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Estimation of Surface Runoff Using GIS Based SCS - CN Method

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ABSTRACT

Water, which is one of the crucial natural resources on the earth, is becoming scarce and there is an ever-increasing need to conserve the water resources. Efficient management of water requires accurate estimation of runoff from the watershed. There are numerous conventional methods available to estimate runoff depth and volume from a given watershed. Out of the Soil Conservation Service Curve Number (SCS-CN) technique is one of the effective methods for rainfall-runoff modeling. The runoff curve number (CN) is a pivotal factor in determining runoff in the SCS- CN-based hydrologic modeling method. The traditional method used for the calculation of composite curve numbers from the readily available tables and curves is very complex and highly time-consuming. In order to overcome this difficulty, the combination of Remote sensing-GIS and SCS-CN methods has been successfully employed to estimate composite curve numbers. In this study, GIS based modified SCS-CN method was applied to estimate runoff values for the Ambika and Purna Watersheds of The Dang district of Gujarat. Estimation of surface runoff potential of Dang district for 32 years period (1982 to 2013) indicated a runoff coefficient of 24.40% (446.88mm) for Purna watershed and 22.80% (419.35mm) for Ambika watershed representing the average annual rainfall of 1833 mm. Amount of runoff estimated from the study could be effectively used for planning and management of the watershed of the study area. Whereas developed runoff equations can also be effectively employed to estimate runoff volume using rainfall data from similar watersheds.

Keywords: *CN, remote sensing, surface runoff, GIS, runoff coefficient, watershed, SCS*

1. Introduction

Runoff stands as a pivotal hydrological factor crucial for effective watershed management, playing a significant role in both conserving and developing natural resources. It serves as an indicator for various aspects such as soil erosion, hydraulic properties, and the potential water yield within a watershed [1]. Precise estimation of runoff depth and volume holds immense importance in water resource planning and management within the watershed context. This includes tasks like irrigation scheduling, flood control, hydroelectric power generation, and the design of drainage networks [2, 3].Hydrological modeling aids in quantifying runoff by considering the impact of land use on the surface water balance. There exist numerous physically based and spatially distributed hydrological computer models designed to compute sequences of runoff generation for specific rainfall events. These models boast accuracy in predictions, yet their utilization demands considerable time, effort, and expertise. Amidst this spectrum, models such as the SCS-CN (Soil Conservation Service curve number) method offer relative ease of use while delivering satisfactory results [4].

Several approaches exist for calculating direct runoff, including the Peak Discharge method, Tabular Method, Unit Hydrograph Method, and the SCS-CN Method [5]. The SCS-CN technique stands out as the simplest approach for modeling rainfall runoff. It relies on the curve number determined by factors like hydrologic soil group area, land use, treatment, and prevailing hydrological conditions [5]. Hydrologic soil groups, categorized as A, B, C, and D, vary in their infiltration rates, with A exhibiting high rates and D displaying low rates [6]. Widely utilized, the SCS-CN method effectively predicts direct runoff volume for specific rainfall events [7]. This study aimed to estimate runoff potential using the curve number method, emphasizing the efficiency of direct rainfall-runoff estimation [8, 9]. Traditional methods for computing the composite curve number through available tables and curves prove intricate and time-consuming. To address this challenge, a successful approach combines GIS and SCS-CN methods to estimate the composite curve number [10, 11, 12]

In the hilly expanse of Dangs district in Gujarat, intersected by the Ambica and Purna rivers, there exists a promising opportunity for constructing water harvesting structures due to the region's distinctive topography and drainage basin attributes. For this study, the Purna and Ambica River sub-basins were specifically chosen to estimate direct runoff. Meteorological data was sourced from the India Meteorological Department (IMD), while soil analysis data was obtained from Krishi Vigyan Kendra (KVK) in Waghai, Gujarat. This investigation aimed to assess runoff using the SCS–CN method, recognized for its simplicity, predictability, and stability [13]. The study utilized conventional databases in conjunction with GIS to analyze the runoff from Ambika and Purna Watersheds within the Dang district of Gujarat. This method proves valuable in estimating runoff depths under varying antecedent moisture conditions (AMC).

2. Description of the study area

The Dang district of Gujrat state is situated in 20.39° to 21.05° N latitude and, 73.29° to 73.51° E longitude (Figure 1). The total

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geographical area of Dang district is 1,764km^2 with average annual rainfall of 1833mm for 32 years (1982–2013). The study area was divided into two watersheds namely Purna watershed (933.50 km^2) and Ambika watershed (830.50 km^2) for assessing the runoff potential.

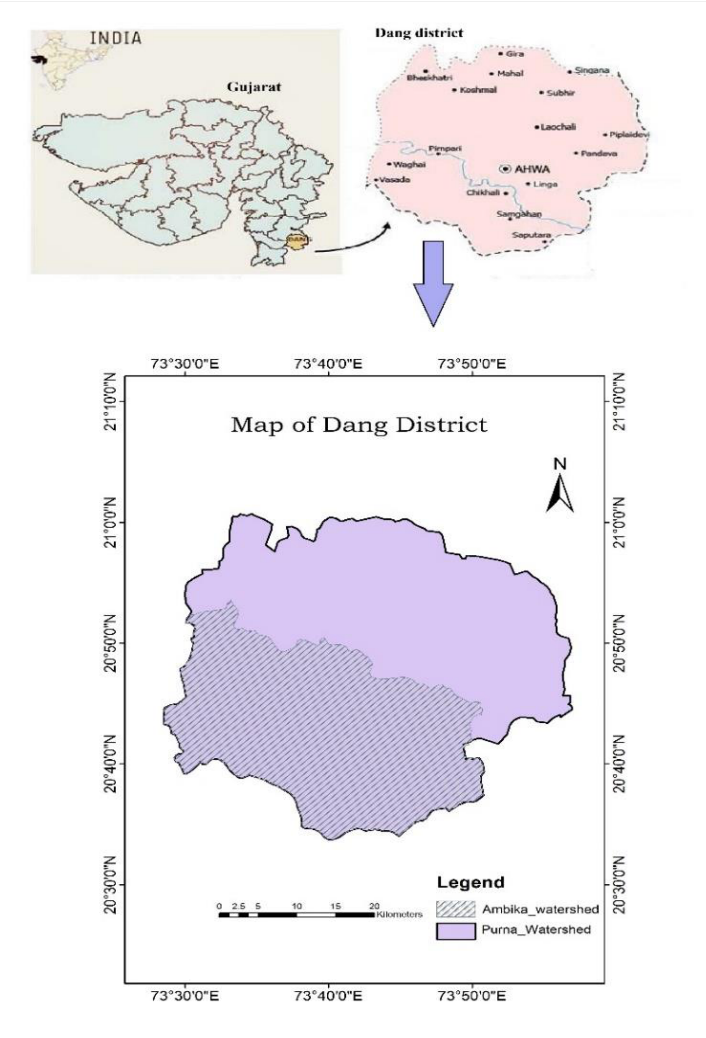

Fig. 1: Location map of Dang district

3. Methodology

3.1 Estimation of runoff using SCS–CN Method

The methodology adopted in assessing the runoff potential of the study area is presented in Figure 2. The direct runoff depth was estimated by adopting Soil Conservation Service-Curve Number (SCS-CN) method based on storm rainfall depth with other remotely sensed inputs like land use/land cover and soil data. The SCS-CN method was developed by the USDA in 1954 for hydrologic studies which is a versatile, conceptual, and widely used method. It can be computed using the following equation,

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)}$$

where Q is the gathered runoff in mm, P is the rainfall depth in mm, Ia is the initial abstraction in mm. Empirical relation was developed for Ia and it is given by, Ia = 0.3S

For Indian condition, S, the potential maximum retention is given by

$$S = \left(\frac{25400}{CN}\right) - 254$$

where, CN is the Curve number. Now the equation can be rewritten as,

$$Q = \frac{(P - 0.3S)^2}{(P + 0.7S)}$$

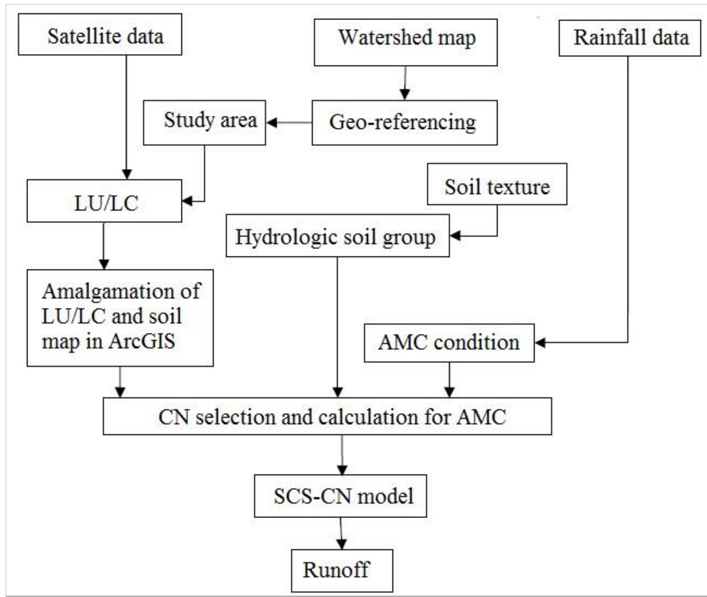

Fig. 2: Flow chart of the methodology for runoff estimation

3.3 Determination of Hydrological Soil Group

The first step is to determine the hydrologic soil group (HSG) of the particular soil. Soil samples were collected and analyzed for various soil properties in the laboratory of KVK Waghai, Dang and these soil data were used for making appropriate hydrological soil classification A, B, C & D (Table 1). All soils are classified in one of four different categories ranked A-D on the basis of their runoff potential.

Table 1. Hydrological soil group classification (USDA 1974)

HSG	Soil Texture	Runoff potential	infiltration rate (mm/hr)	Transmission rate (in/hr)
A	Sand, gravels, loamy sand, sandy loam	Low	>7.5	>0.3 (High rate)
B	Silt loam or loam	Moderate	3.8- 7.5	0.15-0.3 (Moderate rate)
C	Sandy clay loam	Moderate	1.3- 3.8	0.05-0.15 (Low rate)
D	Clay loam, silty clay loam, sandy clay, silty clay, clay	High	<1.3	<0.05 (Very low rate)

3.4 Antecedent Moisture Condition (AMC)

The next step is to determine the five-day antecedent moisture condition of the particular soil from the daily precipitation record. It is an index for basin wetness. AMC indicates the moisture content of soil at the beginning of the rainfall event under consideration. Three levels of AMC were documented by SCS are AMC I, AMC II, and AMC III. The limits of these three AMC classes are based on rainfall magnitude of the previous five days and season (dormant season and growing season). The values of curve number are determined based on the antecedent moisture conditions (Table 2).

Table 2. Group of Antecedent soil moisture classes (AMC)

AMC Group	Soil characteristics	Five day antecedent rainfall (mm)	
		Dormant season	Growing season
I	Soils are dry but not to wilting point. Satisfactory cultivation has taken place (Dry condition)	Less than 13	Less than 36
II	Average condition	13–28	36–53
III	Sufficient rainfall has occurred within the immediate past 5 days. Saturated soil conditions prevail (Wet condition)	Over 28	Over 53

The third step is to decide the actual runoff curve number to use in determining daily runoff from precipitation. This curve number is decided based on the land cover, cultivation treatment, hydrologic condition of the soil, and the hydrologic soil group of the particular soil (SCS, 1972). The CN value for each soil hydrologic group and corresponding land use classes under AMC II is presented in Table 3. CN for AMC I and CN for AMC III were determined using equations given below:

$$CN(I) = \frac{CN(II)}{2.281 - 0.0128\, CN(II)}$$

$$CN(III) = \frac{CN(II)}{0.427 + 0.00573\, CN(II)}$$

The weighed CN number for Antecedent Moisture Condition- II (average condition) as well as computed for AMC-I and III calculated using following equation.

$$\mathrm{CNII} = \frac{\sum \mathrm{CN_i} \times \mathrm{A_i}}{\mathrm{A}}$$

Where, CNII = weighted CN for AMC-I condition, CNi = CN from 1,2, 3....i, Ai = area with curve number CNi, A = total area of the watershed

Table 3. Curve number for HSG under AMC II conditions (Ahmad et al 2015)

Land use	Hydrological soil group			
	A	B	C	D
Agricultural land	76	86	90	93
Built up	69	79	84	87
Forest	26	40	58	61
Barren land	71	80	85	88
Water bodies	97	97	97	97

4. Results & Discussion

4.1 Estimation of runoff using SCS–CN Method

Hydrological Soil Group and AMC

The study area has land use/ land cover of about 67% of forest, 20% of agricultural land, and the remaining 13% of the area is occupied by others such as built-up land, water body and barren land. Analysis of the data revels that soil present in both watersheds of study area falls under all four HSGs i.e., A, B, C and D. The CN value for each soil hydrologic group and corresponding land use classes under AMC II is presented in Table 4. The weighted curve number for the area was calculated and the values of Weighted CN are 53.72 (Purna watershed) and 54.45 (Ambika watershed) for AMC-II; 33.71 (Purna watershed) and 34.38 (Ambika watershed) for AMC-I; and 73.1 (Purna watershed) and 73.7 (Ambika watershed) for AMC -III calculated using equations mentioned above (Table 4-5).

Table 4. Weighted curve number for Purna Watershed (AMC Group II)

LULC class	HSG	CN	Area (Sq km)	% Area	% Weighted CN	WCN
Agricultural land	C	90	36.56	3.92	3.52	AMC I = 33.71 AMC II = 53.72 AMC III= 73.1
	A	76	99.17	10.62	8.07	
	D	93	0.30	0.03	0.03	
	B	86	37.84	4.05	3.49	
Barren land	C	85	10.69	1.14	0.97	
	A	71	10.02	1.07	0.76	
Builtup land	C	84	11.01	1.18	0.99	
	A	69	29.31	3.14	2.17	
	B	79	17.11	1.83	1.45	
Forest	C	58	145.24	15.56	9.02	
	A	26	155.58	16.67	4.33	
	D	61	2.77	0.30	0.18	
	B	40	336.43	36.04	14.42	
Water body	C	97	7.87	0.84	0.82	
	A	97	7.44	0.80	0.77	
	B	97	26.18	2.80	2.72	
			933.50	**WCN**	**53.72**	

Table 5. Weighted curve number for Ambika Watershed (AMC Group II)

LULC class	HSG	CN	Area (Sq km)	% Area	% Weighted CN	WCN
Agricultural land	C	90	31.50	3.79	3.41	AMC I = 34.38 AMC II = 54.45 AMC III= 73.7
	A	76	103.67	12.48	9.49	
	D	93	0.26	0.03	0.03	
	B	86	36.26	4.37	3.75	
Barren land	C	85	8.56	1.03	0.88	
	A	71	7.96	0.96	0.68	
Builtup land	C	84	10.79	1.30	1.09	
	A	69	26.91	3.24	2.24	
	B	79	17.17	2.07	1.63	
Forest	C	58	126.33	15.21	8.82	
	A	26	133.07	16.02	4.17	
	D	61	2.46	0.30	0.18	
	B	40	290.53	34.98	13.99	
Water body	C	97	8.00	0.96	0.93	
	A	97	4.62	0.56	0.54	
	B	97	22.40	2.70	2.62	
			830.50	**WCN**	**54.45**	

The daily rainfall values were used as inputs to compute daily runoff. Based on the precipitation data and weighted Curve numbers, daily runoff for the years 1982 to 2013 was estimated for each storm event. It can be observed that precipitation is more from June to September and thus the runoff was more. The precipitation varies between 1062 mm (year 2002) to 3823 mm (year 2005) in the basin. Runoff varies between 252.63mm (year 2000) to 682.00mm (year 2011) for Purna watershed and 229.30mm (year 2000) to 656.10mm (year 2011) for Ambika watershed (Table 6, Figure 3). The average annual runoff was estimated as 446.88mm for Purna watershed and 419.35 mm for Ambika watershed.

It has been observed during the year 2005, runoff is low (427.36 mm for Purna and 400.62 for Ambika) despite rainfall in the area is relatively high (3823 mm). This may be due to non-continuous rainfall in the months of June, July, Aug, Sept, and Oct resulting in more infiltration, transpiration, and evaporation and thus less runoff.

From Table 6, it is observed that the average annual runoff depth for Purna watershed was 446.88 mm which is 24.4% of the average annual rainfall depth (1833 mm) and the average annual runoff depth for Ambika watershed was 419.35 mm which is 22.8% of average annual rainfall depth. The moderately lower runoff coefficients for both the watersheds observed may be due to the maximum coverage of forest & agriculture under hydrological soil groups A & B (around 75% in both watersheds) which has low runoff potential. The highest runoff percentage for Purna watershed was 43.81% and for Ambika watershed 41.54% was observed in the year 2001.

The Runoff equations (Table 7) for various AMCs based on the average annual rainfall between 1062 mm to 3823 mm were developed and can be used to estimate runoff from Ambika and Purna watersheds of Dang district using daily rainfall data.

Table 6. Annual average rainfall and runoff depth

Year	Rainfall (mm)	Purna Watershed		Ambika Watershed	
		Runoff (mm)	% Runoff	Runoff (mm)	% Runoff
1982	1870.20	446.60	23.88	411.20	21.99
1983	1790.92	440.10	24.57	407.80	22.77
1984	1867.94	290.63	15.56	276.50	14.80
1985	1283.81	343.60	26.76	315.10	24.54
1986	1392.18	279.84	20.10	263.00	18.89
1987	1130.04	339.50	30.04	326.00	28.85
1988	1989.07	455.57	22.90	423.90	21.31
1989	1479.54	605.89	40.95	576.70	38.98
1990	2011.47	616.77	30.66	585.60	29.11
1991	1600.95	318.33	19.88	294.60	18.40
1992	1498.44	353.60	23.60	332.90	22.22
1993	1532.35	595.70	38.87	558.90	36.47
1994	2356.05	396.87	16.84	372.40	15.81
1995	1334.48	361.50	27.09	331.49	24.84
1996	1927.81	444.70	23.07	410.23	21.28
1997	1900.99	544.90	28.66	523.80	27.55
1998	1894.07	570.20	30.10	531.90	28.08
1999	1377.16	366.27	26.60	335.30	24.35
2000	1265.01	252.63	19.97	229.30	18.13
2001	1290.92	565.59	43.81	536.20	41.54
2002	1062.34	326.20	30.71	308.90	29.08
2003	2166.00	427.57	19.74	394.20	18.20
2004	2459.00	522.06	21.23	488.70	19.87
2005	3823.00	427.36	11.18	400.62	10.48
2006	2616.60	514.40	19.66	474.10	18.12
2007	1921.00	447.70	23.31	426.30	22.19
2008	2593.00	477.20	18.40	449.40	17.33
2009	1532.00	286.20	18.68	263.78	17.22
2010	1887.00	497.60	26.37	460.12	24.38
2011	2042.66	682.00	33.39	656.10	32.12
2012	1802.75	536.60	29.77	511.40	28.37
2013	1956.84	566.50	28.95	542.75	27.74
Avg.	**1833.00**	**446.88**	**25.48**	**419.35**	**23.91**

Table 7. Runoff equations based on rainfall for different AMC conditions

	AMC-I	AMC-II	AMC-III
Purna Watershed	$Q=\frac{(P-149.85)^2}{(P+349.6)}$	$Q=\frac{(P-65.65)^2}{(P+153.17)}$	$Q=\frac{(P-28.01)^2}{(P+65.42)}$
Ambika Watershed	$Q=\frac{(P-145.46)^2}{(P+339.36)}$	$Q=\frac{(P-63.75)^2}{(P+148.74)}$	$Q=\frac{(P-27.20)^2}{(P+63.45)}$

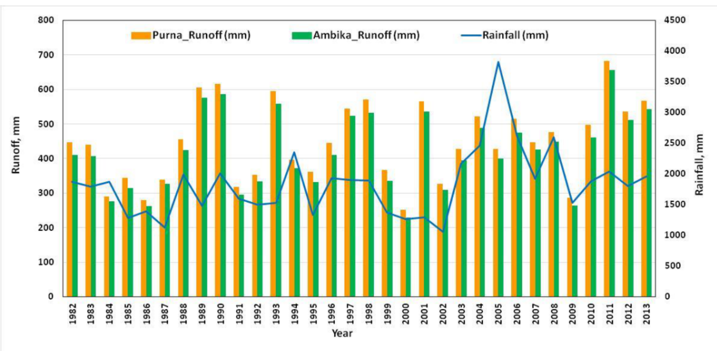

Fig. 3: Annual average rainfall and runoff depth for Purna and Ambika watersheds

Conclusion

In the present study, SCS-CN method was used to estimate surface runoff potential of the Dang district for 32 years period (1982 to 2013). In SCN Curve number method, Antecedent moisture condition of the soil plays a very important role as the Curve number varies according to the soil moisture and that is considered while estimating the runoff depth. Weighted curve numbers estimated are 53.72 (Purna) and 54.45 (Ambika) for AMC-II; 33.71 (Purna) and 34.38 (Ambika) for AMC-I; and 73.1 (Purna) and 73.7 (Ambika) for AMC –III conditions. For Purna watershed, the amount of runoff (446.88 mm) represents 24.40% of the total annual rainfall (1833 mm) whereas for Ambika watershed, runoff (419.35 mm) represents 22.80% of the total annual rainfall. The moderately lower runoff coefficients for both the watersheds observed may be due to the maximum coverage of forest & agriculture under hydrological soil groups A & B (around 75% in both watersheds) which has low runoff potential. SCS-CN method is capably recognized as a good technique, which consumes less time for extensive data sets as well as bigger environmental area to recognize site selection of artificial recharge structures. The Runoff calculated and estimated for can be used for the planning and management of the watershed of the study area. The developed Runoff equations can be used to estimate runoff from Ambikaand Purna watersheds of Dang district using daily rainfall data.

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Conflict of Interest
Dr. M. Singh, corresponding author declares that there are no conflict of interest.

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