coast, with an area of 10,464 km^2 as shown in **Figure 1**. The city lies between Latitudes 28˚22.170'N to 28˚19.560'N and Longitudes 33˚3.10'N to 33˚6.80'N (Ezz, 2017). The total population of Ras Gharib is about 50,000 persons according to the 2016 census.

During the last five decades, flash floods became more frequent in the Eastern Desert causing life losses and significant infrastructure damages (Abdel-Fattah et al., 2015). The flash floods occur once or twice per year and the wadies (valleys) discharge their water towards the Red Sea or the Nile River (Mahmoud, 2014; Abdel-Fattah et al., 2015; Gomaa et al., 2016).

3. Materials and Methods

In this study, watershed is delineated using ESRI ArcGIS and surface runoff simulation have been done using the Soil Conservation Service (SCS) methods. The following sections show the watershed delineation, using the extracted surface of the study area, and the surface runoff calculations.

3.1. Precipitation Data

Low spatial and temporal resolution and limitation of the ground precipitation data considered the main problems facing any hydrological flood analysis study. In order to overcome the absence of ground observation near the study area, Tropical Rainfall Measuring Mission (TRMM) dataset (Huffman et al., 2007) is used.

TRMM which is available at a resolution of 0.25˚ at 3 hourly (3B42) and monthly intervals (3B43) covering the period from 1998 to present, is analyzed in order to estimate the amount of rainfall amounts precipitated on the study area.

Rainfall data from January, 1998 to May, 2018 is used as an input for the Log-Pearson III distribution (Ponce, 1989) in order to calculate the design storm for different return periods.

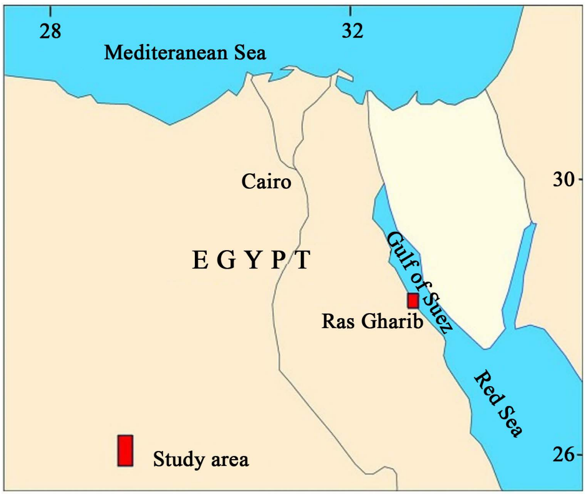

Figure 1. Location map of Ras Gharib area.

3.2. Digital Elevation Model

Digital elevation model (DEM) is a digital representation of the surface topography. The DEM of Ras Gharib region is extracted, using ArcGIS with Spatial Analyst Extension, from ALOS World 3D - 30 m (AW3D30) version 2.1 released in April 2018 (Takaku & Tadono, 2017). The DEM has a resolution of 1-arc second (~30 m). The DEM is essential to calculate topographic parameters needed in watershed delineation such as basin slopes, stream lengths, and sub-catchment boundaries. In addition, it is important in estimating the hydrologic parameters such as flow direction, flow accumulation, stream networks, longest flow length, and watershed delineation. Figure 2 shows the ground elevation of the study area in meters after geo-referencing it to UTM WGS84 36 N, which indicates that the study area is slopping towards the East direction to the Red Sea Coast with elevation ranges from 7 m to about 1500 m.

3.3. Watershed Delineation

The watershed delineation for Ras Gharib region is accomplished using ArcMap10 GIS software. All the morphological parameters needed are calculated using the Hydrology Tool in ArcGIS and the 1-arc second DEM including determining the catchments boundaries, flow direction, flow accumulation, and main streamlines network. Figure 3 demonstrates the basins and main streamlines generated using the ArcGIS after specifying three outlets in the study area. The total area of the three basins conveying their surface runoff to Ras Gharib region is about 1750 km^2. The three basins are then divided to sub-catchments to facilitate the runoff calculations in next steps. The generated streams are compared to Google Earth satellite images where a good matching is observed. Table 1 shows the area and average slopes for each sub-catchments.

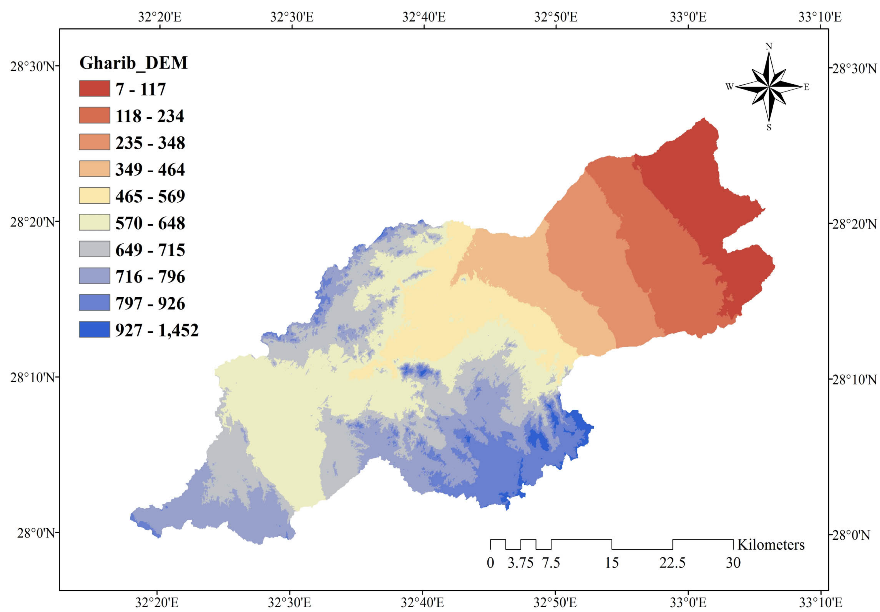

Figure 2. Digital Elevation Model (DEM) of the study area.

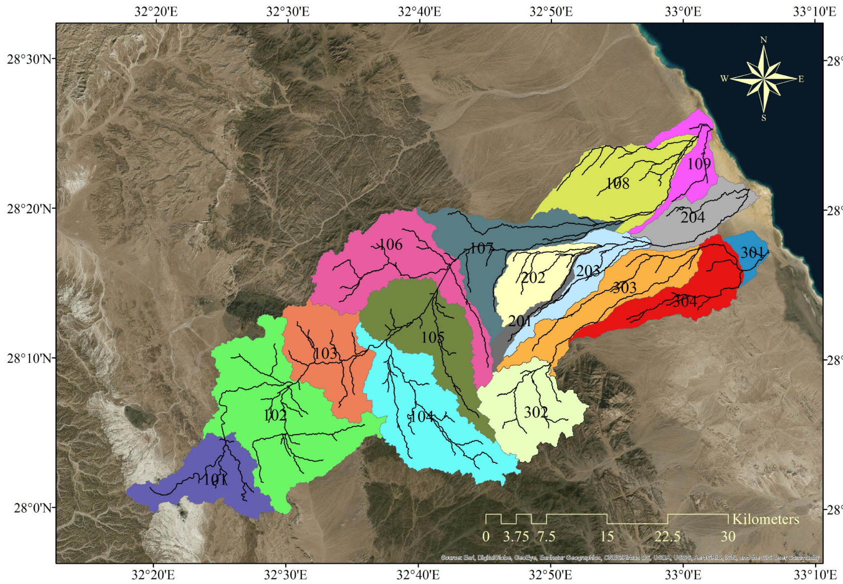

Figure 3. Ras Gharib watersheds and streamlines.

Table 1. Ras Gharib sub-catchments areas and average slopes.

Catchment Label	Sub-Catchment Label	Area (Km^2)	Slope (%)
Basin 1	101	94.84	6.19
	102	242.00	5.42
	103	111.17	12.48
	104	173.21	15.53
	105	132.76	13.13
	106	161.91	15.62
	107	126.88	6.75
	108	129.32	3.12
	109	50.52	1.90
Basin 2	201	19.04	10.41
	202	64.27	5.83
	203	56.41	3.63
	204	65.87	3.06
Basin 3	301	18.64	23.27
	302	107.54	6.69
	303	109.20	4.27
	304	87.74	1.81

3.4. Surface Runoff Calculations

The study area is one of the arid basins with no measured hydrological data. In order to predict the surface runoff, the Soil Conservation Service curve number model (SCS, 1972) is used. The SCS is used to estimate the peak flow discharged from the catchments when the storm intensity exceeds the soil infiltration capacity. The SCS model is widely and successfully applied on similar ungagged basins in Eastern desert and Sinai (Gheith & Sultan, 2002; Masoud, 2011).

The SCS method is capable to estimate precipitation excess (Q) as a function of the cumulative precipitation, soil texture type, and land use, using the following equation:

$$Q = \frac{\left(P - 0.2S\right)^2}{\left(P + 0.8S\right)} \tag{1}$$

where P is rainfall precipitation in (mm), and S represents the soil retention parameter in (mm). Soil retention is calculated using CN values with the formula as:

$$S = \frac{25400}{CN} - 254 \tag{2}$$

where CN is a hydrologic rock-soil-cover coefficient, which represents the runoff potential on each catchment, as a function of hydrologic soil group and land use.

The peak runoff discharge, Q_p, is then calculated using the following equation:

$$Q_p = \frac{0.208QA}{0.5D + L_a} \tag{3}$$

where Q_p is the peak runoff discharge (m^3/s); A is catchment area (km^2); D is the excess rain duration (hr) and equals to $0.5L_a$; and L_a is lag time (hr) which can be calculated using Watershed lag method (NRCS, 2009a), as shown in the following equation:

$$L_a = \frac{l^{0.8}\left(S+1\right)^{0.7}}{1900\sqrt{Y}} \tag{4}$$

where l is flow length (ft), and Y is the average watershed land slope (%). The flow length is defined as the longest path for water to reach the watershed outlet. Both flow length and land slope are calculated using ArcGIS.

3.5. Water Balance Method

According to the water balance equation (Kumar, 1977; Gomaa et al., 2016), the groundwater recharge can be estimated from the following equation:

$$P = Ia + F + Q \quad \text{for} \quad P > Ia \tag{6}$$

where P is the total precipitation (mm). Ia is the initial abstraction (mm). F (mm) is the actual infiltration which if multiplied by the area would give the total volume of recharge to the groundwater. Q is the direct runoff or precipitation excess (Equation (1)).

The initial abstraction equals to 20% of the maximum retention capacity S (mm), which has been estimated from the empirical evidence.

$$Ia = 0.2S \tag{7}$$

4. Results and Discussion

4.1. Effective Rainfall Depths

As discussed in previous section, rainfall data points nearby the study area are extracted from the TRMM data. For each point, Log-Pearson III distribution is used to calculate the design storm for different return periods (100, 50, 25, and 10 years).

Theissen polygon method is applied in order to calculate the effective rainfall depth for each storm event by specifying an area, for each rainfall data. The seven extracted rainfall data points and their Voronoi polygons created by Theissen polygon method are demonstrated in Figure 4.

Using the rainfall depths for different return periods at each point and the Voronoi polygon, an effective rainfall depth for the study area is calculated. The effective rainfall depths are 67.1, 45.7, 30.9, and 18.3 mm for return periods 100, 50, 25, and 10 years respectively, as shown in Table 2.

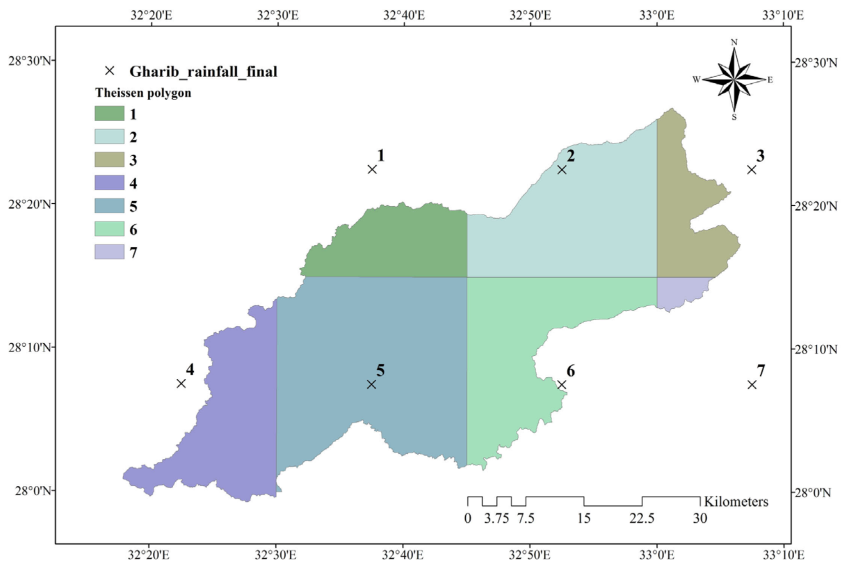

Figure 4. Rainfall data points and their corresponding influenced area.

Table 2. Effective rainfall depths for different return periods.

Rainfall Data Point information			Voronoi Polygons Area (km²)	Rainfall depth (mm) for Return Periods			
Label	X	Y		100 yrs	50 yrs	25 yrs	10 yrs
1	463,257.34	3,138,801.32	160.9	79	53	35	20
2	487,752.49	3,138,750.53	344.3	62	49	37	25
3	512,247.86	3,138,750.53	136.1	53	44	36	26
4	438,618.80	3,111,207.21	247.0	71	43	25	12
5	463,171.54	3,111,106.20	540.6	76	46	28	14
6	487,723.89	3,111,055.70	300.1	55	41	30	19
7	512,276.11	3,111,055.70	22.3	46	36	27	18
Effective Rainfall Depth (mm)				67.1	45.7	30.9	18.3

4.2. CN Selection

The runoff curve number (CN) is an empirical parameter used to calculate surface runoff or infiltration from rainfall excess in SCS method. The CN is based on the area's hydrologic soil group, and land use. The CN varies from 0 to 100, higher values indicate higher surface runoff and lower values indicate higher soil infiltration with lower surface runoff.

The hydrologic soil groups (HSG) are divided into four groups A, B, C, and D (NRCS, 2009b). The soils of group A have the lowest runoff potential, and the highest infiltration rate. The soils of group B have a moderate infiltration rate, and moderate surface runoff potential. The soils of group C have a higher runoff potential, and lower infiltration rate compared to soils of group B. On the other hand, the soils of group D pointed to the highest runoff potential, and the lowest infiltration rate.

All Egyptian Eastern desert land cover is classified as Barren or Sparsely Vegetated. Referring to (Cronshey, 1986) CN values are 49, 68, 79, and 84 for hydrologic soil type A, B, C, and D for Desert shrub in arid and semiarid rangeland. So it is essential to find the hydrologic soil type of the study area to calculate the CN value and their coverage area.

A hydrologic soil group map is extracted, (Hengl et al., 2017), for the study area using ArcGIS as illustrated in **Figure 5**. From the map, it is found that 419.6 Km^2 occupied by soil type B, 1314.7 Km^2 occupied by soil type C and 15.9 Km^2 occupied by soil type D.

A weighted average method is used to calculate an equivalent CN value for the study area according to percentage of the total area with its corresponding CN using the following equation:

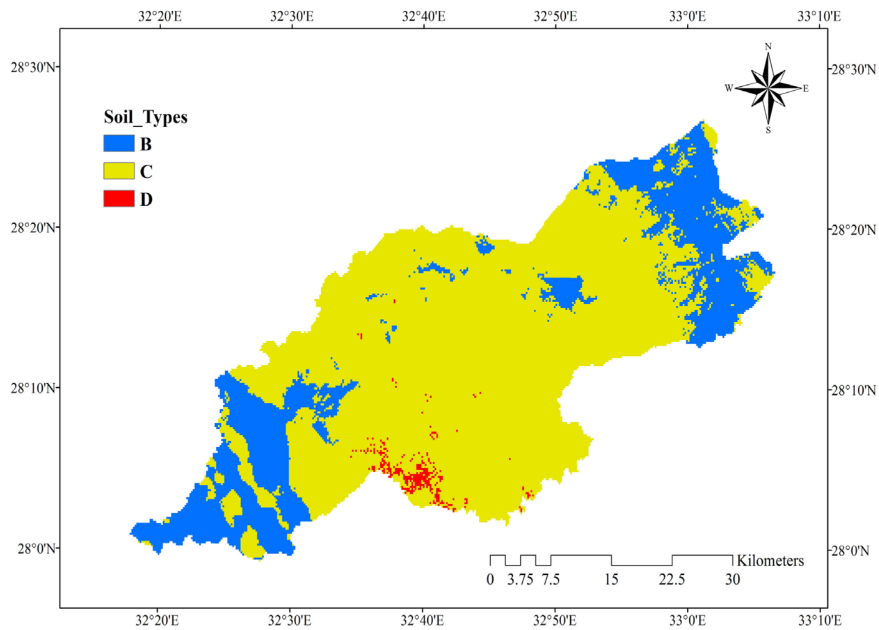

Figure 5. Hydrologic soil group (HSG) map for the study area.

$$CN = \sum_{i=1}^{k} A_i CN_i \Big/ \sum_{i=1}^{k} A_i \quad (5)$$

where CN_i refers to the CN value for the watershed part that has an area A_i. Finally the equivalent CN value for the study area is found to be 76.

4.3. Estimation of Runoff Volume

The results of applying SCS model represented in the previous sections are shown in Table 3. The table shows the peak discharges flowing from the three basins affecting Ras Gharib region when applying different rainfall depths. The table also illustrates the runoff volume for each basin. It is shown that the runoff depths are 19.86, 8.00, 2.32 and 0.06 mm for the return periods 100, 50, 25 and 10 years respectively. As a result of these runoff depths, the total surface runoff volumes reach the study area are 34.78, 14.02, 4.07, and 0.11 Mm^3, respectively for the selected return periods. The total volume of surface runoff represents 13.74% of the applied rainfall. The relationship between rainfall depths and runoff depths for different storm events return periods is shown in Figure 6 where rainfall-runoff depths are well correlated with a relatively high correlation coefficient ($R^2 = 0.96$).

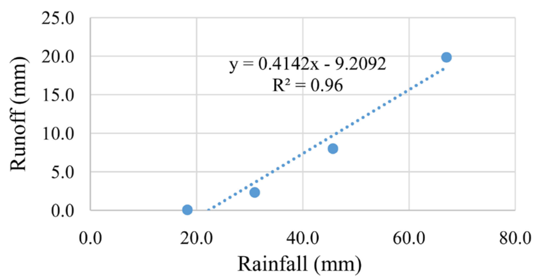

Figure 6. The relationship between rainfall depths and runoff depths for different storm events return periods showing well correlation.

Table 3. Runoff depths, discharges, and groundwater recharge volume values for different storms events return periods.

		Return Period			
		100 yrs	**50 yrs**	**25 yrs**	**10 yrs**
	Rainfall (mm)	67.1	45.7	30.9	18.3
	Runoff (mm)	19.86	8.00	2.32	0.06
Discharge (m^3/s)	**Basin 1**	1157.35	466.56	135.32	3.6
	Basin 2	160.95	64.88	18.82	0.5
	Basin 3	382.88	154.35	44.77	1.19
	Total Discharge	**1701.18**	**685.79**	**198.91**	**5.3**
Runoff Volume × 10^6 (m^3)	**Basin 1**	24.28	9.788	2.839	0.076
	Basin 2	4.083	1.646	0.477	0.013
	Basin 3	6.417	2.587	0.75	0.02
	Total Runoff Volume	**34.78**	**14.02**	**4.07**	**0.11**
Recharge Volume × 10^6 (m^3)	**Basin 1**	49.1465	26.4793	15.3291	2.6873
	Basin 2	8.26431	4.45267	2.57769	0.45189
	Basin 3	0.74929	0.40371	0.23371	0.04097
	Total Recharge Volume	**58.16**	**31.34**	**18.14**	**3.18**

4.4. Groundwater Recharge

The results of the estimated volumes of groundwater recharge are shown in Table 3. The total groundwater recharge volumes for the 100, 50, 25, and 10 years storms return periods are 58.16, 31.34, 18.14, 3.18 million m^3 respectively. The groundwater recharge represents 53%, 47%, 41%, 12% out of the total precipitation for such storm events respectively, while the average runoff represents 26%, 18%, 8%, 0.3% of the total precipitation for the 100, 50, 25, and 10 years storms return periods. These results are typical to the estimated and inferred average recharge in many similar arid and semi-arid catchments which have been found to be close or over 40% of the total rainfall. Milewski et al. (2009) estimated and average annual recharge through infiltration of 23.9% and an average annual runoff of 6.1% for these catchments. JICA (1999) showed an average of 54% recharge and 14% runoff from the total rainfall for Sinai Peninsula.

5. Conclusion

Ras Gharib region is considered promising for urban expansion and sustainable development for the present and future due to the unique location on the Red Sea Coast of Egypt. Estimation of the infrequent runoff and groundwater recharge required detailed hydrological information about the catchment. The ArcGIS and the DEM have been used to identify three basins which are then subdivided to sub-catchments to facilitate the runoff calculations for the study area. The rainfall data points nearby the study area have been extracted from the TRMM data, where the Log-Pearson III distribution for each point has been used to calculate the design storm for different return periods (100, 50, 25, and 10 years). The results of applying the SCS model estimated the runoff depths as 19.86, 8.00, 2.32, and 0.06 mm for the return periods 100, 50, 25, and 10 years respectively, whereas the total surface runoff volumes reached the study area estimated as 34.78, 14.02, 4.07, and 0.11 Mm^3, respectively for the selected return periods. The total groundwater recharge volumes for the selected return periods are 58.16, 31.34, 18.14, 3.18 million m^3 respectively.

According to the results of the study, the following points could be stated:

- The area is promising in terms of water potentialities.
- More studies are needed to assess the groundwater potentialities of the study area.
- Drilling monitoring wells at the outlets of the basins are recommended.
- Many rain gages are required to be installed in the study area.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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