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Development of a Rainfall- Runoff Model for Vamanapuram River Basin

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Abstract

The estimation of rainfall and runoff in a catchment plays a major role for the design of various water management structures. This study is an attempt to develop a rainfall-runoff model for Vamanapuram river basin, Kerala, which is the largest perennial river basin of south Kerala and have a catchment area of 787 sq.km. The rainfall data used for the study corresponds to a 10 years period (2004-2013). The amount of runoff is estimated from the catchment by Soil Conservation Service Curve Number (SCS-CN) Method. The estimated runoff shows a maximum of 2584.87 mm^3/s in the year 2006. A statistical model is developed by multiple linear regression method using Microsoft excel. A good correlation coefficient of 0.9999 obtained which shows the model is fit for further validation. The study is helpful for the estimation of stream flow in the catchment and thus irrigation scheduling and decision making for the release of stored water for various purposes is possible.

Keywords: Catchment, runoff, SCS-CN Method, linear regression method, irrigation scheduling

INTRODUCTION

Hydrologists are concerned with developing a proper relationship between the rainfall and the resulting runoff over the catchment, since the variability of rainfall and water availability as runoff are mutually dependent in a catchment. A catchment or a watershed is the area covering the land which contributes overland flow water to an outlet point. Each watershed has definite characteristics such as size, shape, slope, drainage, vegetation, geology, soil, geomorphology, climate and land use. Watershed management implies the proper use of all land and water resources of a watershed for optimum production with minimum hazard to natural resources. Runoff estimation is one of the important hydrologic aspects used in the water resources applications and management planning [1]. Rainfall-runoff modelling plays an important role in understanding hydrological conditions of the basin and in predicting their behaviour over time. Accurate process for prediction of runoff volume is used for flood warning, navigation, water quality management and many other water resource applications. The first half of the 20^{th} century is considered to be the beginning of the dynamic development of Rainfall-Runoff modelling. A Rainfall-Runoff model is a mathematical model describing the rainfall – runoff relationship of a catchment area, drainage basin or watershed. More precisely, it produces surface runoff hydrographs as output. In other words the model calculates the conversion of rainfall into runoff.

In the present study, an attempt is made to develop a rainfall-runoff model by using empirical and statistical approaches for a catchment. The model has been developed empirically by SCS-CN method (Soil Conservation Service-Curve Number method) and statistically by Multiple Linear Regression method. The SCS-CN method, developed by Soil Conservation Services (SCS) of USA in 1969 is a simple, predictable and stable conceptual method for estimation of direct runoff depth based on storm rainfall depth [2]. It relies on only one parameter, Curve Number (CN). SCS-CN method is used to calculate the discharge from the watershed or catchment since this method is more suitable for runoff calculation for the Western Ghats, India [3]. In this method, data such as rainfall, soil and topography (ie, vegetation above earth surface, building and roads etc.) are required. Coskun et al [4] determined runoff depth of the van lake basin using remote sensing and GIS integration. For determining the results they used various data sets such as Landsat satellite images, 1:25000 scale standard topographic maps and soil map data. Sindhu et al [5] used thematic layers such as land use/land cover and soil maps, derived from remote sensing data and overlayed through Arc GIS software to assign the curve number for the polygons of the study area. The rainfall data of six rainguage stations in and around the watershed were used to estimate the daily runoff from the watershed by using the SCS-CN method. Geena .G.B. and Ballukraya P.N. [6] estimated runoff for red hills watershed using SCS method combined with Geographic Information System. Tandon et al [7] used rainfall and runoff data for a period of 53 years for detailed analysis and developed a rainfall runoff relationship using curve number method. The runoff estimated from the study was used to know the variation of runoff potential with different land use /land cover and soil conditions.

Michael [8], Gunst R.F and Mason R.L[9] applied regression analysis by different classification of regression models for a catchment. The rainfall runoff modelling was statistically analysed using the regression tool of Microsoft Excel in the present study.

MATERIALS AND METHOD

Study Area

The study area considered is Vamanapuram river basin. Fig 1 shows the base map of the Vamanapuram river basin. The Vamanapuram river basin geographically lies between latitude 8°35′ to 8°50′ N latitudes and longitude 76°40′ to 77°15′ E and is spread over Thiruvananthapuram and Kollam districts of Kerala State. The watershed has a total area of 787 sq.km (787000ha) covering two districts, 8 blocks, 33 panchayat, 31 villages. It is bounded by Kottarakara taluk of Kollam district in the North, Nedumangad taluk of Thiruvananthapuram district in the south, Tamil Nadu state in the East and Arabian Sea in the West. The Vamanapuram River emerges from the Chemmunji Motai at 1717 m above MSL and flows into the Anjengo Lake at Chirayankeezhu taluk. The Vamanapuram watershed is divided into 30 sub-watersheds and 52 micro watersheds.

Data Collection

The fig. 2 shows the various steps involved in the present study. The rainfall data for a period of ten years (2004-2013) was collected from Indian Meteorological Department, Thiruvananthapuram, Kerala. The toposheets covering the study area namely, 58D/10, 58D/13, 58D/14, 58H/1 and 58H/2 were procured from Survey of India, Thiruvananthapuram and the maps for the present study was developed using Arc GIS and ERDAS Imagine.

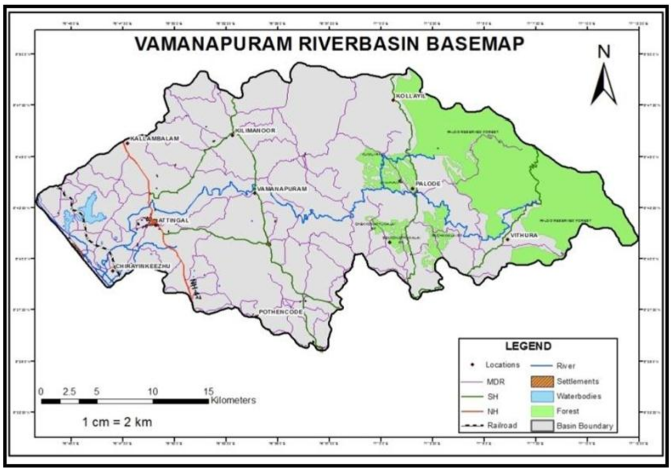

Figure 1: Base map of vamanapuram river basin.

In order to estimate the curve number, land use/land cover and hydrological soil group map are required and was collected from the Kerala State Land Use Board, Thiruvananthapuram, Kerala.

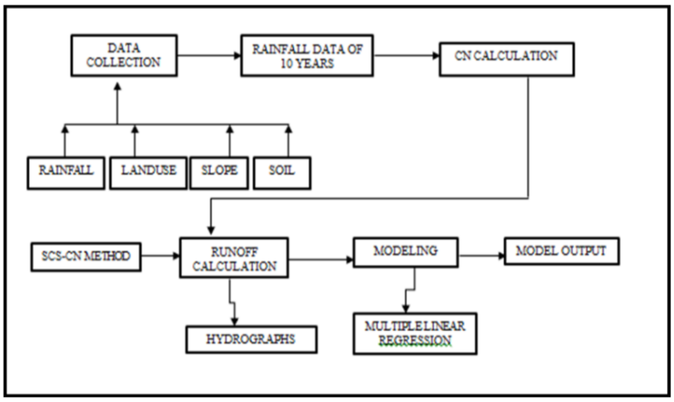

Figure 2: Flow chart showing the various steps of the present study

Rainfall Analysis

To understand the monsoon pattern of the study area and to know the variation and characteristics of rainfall, a rainfall analysis has been carried out for the selected study area for the period of 10 years (2004-2013).

Rainfall- Runoff Modeling

There are two methods used for the estimation of runoff and the rainfall runoff modelling. They are

1. Empirical method – Soil Conservation SCS-CN Method
2. Statistical Method - Multiple Linear Regression Method.

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of the amount of direct surface runoff Q to the total rainfall P (or maximum potential surface to the runoff) with the ratio of the amount of infiltration Fc to the amount of the potential maximum retention S. The second potential hypothesis relates the initial abstraction Ia to maximum retention. Thus, the SCS-CN method consists of the following equations.

(a) Water balance equation:

$$P = I_a + F_c + Q \tag{1}$$

Proportional equality hypothesis

$$\frac{Q}{P - I_a} = \frac{F_c}{S} \tag{2}$$

(b) Ia - S hypothesis

$$I_a = \lambda S \tag{3}$$

Where P is the total rainfall, I_a the initial abstraction, F_c the cumulative infiltration excluding I_a, Q the direct runoff, S the potential maximum retention or infiltration and λ the regional parameter dependent on geologic and climatic factors (0.1<λ<0.3).

Solving equation (2)

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

$$Q = \frac{(P - \lambda S)^2}{P - (\lambda - 1)S}$$

The relation between I_a and S was developed by analyzing the rainfall and runoff data from experimental small watersheds and is expressed as I_a = 0.2S. Combining the water balance equation, SCS-CN method is represented as $Q = \frac{(P-0.2)^2}{P+0.8S}$

The potential maximum retention storage S of watershed is related to a CN, which is a function of land use, land treatments, soil type and antecedent moisture condition of watershed. The CN is dimensionless and its value varies from 0 to 100.The S-value in mm can be obtained from CN by using the relationship,

$$S = \frac{1000}{CN} - 10$$

Soils

In determining the CN, the hydrological classification is adopted. Here soils are classified into four classes A, B, C and D based on the infiltration and other characteristics. The important soil characteristics that influence the hydrological classification of soils are effective depth of soil, average clay content, infiltration characteristics and the permeability.

There are 7 types of soil present in the study area based on colour, texture and structural properties. They are Marukil-Amaravila series, Kazhakkutam-poovar series, Varkala-Thonnakkal series, Nedumangad-Kuttichal series, Kallar-Palode series, Kottur series and Ponmudi series.

Antecedent Moisture Condition (AMC)

AMC refers to the moisture content present in the soil at the beginning of the rainfall-runoff event under consideration. It is well known that initial abstraction and infiltration and are governed by AMC. For purposes of practical application three level of AMC are recognized by SCS as follows:

- AMC-I: Soils are dry but not to wilting point. Satisfactory cultivation has taken place.
- AMC-II: Average conditions.
- AMC-III: Sufficient rainfall has occurred within the immediate past five days. Saturated soil conditions prevail. Table 1shows the AMC values for determination of CN value.

Table 1: Antecedent Moisture Content for determining CN value

AMC Type	Total rain in previous 5 days	
	Dormantseason	**Growing season**
I	Less than 13mm	Less than 36 mm
II	13 to 28 mm	36 to 23 mm
III	More than 28 mm	More than 53 mm

Land Use

The land use/land cover will influence the rate of runoff through the catchment area. The land use/land cover refers to the vegetation available on the surface, buildings and roads etc. It is essential to calculate CN value and it varies for different types of land use/land cover. Fig.3 shows the land use map of the study area. The antecedent moisture conditions also influence the CN value. The AMC conditions vary with curve number. The conversion of CNII to other two AMC conditions can be made through the following correlation equations:

For AMC I

$$\frac{CN_{11}}{2.281 - 0.01281\, CN_{II}}$$

For AMC III

$$\frac{CN_{11}}{0.427 + 0.00573\, CN_{II}}$$

CN-II can be calculated from the table.2. The soil in the study area is under group A.

Table 2: Runoff Curve Number (CNII) for Hydrologic Soil cover under AMC II condition

Land Use	Cover	Hydrological Soil Group
	Treatment Or Practice	A
Cultivated	Straight row	76
	Straight row	76
	Straight row	32
Cultivated	Bunded	59
Cultivated	Paddy	95
Orchards	Forest plantation	39
	Cashew	39
Forest	Scrub	33
Build up area	Buildings	59
Settlement		77
Sand		73
Upland		71
Land with sand		69
Water body		91

The weighted curve number can be calculated from the above table using the formula

$$CN = \frac{\sum[(N_i \times A_i)]}{A}$$

Where, Ni = Weight curve number from 1to any number,

Ai = Area with curve number Ni and

A = Total area of the watershed.

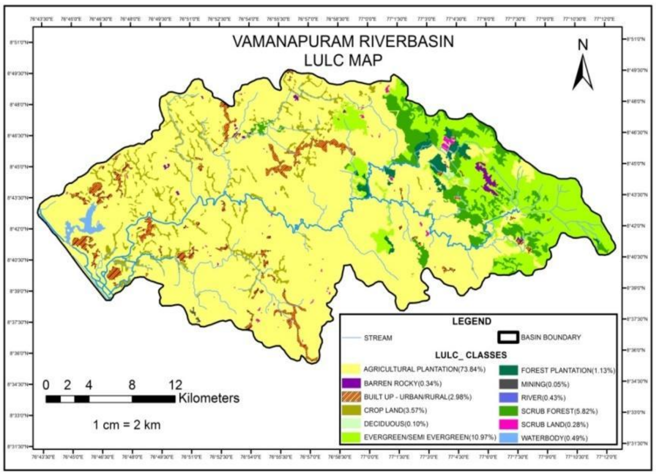

Figure 3: Land Use map of Vamanapuram River Basin

Regression Analysis

The purpose of regression analysis is to determine the values of parameters based on the best-fit curve. In correlation, regression is used to analyze the relation between two continuous (scale) variables. However, regression is better suited for studying functional dependencies between factors. The term functional dependency implies that X partially determines the value of Y. In addition, regression is better suited than correlation for studying samples in which the investigator fixes the distribution of X. Regression analysis is used to predict a continuous dependent variable from a number of independent variables. The independent variables used in regression can be either continuous or discontinuous. Independent variables with more than two levels can also be used in regression analyses but they must be converted into variables that have only two levels. This is called dummy coding. Usually, regression analysis is used with naturally-occurring variables, as opposed to experimentally manipulated variables, although you can use regression with experimentally manipulated variables.

Multi Linear Model

Linear regression models with more than one independent variable are referred to as multiple linear models, as opposed to simple linear models with one independent variable [10]. The formula is given as follows.

$$y = a_0 + a_1x_1 + a_2x_2 + \ldots + a_nx_n$$

y - dependent variable (*experimental value*)

n - number of independent variables (number of coefficients)

X_i (i=1,2, …p) - i^{th} independent variable from total set of p variables a_i (i=1,2, …p) - i^{th} coefficient corresponding to xi b0 - intercept (or constant)

For the present study discharge is taken as Y which is a function of X. X has different values such as rainfall (X_1), slope (X_2), permeability factor (X_3), catchment area (X_4) and percentage of losses occurred (X_5). Implementing the regression analysis we will have the different values for the dependent variables which predict the runoff of the catchment area.

Table 3: Input data for runoff modeling by multiple linear regression method

Y	X1	X2	X3	X4	X5
Y1	2178.65	30	787.43	0.0412	435.73
Y2	2280.45	32.6	785.21	0.0422	433.28
Y3	2590.4	29.7	787.78	0.045	543.98
Y4	2401.05	34.2	786.45	0.0435	444.19
Y5	2069.45	28.1	787.53	0.0405	403.54
Y6	1805.4	27.5	789.10	0.0.385	397.19
Y7	2464.8	33.5	787.59	0.0445	529.93
Y8	1900.3	28	786.67	0.0395	414.26
Y9	1405	27.4	785.99	0.045	288.02
Y10	2197	30.5	787.34	0.0417	435

RESULTS AND DISCUSSION

Rainfall Analysis

The average annual rainfall depth in mm for 10 years is calculated from the monthly rainfall data of the Vamanapuram river basin and it is shown in fig.5. The rainfall over the catchment shows significant variation with respect to the changes in the climate and monsoon season.

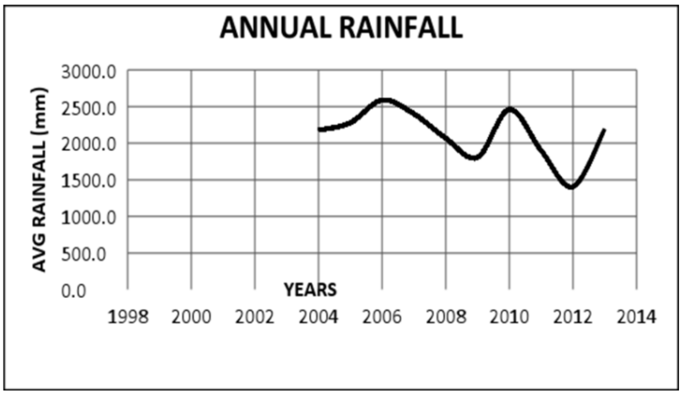

Figure 4: Average annual rainfall vs period

From the fig.4, the mean annual rainfall in the study area between 2004 and 2013 is 2129.27 mm. It is observed that the maximum rainfall of 2590.4 mm was in 2006 and a minimum rainfall was in 2012. Hence the year 2006 can be considered as wet year and 2012 can be termed as dry year among the study period.

Runoff Estimation

The study area constitutes different types of landuse/landcover. The major part of the study area is covered by plantation, 73.84%. The remaining study area is classified as follows: evergreen and semi evergreen area is 10.97%, forest plantation and scrub forest of 6.13%, 3% of area by crop land, 2.98% of area by build-up area, 2.1% of area is upland and 3.08 %of the area is occupied by others such as water body, deciduous and mining. A very large part of the watershed falls under Hydrologic Soil Group A. The antecedent moisture condition in the Vamanapuram river basin is observed as AMC-II. Using the land use and soil maps the weighted curve number value was obtained as 68.42. In general, among the different land cover types the crop land contributes more towards direct surface runoff.

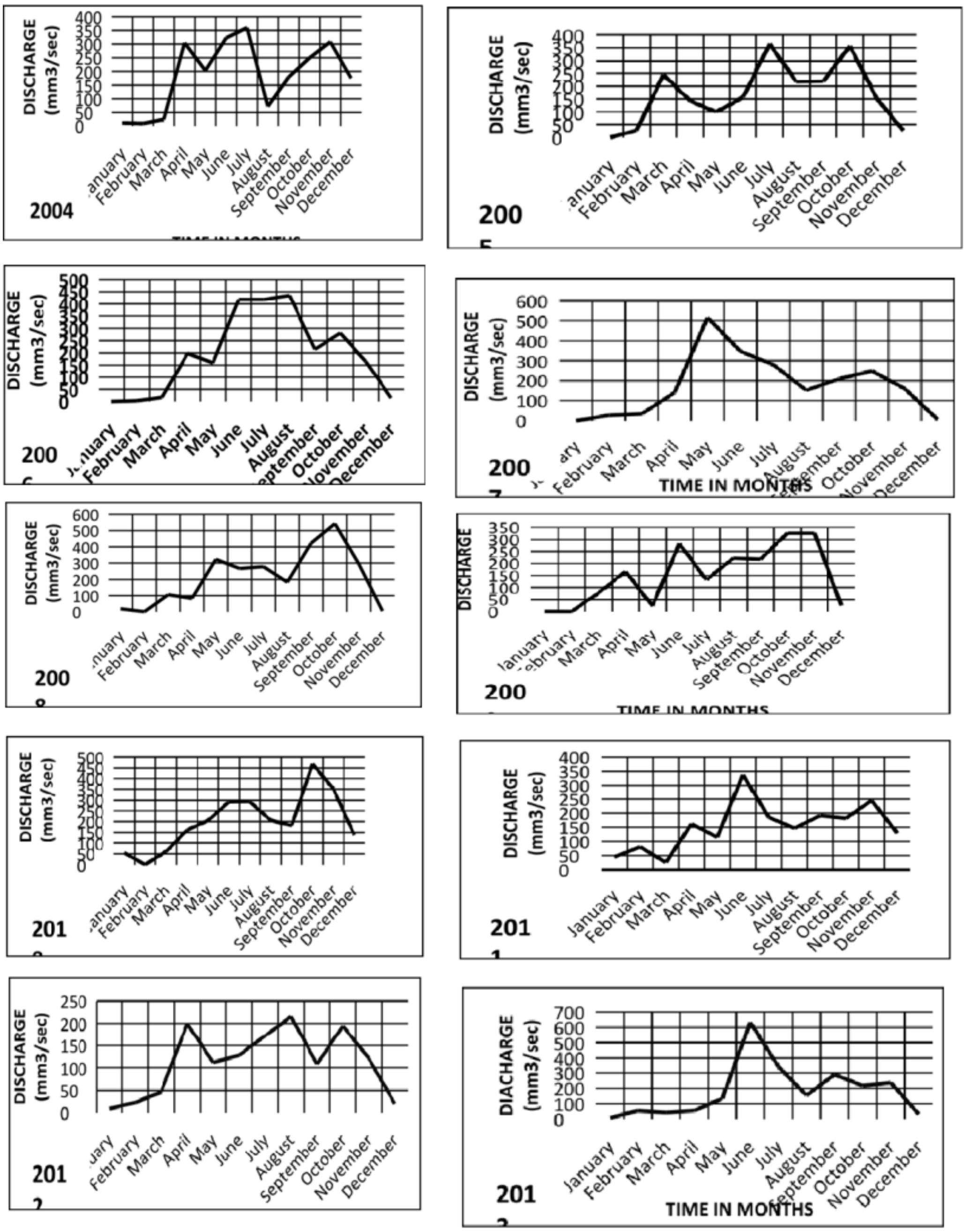

Figure 5: Hydrographs for the years (2004- 2013)

The annual and monthly runoff is estimated using the SCS – CN method. In drought years such as 2009 and 2012 the runoff was very low. The hydrographs plotted for the streamflows of the selected catchment is shown in the Fig.5. It is clearly understood that South-west monsoon is effective in the year 2013 from the hydrograph. As a result of this maximum discharge 631.89mm^3/s is observed in the month of June 2013. A discharge of 542.75mm^3/s is observed in the month of October 2006 which is the second maximum value during the study period. A minimum discharge 0.064 mm^3/s is obtained in the month of February 2009. In 2012, alternative monsoon season experienced higher discharge in the months of April, August and October and minimum discharges in the month of January throughout the study period. In general, the land with more vegetation plays a crucial role in the estimation of runoff. The cultivated land will reduce the total direct runoff compared to the land without cultivation.

Table 5 shows the annual runoff over Vamanapuram catchment area. Fig.6 shows the annual hydrograph of the catchment area. The maximum runoff for the watershed is estimated as 2584.87 mm^3/s in the year 2006 and minimum runoff of 1399.48 mm^3/s in the year 2012.

Table 5: Annual discharge (mm^3/s) over the catchment area

YEAR	DISCHARGE (mm^3/s)
2004	2173.17
2005	2274.97
2006	2584.87
2007	2395.57
2008	2063.97
2009	1799.57
2010	2459.27
2011	1894.77
2012	1399.48
2013	2192.47

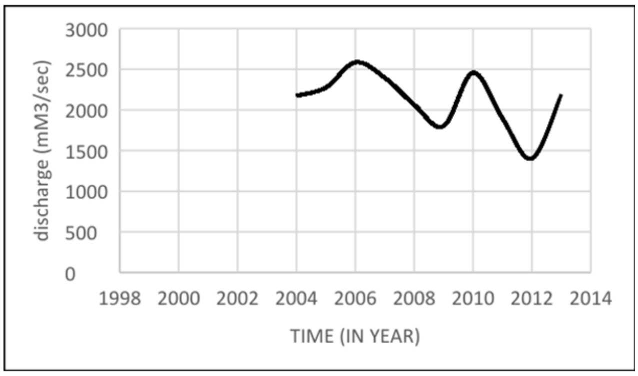

Figure 6: Hydrograph for the annual discharge of the catchment

Rainfall- runoff model

The multiple linear regression method was used for statistical modelling of rainfall- runoff. The results obtained are shown in the table 6 & 7 below.

ANOVA output

Table 6: Formula map of ANOVA output (part I)

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	1114652.411	222930.4823	31819099.88	2.76555E-15
Residual	4	0.028024738	0.007006184		
Total	9	1114652.439			

The regression tool determines the best set of parameters a (a_0, a_1, a_2, … a_n) in the model y = a_0 +a_1x_1+a_2x_2+… a_nx_n by minimizing the error, sum of squares. Coefficients are listed in the table of ANOVA output (Table 6). These coefficients allow the program to calculate predicted values of the dependent variable y (y_1, y_2, … yn), which is observed values of runoff in the catchment area and are part of residual output

Table 7: Formula map of ANOVA output (part II)

	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Intercept	45.51727729	30.52916804	1.490943914	0.210237753	-39.24528188	130.2798365
X1 (Rainfall) in mm	1.000387195	0.00031541	3171.701538	5.929E-14	0.999511476	1.001262914
X2 (Slope) in %	-0.019909419	0.020649816	-0.964145116	0.389571599	-0.077242499	0.037423661
X3 (Area) in sqkm	-0.065152429	0.03842016	-1.695787537	0.165168385	-0.171823895	0.041519037
X4 (permeability) in m/sec	10.25591597	14.59335598	0.702779812	0.520940111	-30.2617358	50.77356775
X5 (losses) in mm	-0.000995972	0.001439335	-0.691967063	0.527027329	-0.004992206	0.003000262

Table 7 shows output obtained from the statistical modelling. Table gives the coefficients of the independent variables in the catchment and the standard error in the model calibration .The rainfall-runoff model obtained from the multiple linear regression method (statistical method) is given below;

$$Y=45.5+X_1-0.019*X_2-0.065*X_3+10.26*X_4-0.000995*X_5$$

The above model equation obtained is helpful for the runoff estimation of different catchment area for future years with respect to the change in independent variables.

Table 8: Formula map of Regression statistics output

Regression Statistics	
Multiple R	0.999999987
R Square	0.999999975
Adjusted R Square	0.999999943
Standard Error	0.083702954
Observations	10

The fact that adjusted R square = **0.9999953** in the study is fairly close to 1 (Table 8). It suggests that overall model is adequate to fit the experimental data presented in Table 3. However, it does not mean that there are no insignificant parameters in it.

CONCLUSION

Based on the annual rainfall analysis of the study area for period 2004 to 2013, the year 2006 can be characterized as the ‘wet year’, the year 2012 as the ‘dry year’. Based on the mean monthly rainfall analysis of the study area for period 2004 to2013, the months May, June, July, August, September and October are characterized as rainy months of the year. The discharge over the catchment area is higher when the precipitation is high. The maximum discharge occurs over the catchment in the year 2006. The estimation of runoff using SCS curve number method can be effectively used in watershed management. The antecedent moisture condition in the Vamanapuram river basin is observed as AMC-II. Using the land use and soil maps the weighted curve number values obtained is 68.42. In general, among the different land cover types the cultivated land plays the major role for the direct surface runoff. Results obtained clearly shows the variation in runoff potential with different land use/land cover and with different soil conditions. Based on the statistical runoff model creation, it can be recommended for estimation of runoff characteristics for the future years even when changes in the independent variables in the catchment area. The fact that adjusted R^2 value in the study is close to 1, makes the study also applicable for different study periods in the basin.

ACKNOWLEDGMENT

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