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RESEARCH ARTICLE

An Integrated Study of Geospatial Information Technologies for Surface Runoff Estimation in an Agricultural Watershed, India

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Abstract Runoff is one of the important hydrologic variables used in most of the water resources applications. The Soil Conservation Service-Curve Number (SCS-CN) method is adopted for the estimation of surface runoff in the Mehadrigedda watershed area, Visakhapatnam district, India using multispectral remote sensing data, curve number approach and normal rainfall data. The main source of water in the Mehadrigedda watershed area is by rain, most of it drains off and only a little percolates into ground. The weighted curve number is determined based on antecedent moisture condition (AMC)-II with an integration of hydrologic soil groups (HSGs) and land use/ land cover LULC categories. An integrated approach is applied to delineate the land use/land cover information as adopted from NRSA classification. The recording of daily rainfall data during the years 1997-2006 is collected from Indian Meteorological Department (IMD) rainguage center at Kottavalasa. It is observed that the annual rainfall-runoff relationship during 1997-2006, which is indicating that the overall increase in runoff with the rainfall of the watershed area. Integration of remote sensing (RS) and geographical infomation system (GIS) techniques provide reliable, accurate and up-to-date information on land and water resources.

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Introduction

Runoff is the part of precipitation which appears in surface streams of either perennial or intermittent form. It may generally be either the surface runoff or the sub-surface runoff or the groundwater runoff. The direct surface runoff or storm runoff is that part of runoff which enters the stream immediately after the rainfall. Topographic features, the degree of development, the gradient of channels, and the extent and number of the depressed areas affect the rates and volumes of runoff. Watersheds having extensive flat areas or depressed areas without surface outlets have lower runoff than the areas with steep, well defined drainage patterns. The geologic or soil material contribute to a large degree of the infiltration rate, and thus affect runoff vegetation and the practices incident to agriculture and forestry (Schwab *et al*., 2002). The method most commonly used for rain storm events in unguaged basins relies on runoff curve numbers developed by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS, 1985). The SCS-CN method is a well accepted tool in applied hydrology. The LULC, hydrologic soil groups (HSGs) and storm rainfall data were utilized to estimate the runoff (Durbude *et al.,* 2001; Tripathi *et al.,* 2002; Ambazhagan *et al.,* 2005; Zade *et al.,* 2005; Jasrotia and Singh, 2006). Geospatial Information Technology and RS can augment the conventional methods to a great extent in rainfall-runoff studies. The role of remote sensing in runoff calculation is generally in providing a source of input data or as an aid for estimating equation coefficients or generating thematic layers such as land use, soil, drainage etc. The Mehadrigedda reservoir is one of the main sources of water supply to the Visakhapatnam city. Visakhapatnam is the second largest city in the state of Andhra Pradesh (AP), its population is increasing rapidly due to migration of people from other parts of state besides the tourist population. Demand for domestic water requirements is increasing with growing population and rising living standards besides the existing irrigation demand. Even though the area receives sufficient rainfall (110 cm per annum), runoff resulting drains out of the watershed, resulting the water scarcity during the summer season. In the study area, most of the rural population dependent on groundwater resources for domestic and agricultural purposes. The main objective of the study is to estimate the runoff potential from rainfall and other ancillary data such as LULC soil using SCS curve number method applying RS and GIS techniques.

Study area

The Mehadrigedda watershed, a significant drainage basin in the central portion forms a reservoir downward and is bounded with arcuate hill ranges of Eastern Ghats province in Visakhapatnam district, Andhra Pradesh. Geographically the area under study covering 364 km^2 lies between 17º 43' N to 17º 57' N latitudes and 83º 02' E to 83º 17' E longitudes falling in Survey of India (SOI) toposheet NOs: 65 O/1, 65 O/2, 65 O/5 on 1:50,000 scale. The location of the watershed area is about 13 km north of Visakhapatnam city (Fig. 1). Major portion of the study area covers in Kottavalasa, Pendurthi and Sabbavaram Mandal regions. The area enjoys subtropical climate of semi-arid in nature (Thornthwaite and Mather, 1957) and the temperature ranges from 14 to 20ºC in December and 33 to 39ºC in May.

Physiographically the area under study is occupied by 96% khondalite group (quartz-feldspar-garnetsillimanite-gneiss), 2% calc-granulite and quartzite bands and 2% intrusive charnockitic bands within the khondalite group of meta-sediments of Archaean age. The area is well represented by denudation hills, burried pediments, valley fills and plains forming soil covers of silty clay, red sandy and red loamy and alluvium. Topographically the area is undulated with eroded rocky hills. The major hill ranges of the study are Nallakonda, Boddakonda and Narava. Drainage patterns of stream network from the Mehadrigedda watershed have been observed as mainly dendritic type which indicates the homogeneity in texture and lack of structural control. While in some parts of the watershed represent parallel and radial pattern types indicating that the

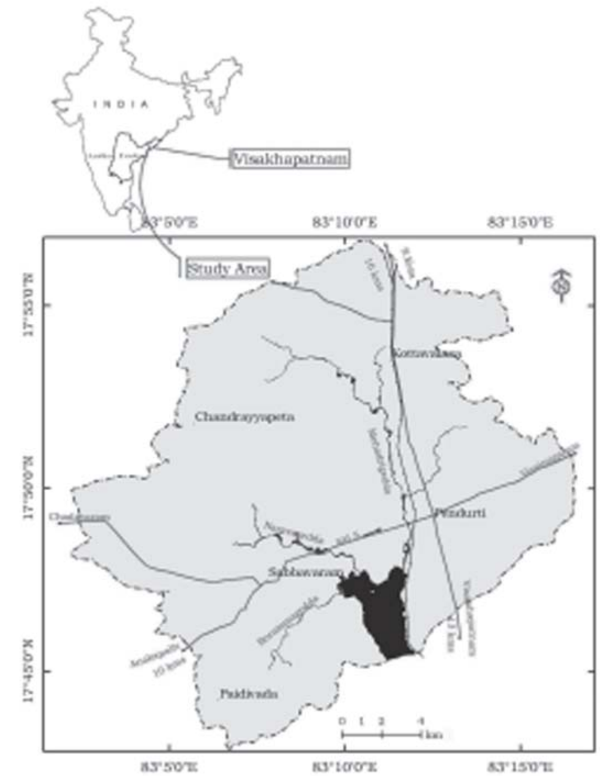

Fig. 1 Location map of the study area

topographical features are dipping, folded and highly jointed in the hilly terrains. The Mehadrigedda reservoir forms from the three following main streams, the Mehadrigedda stream drains from the north and Naravagedda and Borammagedda streams from the west. The combined runoff of these three streams reaches to the Mehadrigedda reservoir dam portion.

Materials and methods

Pentium-IV Personal Computer (PC) with image processing (ERDAS IMAGINE: 8.7) and GIS (ArcGIS: 9.0) softwares were used for digital image processing and statistical spatial analysis studies. The SOI toposheets: 65 O/1, O/2 and O/5 were used for demarcation of watershed boundary. The watershed is further divided into six sub-watersheds namely M-I, M-II, M-III, M-IV, N-I and NB-I according to IMSD (1995) technical guidelines (Fig. 2). Out of six sub-watersheds, M-IV is the trunk stream of 6th order and M-III, NB-I are of 5th order, while remaining sub-watersheds: M-I, M-II, N-I are of 4th order (Narendra and Rao, 2006). The precision geocoded digital data format from Indian Remote sensing satellite, Resourcesat-I (IRS-P6) LISS-IV with 5.8 m high spatial resolution sensors covering the path/rows (102/85,86,91,92) in March, 2005 were used to meet the requirement of area under study. The entire watershed area under study, one particular rainguage center at Kottavalasa set up by Indian Meteorological Department (IMD) is chosen for collection of the daily

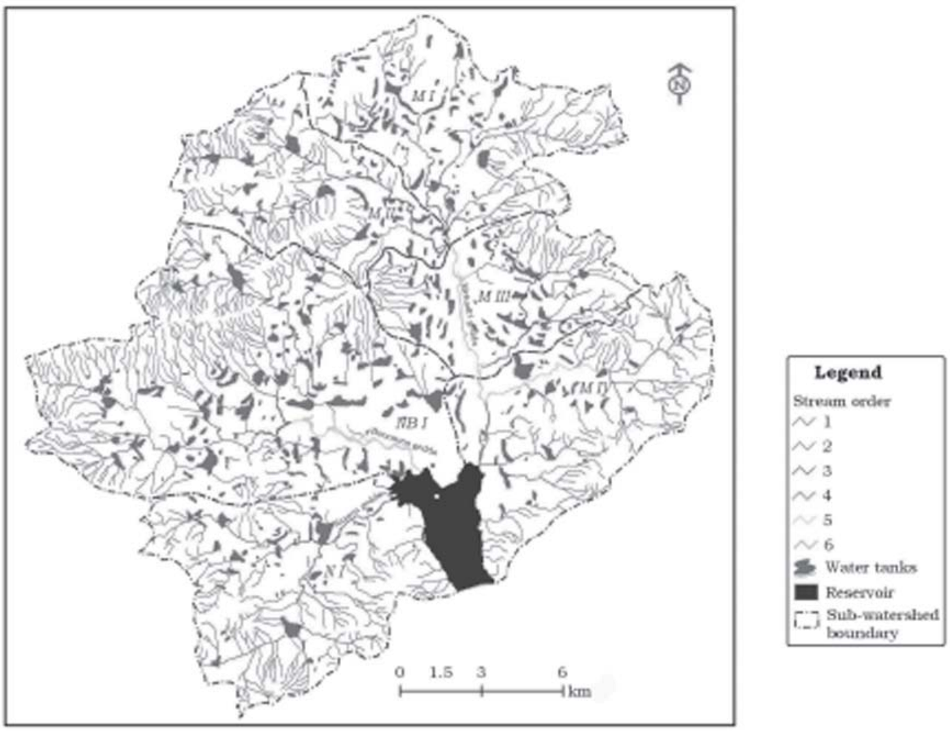

Fig. 2 Drainage map showing sub-watershed with their streams orders of Mehadridgedda watershed

rainfall data for 10 years. Soil textural map was obtained from agricultural department.

The SCS-CN method is a simple predictable and stable conceptual method to estimate the direct runoff from a watershed (SCS, 1985). The infiltration losses are combined with surface storage by the relation of

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

The initial abstraction I_a is all the losses before runoff begins. It includes the water retained in surface depressions and the water intercepted by vegetation, evaporation and infiltration. So I_a is highly variable but generally is correlated with soil and cover parameters. After several studies empirical relation was developed for the term I_a and it is given for Indian conditions (Narayana, 2002),

$$I_a = 0.3S \quad (2)$$

The following equation was adopted for the estimation of runoff in the present study which is applicable to all soil regions in India except the black soil areas.

$$Q = \frac{[P - 0.3S]^2}{[P + 0.7S]} \quad (3)$$

where

Q = actual direct runoff (mm); P = total storm rainfall (mm); S= potential maximum retention of water by the soil (mm)

The retention parameter (S) varies spatially, due to changes in soils, land use and slope, and temporally due to changes in soil-water content. For convenience in evaluating antecedent rainfall, soil conditions, land use and conservation practices (SCS, 1985) defines:

$$S = \frac{25400}{CN} - 254 \quad (4)$$

where, CN is an arbitrary curve number varying from 0 to 100.

Land use pattern of any watershed influences the surface runoff. To compute hydrological elements more accurately more accurate LULC map is required. Digital analysis of LULC changes has been carried out through false color composite (FCC) image of the watershed area. Soil textural map was updated from satellite imageries through visual interpretation.

Results and discussion

In the present study, an attempt has been made to estimate the runoff volume due to the rainfall occurred in Mehadrigedda watershed area. The precipitation is concentrated mainly during the two rainy seasons, from June to September and October to November. The watershed area receives about 66% of rainfall from the south-west monsoon during the months of June to September, north-east monsoon rains are contributing 21% of the annual rainfall during October to November. Precipitation in arid and semi-arid zones results mainly from convective mechanisms, which typically produce storms of short duration, relatively of high intensity and limited areal extent.

The soil textural map (Fig. 3) was generated using GIS software with the help of a soil map from the State Agricultural Department (SAD) published in the year 2003, Anakapalle, on a 1:250,000 scale as a reference. A collective approach, involving a systematic visual interpretation of standard FCC images in conjunction with the collateral information and an adequate field check was followed for deriving information on soils. Eight types of soil textural classes have been identified in the study area i.e. sandy loam, loamy sand, sandy clay loam, clay loam, clay, silty loam soils, rock land with clay and sandy clay classes.

Soils are classified into HSGs to indicate the minimum rate of infiltration obtained for bare soil after

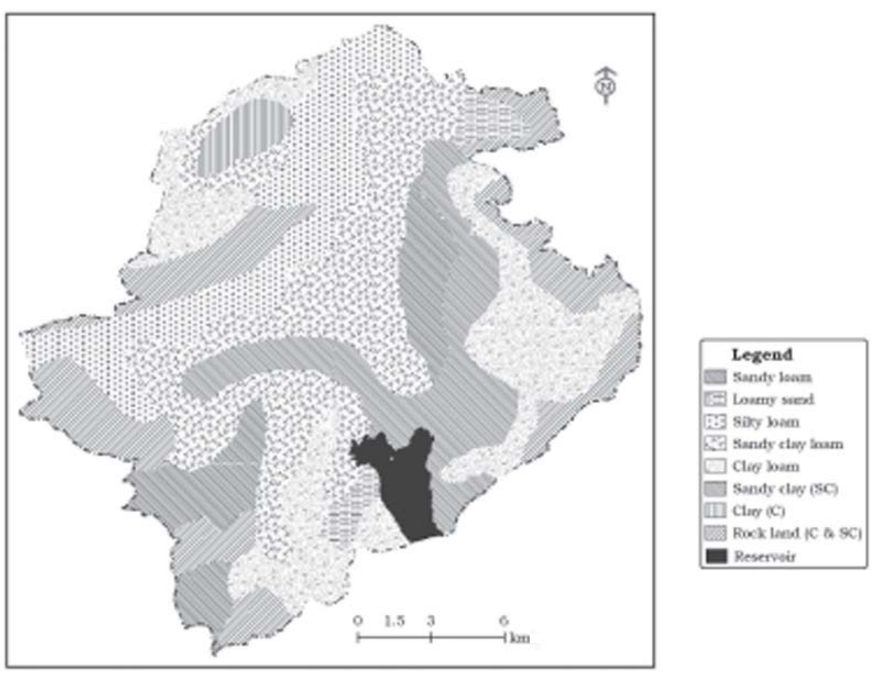

Fig. 3 Soil textural map of the Mehadrigedda watershed area

prolonged wetting. The infiltration rate is the rate at which water enters the soil at the soil surface. It is controlled by surface conditions. HSGs also indicates the transmission rate, the rate at which the water moves within the soil. This rate is controlled by the soil profile. To determine HSGs according to the texture of soils was standardized by SCS soil scientists (Table 1) (USDA, 1986). The hydrologic soil groups based on the texture of soils of the watershed area are derived corresponding to the standard HSGs and their textural classes are presented

Table 1 USDA-SCS soil classification

Soil group	Description
Group A	These soils have low runoff potential and infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (> 0.30 in/hr).
Group B	These soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15-0.30 in/hr).
Group C	These soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05-0.15 in/hr).
Group D	These soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-0.05 in/hr).

in the Table 2. The spatial distribution of four HSGs for the watershed area is shown in Fig. 4. The HSG-A consists of sandy loam and loamy sand, which is

Table 2 HSGs and their textural classes of the study area

Soil textural class	HSG	Area	
		km^2	%
Sandy loam, loamy sand	A	28.7	7.9
Silty loam	B	47.6	13.1
Sandy clay loam	C	91.0	25.0
Clay loam, sandy clay and clay	D	188.4	51.8

covering an area of about 28.7 km^2. These soils have low runoff potential. Group-B soils comprising silty loam and occupies an area of 47.6 km^2, stretching from north to west side of the watershed. Sandy clay loam soil (C-group) is covering in the central portion of the watershed at about 25% of Total Geographical Area (TGA). HSG-B and -C group soils have moderate runoff potential. The D-group includes clay loam, sandy clay and clay soils which covers an area of 188.4 km^2 and occupies half of the watershed area. The group-D soils have very low infiltration and high runoff potential.

Digital analysis of LULC changes has been carried out using supervised classification through FCC image of the watershed area. Image classification procedures were used to classify multi-spectral pixels into different land cover classes. For supervised classification, training sites were made by demarcating a polygon or an area of interest for the known cover types that are later applied to the entire image. Ground truth information was incorporated in the refinement of training site selection during final classification of image analysis. About 20 locations for each intended LULC categories were identified as a training data set for supervised classification. The training sites delineation technique is a traditional approach whereby training sites polygons are created visually by onscreen digitizing of features on the display system. The training sites were selected with criteria

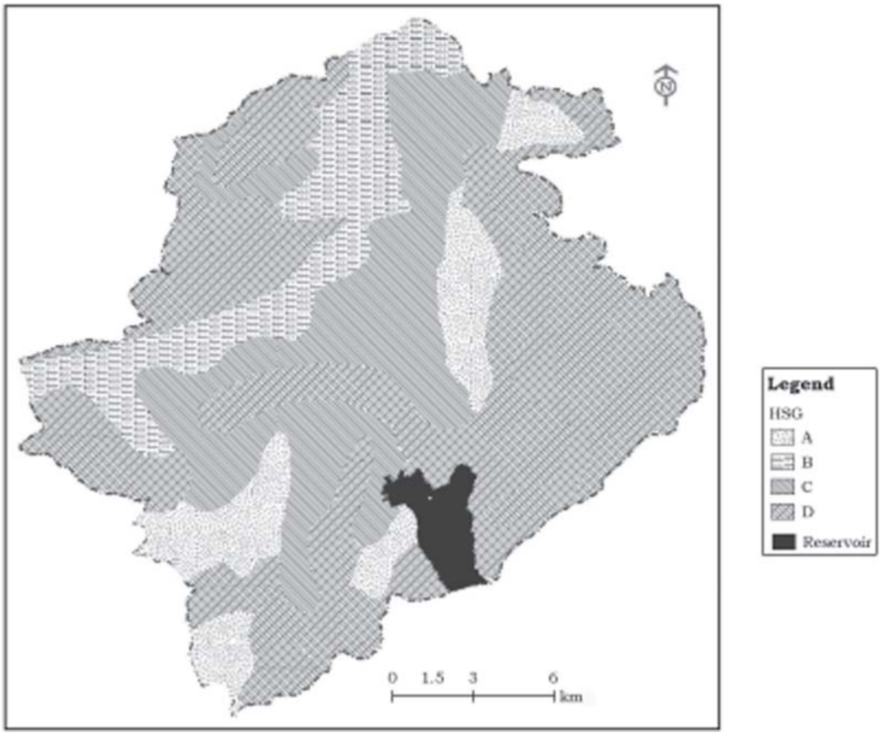

Fig. 4 Hydroligic soil groups obtained from soil textural classes of the watershed area

so that they represent the area of each class throughout the image. The reflectance of the signatures chosen in the analysis was classified through a maximum likelihood classification decision rule (Rao and Narendra, 2006). The final LULC map derived is shown in figure 5 and results presented in Table 3.

The land use categories are considered from LULC map of Mehadrigedda watershed area in order to determine the curve number values. The broad LULC classes in the present study are settlements, industries, layouts, crop land, fallow lands, plantations, forest land, scrub and wastelands have been taken into consideration and overlaid the HSGs. Standard SCS-CN (USDA, 1986) are assigned for each land use-soil group combination. Table 3 represents each and every land use categories used for hydrologic analysis, along with corresponding curve numbers for each land use-soil group combination. The weighted hydrologic curve number was determined for Mehadrigedda watershed based on antecedent moisture condition (AMC)-II. Generally, curve numbers are to be calculated for AMC-II, then adjusted over to simulate AMC-III or down to simulate AMC-I. The AMC as described by McCuen (1982) is the initial moisture condition of the soil, prior to the storm event of interest and this parameter is taken as an index based on seasonal limits for the total 5-day antecedent rainfall (Table 4).

For calculating the weighted curve number, the following equation is standardized.

$$CN = \sum_{i=1}^{n} \frac{CN_i \times A_i}{A_i} \tag{5}$$

where, CN_i = the curve number for each land use-hydrologic soil group; A_i = the area for each land use-hydrologic soil group; n = the class number of land use-hydrologic soil group polygons

Table 3 The assigned curve numbers and statistical distribution of land use categories and HSGs of Mehadrigedda watershed

Class number	Land use	HSG	Curve number (CN)	Area km^2A	CN×A
1.	Settlements	A	77	3.52	69.50
		B	85	5.34	50.50
		C	90	28.30	2547.00
		D	92	55.90	5142.80
			Total	93.00	8409.80
2.	Industries	A	81	0.95	76.95
		B	88	0.01	0.88
		C	91	0.05	4.55
		D	93	0.76	70.68
			Total	1.77	153.06
3.	Layouts	A	77	7.80	600.60
		B	86	0.00	0.00
		C	91	4.54	413.14
		D	94	15.06	1415.64
			Total	27.40	2429.38
4.	Crop land	A	67	5.25	351.75
		B	78	7.50	585.00
		C	85	23.60	2006.00
		D	89	11.80	1050.20
			Total	48.15	3992.95
5.	Fallow lands	A	76	0.62	47.12
		B	85	3.77	320.45
		C	90	3.35	301.50
		D	93	4.56	424.08
			Total	12.30	1093.15
6.	Plantations	A	65	0.08	5.20
		B	73	10.18	743.14
		C	79	10.17	803.43
		D	81	28.70	2324.70
			Total	49.13	3876.47
7.	Forest land	A	48	2.10	100.80
		B	67	7.48	501.16
		C	77	0.00	0.00
		D	83	27.80	2307.40
			Total	37.38	2909.36

Class number	Land use	HSG	Curve number (CN)	Area km^2A	CN×A
8.	Scrub	A	68	4.10	278.80
		B	79	4.78	377.62
		C	86	3.45	296.70
		D	89	21.90	1949.10
			Total	34.23	2902.22
		A	64	1.20	76.80
		B	75	2.50	187.50
		C	83	6.10	506.30
		D	85	9.95	845.75
9.	Wastelands	A	64	1.20	76.80
		B	75	2.50	187.50
		C	83	6.10	506.30
		D	85	9.95	845.75
			Total	19.75	1616.35

Table 4 Classification of antecedent moisture conditions

AMC class	5 day total antecedent rainfall mm	
	Dormant season	Growing season
I	<12.5	<35
II	12.5 to 27.5	35 to 52.5
III	>27.5	>52.5

The weighted curve number has been calculated using the equation 5 as follows.

$$\sum_{i=1}^{n} CN_i x A_i = \sum_{i=1}^{9} CN_i x A_i = 8409.8+153.06+2429.38+3992.95+1093.15+3876.47+2909.36+2902.22+1616.35 = 27382.74$$

$$\sum_{i=1}^{n} A_1 = \sum_{i=1}^{9} A_i = 93.0+1.77+27.4+48.15+12.3+49.13+37.38+34.23+19.75=323.11$$

$$\sum_{i=1}^{9} \frac{CN_i \times A_i}{A_i} = \frac{27382.74}{323.11} = 84.75$$

CN (weighted) = 85

The CN values that are given in Table 3 coincides with the standard AMC-II values. The assigned curve numbers have been taken for estimating the potential maximum retention (S) of the soil with water for AMC-II of CNII using the equation (4) as follows.

$$S = \frac{25400}{85} - 254 = 298.8 - 254 = 44.8$$

CN values for AMC-I and AMC-III can be obtained using the following empirical equations (Chow, 1964).

$$CN\,I = \frac{4.2 \times CN\,II}{10 - (0.058 \times CN\,II)}$$

$$CN\,III = \frac{23 \times CN\,II}{10 + (0.13 \times CN\,II)}$$

The weighted curve number obtained from the calculations for AMC-II is around 85, corresponding to this value of the conversion curve numbers for CNI and CNIII are 70 and 93, respectively.

The runoff was calculated from the different storm events of observed rainfall during the years 1997 to corresponds to about 24.2% of average annual rainfall of the watershed area (Table 6). The linear diagram (Fig. 6) represents the annual rainfall-runoff relationship during 1997-2006, which is indicating that

Table 5 Runoff estimation for different storm events using hydrological weighted curve numbers of Mehadrigedda watershed area

Date of storm-event	Storm rainfall mm	5-day total antecedent rainfall mm	AMC class	Storm-runoff Q	
				mm	%
11.08.97-13.08.97	61.2	0.0	I	5.9	9.7
15.08.97-18.08.97	52.8	61.2	III	33.5	63.4
12.09.97-16.09.97	69.8	93.1	III	49.4	70.7
20.09.97-26.09.97	209.2	19.2	I	109.2	52.2
06.10.97-08.10.97	99.3	1.0	I	25.3	25.5
02.03.98-05.03.98	92.2	0.0	I	21.1	22.8
13.06.98-15.06-98	110.3	0.0	I	32.3	29.3
16.07.98-18.07.98	73.2	0.0	I	11.0	15.0
03.08.98-05.08.98	61.0	107.0	III	41.1	67.3
21.08.98-28.08.98	151.5	41.8	II	104.2	68.8
27.09.98-29.09.98	93.2	3.2	I	32.3	29.3
09.10.98-17.10.98	180.6	25.8	I	85.2	47.2
29.10.98-02.11.98	154.6	0.0	I	64.4	41.7
15.06.99-21.06.99	181.6	0.0	I	86.1	47.4
16.08.99-21.08.99	142.6	60.2	III	120.1	84.2
06.09.99-11.09.99	78.4	3.2	I	13.5	17.3
05.10.99-08.10.99	65.2	13.6	I	7.5	11.5
04.06.00-09.06.00	100.8	4.0	I	26.2	26.0
22.08.00-27.08.00	93.2	3.8	I	21.6	23.2
02.08.01-06.08.01	80.4	19.6	I	14.6	18.1
08.08.01-10.08.01	52.2	80.4	III	32.9	63.1
25.08.01-27.08.01	77.9	10.0	I	13.3	17.1
02.09.01-04.09.01	66.4	0.0	I	8.0	12.0
25.09.01-30.09.01	122.1	2.0	I	40.3	33.0
01.10.01-08.10.01	139.7	117.6	III	117.3	84.0
09.11.01-12.11.01	73.8	12.5	I	11.3	15.3
09.06.02-13.06.02	71.8	12.0	I	10.4	14.4
17.06.02-20.06.02	61.2	9.4	I	5.9	9.7
30.07.02-01.08.02	195.8	0.0	I	97.9	50.0
21.08.02-23.08.02	68.8	0.0	I	9.0	13.1
13.10.02-17.10.02	102.4	6.2	I	27.2	26.6
10.07.03-13.07.03	108.6	14.6	I	31.2	28.7
18.08.03-23.08.03	106.4	19.6	I	29.8	28.0
24.09.03-27.09.03	117.8	48.1	II	73.0	62.0

04.10.03-08.10.03	125.5	0.0	I	42.7	34.1
22.10.03-25.10.03	143.4	16.3	I	55.9	39.0
14.12.03-16.12.03	102.4	0.0	I	27.2	26.6
10.06.04-14.06.04	170.0	27.8	III	147.2	86.6
03.07.04-06.07.04	95.6	34.8	I	23.1	24.1
09.07.04-16.07.04	116.6	87.2	III	94.6	81.1
25.08.04-26.08.04	61.2	5.2	I	5.9	9.7
03.10.04-06.10.04	130.0	7.1	I	46.0	35.4
21.06.05-23.06.05	58.2	1.2	I	4.9	8.3
15.08.05-17.08.05	77.2	7.0	I	12.9	16.8
04.09.05-06.09.05	100.6	2.8	I	26.1	26.0
19.09.05.24.09.05	369.0	2.6	I	254.1	68.9
28.09.05-02.10.05	80.6	61.2	III	59.6	74.0
10.10.05-16.10.05	220.0	0.0	I	118.5	53.9
28.10.05-03.11.05	98.8	37.4	II	56.0	56.7
22.06.06-29.06.06	157.9	12.6	II	110.3	69.8
01.08.06-07.08.06	300.6	90.0	III	276.9	92.1
16.09.06-22.09.06	205.3	0.0	I	105.9	51.6
28.10.06-02.11.06	89.6	0.0	I	19.6	21.9

Runoff (Q) is calculated using the formula

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

Where

S= 44.8 S for AMC-II

S= 108.8 S for AMC-I

S= 19.1 S for AMC-III

the overall increase in runoff with the rainfall of the watershed area.

Conclusion

Geospatial information technology can augment the conventional methods to a great extent in rainfall-runoff studies. The proposed site of Mehadrigedda reservoir lies 8 miles north-west of Visakhapatnam. This project is mainly intended to augment water supply to industries around Visakhapatnam and incidentally afford relief to the low lying areas of Visakhapatnam city from heavy damage to property caused by floods. The rainfall data of the watershed area has been collected during the years 1997-2006 from IMD rainguage center. Most of the rain water goes as surface runoff. The elongated basin with low form factor indicates that the Mehadrigedda watershed will have a flatter peak of flow for longer duration (Narendra and Rao, 2006). Eight soil textural classes were identified in the present study to derive HSGs. The rainfall data and CN values have been considered to estimate the runoff using SCS-CN method. With the help of RS, GIS and SCS-CN method; it is possible to make management plans for usage and development of a watershed. Although

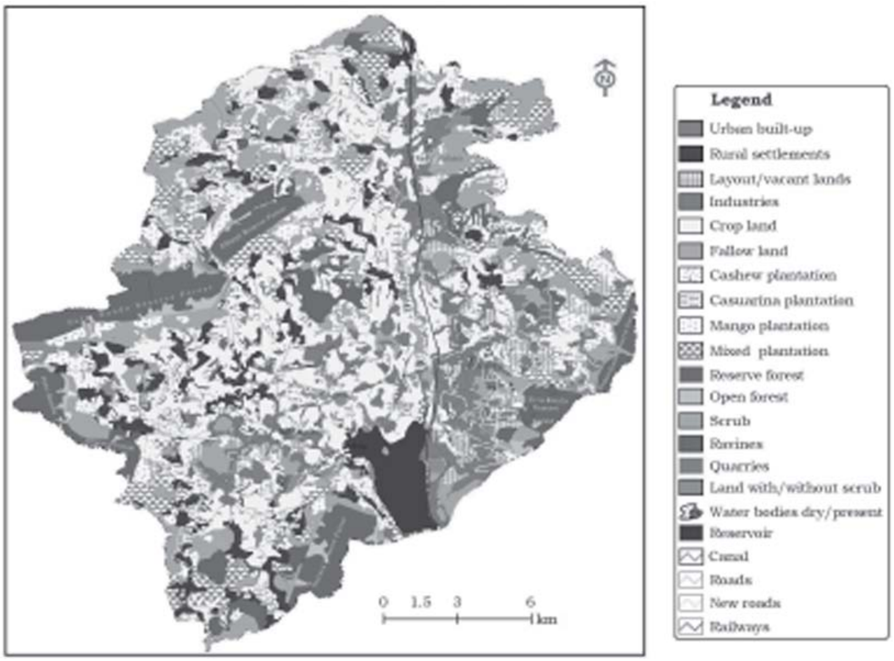

Fig. 5 Land use land cover map of the study area

Table 6 Estimated annual runoff in comparison with rainfall data of the watershed area

Year	Rainfall mm	Total runoff mm	%
1997	1143.9	223.3	19.5
1998	1573.3	381.0	24.2
1999	1058.4	227.2	21.5
2000	874.5	47.9	5.5
2001	1298.9	237.6	18.3
2002	890.5	150.4	16.9
2003	1276.3	259.8	20.3
2004	1123.8	316.7	28.2
2005	1404.6	532.2	37.9
2006	1346.9	525.0	39.0
Average	1199.1	290.1	24.2

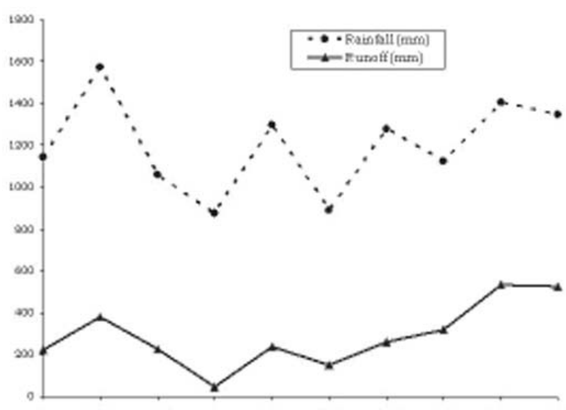

Fig. 6 Linear pattern shows the average annual rainfall-runoff with time period

SCS-CN method is an empirical approach to determine the runoff depth from the watershed area but it can be helpful for estimating the runoff for places, which do not have runoff records.

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