GIS Based Runoff Estimation Using NRCS Method and Time-Area Method

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***Abstract*— The problems of soil erosion and, in turn, land and water quality degradation can be mitigated to a great extent by judicious watershed management. Runoff estimation is very important in the implementation of watershed development programs. The techniques that can be used for estimating direct surface runoff from rainfall are the Rational method, Natural Resources Conservation Service (NRCS) Curve number (CN) method and Time-Area method. This study involves estimation of runoff in Vamanapuram river basin (upstream of Valayinkil discharge station) using NRCS method with different initial abstraction values such as, I_a = 0.2S and I_a = 0.3S using composite and distributed curve number and by the Time-area method. Curve number determination and Isochrone map preparation was done in Arc GIS 9.3. Using the time-area histogram instantaneous unit hydrograph was derived, from which 2-hr unit hydrograph was derived. Runoff is estimated by multiplying the 2-hr unit hydrograph ordinates with the effective rainfall. Base flow separation was done by a digital filter, which was done in MATLAB R2013a. In NRCS-CN method runoff estimated for both composite and distributed CN with Ia = 0.2S is found to be better than that with I_a = 0.3S and also it is found that with I_a = 0.2S, the distributed CN method is giving better results. In the Time-area method runoff estimation includes routing by Muskingum method. The time-area method estimates the runoff more accurately than NRCS-CN method.**

Keywords—composite CN; distributed CN; time-area histogram; isochrones; unit hydrograph; runoff estimation

I. INTRODUCTION

In many instances, non availability of data of runoff, sediment yield, and nutrient loss is a major handicap in implementation of watershed development programs. There exist a multitude of models for estimation of runoff from ungauged watersheds useful for design of hydraulic structures, flood forecasting, erosion prediction, and water quality. The techniques that can be used for estimating direct surface runoff from rainfall are the Natural Resources Conservation Service (NRCS) curve number (CN) method and Time-area histogram method.

SCS model of a catchment was developed using remote sensing and GIS. For the study weighted average curve number of Karaman basin was determined using ILWIS 2.1 GIS software. The model developed was verified using the observed runoff data. Daily and total monthly runoff in the Karamana basin was computed. Correlation between observed daily/total monthly and predicted daily/total monthly was found out. Good correlation was obtained for daily and total monthly flows.[5] The runoff volume can be computed using NRCS-CN procedure by employing antecedent moisture conditions (AMC). The Remote Sensing (RS) and geographic information system (GIS) approach has been widely used for estimation of CN in the recent past [2].

For runoff estimation, the composite CN technique of NRCS-CN methodology is frequently and traditionally used. This averaging technique was more popular for reasons of easy manual calculations in its early stage of development. Despite availability of high-speed personal computers, runoff is still computed using the traditional composite technique. Of late, easy availability of spatially distributed digital database and use of GIS have accelerated the use of distributed curve numbers for runoff estimation.

A time-area histogram is a graph that explains which parts of a watershed contribute to direct runoff at a point of interest within the watershed during a specific period. It is constructed from a cumulative travel time map, which consists of isochrones that join areas in the same travel time zone at a specific time. The time-area histogram can be used as a function to translate excess rainfall into a runoff hydrograph by considering characteristics of the watershed such as shape, roughness, and slope. Since Clark (1945) applied the time-area method in developing a unit hydrograph with a linear reservoir at the outlet many other studies have tried to relate hydrologic responses to characteristics of a watershed using the time-area method [6].

Rainfall runoff modeling was done using distributed unit hydrograph approaches. The hydrograph simulated using distributed velocity field approach follows more closely to the observed values than the hydrograph simulated using SCS time lag equation [1]. Remote sensing and GIS were integrated to evaluate a distributed unit hydrograph which is linked to an excess rainfall model for calculating the stream flow response. A probability distributed model is used for calculating the rainfall excess. The simulated hydrograph agrees well with the observed hydrograph [4].

The main objectives of the present study includes: estimation of runoff using NRCS curve number method with composite and distributed curve numbers for I_a = 0.2S and I_a = 0.3S, development of time-area histogram, runoff estimation by time-area method and finally the performance evaluation of the above methods.

II. METHODOLOGY

This chapter describes the procedure and theoretical background of NRCS-CN method and Clark's IUH (Time-area histogram) method for the estimation runoff in the study area. CN preparation uses land use and soil data. IUH is derived from the time-area histogram, which is obtained from the isochrones. Land use map, soil map and isochrones were prepared using Arc GIS software. Routing is carried out using Muskingum routing method. Base flow separation is done by using a digital filter.

A. *NRCS-CN method*

The NRCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis states that the ratio of the actual amount of direct runoff to the maximum potential runoff is equal to the ratio of the amount of actual infiltration to the amount of the potential maximum retention. The second hypothesis states that the amount of initial abstraction is some fraction of the potential maximum retention. Expressed mathematically [3], the water balance equation and the two hypotheses, respectively, are

.

$$P = I_a + F + Q \quad (1)$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \quad (2)$$

$$I_a = \lambda S \quad (3)$$

Where P = total precipitation (mm); I_a = initial abstraction (mm) ; F = cumulative infiltration excluding I_a (mm) ; Q = direct runoff (mm); and S = potential maximum retention or infiltration (mm). The current version of the NRCS-CN method assumes λ equal to 0.2 for usual practical applications.

As the initial abstraction component accounts for surface storage, interception, and infiltration before runoff begins, λ can take any value ranging from 0 to ∞. Combining Eqs. (1) and (2), one can write an equation for Q as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad (4)$$

Substituting I_a = 0.2S, the equation in its standard form is

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (5)$$

Where Q = 0 for P ≤ 0.2S. S is mapped on to CN as follows:

$$S = \frac{25400}{CN} - 254 \quad (6)$$

Where CN = curve number, which depends on land use,hydrologic soil group, and AMC.

B. *Determination of runoff using composite CN*

Composite (or area weighted) CN is estimated by compositing the area-weighted average CNs calculated for the entire watershed. To this end, land use and soil maps are overlaid to delineate polygons with unique land use and hydrologic soil group (HSG) combinations for determination of CN for each grid using Arc GIS and then computation of the area-weighted average CN..

The runoff resulting from the daily average of monthly rainfall values were computed using estimated composite curve number for two different initial abstraction values. ie., Ia = 0.2S and Ia = 0.3S. The runoff calculated using NRCS equation is assumed to be spread over the entire watershed. This depth is multiplied by the drainage basin area to get the runoff volume. Since the SCS equation does not account for the time distribution of intensity of rainfall, that also is to be considered. The estimated discharge is converted to cumec before comparing it with observed discharge.

C. *Determination of runoff using distributed CN*

Using the land use and soil information, curve numbers is determined for each of the cells or polygons and runoff computed for each cell or polygon. These runoff values are weighted for area to yield the average runoff from the watershed.

D. *Time-area method*

This method aims at developing an IUH due to an instantaneous rainfall excess over a catchment. It is assumed that the rainfall excess first undergoes pure translation and then attenuation. The translation is achieved by the travel time-area histogram and the attenuation by routing the above through a linear reservoir at catchment outlet.

In time-area histogram, time refers to time of concentration and area refers to inter isochronal area. Time of concentration is the time required for a unit volume of water from the farthest point of catchment to reach the outlet. It represents the maximum time of translation of the surface runoff of the catchment. It can be determined using Kirpich's equation. According to Kirpich's

$$T_c = 0.0195 L^{0.77} s^{-0.385} \quad (7)$$

Where, T_c = time of concentration in hours

L = distance from the upstream farthest point to the outlet in kilometers

S = slope of the area

Inter-isochronal areas can be found out using ArcGIS software. Using the inter-isochronal areas and time-histogram can be plotted. Then routing is done using Muskingum method.The linear reservoir at the outlet is assumed to be described by S=KQ, where K is the storage time constant (taken as equal to the time of travel). Time of travel can be calculated using the formula

$$t = \frac{T_c}{N} \quad (8)$$

Where, t = computed time of travel in hours

T_c = time of concentration in hours
N = Number of inter isochronal areas

The inflow rate between an inter-isochronal area A_r (km^2) with time interval Δt_c (hrs) can be calculated using the formula

$$I = 2.78 \frac{A_r}{\Delta t_c} \quad (9)$$

Knowing the values of K of the linear reservoir, the inflows at various times are routed by the Muskingum method. Since it is a linear reservoir the weighting factor, x=0, then the Muskingum equation can be written as

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1 \quad (10)$$

Where,

$$C_0 = \frac{0.5\Delta t_c}{K + 0.5\Delta t_c} \quad (11)$$

$$C_1 = \frac{0.5\Delta t_c}{K + 0.5\Delta t_c} \quad (12)$$

$$C_2 = \frac{K - 0.5\Delta t_c}{K + 0.5\Delta t_c} \quad (13)$$

ie, $C_0=C_1$, Also since the inflows are derived from the histogram $I_1=I_2$ for each interval. Then the equation becomes

$$Q_2 = 2C_1 I_1 + C_2 Q_1 \quad (14)$$

Where, Q_2 is the ordinate of instantaneous unit hydrograph in cumecs. From this IUH, 2 hr unit hydrograph ordinates are derived. Effective rainfall for each day (24 hr duration) is calculated by NRCS-CN method. Effective rainfall values corresponding to the interval of the UH ordinates (2 hr) are then found out using conversion ratios from the CWC flood estimation report for west coast zones 5(a) and 5(b) [8]. This corrected effective rainfall is then multiplied with the ordinates of UH to give the runoff.

In order to compare the runoff ordinates obtained by this method with observed runoff, base flow is separated from the observed runoff by using the digital filter proposed by Nathan and McMahon [7]. The filter relationship of Nathan and McMahon in terms of base flow Q_b and total stream discharge is given by

$$Q_b(i) = kQ_b(i-1) + \frac{1-k}{2}[Q(i) + Q(i-1)] \quad (15)$$

Where k is the filter parameter and Q is the measured daily discharge at day i. The filter parameter k was optimized by systematically changing its value in the equation, starting from a minimum trial value of 0.01 and increasing it by 0.01 up to 0.99 (k<1). With each k value chosen, estimated base flow time series were created for the gauging station. Graphs were plotted for the discharge Q and the base flow Q_b against time, shown in Fig. 1. From the graph N_d was obtained as the difference between the local maxima of Q and the intersection point of Q and Q_b. The average N_d (ie, the time in days between the peak of the measured discharge and the event when the simulated flow first becomes constrained by the measured discharge) was obtained. The optimized value of k is the one in which the resulting N_d estimate is identical in average to the N_d value given by Linsely's equation ($N_d = A^{0.2}$ where A is the drainage area for surface runoff above the gauging station, measured in square miles). The optimized value of k and the Q_b values were obtained by writing two programs in MATLAB R2013a. After separating the base flow from the observed discharge, it is compared with the estimated runoff hydrograph ordinates.

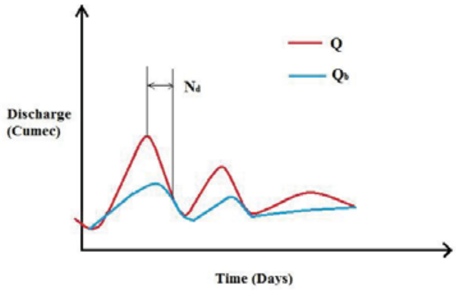

Fig. 1. Schematic Diagram for the Determination of N_d

E. Model performance

After computations the model performances were evaluated using statistical techniques such as coefficient of determination (R^2) and the coefficient of residual mass (CRM).

The coefficient of determination (R^2) describes the proportion of total variance in the observed data that can be explained by the model. Expressed mathematically,

$$R^2 = \left\{ \frac{\sum_{i=1}^{N}(O_i - O_{avg})(S_i - S_{avg})}{\left[\sum_{i=1}^{N}(O_i - O_{avg})^2\right]^{0.5}\left[\sum_{i=1}^{N}(S_i - S_{avg})^2\right]^{0.5}} \right\}^2 \quad (16)$$

Where O_i = the i[th] observed data; O_{avg} = mean of the observed data; S_i = the i[th] simulated value; S_{avg} = the mean of simulated value; and N = total number of events. R^2 ranges from 0.0 to 1.0, with higher values indicating better agreement, and vice versa.

The coefficient of residual mass (CRM) indicates the degree to which the prediction is over or under estimated. Its positive value indicates the model to have underestimated the prediction, whereas the negative value indicates overestimation. CRM is expressed as follows:

$$CRM = 1 - \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} S_i}{\sum_{i=1}^{N} O_i} \quad (17)$$

III. STUDY AREA AND DATA USED

Study area is a sub basin in Vamanapram river basin, which includes upstream portion of Valayinkil discharge station and has an area of about 56.154 km^2. Study area is shown in Fig. 2

Daily rainfall and runoff data for the year 2001 at Valayinkil station for the monsoon season was collected from IDRB, Trivandrum. Land use and soil maps are obtained from KSREC. Elevation data is obtained from SRTM DEM of 90mx90m resolution. The softwares used for the study is Arc GIS 9.3 and MATLAB R2013a.

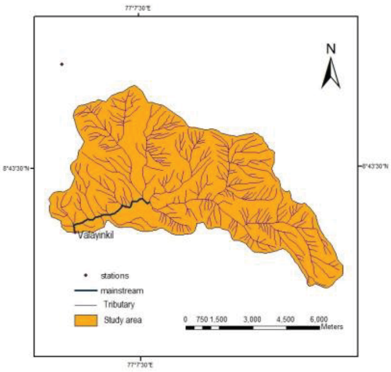

Fig. 2. Map of study area

IV. RESULTS AND DISCUSSION

Land use and soil maps were prepared for the determination of curve number for the estimation of runoff using NRCS method. Isochrone map was prepared for obtaining the time-area histogram. Using the time-area diagram Clark's IUH was developed. From the IUH 2hr unit hydrograph ordinates were derived. By multiplying the unit hydrograph ordinates with the effective rainfall direct runoff values were obtained. Base flow separation was done by writing program in MATLAB 2013. After the computations observed and estimated runoff values were compared and model performance were evaluated by determining the R^2 value. The land use, soil and curve number maps prepared are shown in Fig. 3, Fig. 4 and Fig. 5 respectively.

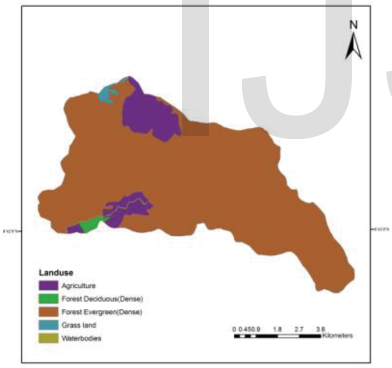

Fig. 3. Land use map of study area

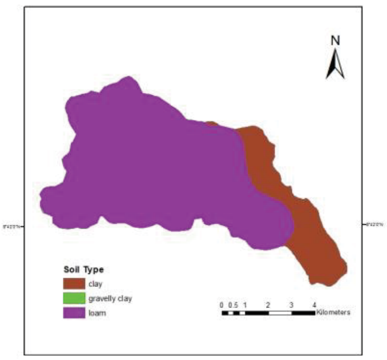

Fig. 4. Soil map of study area

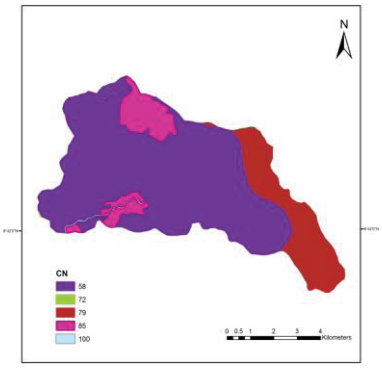

Fig. 5. Curve number map

The common types of land use found are forest, agriculture, grass land and water body. Major part of study area is covered by evergreen dense forest. Common types of soil found in the area are clay, gravelly clay and loam. Majority of study area consists of loam. The curve number value ranges from 58 to 100.

A. Determination of runoff using composite CN

Composite CN is obtained as 65. Fig. 6 and Fig. 7 represents the Scatter plot between estimated and observed runoff for $I_a = 0.2S$ and $I_a = 0.3S$ respectively.

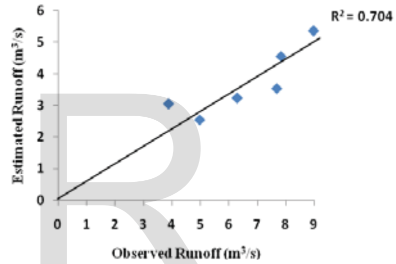

Fig. 6. Scatter plot between observed and estimated runoff with Ia=0.2S

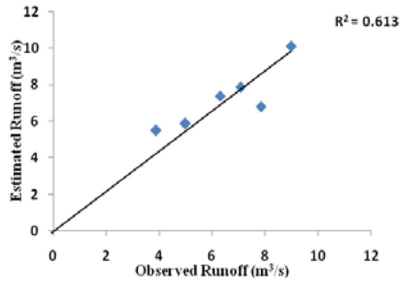

Fig. 7. Scatter plot between observed and estimated runoff with Ia=0.3S

The coefficient of determination (R^2) is obtained as 0.704 and the coefficient of residual mass (CRM) is obtained as 0.438 for $I_a = 0.2S$. Since CRM is positive it indicates that the model underestimated the prediction. The coefficient of determination (R^2) is obtained as 0.613 and the coefficient of residual mass (CRM) is obtained as -0.102 for $I_a = 0.3S$. Since CRM is negative it indicates that the model overestimated the prediction.

B. Determination of runoff using distributed CN

Fig. 8 and Fig. 9 represents the Scatter plot between estimated and observed runoff for I_a = 0.2S and I_a = 0.3S respectively.

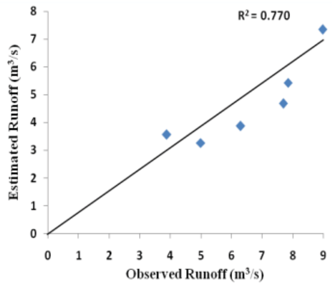

Fig. 8. Scatter plot between observed and estimated runoff with Ia=0.2S

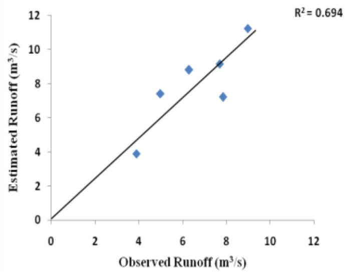

Fig. 9. Scatter plot between observed and estimated runoff with Ia=0.3S

The coefficient of determination (R^2) is obtained as 0.770 and the coefficient of residual mass (CRM) is obtained as 0.290 for I_a = 0.2S. Since CRM is positive it indicates that the model underestimated the prediction. The coefficient of determination (R^2) is obtained as 0.694 and the coefficient of residual mass (CRM) is obtained as -0.204 for I_a = 0.3S. Since CRM is negative it indicates that the model overestimated the prediction.

C. Runoff estimation using Time-area method

Time-area histogram is the basic input for the estimation of runoff using this method. To develop the time-area histogram digital elevation model (DEM), travel time map and isochrone map were prepared. Using the isochrone map inter isochronal area was obtained and time-area histogram was developed. The DEM and travel time map for the study area are shown in Fig. 10 and the isochrone map is shown in Fig. 11. The time-area histogram was derived using time and inter- isochronal area and is shown in Fig. 12, using this the inflow values were computed and are shown in Table I.

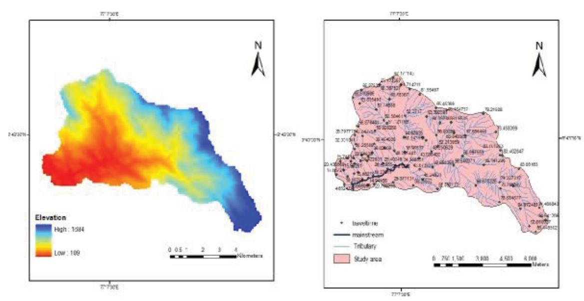

Fig. 10. Digital elevation model and travel time map of study area

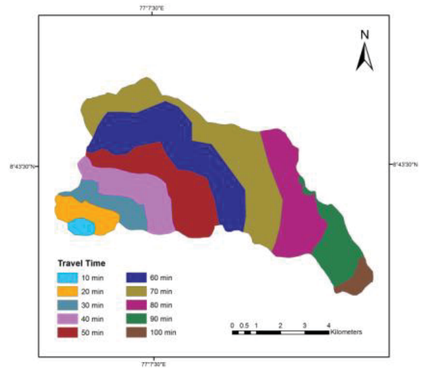

Fig. 11. Isocrones for the study area

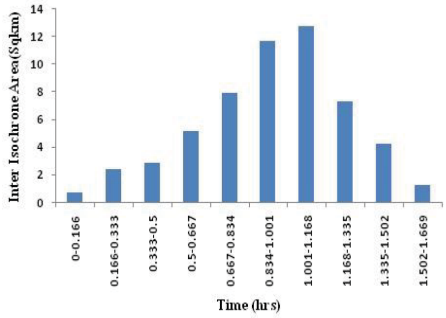

Fig. 12. Time-area histogram

TABLE I. INFLOW VALUES

Time (hrs)	Inter isochronal area (sqkm)	Inflow (cumec)
0.166	0.6653	11.1434
0.333	2.3474	39.3125
0.5	2.8159	47.1589
0.667	5.1702	86.5855
0.834	7.9188	132.6174
1.001	11.6772	195.5587
1.168	12.7795	214.0192
1.335	7.3004	122.2599
1.502	4.2644	71.4160
1.669	1.2152	20.3510

Then the IUH ordinates are derived and it is plotted in Fig. 13. From this IUH 2 hr UH ordinates are derived and is shown in Fig. 14.

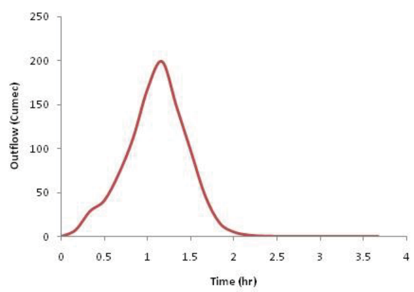

Fig. 13. Instantaneous unit hydrograph

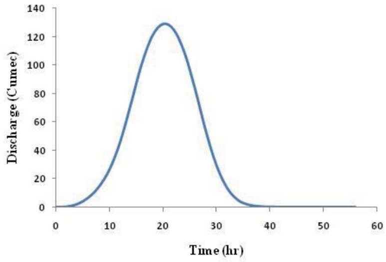

Fig. 14. Unit hydrograph ordinates

Effective rainfall values for each day of monsoon season were calculated and are made equivalent to the time increment of UH. Then the runoff was computed for each month. Base flow is separated from the observed discharge by using a digital filter. The filter parameter k was obtained as 0.83 for an N_d average of 3.05 days. Then the observed and estimated runoff was compared. Scatter plot between observed and estimated runoff for the six months are shown in Fig. 15 to Fig. 20.

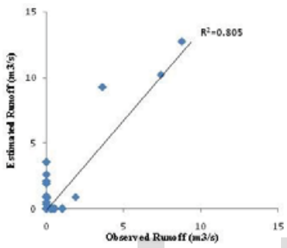

Fig. 15. Runoff comparison for the month of June

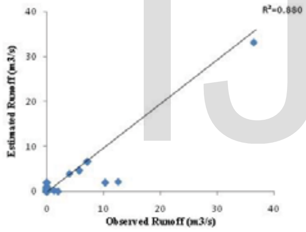

Fig. 16. Runoff comparison for the month of July

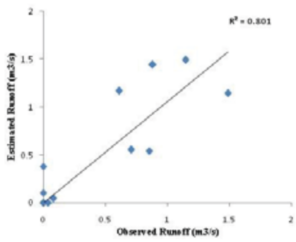

Fig. 17. Runoff comparison for the month of August

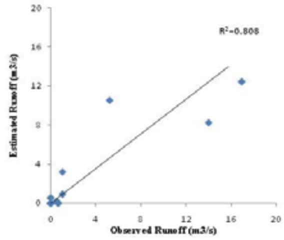

Fig. 18. Runoff comparison for the month of September

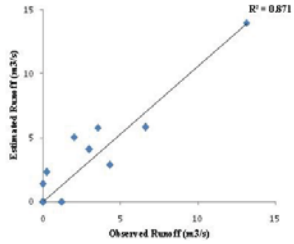

Fig. 19. Runoff comparison for the month of October

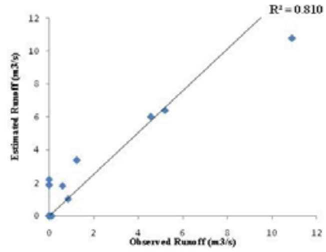

Fig. 20. Runoff comparison for the month of November

The summarized results of the time-area method are shown in Table II

TABLE II. RESULTS OF TIME-AREA METHOD

Month	R^2
June	0.805
July	0.880
August	0.801
September	0.808
October	0.871
November	0.810

The runoff estimated for all the 6 months of the monsoon season is having R^2 value in the range of 0.8 to 0.88. Hence the time-area method which includes routing by Muskingum method is found to give better prediction. Best result is obtained for the month of July and its time series plot is shown in Fig. 21.

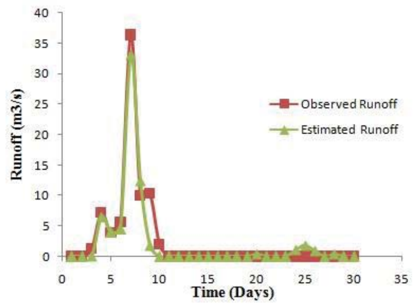

Fig. 21. Time series plot for the month of July

V. CONCLUSIONS

In this study runoff estimation is done by NRCS-CN method with composite and distributed curve number for different initial abstraction values and by time-area method using GIS by integrating data on land use, soil type and elevation of the catchment. The R^2 value and CRM obtained for runoff estimated are (0.704, 0.438) with composite CN for I_a = 0.2S and (0.613, -0.102) for I_a = 0.3S. With distributed CN the corresponding values are (0.770, 0.290) for I_a = 0.2S and (0.694, -0.204) for I_a = 0.3S. Runoff is underestimated for composite and distributed CN with I_a = 0.2S and is over estimated for composite and distributed CN with I_a = 0.3S. It is found that with I_a = 0.2S, the distributed CN method is giving better results. For runoff estimated by time-area method, R^2 values obtained are in the range of 0.8 to 0.88. The time-area method estimates the runoff more accurately than NRCS-CN method.

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