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Spatial and temporal estimation of runoff in a semi-arid microwatershed of Southern India

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Abstract In a semi-arid microwatershed of Warangal district in Southern India, daily runoff was estimated spatially using Soil Conservation Service (SCS)-curve number (CN) method coupled with GIS. The groundwater status in this region is over-exploited, and precise estimation of runoff is very essential to plan interventions for this ungauged microwatershed. Rainfall is the most important factor governing runoff, and 75.8 % of the daily rainfall and 92.1 % of the rainy days which occurred were below 25 mm/day. The declines in rainfall and rainy days observed in recent years were 9.8 and 8.4 %, respectively. The surface runoff estimated from crop land for a period of 57 years varied from 0 to 365 mm with a mean annual runoff of 103.7 mm or 14.1 % of the mean annual rainfall. The mean annual runoff showed a significant reduction from 108.7 to 82.9 mm in recent years. The decadal variation of annual runoff from crop land over the years varied from 49.2 to 89.0 % which showed the caution needed while planning watershed management works in this microwatershed. Among the four land use land cover conditions prevailing in the area, the higher runoff (20 % of the mean annual rainfall) was observed from current fallow in clayey soil and lower runoff of 8.7 % from crop land in loamy soil due to the increased canopy coverage. The drought years which occurred during recent years (1991–2007) in crop land have increased by 3.5 %, normal years have increased by 15.6 %, and the above normal years have decreased by 19.1 %. This methodology can be adopted for estimating the runoff potential from similar ungauged watersheds with deficient data. It is concluded that in order to ensure long-term and sustainable groundwater utilization in the region, proper estimation of runoff and implementation of suitable water harvesting measures are the need of the hour.

Keywords ARCGIS · Curve number · LULC · SCS-CN method · Slope · Surface runoff

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Introduction

India with 2.3 % of the world's land supports more than 16 % of the population with 4 % of freshwater resource (Manorama Yearbook 1999). The growing population exerts tremendous pressure on water resources. The annual per capita water availability in India has decreased from 5177 m^3 in 1951 to 1654 m^3 in 2007. It is projected to decrease further to 1341 m^3 by 2025 and 1140 m^3 by 2050, thereby approaching a water scarce condition of less 1000 m^3 per year (MOWR 2008). According to the Central Ground Water Board, 15 % of the administrative blocks are over-exploited and are growing at a rate of 5.5 % per year. According to the Ministry of Water Resources, Government of India, the groundwater levels in 16 states of India have dropped more than 4 m during 1981–2000 period (Rejani et al. 2009). The most substantial decline in groundwater level is observed in north western India during 1980 to 2010 (30 years). In many parts of rainfed regions like Gujarat and Rajasthan, groundwater level declined more than 16 m (Sheetal Sekhri 2012). Between 2002 and 2008, water levels in northern India had declined by 40.5 mm per year and more than 109 km^3 of groundwater has disappeared from aquifers (Ranuzzi and Srivastava 2012). In the coming decades, accelerating population growth with surface water pollution and climate change may produce a drastic decline in fresh water supply.

Rainfed agriculture is practiced in 80 % of the world's agricultural land which generates 70 % of the staple foods, mainly the food for poor communities in developing and least-favoured areas (Sharma et al. 2010). Rainfed agriculture in India contributes 40 % to the national food basket and supports 40 % of the population and 60 % of livestock. It significantly contributes to 90 % of the coarse cereals, 87 % of the pulses and 74 % of the oil seeds (Srinivasarao et al. 2013a). Fragile agro-ecosystem with low farm productivity is a common feature of rainfed agriculture largely practiced in arid, semi-arid and dry sub-humid zones. Indian agriculture is highly vulnerable to climate change impacts since 60 % of the agricultural area is rainfed and more than 80 % of farmers are small and marginal (<1 ha land holding) having less adaptive capacity (Ranuzzi and Srivastava 2012; Srinivasarao et al. 2014). Rainwater management is one of the most critical components of rainfed farming, and the successful production of crops largely depends on how efficiently the soil moisture is conserved in situ and the surplus runoff is harvested and utilized (Rao et al. 2010; Srinivasarao et al. 2013b).

The watershed-based approach for planning soil and water conservation interventions is considered as an effective method for controlling erosion, harvesting the rainwater and utilizing it for supplementary irrigation and to recharge the aquifers in a watershed. Still, the planning of soil and water conservation interventions by taking microwatershed as a hydrological planning unit is considered to be very effective (Saptarshi and Raghavendra 2009). Microwatershed (area <5 km^2) development approach calls for a detailed understanding and analysis of various rainfall-runoff-related parameters such as land use, hydraulic properties of soil, soil moisture, slope, rainfall characteristics, etc. (Ramakrishnan et al. 2009).

The estimation of runoff and its long time variability is essential for the assessment of water yield potential and planning of soil and water conservation measures. In India, the availability of accurate information on runoff is scarcely available and that too in a few selected sites where recording and automatic hydrologic gauging stations are installed (Patil et al. 2008). Thus, there is an urgent need to develop techniques for estimation of surface runoff from ungauged basins (Zade et al. 2005). The Goparajpalli microwatershed is one among them with no gauging station. Even though there is deficit rainfall and frequent droughts, still large amount of water is flowing out into the drains during monsoon season in normal and above normal years and there is insufficient water during summer season (February to May). The groundwater status in the region is in over-exploited category. Hence, precise estimation of runoff is essential to plan the rainwater harvesting and in situ moisture conservation techniques for ungauged microwatersheds.

The curve number (CN) method, developed by the USDA-Soil Conservation Service, for predicting surface runoff from rainfall, is a widely accepted method in the world. Many researchers directly used, modified and evaluated the Soil Conservation Service (SCS)-CN model (Pandey and Sahu 2002; Mishra et al. 2008a; Mishra et al. 2008b; Soulis et al. 2009; Rejani et al. 2012) and estimated runoff. The use of Geographic Information System (GIS) is preferred over the traditional techniques in accurate estimation of surface runoff by storing and analyzing the factors responsible for runoff generation such as precipitation, topological, land use and soil physical properties of the land surface. Traditionally, an area-weighted average CN for the entire watershed is used to study the runoff of a watershed, and in this case, the details of spatial variation in the watershed are often lost (Kadam et al. 2012). Therefore, in this study, an attempt was made to develop a spatial surface runoff estimation model for Goparajpalli microwatershed using the SCS-CN techniques coupled with ARCGIS to obtain the spatial and temporal variation of the runoff.

Materials and methods

Study area

The study area, Goparajpalli microwatershed, lies in Warangal District of Telangana State, covering an area of 1660 ha (Fig. 1). It lies between 17° 46′ and 17° 50′ N

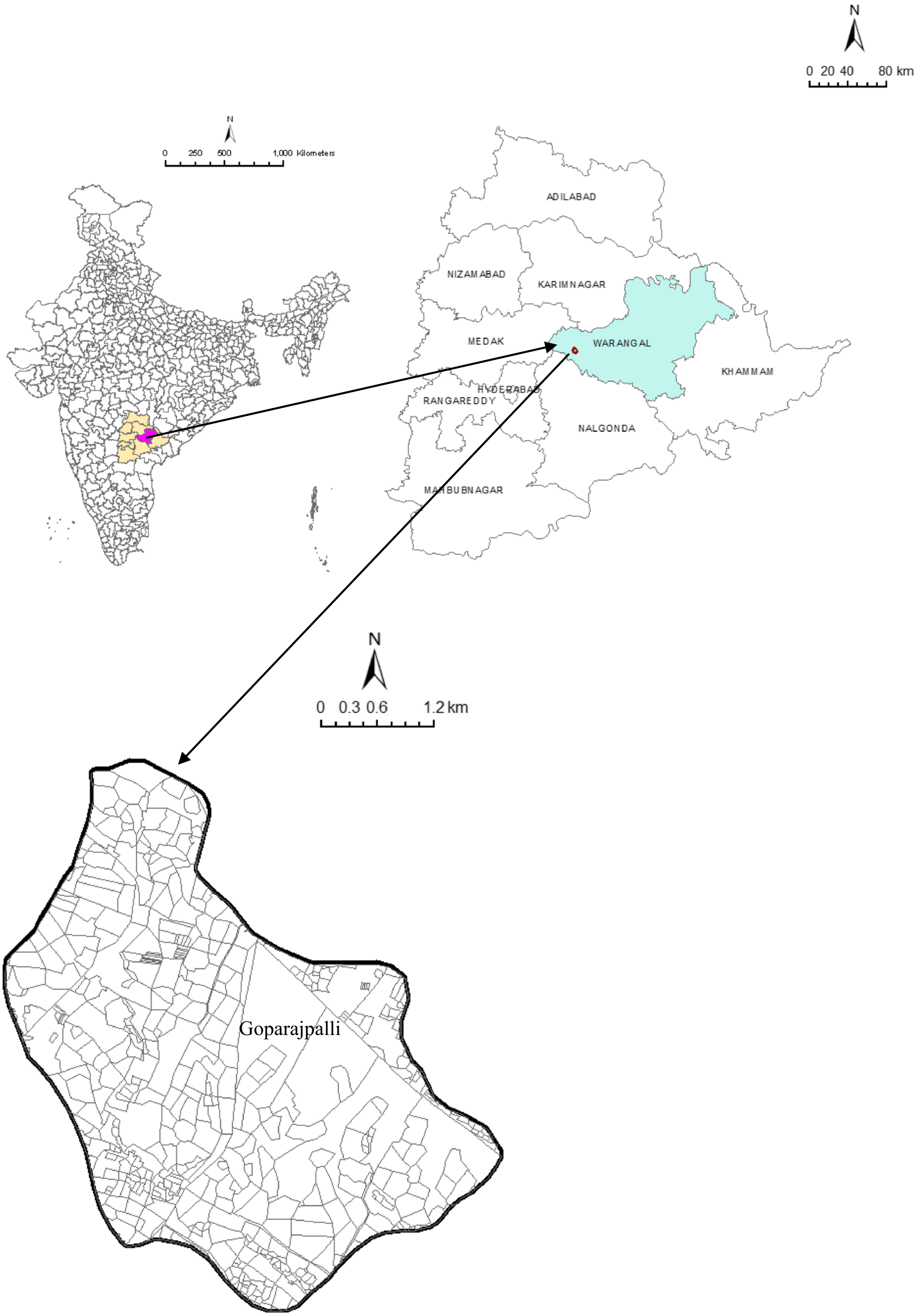


Fig. 1 Location map of the study area

latitude and 79° 4′ and 79° 8′ E longitude and is located in the semi-arid region of Deccan plateau, made up of granite rocks and hill formations, and cultivation depends mainly on seasonal rainfalls. Major portion of Goparajpalli microwatershed is characterized by clayey and cracking clayey soil with moderate to severe erosion, and the depth of the soil ranged from moderate to very deep (source: NBSS & LUP). Most of the streams/drains in this region are rainfed and therefore remain dry throughout the summer. The mean annual rainfall was estimated at 735 mm with 80 % of its contribution during southwest monsoon from June to September (Aphrodite data). The temperature of the region varies from a minimum of 11 °C in December–January to 45 °C in April–May (source: NICRA, CRIDA). The selected area is prone to weather shocks like deficient south-west monsoon, drought/deficient rainfall and delayed and deficient monsoon. In major portion of microwatershed, groundwater is extracted mainly by bore wells and utilized for drinking and irrigation purposes. The over-exploitation of groundwater for irrigation by bore wells in recent years has resulted in declining groundwater levels in the microwatershed. More than 90 % of the district is under rainfed agriculture. The major crops grown are paddy, cotton, maize, red gram, black gram, green gram, fodder and vegetables like chilli and tomato. Changing and increasingly variable climate is recognized as a potent threat to agriculture and food security. In view of this, the present work is focused on the development of a suitable runoff estimation model for the estimation of runoff potential and its variability, needed for the sustainable planning of the microwatershed.

Analysis of rainfall data

The daily rainfall is the major factor governing daily runoff, and rainfall data analysis is very important in runoff studies. Hence, Aphrodite daily rainfall data for 57 years (1951 to 2007) (0.25°×0.25°) was used for the data analysis. Overlaying of selected microwatershed boundary with the rainfall grid data showed that one rainfall grid is covering the entire study area, and hence, that grid data was selected and analyzed. The annual, mean annual and number of rainy days/year were estimated. The temporal variation (decadal and total) in mean annual rainfall and number of rainy days was worked out using coefficient of variation (CV). From hydrologic point of view, the daily rainfall events contributing to runoff are very important. Hence, number of rainy days, % rainfall and % rainy days which contributed to rainfalls <25, 25 to 50, 50 to 75, 75 to 100 and more than 100 mm/day were also estimated. A cumulative sum (CUSUM) chart is a plot of the cumulative differences between successive values and a target value. CUSUM method was used to determine the change in trend of annual rainfall over the years from the normal rainfall.

Analysis of land use land cover data

Land use land cover (LULC) patterns are highly dynamic and are rarely in stable equilibrium. The strongest seasonal variation of land cover occurs predominantly for arable land but is an important factor for other land use types, and it significantly influences the runoff generated. Land cover characteristics influence the infiltration conditions of the soil, temporal and spatial dynamics of rainfall events, runoff generation processes and initial conditions of the flood event particularly regarding antecedent moisture conditions in the catchment. Land use changes may have regional or even global effects and as a result of the accumulation of much small-scale local changes (Niehoff et al. 2002). Hence, it is important to note the changes in LULC over a period of time. Based on the availability of data, the variation in LULC for the period 2004 to 2012 was derived using the LULC map (NRSC) using spatial analyst extension. In order to study the effect of rainfall distribution on crop area, the variation in LULC area was related with the available rainfall data (mandal data) during this period.

Data collection and estimation of runoff

On a regional scale, the collection of small amounts of runoff using macro-catchments during rainy season and using this water for supplementary irrigation can increase the crop yield considerably. The adoption of improved agronomic practices can further increase the agricultural production in rainfed areas (Pathak et al. 2009). Estimation of runoff needs the data pertaining to rainfall, soil type and LULC of the area. The 57-year daily rainfall grid data (Aphrodite), LULC map of NRSC and soil map of NBSS & LUP were used in the present study. The contours from SOI toposheet (1:25,000) were digitized and digital elevation model (DEM) was generated from contours. The slope map was derived from DEM using ARCGIS 10. These thematic layers were clipped using the microwatershed boundary. Soil and LULC data was intersected to generate new polygons associated with soil type and LULC. The runoff was estimated using the SCS-CN method given below.

SCS-CN method

The SCS-CN method (SCS 1972) is an empirical equation predicting runoff from rainfall, using a shape parameter S based on soil, vegetation, land use and soil moisture prior to a rainfall event

$$Q = \frac{(P{-}0.2S)^2}{P + 0.8S} \text{ for } P > 0.2 \text{ S} \quad (1)$$

$$Q = 0 \text{ for } P \leq 0.2 \text{ S} \quad (2)$$

where P=total precipitation (mm), Q=surface runoff (mm) and S=potential maximum retention or infiltration (mm). The value of S is given as

$$S = \frac{25400}{\text{CN}} - 254 \quad (3)$$

The potential maximum retention storage (S) is related to a curve number (CN), which is a function of land use, land treatments, soil type and antecedent moisture condition of the area. CN is dimensionless, and its value varies from 0 to 100. It can be obtained from standard tables; however, CN estimation based on real data from local or nearby similar watersheds was used. The daily runoff depends on the daily rainfall, antecedent moisture condition (AMC), soil properties, LULC and slope of the land. The entire area was classified in terms of areas under crops, current fallow, other waste land and scrub land using LULC map. About 90 % of the area was characterized by clayey soil and remaining by gravelly loam textured soil (Fig. 2).

Based on soil characteristics, such as infiltration characteristics, depth and texture of the soil profile, the soils were classified into two major hydrologic groups, namely, B (moderately low runoff potential) and C (moderately high runoff potential) (Tripathi and Singh 1993). The three levels of AMC used were AMC I (low runoff potential; soils are dry; 5-day antecedent rainfall <35 mm), AMC II (average condition; 35 mm>5-day antecedent rainfall <52.5mm) and AMC III (high runoff potential; soil is saturated; 5-day antecedent rainfall >52.5 mm) (Kadam et al. 2012). Hence, the different thematic layers were prepared in ARCGIS and intercepted and CN values corresponding to three AMC conditions, namely, CN_2, CN_3 and CN_1 were assigned (Table 1) for each new polygon, and the runoff was estimated spatially and temporally.

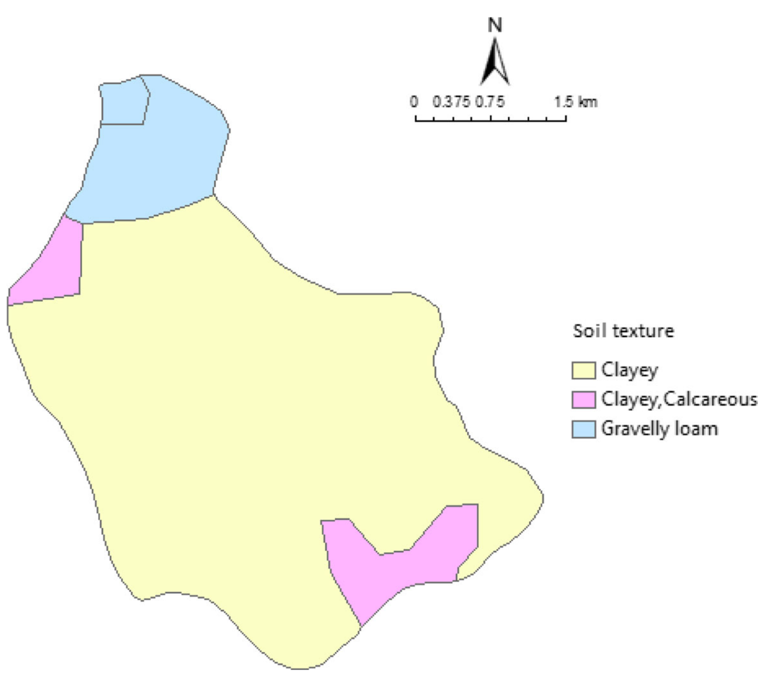


Fig. 2 Soil texture map of Goparajpalli microwatershed

Table 1 CN values corresponding to three AMC conditions for Goparajpalli microwatershed

Land use land cover	CN_2 values	Factor for CN_2 to CN_3	Factor for CN_2 to CN_1
Crop land (clayey soil)	80	1.14	0.79
Crop land (loamy soil)	66	1.30	0.67
Scrub land (clayey soil)	82	1.14	0.79
Scrub land (loamy soil)	68	1.30	0.67
Other waste land (clayey soil)	82	1.14	0.79
Other waste land (loamy soil)	68	1.30	0.67
Current fallow (clayey soil)	83	1.14	0.79
Current fallow (loamy soil)	69	1.30	0.67

Based on CN_2 values of nearby areas and CN_3 and CN_1 factors from Murty and Takeuchi (1982)

The daily runoff corresponding to different LULC conditions was estimated, and annual runoff was derived spatially. The annual rainfall and runoff for the selected period (1951 to 2007) were analyzed for its temporal variation. Cumulative sum method (CUSUM method) was used to determine the change in trend of annual rainfall over the years from the normal rainfall.

The thematic layer of mean annual runoff (mm) was intercepted with the catchments generated from DEM, and mean annual runoff volume was estimated using this runoff and shape area of the new polygons generated. This runoff volume was dissolved for the corresponding catchment polygons using the data management-dissolve tool bar. This runoff potential estimated can be utilized for planning water harvesting structures.

Rainfall and runoff distributions from crop land during drought and normal years

The annual runoffs occurring in an area during normal, above normal and drought years are very essential for planning the water harvesting structures needed for supplementary irrigation. The mean annual rainfall during 1961–1990 (base line period) was estimated for categorizing the years into normal, above normal and drought years. The years with mean annual rainfall >+19 % was classified as above normal year, −19 to +19 % as normal year rainfall, −19 to −25 % as mild drought year, −25 to −50 % as moderate drought year and <−50 % as severe drought year. In order to observe the variability of the rainfall and runoff over the long period of 57 years (1951 to 2007), the mean annual rainfall and runoff which occurred during this period were divided into two blocks, namely, 1951 to 1990 for analyzing the variability of these two parameters in the past and 1991 to 2007 for estimating the recent variability.

Results and discussion

Temporal variation of rainfall and rainy days in the microwatershed

The analysis of 57-year daily rainfall data (Aphrodite) showed that the number of rainy days varied from 37 to 86 per year with a mean value of 63 rainy days. The annual rainfall ranged from 390 to 1181 mm with a mean annual rainfall of 735 mm (Fig. 3). The decadal variation (CV) of rainfall ranged from 14.8 to 31.1 %, and rainy days ranged from 10.4 to 22.6 % during 1951–2007. The variation (CV) of annual rainfall and rainy days over the 57 years was estimated as 24.3 % and rainy days as 18.5 % (Table 2). Around 75.8 % of the daily rainfall and 92.1 % of the rainy days which occurred were below 25 mm/day (Tables 3 and 4). Extreme rainfall events with more than 75 mm/day have occurred only seven times in the microwatershed during the 57-year period. These results showed uniform distribution of rainfall in the microwatershed for most of the period.

The change in the trend of annual rainfall over the years from the normal rainfall was determined using the CUSUM method, and the highest CUSUM value obtained during 1997 showed the change point. The mean annual runoff has decreased from 749.3 mm (1951 to 1997) to 665.7 mm (1998 to 2007) (Fig. 4). The declines in rainfall and rainy days were 9.8 and 8.4 %, respectively, in these periods.

Generation of DEM and slope

The DEM of Goparajpalli microwatershed was generated using the digitized contour map, and the elevation of the microwatershed ranged from 432 to 510 m above MSL (Fig. 5). Majority of the study area falls under very

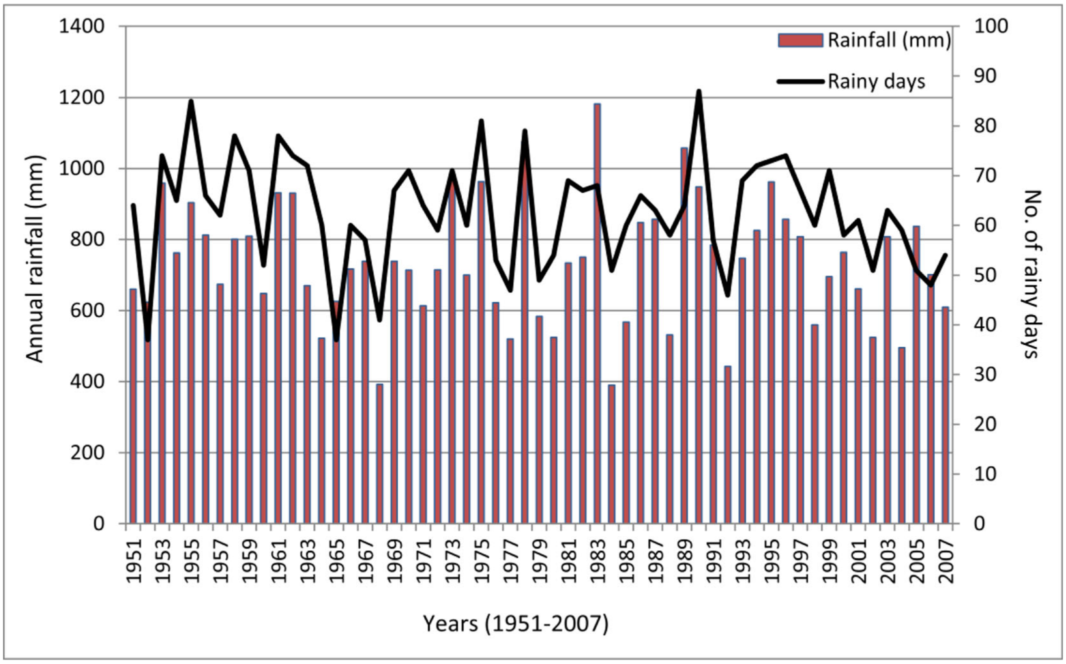


Fig. 3 Temporal variation of rainfall and rainy days in the microwatershed

gentle to gentle slope class with clayey soil indicating the need of water retention for longer time to enhance the chance of infiltration and recharge. The slope of the area influences the runoff, recharge and flow direction of surface water. As per the IMSD guidelines, the slopes ranging from 0 to 1 % are classified as level, 1–3 % as very gentle slope, 3–5 % as gentle, 5–10 % as moderate, 10–15 % as slightly steep, 15–35 % as moderately steep and >35 % as very steep (Ramakrishnan et al. 2009). The slope map derived using ARCGIS showed that out of 1660 ha of the microwatershed, 1353-ha area has a slope less than 5 % (Fig. 6). Hence, the SCS-CN model can be directly applied in this microwatershed without slope adjustment in the CN.

Table 2 Decadal and overall variation (CV) of annual rainfall and rainy days in the microwatershed

Years	Mean annual rainfall (mm)	CV of rainfall (%)	Mean of rainy days	CV of rainy days (%)
1951–1960	765.5	14.8	65.4	20.7
1961–1970	698.4	23.5	61.7	22.3
1971–1980	728.6	27.6	61.7	19.4
1981–1990	786.7	31.1	65.3	14.3
1991–2000	744.7	20.0	64.7	14.1
2001–2007	662.4	19.8	55.3	10.4
1951–2007	734.7	24.3	62.7	18.5

Spatial and temporal variation of LULC

Land use pattern of a watershed influences its runoff and evapotranspiration. The LULC of the selected study area consists of area under crops, current fallow, other waste land, scrub land and water bodies. The major portion of the area is under crop followed by current fallow (Fig. 7). The LULC data for the period 2004–12 showed a significant variation in the area under crops and current fallow due to the aberrations in the south-west monsoon (Table 5). The area covered under water bodies declined over the years. The area under crops showed a significant reduction, and area under current fallow increased during 2004–2005 due to deficient south-west monsoon and 2009–2010 due to non-uniform distribution of south-west monsoon. The change in area under the crops significantly influences the runoff.

Runoff corresponding to different LULC

The runoff corresponding to two different soils, AMC conditions and LULC varied considerably (Fig. 8a, b). The annual runoff from loamy soil ranged from 8.7 to

Table 3 Daily rainfall thresholds in the microwatershed (1951–2007)

Year	Rf <25 mm/day		Rf 25<50 mm/day		Rf 50<75 mm/day		Rf 75<100 mm/day		Rf >=100 mm/day	
	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall
1951	95.3	85.9	4.7	14.1	0.0	0.0	0.0	0.0	0.0	0.0
1952	86.5	48.7	8.1	20.7	2.7	9.3	0.0	0.0	2.7	21.3
1953	91.9	77.5	8.1	22.5	0.0	0.0	0.0	0.0	0.0	0.0
1954	89.2	66.2	7.7	18.5	3.1	15.3	0.0	0.0	0.0	0.0
1955	95.3	85.7	4.7	14.3	0.0	0.0	0.0	0.0	0.0	0.0
1956	90.9	66.7	7.6	25.0	1.5	8.3	0.0	0.0	0.0	0.0
1957	95.2	88.3	4.8	11.7	0.0	0.0	0.0	0.0	0.0	0.0
1958	93.6	75.8	5.1	16.3	1.3	8.0	0.0	0.0	0.0	0.0
1959	90.1	72.9	9.9	27.1	0.0	0.0	0.0	0.0	0.0	0.0
1960	96.2	86.7	3.8	13.3	0.0	0.0	0.0	0.0	0.0	0.0
1961	92.3	75.3	6.4	18.6	1.3	6.0	0.0	0.0	0.0	0.0
1962	86.5	65.2	13.5	34.8	0.0	0.0	0.0	0.0	0.0	0.0
1963	97.2	87.8	2.8	12.2	0.0	0.0	0.0	0.0	0.0	0.0
1964	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1965	86.5	58.6	10.8	27.1	0.0	0.0	2.7	14.4	0.0	0.0
1966	95.0	83.2	3.3	9.7	1.7	7.1	0.0	0.0	0.0	0.0
1967	84.2	60.4	15.8	39.6	0.0	0.0	0.0	0.0	0.0	0.0
1968	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1969	91.0	74.9	9.0	25.1	0.0	0.0	0.0	0.0	0.0	0.0
1970	95.8	87.8	4.2	12.2	0.0	0.0	0.0	0.0	0.0	0.0
1971	98.4	92.2	1.6	7.8	0.0	0.0	0.0	0.0	0.0	0.0
1972	89.8	68.4	6.8	15.5	3.4	16.1	0.0	0.0	0.0	0.0
1973	87.3	65.4	12.7	34.6	0.0	0.0	0.0	0.0	0.0	0.0
1974	91.7	74.9	8.3	25.1	0.0	0.0	0.0	0.0	0.0	0.0
1975	92.6	73.6	6.2	20.3	1.2	6.1	0.0	0.0	0.0	0.0
1976	94.3	80.1	5.7	19.9	0.0	0.0	0.0	0.0	0.0	0.0
1977	95.7	88.5	4.3	11.5	0.0	0.0	0.0	0.0	0.0	0.0
1978	86.1	59.5	12.7	32.2	0.0	0.0	1.3	8.3	0.0	0.0
1979	89.8	75.6	10.2	24.4	0.0	0.0	0.0	0.0	0.0	0.0
1980	98.1	92.8	1.9	7.2	0.0	0.0	0.0	0.0	0.0	0.0
1981	94.2	81.4	5.8	18.6	0.0	0.0	0.0	0.0	0.0	0.0
1982	92.5	75.3	7.5	24.7	0.0	0.0	0.0	0.0	0.0	0.0
1983	80.9	52.6	13.2	25.1	4.4	15.9	1.5	6.5	0.0	0.0
1984	94.1	77.3	5.9	22.7	0.0	0.0	0.0	0.0	0.0	0.0
1985	98.3	94.9	1.7	5.1	0.0	0.0	0.0	0.0	0.0	0.0
1986	86.4	57.9	12.1	33.8	1.5	8.2	0.0	0.0	0.0	0.0
1987	92.1	76.7	6.3	16.2	1.6	7.1	0.0	0.0	0.0	0.0
1988	96.6	87.4	3.4	12.6	0.0	0.0	0.0	0.0	0.0	0.0
1989	84.4	52.5	10.9	25.2	3.1	11.6	0.0	0.0	1.6	10.7
1990	93.1	78.8	6.9	21.2	0.0	0.0	0.0	0.0	0.0	0.0
1991	87.7	64.4	10.5	28.5	1.8	7.1	0.0	0.0	0.0	0.0

Table 3 (continued)

Year	Rf <25 mm/day		Rf 25<50 mm/day		Rf 50<75 mm/day		Rf 75<100 mm/day		Rf >=100 mm/day	
	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall	% of rainy days	% of cumulative rainfall
1992	97.8	92.2	2.2	7.8	0.0	0.0	0.0	0.0	0.0	0.0
1993	95.7	83.1	2.9	8.3	1.4	8.5	0.0	0.0	0.0	0.0
1994	94.4	80.8	4.2	12.5	1.4	6.7	0.0	0.0	0.0	0.0
1995	89.0	70.7	9.6	23.2	1.4	6.1	0.0	0.0	0.0	0.0
1996	86.5	57.9	10.8	28.1	2.7	14.0	0.0	0.0	0.0	0.0
1997	89.6	65.2	9.0	26.3	1.5	8.6	0.0	0.0	0.0	0.0
1998	98.3	95.5	1.7	4.5	0.0	0.0	0.0	0.0	0.0	0.0
1999	94.4	82.3	5.6	17.7	0.0	0.0	0.0	0.0	0.0	0.0
2000	93.1	73.0	5.2	14.5	0.0	0.0	1.7	12.6	0.0	0.0
2001	91.8	75.7	8.2	24.3	0.0	0.0	0.0	0.0	0.0	0.0
2002	94.1	81.1	5.9	18.9	0.0	0.0	0.0	0.0	0.0	0.0
2003	95.2	85.7	4.8	14.3	0.0	0.0	0.0	0.0	0.0	0.0
2004	93.2	76.7	6.8	23.3	0.0	0.0	0.0	0.0	0.0	0.0
2005	80.4	56.8	19.6	43.2	0.0	0.0	0.0	0.0	0.0	0.0
2006	89.6	57.5	4.2	9.3	4.2	18.7	0.0	0.0	2.1	14.5
2007	90.7	70.0	7.4	20.7	1.9	9.3	0.0	0.0	0.0	0.0

13.1 % whereas, from clayey soil, it ranged from 14 to 20 % of the mean rainfall. No runoff was observed during 1964, 1968, 1971, 1977, 1980, 1984, 1992, 1998 and 2004 due to low-intensity storms (Fig. 8a and Table 3) with 75 to 100 % of rainfall below 25 mm/day, and remaining rainfall ranged from 25 to 50 mm/day. The annual rainfall in these years was less than 560 mm except in 1971. The annual rainfall received in 1971 was 613.7 mm, but no runoff was observed because 92.2 % rainfall was less than 25 mm/day and remaining rainfall was less than 50 mm/day (Table 3). The soil map of the microwatershed showed that more than 90 % of the area is characterized by clayey soil. Hence, the runoff variation in clayey soil under different LULC conditions is more important.

Among the four LULCs prevailing in the clayey soil area, higher runoff (20 % of the mean annual rainfall) was observed from current fallow because of the disturbed soil left without vegetative cover. The lower runoff (14.1 % of the mean annual runoff) was observed from crop land due to the higher canopy coverage existing during the monsoon period. The runoff observed from scrub land and other waste land was estimated as 17.6 % of the mean annual rainfall.

Table 4 Rainy days and rainfall corresponding to different rainfall thresholds (1951–2007)

% Rainy days	% Rainfall	Rainfall threshold (mm/day)
92.1	75.8	<25
6.9	19.2	25 to <50
0.8	3.5	50 to <75
0.1	0.7	75 to <100
0.1	0.8	>100

Temporal variation of runoff from crop land over the years

The temporal variation of long-term runoff from crop land for a period of 57 years is presented in Fig. 8a. The surface runoff estimated using the SCS-CN model showed that the annual runoff varied from 0 to 365 mm with a mean annual runoff of 103.7 mm (14.1 % of the mean annual rainfall).

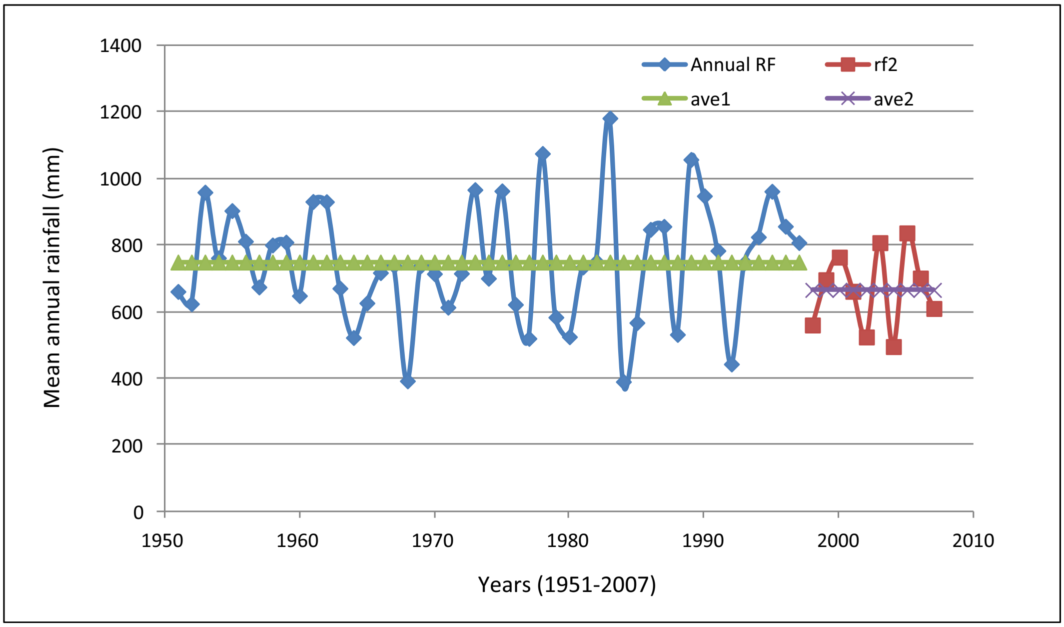


Fig. 4 Variation in the trend of rainfall over the years (1951–2007)

The change point in the trend of annual runoff determined using the CUSUM method was 1996. The mean annual rainfall showed a significant reduction from 108.7 to 82.9 mm during 1951–1996 to 1997–2007. No significant variation in decadal runoff over the years was noted. The mean annual runoff (decadal) for the

Fig. 5 DEM generated from contours of Goparajpalli

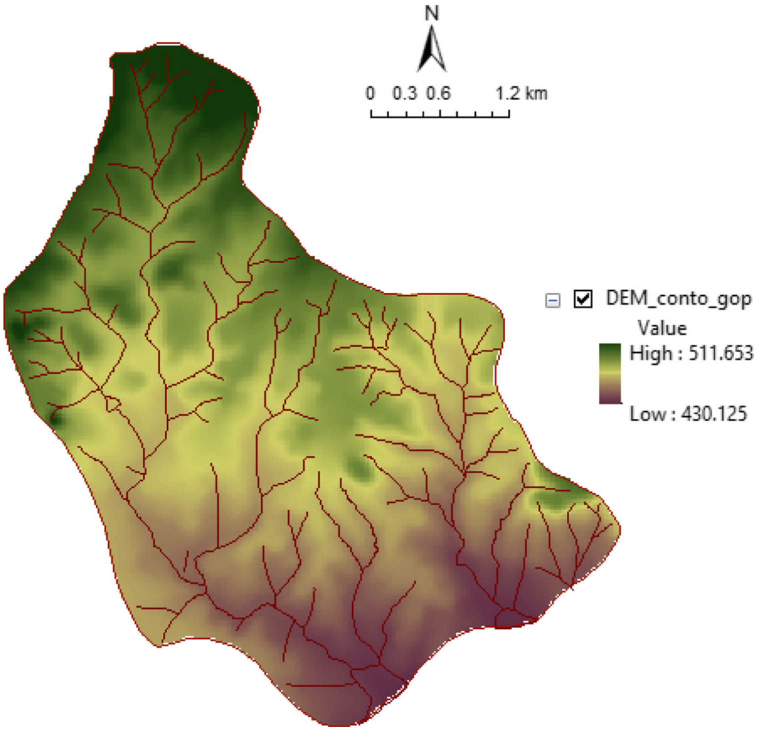
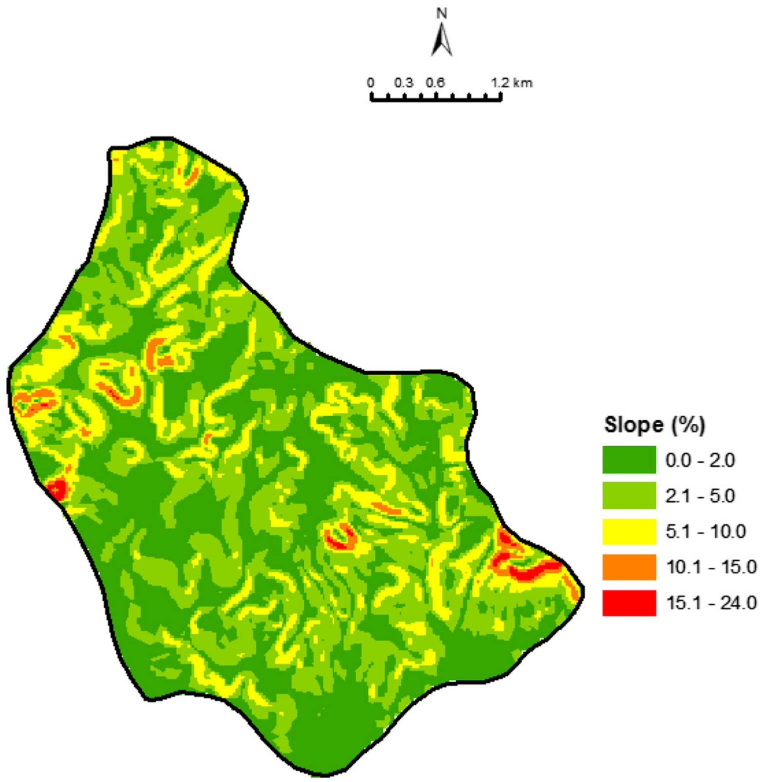


Fig. 6 Slope map (%) of Goparajpalli microwatershed



period 1951–2007 was highest during 1981–1990. The decadal variation of annual runoff over the years varied from 49.2 to 89.0 % with a mean value of 73 % (Table 6). This wide range of variation in the annual runoff (decadal) showed the caution needed while planning watershed management works in the

Fig. 7 Land use land cover map of the microwatershed during 2011–2012 (source: NRSC)

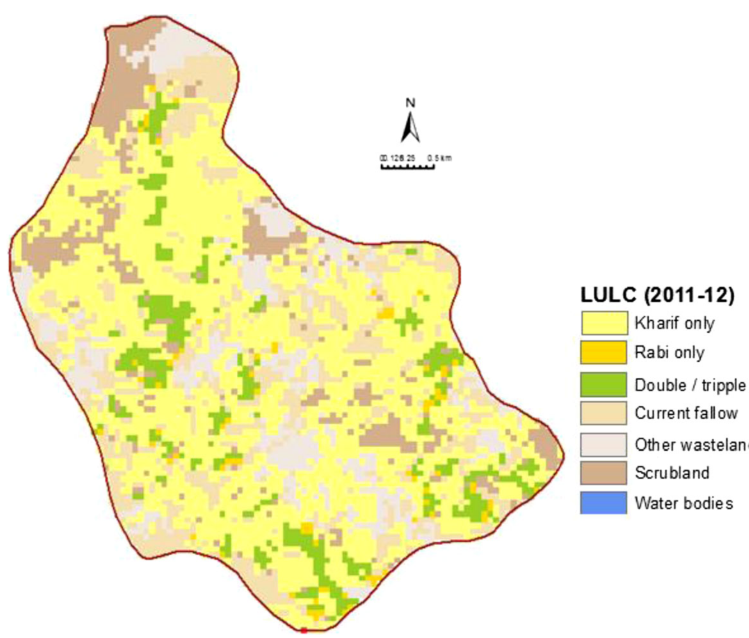


Table 5 Changes in the land use land cover and rainfall (mandal data) for the period 2004–12

Years	Area under different land use land cover (ha)								Rainfall (mm)
	Kharif crop	Rabi crop	Double crop	Total crop area	Current fallow	Other waste land	Scrub land	Water bodies	
2004–2005	504.1	139.0	55.3	698.4	542.9	221.9	190.6	–	495.0
2005–2006	367.6	198.2	288.4	854.2	393.5	220.3	182.5	5.8	837.0
2006–2007	609.6	36.9	487.2	1133.7	114.1	217.0	182.3	6.8	949.0
2007–2008	391.6	59.8	637.5	1088.9	162.8	203.2	191.4	7.2	976.0
2008–2009	744.9	29.3	221.9	996.1	293.8	182.3	180.4	1.1	995.0
2009–2010	470.9	47.4	101.7	620.0	663.0	176.3	191.7	–	706.0
2010–2011	960.7	11.3	189.8	1161.8	117.1	190.2	181.9	–	880.0
2011–2012	816.2	25.8	126.4	968.4	319.5	190.3	175.1	–	753.0

microwatershed. This methodology can be adopted for estimating the runoff potential from similar ungauged watersheds with deficient data.

Spatial variation of runoff in the catchment

The mean annual runoff corresponding to each LULC was estimated spatially using the daily runoff. This mean annual runoff was intercepted and dissolved with the catchments generated from DEM, and the runoff volume was generated catchment wise (Fig. 9). These runoff volumes estimated catchment wise for the microwatershed could be utilized for planning the site-specific water harvesting structures needed for the sustainable management of the microwatershed. The runoff (as % of mean annual rainfall) was slightly less (8.7 to 13.1 % of the mean annual rainfall) in the upstream of the microwatershed because of the high seepage from the loamy soil, and the runoff was high (14.1 to 19.7 % of the mean annual rainfall) in the downstream due to the low seepage in the clayey soil (Fig. 10). The mean annual runoff from major portion of the microwatershed ranged from 12.0 to 20.0 % of the mean annual rainfall.

Rainfall and runoff distributions in crop land during normal and drought years

The mean annual rainfall during 1961–1990 (base line period) was determined as 737.9 mm. The rainfall during above normal years was >878.2 mm, normal years ranged from 597.7 to 878.1 mm, mild drought years ranged from 553.5 to 597.6 mm, moderate drought years ranged from 369.0 to 553.4 mm, and severe drought years were <368.9 mm (Table 7). The relationship between rainfall and runoff which resulted from crop land was analyzed. During 1951 to 2007 (57 years), 21.1 % of the years were drought years which resulted in 4.8 to 9.4 % of annual rainfall as runoff, 59.6 % were normal year with 13.9 % runoff, and 19.3 % were above normal year with the higher runoff of 18.7 %. In order to observe the variability of the rainfall and runoff over the 57 years, the period was divided into two blocks. During the first 40-year period (1951–1990), the number of drought-affected years was 20 % whereas number of normal years was 55 % and above normal years was 25 %. During the recent 17-year period (1991–2007), the number of drought-affected years was 23.5 % whereas number of normal years was 70.6 %, and above normal year was 5.9 %. The drought years which occurred during recent years (1991–2007) have increased by 3.5 %, normal years have increased by 15.6 %, and the above normal years have decreased by 19.1 %. During 1951–1990, the mean annual runoffs which occurred during mild and moderate drought years were 3.5 and 9.4 %, normal year was 13.5 %, and above normal year was 19.0 % of the mean annual rainfall. The mean annual runoff which occurred during recent years (1991–2007) in above normal years and mild drought years has decreased by 3.3 and 9.4 % of the annual rainfall, respectively. This information on runoff potential available during normal, above normal and dry years should be

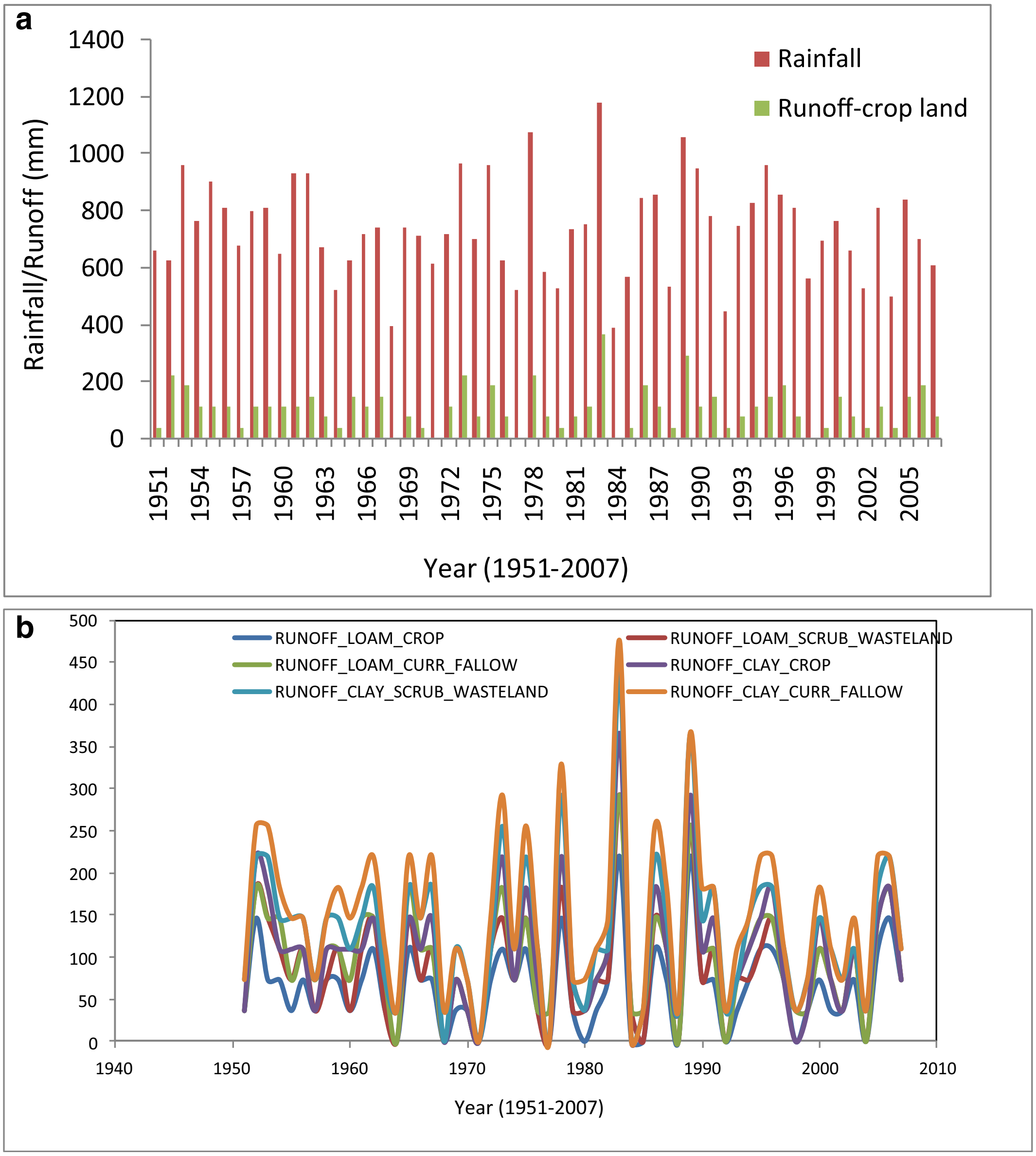


Fig. 8 **a**. Temporal variation of long-term rainfall and runoff from crop area in the microwatershed. **b** Long-term variability of annual runoff under different land use land cover

Table 6 Decadal and overall variation (CV) of mean annual runoff from the crop land

Period	Mean annual runoff (mm)	Coefficient of variation of runoff (CV) (%)
1951–1960	113.2	49.2
1961–1970	87.6	59.6
1971–1980	98.6	83.8
1981–1990	131.4	89.0
1991–2000	94.9	63.3
2000–2007	93.9	58.8
1951–2007	103.7	73.0

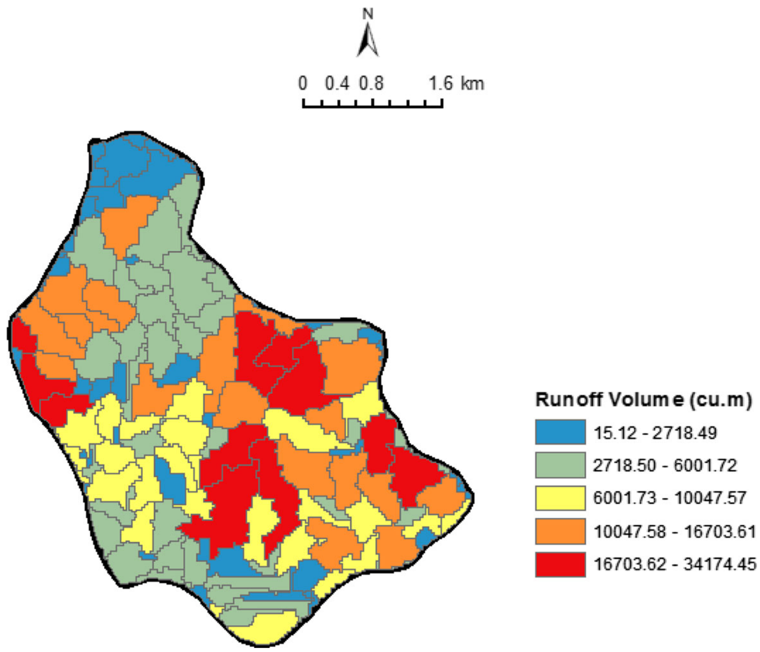


Fig. 9 Spatial distribution of mean annual runoff volume (m^3) (1951–2007)

considered while planning the interventions in the microwatersheds.

Summary and conclusions

In this study, the SCS-CN model coupled with ARCGIS was used to estimate the surface runoff from Goparajpalli semi-arid microwatershed in Southern India. It was revealed that the runoff corresponding to different soils, AMC conditions and LULC varied significantly. Among the four LULCs prevailing in the area, higher runoff (19.7 % of the mean annual rainfall) was observed from current fallow in the clayey soil because of the disturbed soil left without vegetative cover, and lower runoff (8.7 % of the mean annual

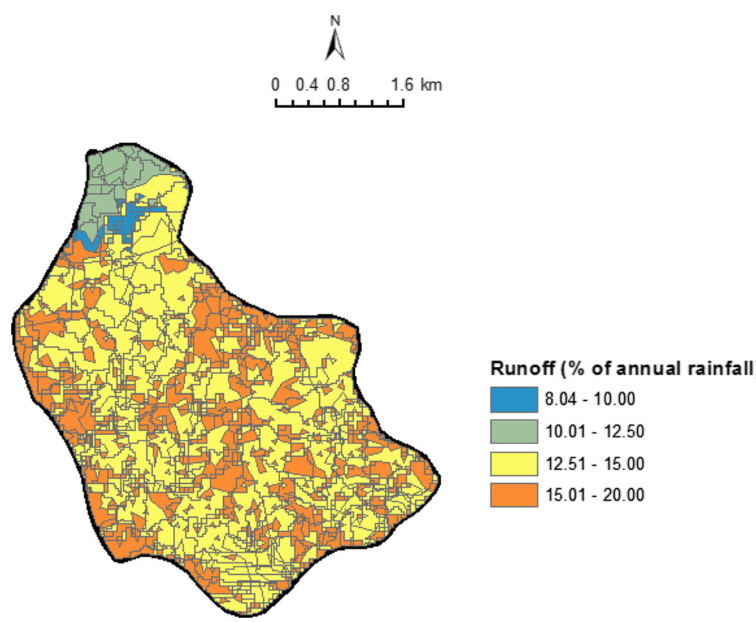


Fig. 10 Spatial distribution of runoff (% of mean annual rainfall) (1951–2007)

Table 7 Runoff from crop land of the Goparajpalli microwatershed during normal, above normal and dry years (1951–2007)

Categorization of years	1951–1990		1991–2007		1951–2007	
	No. of years (% of years)	Mean runoff and runoff range in crop land (% of mean annual rainfall)	No. of years (% of years)	Mean runoff and runoff range in crop land (% of mean annual rainfall)	No. of years (% of years)	Mean runoff and runoff range in crop land (% of mean annual rainfall)
Above normal years (>878.2 mm)	10 (25.0)	19.0 (11.5 to 30.6)	1 (5.9)	15.7 (15.7)	11 (19.3)	18.7 (11.5 to 30.8)
Normal years (597.7 to 878.1 mm)	22 (55.0)	13.5 (0.0 to 35.0)	12 (70.6)	14.6 (5.5 to 26.0)	34 (59.6)	13.9 (0.0 to 35.0)
Mild drought (553.5 to 597.6 mm)	2 (5.0)	9.4 (6.4 to 12.5)	1 (5.9)	0 (0.0)	3 (5.3)	9.4 (6.4 to 12.5)
Moderate drought (369.0 to 553.4 mm)	6 (15.0)	3.5 (0.0 to 6.9)	3 (17.6)	7.5 (6.9 to 8.2)	9 (15.8)	4.8 (0.0 to 8.2)
Severe drought (<368.9 mm)	0 (0)	0.0 (0.0)	0 (0.0)	0.0 (0.0)	0 (0)	0.0 (0.0)

runoff) was observed from crop land in loamy soil. The catchment-wise runoff volumes estimated spatially could be utilized for planning in situ and ex situ soil and water conservation interventions for the sustainable management of the microwatershed. The mean annual rainfall during 1961–1990 (base line period) was determined as 737.9 mm. The rainfall during above normal years was >878.2 mm, normal years ranged from 597.7 to 878.1 mm, mild drought years ranged from 553.5 to 597.6 mm, moderate drought years ranged from 369.0 to 553.4 mm, and severe drought years were <368.9 mm. The drought years which occurred during recent years (1991–2007) have increased by 3.5 %, and the above normal years have decreased by 19.1 % compared to 1951–1990. The mean annual runoff which occurred during recent years in crop land has decreased by 3.3 and 9.4 % of the annual rainfall in above normal years and mild drought years, respectively. The spatial information on runoff potential and its availability during normal, above normal and dry years should be considered while planning the interventions in the microwatersheds. This methodology can be adopted for estimating the runoff potential from similar ungauged watersheds with deficient data.

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