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Research Article

Surface runoff estimation using geographic information system and soil conservation service-curve number method for sub catchments of Karamadai, Tamil Nadu

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Abstract
Water conservation becomes essential as the resource becomes scarcer. The most important step in managing water resources is estimating watershed runoff generated from rainfall, as the runoff and rainfall are the key factors in determining water availability for surface storage and groundwater recharge. So, this study is mainly focused on estimating the surface runoff generated from the three sub-catchments of Karamadai, Tamil Nadu, India, using the heavy to extreme daily rainfall events received in the study area within the span of 20 years (2000–2019). The study was performed in the ArcGIS environment using remote sensing data. The SCSCN (Soil Conservation Service-Curve Number) method was used to estimate surface runoff. The changes in the land use in each sub-catchment were analysed in each decade and studied for their impact on the runoff depth. The land use and land cover classification map of the study area was prepared from LISS III satellite imagery for the years 2006 and 2016 by using supervised classification. The curve number was assigned based on land use as well as the hydrologic soil group. The weighted curve number was calculated from the area under each land use and then used to calculate storm runoff. The maximum runoff occurred in 2011 in all the catchments of the Karamadai block. It was found that more runoff occurred in the Mandrai Pallam catchment compared to Periya Pallam and Pare Pallam, as the Mandrai Pallam catchment had less soil moisture retention capacity than the other two catchments. So, more priority must be given to this catchment while planning to implement the soil and water conservation measures.

Keywords: Antecedent Moisture Condition, Curve Number, GIS, Hydrologic Soil group, Runoff

INTRODUCTION

Water is one of the most valuable assets of the earth, which has been considered the supreme natural resource and an essential commodity for the socio-economic development of any country. Even though the water is available abundantly over the earth, the share of freshwater availability is only 3%. Also, the quantity and quality distribution vary spatially and temporally. So, water crises are increasing drastically in almost all of the world. Many parts of India face drought problems due to the limited water resources. Also, soil erosion is more frequent due to intense rainfall, floods, and severe runoffs. So, the use of runoff estimation models imparts a crucial effect on the proper management of water resources, especially for mitigating floods (Hadid *et al.*, 2019; Ferreira *et al.*, 2020).

The study of the storm-wise rainfall-runoff relationship is needed to properly plan the sustainable management and conservation of the resources. Runoff plots are the widely used conventional model for the reliable prediction and quantification of surface runoff. However, this method is more time-consuming and expensive (Ponce and Hawkins, 1996; Kumar *et al.*, 2010). The Soil Conservation Service-Curve Number (SCSCN) method, developed by the National Resources Conservation Service (NRSC), United States Department of Agriculture (USDA) is the reliable and most widely used and accepted model for the estimation of surface runoff at watershed scale which nullifies the drawbacks of the conventional methods of runoff estimation (Greene and Cruise, 1995; Tsihrintzis and Hamid, 1997; Lewis *et al.*, 2000; Tasdighi *et al.*, 2018; Ahmadi-Sani *et al.*, 2022; Muneer *et al.,* 2022). The SCSCN makes the runoff estimation much easier, even for hilly and inaccessible terrain, with the integration of GIS (Geographic Information System) and Remote sensing technology (Murmu and Biswas, 2012; Singh, 2014; Viji *et al.*, 2015). This method accounts for many factors which influence runoff generation, including land use land cover (LULC), surface condition, soil type and antecedent moisture condition (AMC), and incorporated into a single factor called curve number (CN).

The SCSCN model is generally designed to estimate storm-generated runoff. So, rainfall data should be applied correctly. Otherwise, it may overestimate the results. In the present study, the SCSCN method was employed along with the GIS to estimate the runoff in the Karamadai block of Tamil Nadu.

MATERIALS AND METHODS

The Karamadai block of the upper Bhavani basin was considered for the study. The entire block was divided into three sub-catchment, namely Pare Pallam (C1), Mandrai Pallam (C2) and Periya Pallam (C3). The areal extent of C1, C2 and C3 were 21.19 km^2, 51.22 km^2 and 135.48 km^{2,} respectively (Fig. 1). The detailed methodology adopted is given in Fig. 2.

SCSCN method

This model returns the direct runoff (Q, in mm) generated from a particular storm considering the potential maximum retention (S, in mm) of the watershed obtained from the AMC and the physical characteristics of the watershed. Direct runoff was calculated from Eq. 1.

$$Q = \frac{(P-Ia)^2}{(P-Ia+S)} \quad (1)$$

Where, *P* is daily rainfall (mm), I_a is initial abstraction (mm), where I_a= 0.3S for study area condition. The potential maximum retention of the soil was determined by selecting the curve number for different land use in the catchments (Eq. 2).

$$CN = \frac{25400}{254+S} \quad (2)$$

Where, CN values corresponding to landuse and hydrologic soil group (HSG) were taken from the CN table (CN_{II}) given by USDA. For this, the soil was classified into four HSG called as A, B, C, and D based on the

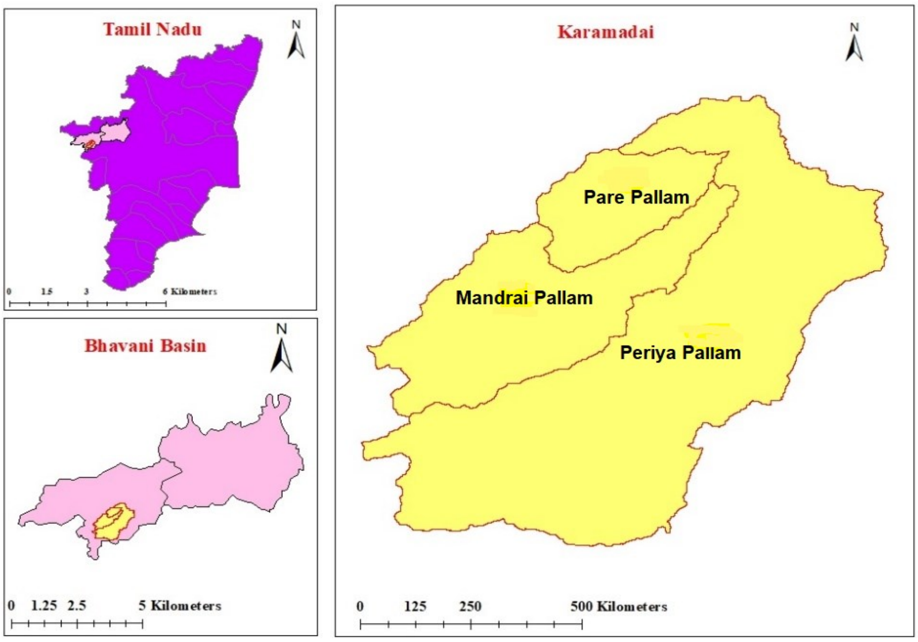

Fig. 1. *Location of the study area*

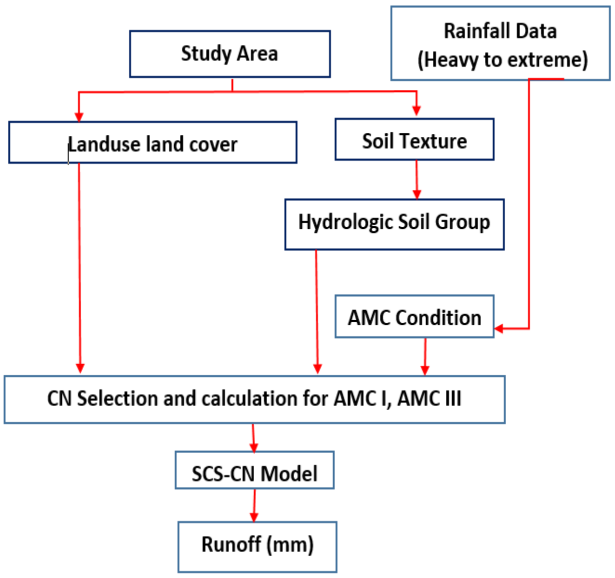

Fig. 2. *SCSCN model – Flow chart*

infiltration rate where A stands for extremely high infiltration rate and D for significantly less infiltration rate (Infiltration rate decreases from A to D). The SCSCN method was originally designed for use in watersheds of 15 km^2, and it has been modified for application to larger watersheds by weighing curve numbers with respect to watershed/land cover area (Eqn. 3) (United States Department of Agriculture, 1986).

$$CNw = \frac{\Sigma(CNi*Ai)}{A} \qquad (3)$$

Where CN_w = weighted curve number.
CNi = curve number from 1 to any no.
Ai = area with curve number CNi

Antecedent moisture condition (AMC)

The SCSCN model considered three AMCs and labelled them as I, II, III, according to previous five days rainfall of particular storm based on the season at which storm received. The classification of AMC is shown in Table 1.

The conversion of CN_{II} to either CN_I or CN_{III} based on the AMC conditions was performed using the equations 5-6.

$$\text{CN I} \quad \text{for AMC I} = \frac{\text{CN II}}{2.281-(0.01281*\text{CN II})} \qquad (4)$$

$$\text{CN III} \quad \text{for AMC III} = \frac{\text{CN II}}{0.427+(0.00573*\text{ CN II})} \qquad (5)$$

Thematic maps and data used

The LULC map of the study area was prepared from LISS III images for the years 2006 and 2016 by using supervised classification under ArcGIS platform. The soil map was obtained from the Department of Remote Sensing and GIS, Tamil Nadu Agricultural University, Coimbatore. The rainfall data received at the nearest gauging station, Mettupalayam, was collected from the Tamil Nadu Surface and Groundwater Data Centre, Taramani. The daily rainfall events that come under the high, very high and extreme categories (> 64.5 mm) were only considered for runoff estimation to reduce bias (Hawkins, 1993). There were 34 storm events under this category. The corresponding AMC group was identified for each event (Table 2).

RESULTS AND DISCUSSION

The SCSCN method was adopted to estimate runoff generated in three sub-catchments of the Karamadai block: Pare Pallam, Mandrai Pallam and Periya Pallam of Tamil Nadu. The CN_w and S values (using Eq. 3) for sub-catchments were calculated for each AMC condition and applied to the storm events to calculate the runoff. The soil texture map of the three sub-catchments is shown in Fig. 3. The sandy clay loam texture is dominant in all three sub-catchments. The HSG was identified according to the soil textures. The

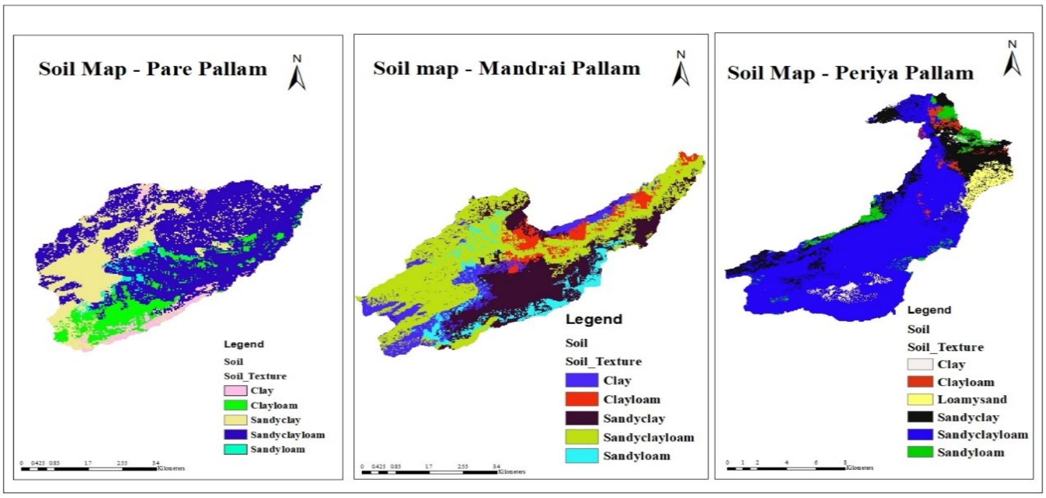

Fig. 3. *Soil texture map of Karamadai region*

Table 1. Classification of AMC

AMC Group	Total 5-day antecedent rainfall (mm)	
	Season-Dormant	Season- Growing
I	<13.0	<36.0
II	13.0-28.0	36.0-53.0
III	>28.0	>53.0

Source: Subramanya, 2008

Table 2. Selected storms with AMC condition

Year	Selected storm events with Rainfall depth (mm)	AMC
2000	74	I
	76	I
	101	I
2001	80.2	I
	75	III
2003	95.3	III
	67.6	III
2005	72	I
	120	I
	73	I
2006	90	III
2008	72	I
	65	II
2009	68	I
	65.2	III
2010	103	II
	84.2	II
2011	73	I
	66	III
	94	I
	97	III
2012	65.4	III
	76	II
2014	97.2	I
	97.1	III
2015	67.3	III
	82.3	III
	68	I
2016	220	I
2018	72	III
	80	I
2019	87.3	III
	89.1	I
	180.3	I

land-use map of the year 2006 was used to estimate runoff for the years 2000-2009, whereas the land use map of 2016 was used to estimate runoff for 2010-2019. The land use map prepared for the years 2006 and 2016 is shown in Fig. 4-5.

The weighted curve numbers obtained at three sub-catchments of the Karamadai block (normal, wet and dry conditions) are given in Tables 3-8. For the Pare Pallam catchment in the year 2006, the weighted CN number calculated at three AMC conditions (I, II, and III) was 34.96, 55.08, and 74.17, and the corresponding potential maximum soil moisture retention of soil was 472.497 mm, 207.1 mm, and 88.45 mm, respectively (Table 3). Similarly, in the year 2016, the weighted CN number was calculated at three AMC conditions (I, II, and III) and was 35.6, 55.79, and 74.71 and the corresponding potential maximum soil moisture retention of soil was 459.3 mm, 201.25 mm, and 85.93 mm, respectively (Table 4). The decrease in maximum soil moisture retention is mainly due to the increase in the built-up land area since 2016. Shrestha *et al.* (2021) also reported that changes in land use, particularly urban development, significantly impact runoff volume in Xiamen City, China. Chen *et al.* (2017), Astuti *et al.* (2019) and Hu *et al.* (2020) observed similar changes in runoff volume due to the changes in land use pattern in the contiguous United States (48 adjoining states and the District of Columbia (DC)), the Upper Brantas watershed of East Java, Indonesia and the area of Beijing, respectively.

For the Mandrai Pallam catchment, in the year 2006, the weighted CN numbers calculated at three AMCs (I, II and III) were 38.79, 59.13 and 77.21 and the potential maximum soil moisture retention of soil is obtained from CN value were 400.69 mm, 175.55 mm and 74.96 mm respectively (Table 5). Similarly, in 2016, the weighted CN number calculated at three AMCs were 39.01, 59.34 and 77.37, respectively. The corresponding potential maximum soil moisture retention of soil obtained from CN value were 397.09 mm 173.97 mm and 74.28 mm respectively (Table 6). For the Periya Pallam catchment in the year 2006, the weighted CN number calculated at three AMC conditions (I, II, and III) was 32.93, 52.8, and 72.4, and the corresponding potential maximum soil moisture retention of soil obtained from the CN value was 517.44 mm, 226.74 mm, and 96.82 mm, respectively (Table 7). In the year 2016, the weighted CN number was calculated to be 32.71 for AMC-I, 52.57 for AMC-II, and 72.19 for AMC-III. The potential maximum soil moisture retention of soil obtained from the CN value was 522.62 mm for AMC-I, 229.12 mm for AMC-II, and 97.83 mm for AMC-III (Table 8). The soil characteristics improved from 2006 to 2016 in this catchment, mainly due to the increase in open forest land, the cultivation of plantations, and banana crops. Du *et al.* (2022) observed that agroforestry and cover cropping increased aggregation and infiltration, which led to a reduction in runoff and soil erosion in 432 data points collected from China, USA, Europe, and Africa.

Table 3. CNw at Pare Pallam sub-catchment (2006)

Pare Pallam, 2006					
LULC	**HSG**	**Area in km^2**	**CN**	**Area * CN**	**CN_W**
Agriculture	A	0.17	49	8.33	
	B	1.68	69	115.92	
	C	0.97	74	71.78	
	D	0.02	79	1.58	
Banana and other plantation	A	0.04	39	1.56	
	B	0.70	60	42	
	C	0.44	71	31.24	
	D	0.03	80	2.4	
Beetalnuts	B	0.07	40	2.8	
	C	0.02	52	1.04	
Builtup land	B	0.03	70	2.1	
	C	0.01	80	0.8	
Coconut	A	0.07	40	2.8	
	B	1.88	61	114.68	
	C	0.97	72	69.84	
	D	0.09	80	7.2	
Dense Forest	A	0.01	19	0.19	
	B	2.67	38	101.46	
	C	2.86	58	165.88	
	D	0.17	61	10.37	
Open forest	A	0.01	26	0.26	
	B	3.06	40	122.4	
	C	0.81	60	48.6	
	D	0.19	63	11.97	
Scrub forest	A	0.07	33	2.31	
	B	2.13	47	100.11	AMC-I=34.96
	C	1.64	62	101.68	AMC-II =55.08
	D	0.41	67	27.47	AMC-III=74.17

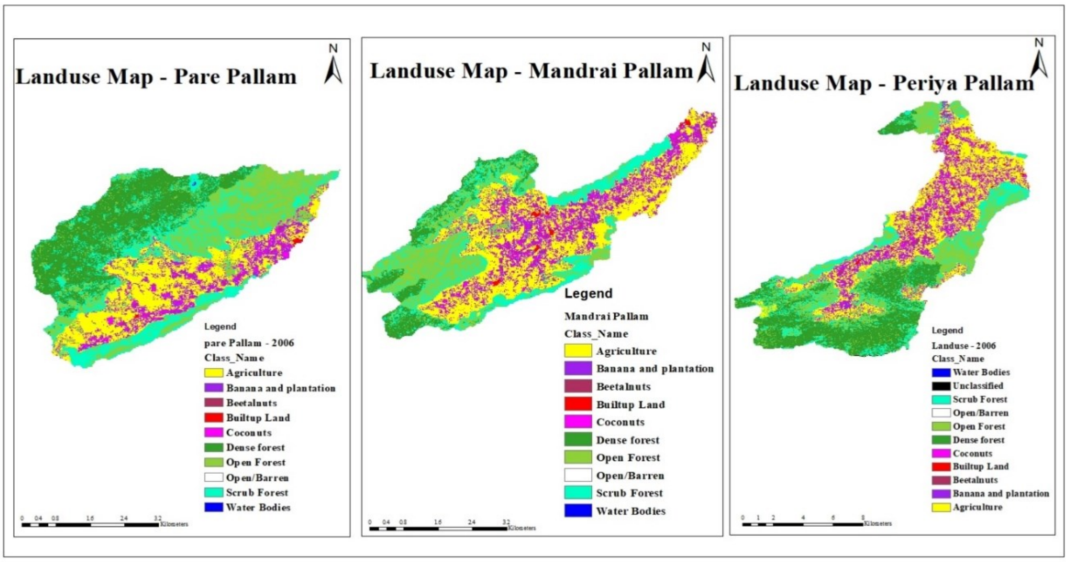

Fig. 4. *LULC map of Karamadai (year 2006)*

Table 4. CNw at Pare Pallam sub-catchment (2016)

Pare Pallam, 2016					
LULC	**HSG**	**Area in km^2**	**CN**	**Area * CN**	**CNw**
Agriculture	A	0.077	49	3.773	
	B	2.24	69	154.56	
	C	1.10	74	81.4	
	D	0.14	79	11.06	
Banana and other plantation	A	0.11	39	4.29	
	B	1.40	60	84	
	C	1.47	71	104.37	
	D	0.13	80	10.4	
Builtup land	A	0.02	54	1.08	
	B	0.19	70	13.3	
	C	0.24	80	19.2	
	D	0.03	85	2.55	
Coconut	A	0.04	40	1.6	
	B	1.19	61	72.59	
	C	0.31	72	22.32	
	D	0.05	80	4	
Dense Forest	A	0.01	19	0.19	
	B	0.21	38	7.98	
	C	2.26	58	131.08	
	D	0.13	61	7.93	
Open forest	A	0.05	26	1.3	
	B	7.23	40	289.2	
	C	1.44	60	86.4	
	D	0.37	63	23.31	
Scrub forest	A	0.03	33	0.99	
	B	0.08	47	3.76	
	C	0.59	62	36.58	
	D	0.02	67	1.34	
Open/Barren	A	0.004	69	0.276	
	B	0.01	74	0.74	AMC-I=35.61
	C	0.013	79	1.027	AMC-II =55.79
	D	0.003	84	0.252	AMC-III=74.72

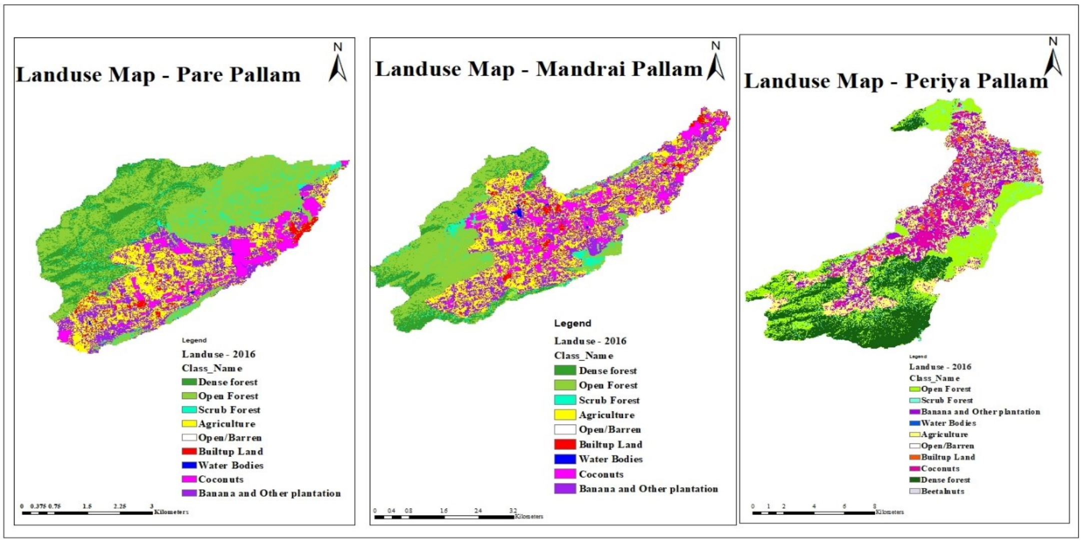

Fig. 5. *LULC map of Karamadai (year 2016)*

Table 5. CNw at Mandrai Pallam sub-catchment (2006)

Mandrai Pallam, 2006					
LULC	**HSG**	**Area in km^2**	**CN**	**Area * CN**	**CNw**
Agriculture	A	1.39	49	68.11	
	B	3.62	69	249.78	
	C	5.25	74	388.5	
	D	1.24	79	97.96	
Banana and other plantation	A	0.62	39	24.18	
	B	1.68	60	100.8	
	C	2.85	71	202.35	
	D	0.60	80	48	
Beetalnuts	A	0.002	35	0.07	
	B	0.08	40	3.2	
	C	0.11	52	5.72	
Builtup land	B	0.07	70	4.9	
	C	0.19	80	15.2	
Coconut	A	0.68	40	27.2	
	B	4.56	61	278.16	
	C	5.60	72	403.2	
	D	0.46	80	36.8	
Dense Forest	A	0.01	19	0.19	
	B	2.04	38	77.52	
	C	0.38	58	22.04	
	D	1.98	61	120.78	
Open forest	A	0.47	26	12.22	
	B	6.60	40	264	
	C	0.67	60	40.2	
	D	0.86	63	54.18	
Scrub forest	A	0.92	33	30.36	
	B	4.56	47	214.32	AMC-I= 38.79
	C	2.16	62	133.92	AMC-II = 59.13
	D	1.54	67	103.18	AMC-III= 77.21

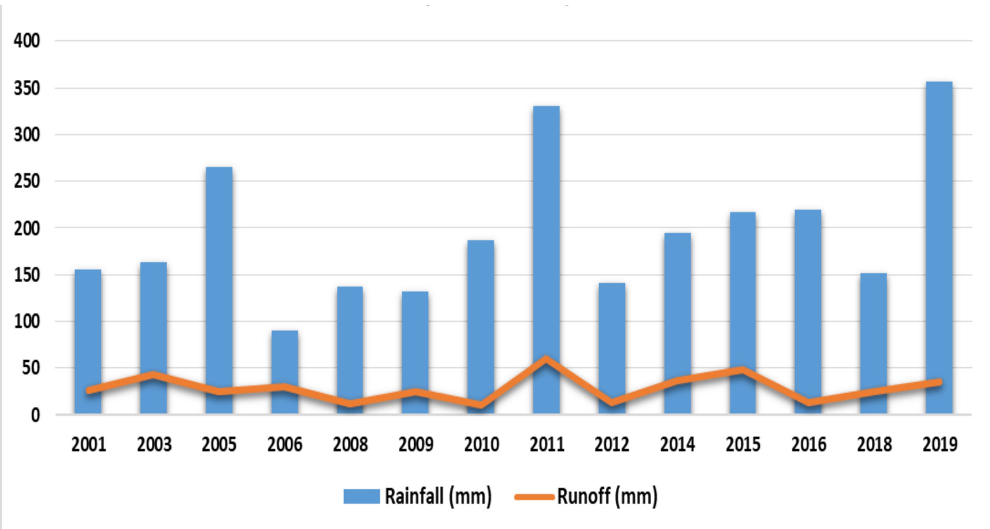

Fig. 6. *Yearly variation in runoff depth at Pare Pallam catchment*

Table 6. CNw at Mandrai Pallam sub-catchment (2016)

Mandrai Pallam, 2016					
LULC	**HSG**	**Area in km^2**	**CN**	**Area * CN**	**CNw**
Agriculture	A	1.04	49	50.96	
	B	4.72	69	325.68	
	C	5.15	74	381.1	
	D	2.18	79	172.22	
Banana and other plantation	A	1.30	39	50.7	
	B	2.46	60	147.6	
	C	5.94	71	421.74	
	D	0.74	80	59.2	
Builtup land	A	0.32	54	17.28	
	B	0.37	70	25.9	
	C	1.31	80	104.8	
	D	0.05	85	4.25	
Coconut	A	0.12	40	4.8	
	B	2.86	61	174.46	
	C	2.73	72	196.56	
	D	0.05	80	4	
Dense Forest	A	0.12	19	2.28	
	B	0.40	38	15.2	
	C	0.71	58	41.18	
	D	2.41	61	147.01	
Open forest	A	0.89	26	23.14	
	B	11.85	40	474	
	C	0.69	60	41.4	
	D	0.60	63	37.8	
Scrub forest	A	0.24	33	7.92	
	B	0.47	47	22.09	
	C	0.52	62	32.24	
	D	0.47	67	31.49	
Open/ Barren	A	0.09	69	6.21	
	B	0.05	74	3.7	AMC-I= 39.01
	C	0.13	79	10.27	AMC-II =59.35
	D	0.02	84	1.68	AMC-III=77.37

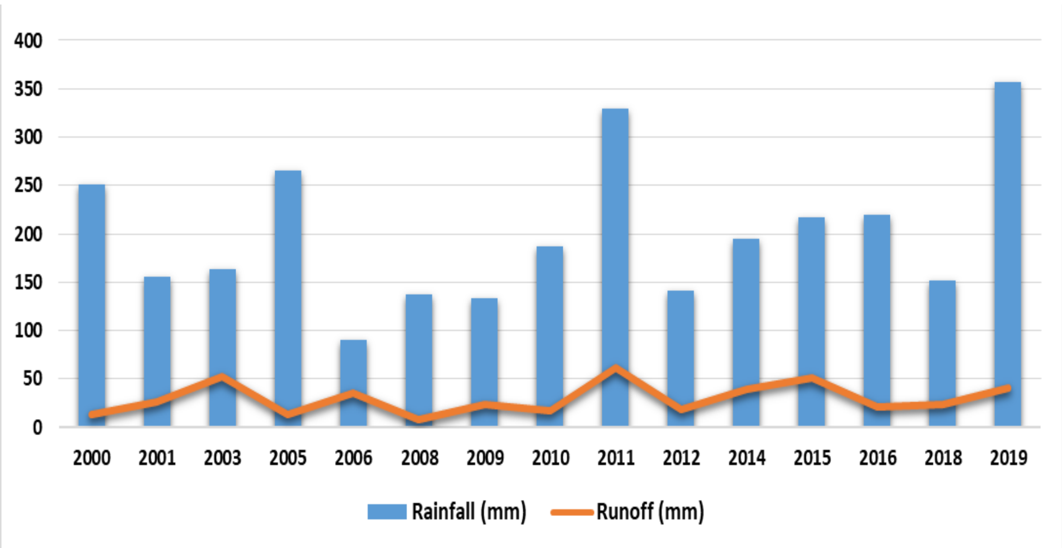

Fig. 7. *Yearly variation in runoff depth at Mandrai Pallam catchment*

Table 7. CNw aimed at Periya Pallam sub-catchment (2006)

		Periya Pallam, 2006			
LULC	**HSG**	**Area in km^2**	**CN**	**Area * CN**	**CNw**
Agriculture	A	3.24	49	158.76	
	B	19.6	69	1352.4	
	C	10.35	74	765.9	
	D	0.55	79	43.45	
Banana and other plantation	A	0.55	39	21.45	
	B	5.64	60	338.4	
	C	2.58	71	183.18	
	D	0.11	80	8.8	
Beetalnuts	A	0.20	35	7	
	B	0.12	40	4.8	
	C	0.23	52	11.96	
Builtup land	A	0.05	54	2.7	
	B	0.3	70	21	
	C	0.15	80	12	
	D	0.001	85	0.085	
Coconut	A	0.42	40	16.8	
	B	12.64	61	771.04	
	C	2.83	72	203.76	
	D	0.13	80	10.4	
Dense Forest	A	0.06	19	1.14	
	B	29.35	38	1115.3	
	C	2.61	58	151.38	
	D	1.13	61	68.93	
Open forest	A	3.01	26	78.26	
	B	16.23	40	649.2	
	C	3.35	60	201	
	D	0.68	63	42.84	
Scrub forest	A	3.69	33	121.77	
	B	11.61	47	545.67	
	C	3.24	62	200.88	
	D	0.56	67	37.52	
Open/Barren	A	0.002	69	0.138	
	B	0.02	74	1.48	AMC-I= 32.92
	C	0.04	79	3.16	AMC-II = 52.83
	D	0.003	84	0.252	AMC-III=72.40

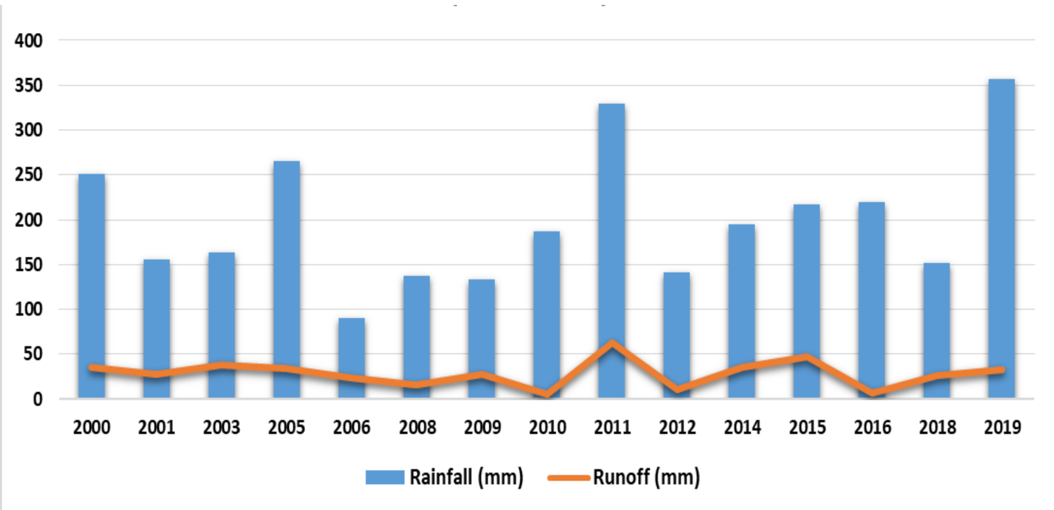

Fig. 8. *Yearly variation in runoff depth at Periya Pallam catchment*

Table 8. CNw aimed at Periya Pallam sub-catchment (2016)

Periya Pallam, 2016					
LULC	**HSG**	**Area in km^2**	**CN**	**Area * CN**	**CNw**
Agriculture	A	1.34	49	65.66	
	B	19.0	69	1311	
	C	5.54	74	409.96	
	D	0.37	79	29.23	
Banana and other plantation	A	3.21	39	125.19	
	B	9.00	60	540	
	C	5.66	71	401.86	
	D	0.23	80	18.4	
Beetalnuts	B	0.16	40	6.4	
	C	0.10	52	5.2	
Builtup land	A	0.34	54	18.36	
	B	1.58	70	110.6	
	C	1.76	80	140.8	
	D	0.1	85	8.5	
Coconut	A	0.29	40	11.6	
	B	10.37	61	632.57	
	C	2.70	72	194.4	
	D	0.12	80	9.6	
Dense Forest	A	0.20	19	3.8	
	B	30.56	38	1161.28	
	C	1.80	58	104.4	
	D	0.81	61	49.41	
Open forest	A	4.89	26	127.14	
	B	21.72	40	868.8	
	C	4.55	60	273	
	D	1.12	63	70.56	
Scrub forest	A	0.71	33	23.43	
	B	2.67	47	125.49	
	C	2.21	62	137.02	
	D	0.58	67	38.86	
Open/Barren	A	0.13	69	8.97	
	B	0.16	74	11.84	AMC-I=32.71
	C	0.18	79	14.22	AMC-II =52.57
	D	0.006	84	0.504	AMC-III=72.19

Askar (2014) used mean monthly rainfall data and observed a large deviation in the actual runoff depth at many parts of the Gomal watershed, Dohuk, However, Verma *et al.* (2021) considered large storm events for estimating surface runoff in in central and north-eastern regions of the United States. They observed better performance based on seven different performance indices compared to those estimated from all the storm events. So, daily rainfall events that fall under the heavy to the extreme category were used to avoid overestimating the results, where the rainfall ranges from 90 mm to 356.7 mm (heavy to extreme) in the catchment. The runoff depth in the Pare Pallam, Mandrai Pallam and Periya Pallam catchments varies from 9.97 mm to 60.35 mm, 7.4 mm to 61.4 mm and 5.4 mm to 62.2 mm (Minimum to maximum), respectively. The variation in annual runoff during 2000-2019 were shown in Fig. 6-8. In the Pare Pallam catchment, the average annual rainfall falls under heavy to extreme categories within the span of 20 years was 149.675 mm and the average runoff generated out of the same was 21.4 mm and a volume of 453228.79 m^3.

The runoff generated strongly depends not only on rainfall, but also on the AMC condition as well as the season of occurrence (Rao, 2020). It is evident that in 2008, there were two rainfall events with AMCI and AMC II, respectively, producing a runoff of 12.12 mm out of 137.0 mm. But in 2009, 25.40 mm of runoff was generated from 132.0 mm of rainfall as it was generated out of two rainfall events with AMC I and AMC III, respectively. The maximum runoff was generated in 2011 (60.35 mm) (Fig. 6).

Similarly, in the Mandrai Pallam catchment, the average annual rainfall falls under heavy to extreme categories within the span of 20 years was 149.675 mm and the average runoff generated out of the same was 22.14 mm and the volume of 1134328.222 m^3. The maximum runoff was generated in 2011 (61.42 mm) (Fig. 7).

Similarly, in the Periya Pallam catchment, the average annual rainfall falls under heavy to extreme categories within the span of 20 years was 149.625 mm and the average runoff generated out of the same was 21.42 mm and the volume of 2902078 m^3. The maximum runoff was generated in the year 2011 (62.22 mm) (Fig. 8). The above results show that the runoff volume will increase with increasing the catchment area (Subramanya, 2008).

Runoff created from almost similar amounts of rainfall with the same AMC conditions was considered to understand the effect of land use changes on runoff. In the Periya Pallam catchment, roughly 28.2 per cent runoff was generated from 95.2 mm rainfall in 2003 under AMC III conditions, whereas about equal runoff was generated from 97 mm rainfall in 2011, despite the open land having increased by 0.411 km^2. When the Periya Pallam catchment was examined as a whole, the effect was nullified due to vegetation enhancement in other parts of the catchment. Sajikumar and Remya (2015) studied the impact of LULC on the surface runoff in Manali Watershed of Kerala and observed a 60% reduction in the forest area. But the runoff estimated was not commensurate as the forest area has been converted to other land uses with similar characteristics.

Conclusion

On the basis of the study of surface runoff estimation using GIS and SCSCN method for sub-catchments of Karamadai block of Tamil Nadu, it was found that more runoff occurred in the Mandrai Pallam catchment compared to Periya Pallam and Pare Pallam of Karamadai , as the Mandrai Pallam catchment has less soil moisture retention capacity compared to the other two catchments. So, this catchment must be prioritised while implementing soil and water conservation measures. The AMC of the soil is highly important in the SCNCN approach since the CN varies depending on the soil and is considered when predicting runoff depth. So, the SCSCN methodology has been demonstrated to be the most effective method for handling huge data sets and wider catchment areas, and it aids in prioritising the regions where soil and water conservation measures should be implemented.

Conflict of interest

The authors declare that they have no conflict of interest.

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