Effect of LULC & Initial Abstraction in Computing Runoff Using SCS-CN Method for Kalangi Watershed in Tirupati District of Andhra Pradesh

U. Venkata Hemanth[1], D. V. Satyanarayana Moorthy[2]

[1]PG Student, Department of Civil Engineering, Sri Venkateswara University College of Engineering, Sri Venkateswara University, Tirupati, Andhra Pradesh, India.
usugarivenkatahemanth[at]gmail.com

[2]Professor, Department of Civil Engineering, Sri Venkateswara University College of Engineering, Sri Venkateswara University, Tirupati, Andhra Pradesh, India.
dvsmsvu[at]gmail.com

Abstract: ***Runoff data plays a vital role for planning water control practices, including waterway design, storage facilities, and erosion protection structures. Among various runoff estimation methods, SCS-CN approach integrates the key parameters such as soil infiltrability, land use/land cover and antecedent moisture condition (AMC). LULC effects on CN values by infiltration rate and effect of variation of initial abstraction using SCS-CN by Water Year (WY) model and Rainfall Event (RE) model are studied. Initial abstraction values 0 to 0.3 are explored to understand model responsiveness. Increase in built up area results in decrease in runoff. Initial abstraction (I_a) of less than 0.2S in RE model significantly improves the correlation between rainfall and runoff in watershed runoff calculations.***

Keywords: RUNOFF, SCS-CN METHOD, LULC, Initial Abstraction, Watershed, AMC, WY, RE, GIS

1.Introduction

Runoff data plays a vital role for planning and implementing water control practices, including the design of waterways, storage facilities, and erosion protection structures (Chow et al., 1988) [1]. The runoff of precipitation which appears in the surface streams is called runoff. In general, it is the precipitation excess of the meeting the evaporation, interception, infiltration, surface retention, channel detention demands. The primary goal of runoff analysis in hydrology is to establish a relationship between the magnitude of extreme events and their frequency of occurrence, utilizing Geographic Information Systems (GIS) techniques to achieve this objective (Maidment, 2002) [2]. Watershed refers to the area drained by a stream in such a way that all flow originating in that area is discharged to a single outline (USDA, 1986) [3]. The changes in runoff characteristics induced by intensive human activities are important to understand the effects of land use/land cover change (LULC) on the hydrological processes of watershed surface (Foley et al., 2005) [4]. Therefore, there has been a growing need to quantify the impacts of land use changes on hydrology for small watershed management from the standpoint of anticipating and minimizing the potential environmental impacts (Bhadra et al., 2008) [5]. In general, it is the precipitation excess of meeting the evaporation, interception, infiltration, surface retention, channel detention demands (Hewlett, 1982) [6]. Among various runoff estimation methods, the SCS-CN curve number approach stands out for its integrated assessment of influential parameters such as soil infiltrability, land use/ land cover and pre-existing moisture levels such as antecedent moisture condition (AMC) (USDA, 1986) [3].

2.Study Area

The Kalangi River basin is situated in the North-eastern parts of Tirupati district. Kalangi river is non-perennial i.e., they don't flow year-around. It is bounded by the Arani river, Swarnamukhi river and Pulicat lake. In a typical year, the Kalangi river has flowing water for short periods of time following precipitation events. The study area is located between longitudes E 79°38'13.2" to 80°4'19.2" and latitudes N 13°25'30" to 13°51'of Survey of India (SOI) Toposheet no. 570 /9, 570 /10, 570 /11, 570 /13, 570 /14, 570 /15, 66C /1, 66C /2 with an aerial extent of 1324.774 sq.km. The study area is covered by B.N. Kandriga (Buchinaidu Kandriga), Doravarisatram, K.V.B. Puram (Kumara Venkata Bhupala Puram), Sullurupeta, Tada, Thottambedu and Varadaiahpalem.

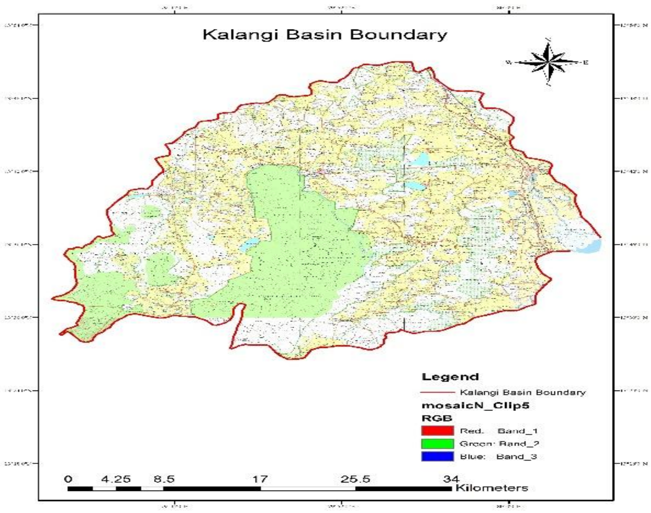


Figure 1: Kalangi Basin Boundary

Data Used

Satellite Data

The LISS-III satellite data downloaded for the years 2004 and 2024 to generate land use/land cover maps, providing the valuable perception into environmental changes over time.

There is time gap of 20 years between the two satellite images which are wide enough to show the changes and the trends in Land use and Land cover in the study area.

Rainfall Data

Daily rainfall data of seven regions in study area i.e., B.N. Kandriga (Buchinaidu Kandriga), Doravarisatram, K.V.B. Puram (Kumara Venkata Bhupala Puram), Sullurupeta, Tada, Thottambedu and Varadaiahpalem for the period 2004-2024 is collected from the NASA POWER website.

Water Year (WY) Model

In Water Year model the runoff depth is estimated by considering the rainfall. In this method the days without rainfall are also considered for calculation of runoff. This model is varied with the initial abstraction values ranging from 0 to 0.3.

Rainfall Event (RE) Model

In Rainfall Event model the runoff depth is estimated by considering the rainfall. In this method the days with rainfall are only considered for calculation of runoff. This model is also varied with the initial abstraction values ranging from 0 to 0.3.

Soil map plays an important role in the estimation of surface runoff by using SCS-CN method because the type of soil will affect infiltration thereby affecting the surface runoff, the study of soil helps to find out the types and its properties. The study area consists of clayey and loam soil.

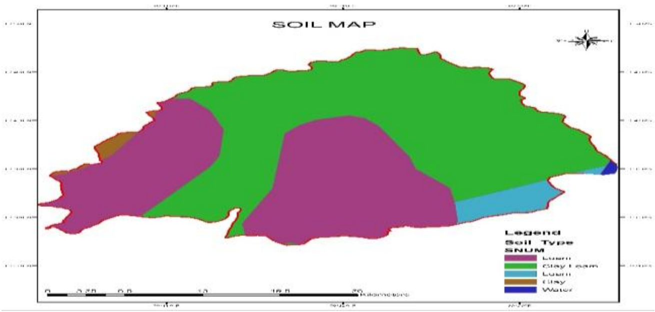


Figure 3: Soil map

Land use has effects on hydrological processes, including infiltration, evapotranspiration, a surface runoff (Chow et al., 1988) [1]. Surface cover affects the roughness of the terrain, reducing discharge and increasing infiltration (Horton, 1945) [7]. In forested areas, infiltration rates are higher, resulting in lower runoff. Remote sensing offers an efficient and cost-effective means of obtaining information on land use, providing insights into the spatial distribution of vegetation types (Lillesand et al., 2014) [9]. This study analysed the LULC of the study area for the years 2004 and 2024 using LISS III image data (NRSC, 2019) [10]. LULC also effects on curve number. Curve Number is a dimensionless parameter that, lacks the direct physical interpretation, which has effect on the characterization of hydrological responses. CN values range from 0 to 100 serves as an indicator of the soil's infiltration capacity, which helps to understand the runoff patterns. Curve Number values are inversely related to infiltration capacity. Lower CN values show high infiltration rates, whereas higher values indicate the low infiltration rates. CN value of 100 indicates that there is no infiltration, whereas a CN value of 0 indicates the high infiltration. Curve number values depend upon the soil type, land use, hydrologic soil group, slope, and antecedent moisture condition. CN is derived from Land use/Land cover classification and hydrological soil group maps.

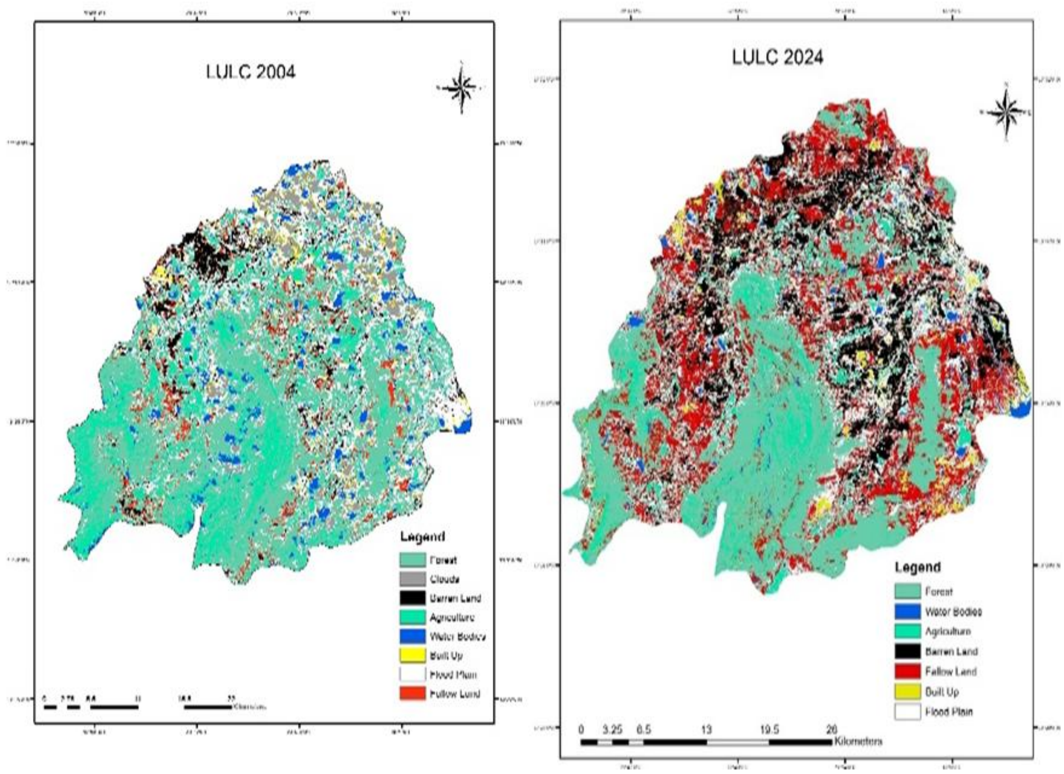


Figure 4: LULC 2004 &2024

Table. 1: Changes in Spatial Distribution of land use between the Years 2004-2024

LAND USE CLASS	OLD LAND USE (2004)		RECENT LAND USE (2024)		LAND USE CHANGES	
	Area (Sq.km)	Percentage (%)	Area (Sq.km)	Percentage (%)	Sq.km	Percentage (%)
Agriculture	198.7316156	15.00227727	97.87189366	7.388302644	100.859722	1.970376398
Barren Land	68.07482912	5.138978309	218.7008964	16.50962652	-150.62607	0.451945871
Built Up	19.10638696	1.442343806	34.68697326	2.618503093	-15.580586	1.226294479
Clouds	67.24393128	5.076253716	0	0	67.2439313	1
Fallow Land	70.4604919	5.319072324	276.948377	20.90670109	-206.48789	0.341233055
Flood Plain	307.023708	23.17726238	311.4771786	23.51326388	-4.4534705	68.94032557
Forest	529.6583354	39.98398134	360.1168327	27.18504821	169.541503	3.124062999
Water Bodies	64.37702889	4.859830856	24.88497038	1.878554564	39.4920585	1.630125937
Total	1324.676327	100	1324.687122	100	-0.0107948	63.23523364

Soil Conservation Service Curve Number (SCS-CN) Method

Out of several methods for runoff estimation, the Natural Resources Conservation Service Curve Number (NRCS-CN) method widely used and proved to be a quicker and accurate estimator of surface runoff other than empirical and lumped parameter models. The soil conservation service (1972) developed a method for calculating and removing the characteristics in order to a set of essential characteristics. Scientists, hydrologists, water resources planners, agriculturists, foresters, and engineers have widely embraced the Soil Conservation Service Curve Number (SCS-CN) method (SCS 1956) since its inception for the purpose of estimating surface runoff. Curve number is the controlling factor that affects the runoff amount which flows over the land after satisfying all losses. It serves to evaluate the possibilities for runoff and represents the soil's capacity to absorb rainwater. All the rainfall water will flow as surface flow as soil is in the saturation limit that happens in continuous rainfall events. As soon as CN is increased, runoff will also increase. Accurate CN estimation is essential for flood risk management, hydrological modelling, and climate change impact studies.

Equivalent curve numbers can be computed by:

Weighted CN Value: A_1CN_1

$$CN_W = \frac{A_1CN_1 + A_2CN_2 + A_3CN_3 + A_44 + A_5CN_5 + --------\mp A_nCN_n}{A_1 + A_2 + A_3 + A_4 + A_5 \pm ---------\mp A_n} \quad (1)$$

For AMC I: $CN(I) = \frac{CN(II)}{2.281 - 0.01281\, CN(II)}$ (2)

For AMC III: $CN(III) = \frac{CN(II)}{0.427 + 0.00573\, CN(II)}$ (3)

Above two equations are applicable in the range of 55 to 95 which covers most of the practical ranges.

Rainfall = Runoff + losses

$P = I_a + F_C + Q$ (4)

$Q\,(P - I_a) = F_c\, S$ (5)

$I_a = \lambda\, S$ (6)

Where, P = total rainfall, Ia = Initial abstraction, Fc = Retention after runoff begins, Q = direct runoff, S = Potential maximum retention or infiltration, CN = Curve number and λ is the regional parameter dependent on geologic and climatic factors ($0 < \lambda < \infty$). In general λ is taken in between 0.1 to 0.3.

The SCN-CN method is represented as: $Q = \frac{(P - I_a)^2}{(P - I_a + S)}$ by combining the water balance equation and proportional equality hypothesis.

The concept of zero initial abstraction (Ia = 0) is used to determine the runoff depth (Q) from a given rainfall (P). Using this concept in the original NRCS-CN proportionality hypothesis, the resulting equation for surface runoff estimation was obtained as: $= \frac{P^2}{(P+S)}$.

The computed values of average CN, S and Ia for the year 2004 and 2024 have been given in table. These values have been in SCS model to get the direct runoff volume for given rainfall for different AMC conditions.

AMC

AMC refers to the Antecedent moisture conditions present in the soil at the beginning of the rainfall event consideration. The initial abstraction and infiltration are governed by AMC. For the practical purpose the AMC is divided into three stages.

Table 2: Computed Values of CN, S and I_a for the Year 2004-2024

Antecedent Moisture Condition	Year 2004			Year 2024		
	AMC I	AMC II	AMCIII	AMC I	AMC II	AMCIII
Curve Number, CN	62.15766	78.93246	89.76912	75.05725	87.28373	94.14342
Potential Retention, S	154.6383	67.7941	28.94808	84.40835	37.00497	15.80112
Initial Abstraction, I_a=0.1*S	15.46383	6.77941	2.894808	8.440835	3.700497	1.580112
Initial Abstraction, I_a=0.2*S	30.92766	13.55882	5.789616	16.88167	7.400995	3.160225
Initial Abstraction, I_a=0.3*S	46.39149	20.33823	8.684424	25.3225	11.10149	4.740337

Daily rainfall data of seven mandals in Tirupati around Kalangi basin were taken by entered the latitudes and longitudes of study area in the NASA power website and download the daily rainfall data. Thiessen polygon method was created using the mandals shape as input. After creating thiessen polygon of the watershed, the area of influence under each mandal was calculated. From the precipitation data and area of influence under each mandal precipitation over the catchment is calculated using the formula.$P = \frac{\Sigma AP}{\Sigma A}$.

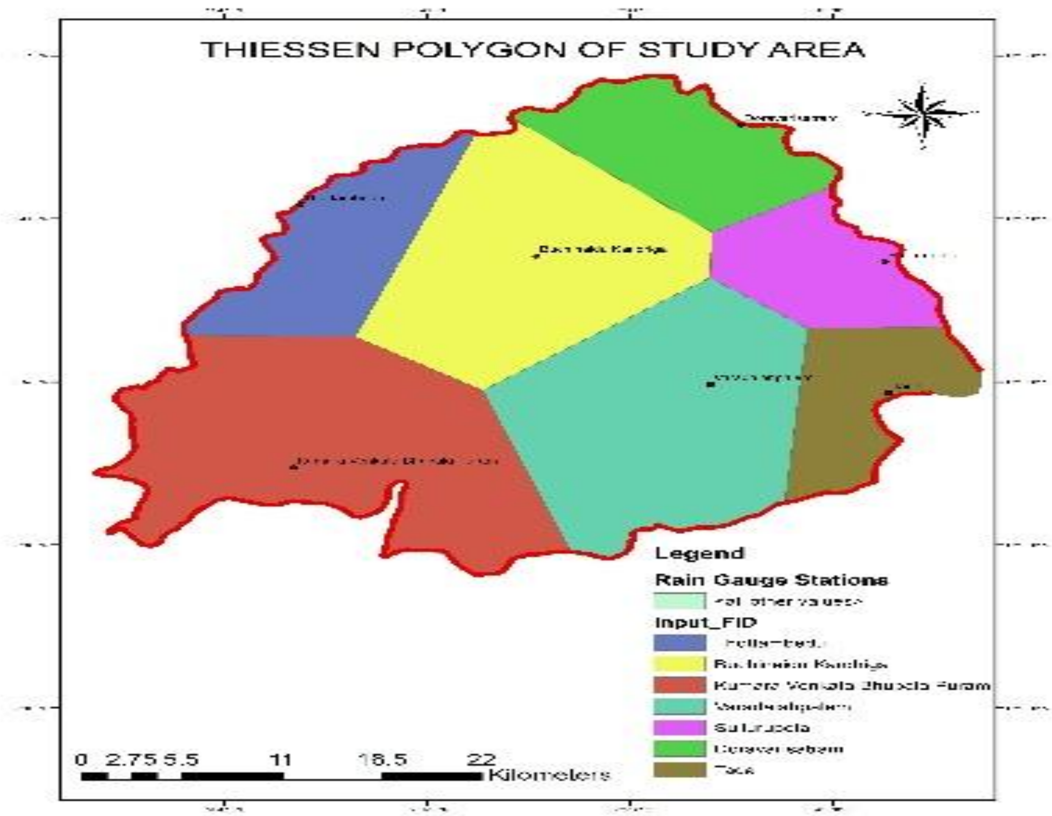


Figure 5: Thiessen Polygon Method

Table 3: Area of Influence under each rain gauge station developed from thiessen polygon method

Name of the Rain Gauge Station		Area (sq.Km)	Ai/A
A1	Thottambedu	263.210751	0.198683
A2	Buchinaidu Kandriga	96.432094	0.072791
A3	Kumara Venkata Bhupala Puram	125.891652	0.095029
A4	Varadaiahpalem	124.966581	0.09433
A5	Sullurupeta	329.266853	0.248546
A6	Doravarisatram	97.944766	0.073933
A7	Tada	287.061763	0.216687
Total area		1324.77446	1

3.Results & Discussion

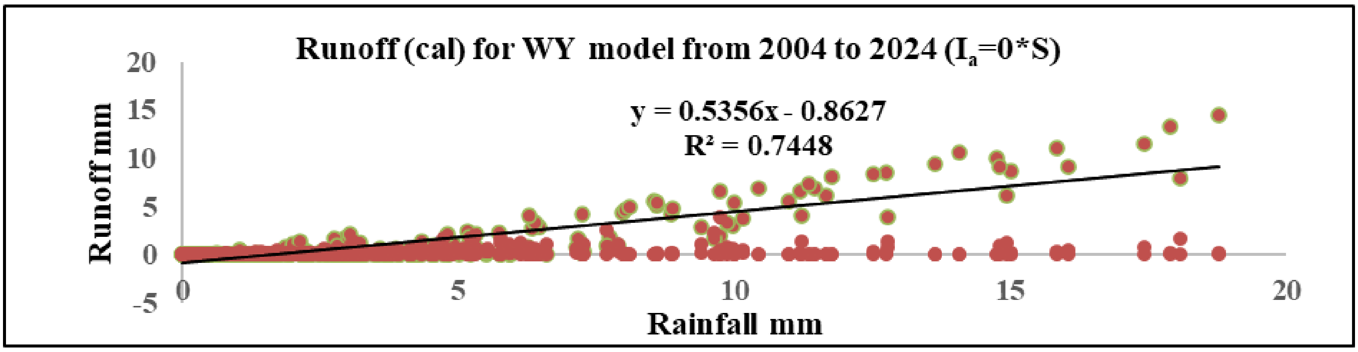
The daily runoff is estimated for both Water-year (WY model) and Rainfall-Event (RE model) using SCS-CN method and Initial abstraction values (I_a =0, 0.1 S, 0.2 S and 0.3 S) the following results are obtained.

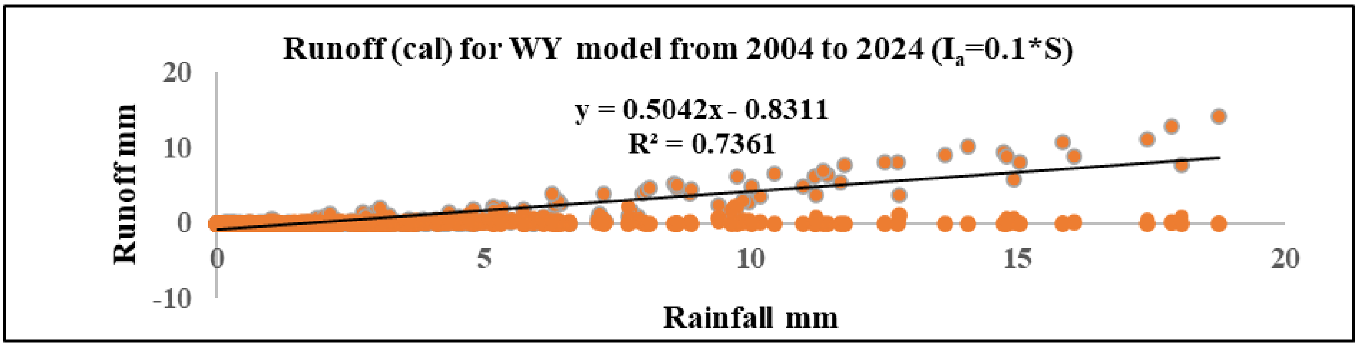
Table 4: Water Year Model Calculation

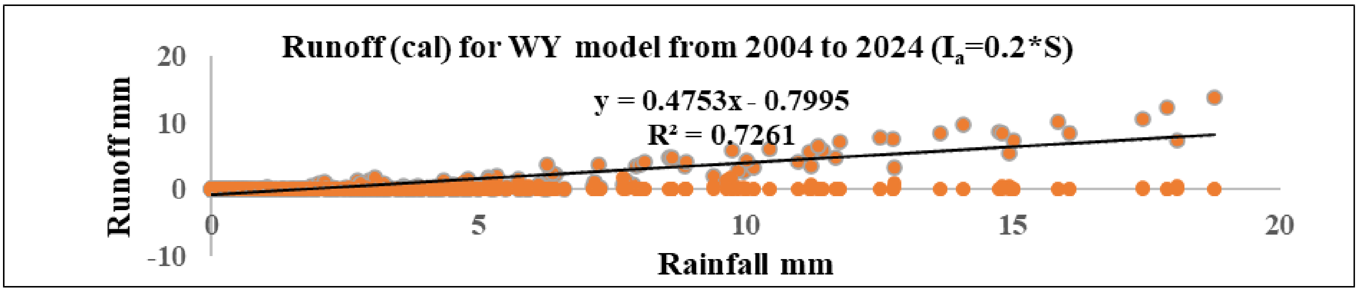
Year	Rainfall mm	Runoff			
		0	0.1	0.2	0.3
2004-2005	1153.35	138.647	111.4026	96.4193	85.7088
2005-2006	1571.383	254.2043	223.7606	204.4307	188.9954
2006-2007	1086.214	131.0134	107.7071	95.3935	86.036
2007-2008	1376.4257	172.4566	134.9533	117.2793	104.8977
2008-2009	1123.6871	168.5342	148.1937	137.4999	129.3815
2009-2010	1184.0971	161.4367	134.0142	117.4818	105.734
2010-2011	1240.4843	124.9433	93.84101	78.65419	68.2387
2011-2012	1194.8386	137.6664	108.8379	93.5934	83.59
2012-2013	943.4257	87.657	64.0654	52.6199	45.0201
2013-2014	942.6686	69.4749	43.4983	30.9634	23.1895
2014-2015	1012.7729	93.7827	67.1929	53.7705	45.7405
2015-2016	1858.3343	323.4265	290.0868	270.8753	255.9795
2016-2017	643.4771	43.8348	27.1872	20.8154	16.7705
2017-2018	1195.8943	112.2358	79.6772	63.8089	53.7427
2018-2019	673.6971	51.102	33.9269	26.753	23.0088
2019-2020	1206.8743	118.6616	85.9713	67.6392	55.1213
2020-2021	1538.8957	189.1526	153.3628	134.4513	120.7637
2021-2022	1559.3457	206.5335	172.794	154.2885	141.0638
2022-2023	1341.0186	138.9547	106.6437	91.5975	81.3001
2023-2024	1354.29	186.6088	156.3821	139.3405	127.5835

Table. 5: Rainfall Event Model Calculation

Year	Rainfall mm	Runoff			
		0	0.1	0.2	0.3
2004-2024	8568.1645	1030.9962	830.3214	652.1549	652.1549







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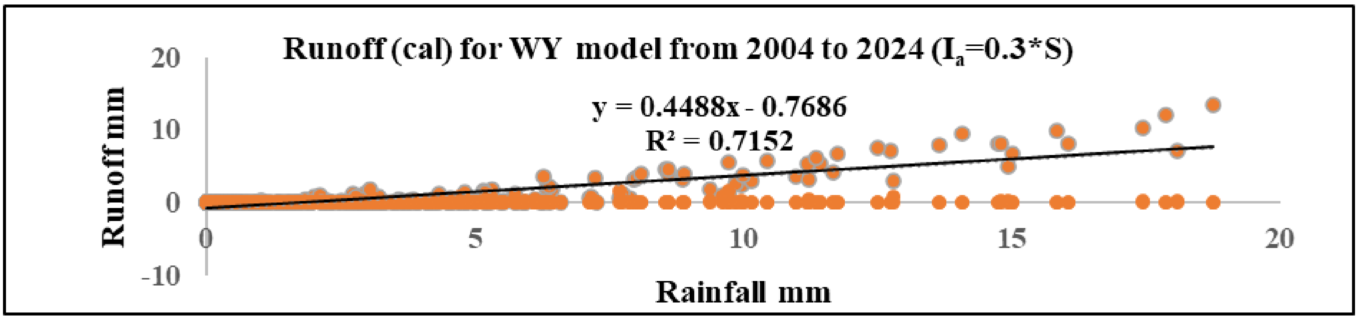

Figure 4: Runoff graph of WY Models for Initial Abstraction of 0, 0.1 S, 0.2 S and 0.3 S

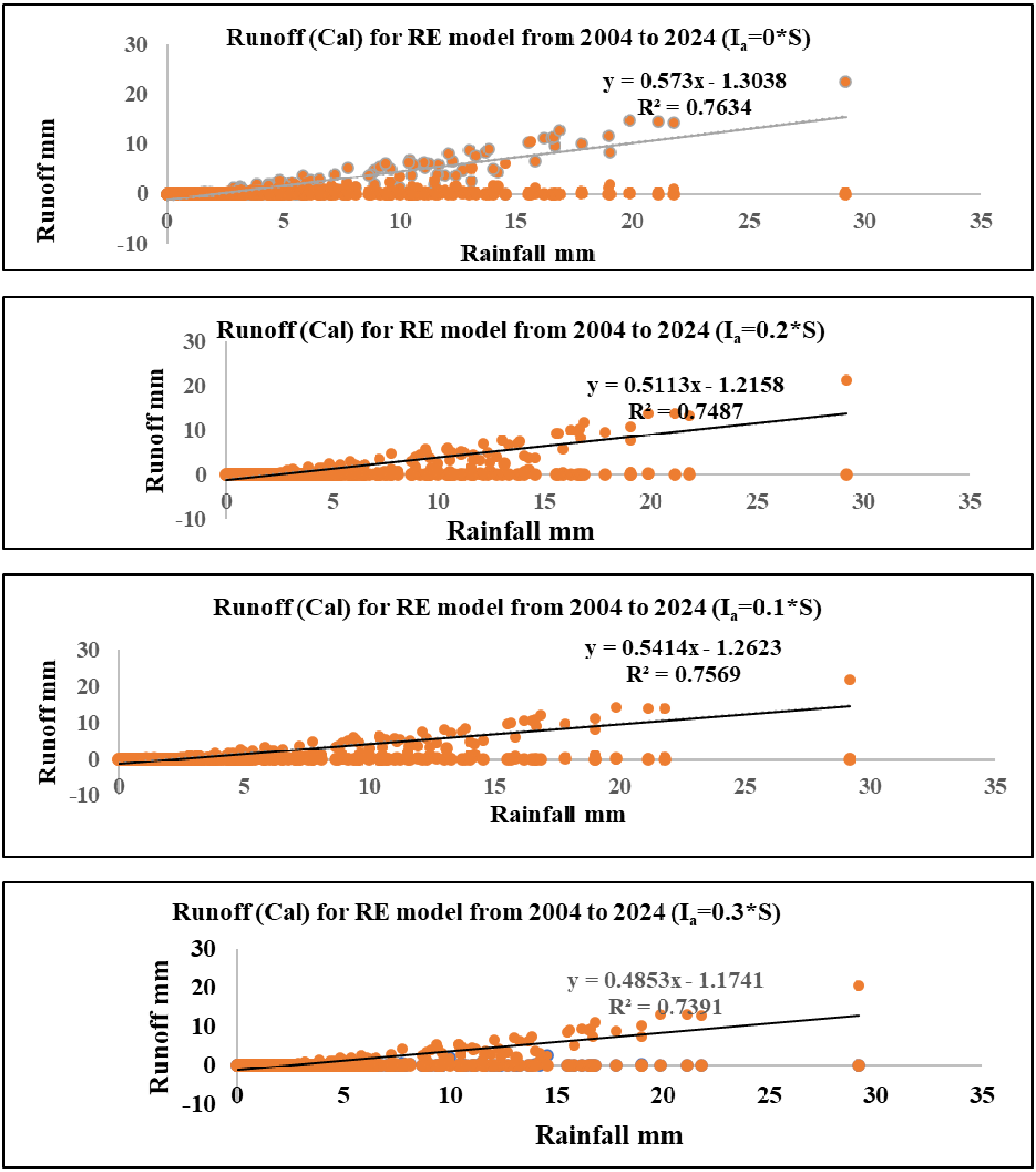

Figure 5: Runoff graph of RE Models for Initial Abstraction of 0, 0.1 S, 0.2 S and 0.3 S

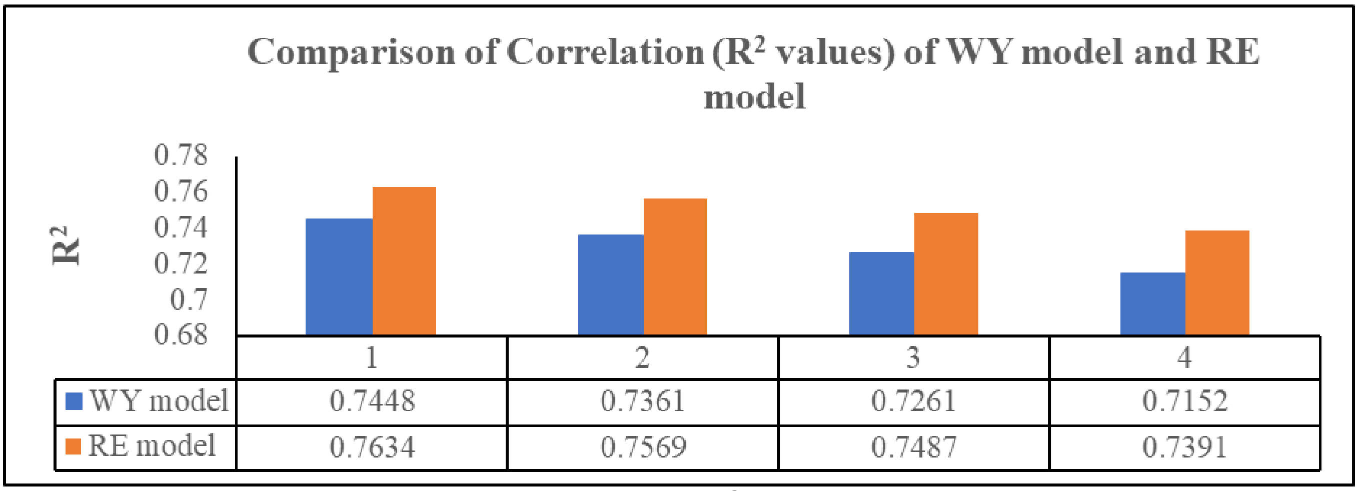

Figure 6: Comparison of Correlation values (R^2 values) of WY model and RE model

The values of λ (0, 0.1, 0.2 and 0.3) in the RE model shows higher values than WY model. The Initial abstraction coefficient (I_a) less than 0.2 S has demonstrated a stronger correlation between rainfall and runoff. The values greater than or equal to 0.2 S are commonly employed in SCS-CN method. The analysis revealed that incorporating an initial abstraction coefficient (I_a) of less than 0.2S in RE model significantly improves the correlation between rainfall and runoff in watershed runoff calculations. The Fig 2. Reveals that the areas under forest, waterbodies and agriculture areas are converted to flood plain, barren land, built up and fallow land during the reported area. The area under barren land, flood plain, built up and fallow land has doubled there by affecting the runoff. Increase in built up area results in decrease in runoff.

4.Conclusion

The SCS-CN method, incorporating the WY and RE models, was employed to estimate the runoff depth, runoff volume and runoff coefficient in the watershed. The estimated runoff values showed a strong correlation with mean rainfall depth, with the RE model resulting higher values. The results indicate that SCN-CN method provides an accurate fit, characterized by a high correlation between estimated runoff values. The critical analysis of the Initial abstraction concept in the NRCS runoff curve number method reveals that using initial abstraction values less than 0.2 S results in a better fit to rainfall-runoff data compared to the traditional 0.2 S value. This finding highlights the need for revising the existing concept and establishing a new standard, which would enable various models to produce more consistent and comparable results. The study further investigates the influence of land use changes on the rainfall-runoff relationships, utilizing the SCS-CN methodology to quantify these impacts.

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Author Profile

U. Venkata Hemanth received B. Tech degree in Civil Engineering from K.S.R.M. College of Engineering, Kadapa, Andhra Pradesh, India in 2022. Currently pursuing his M. Tech in the stream of Water resource engineering at Sri Venkateswara University College of Engineering, Sri Venkateswara University, Tirupati, Andhra Pradesh, India.

Dr. D.V. Satyanarayana Moorthy received B. Tech. program Civil Engineering from Sri Venkateswara University College of Engineering, Tirupati Andhra Pradesh, India in 1982. Later he joined as Scientist/Engineer-SB at prestigious Sriharikota Space Centre as a Civil Engineer in Civil Engineering Division of Department of Space on 11th August 1983. While in service at Sriharikota, he enthusiastically studied M.Tech. in Remote Sensing from Anna University, Madras under sponsorship from the Department of Space and procured first rank M. Tech. Remote Sensing in the year 1991. Later he joined SVU as Reader in Civil Engineering 4thNovember 1992. He continued in the services of SV University and got promoted to the post of professor in Civil Engineering from 1stFebruary, 2012. He published number of papers in International and National Journals and guided around 25 number of M. Tech. students for their project works.