RAINFALL AND RUNOFF PROCESS USING BY OVERLAND TIME OF CONCENTRATION MODEL AND GIS MODULES

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Abstract:

The integration strategy for a watershed can be carried out by various procedures. However a first step is usually a resource survey or inventory. This attempts to answer the question of the supply and demand for resources both natural and human resources. Depending upon the area involved, a survey may include socio-economic characteristics, soil characteristics, land capacity/suitability classifications, hydrological assessment including climate characteristics, water use and other parameters as needed. Runoff is one of the important integral part of the integrated watershed management, so for this estimation of runoff is required. The rainfall-runoff process in a catchment is a complex and complicated phenomenon governed by large number of known and unknown physiographic factors that vary both in space and time. Application of mathematical modeling techniques to the constituent processes involved in the physical processes of runoff generation has led to better understanding of the processes and their interaction. Conventional hydrological models for the prediction of runoff particularly over a basin require considerable hydrological and meteorological data. Collection of these data is expensive, time consuming and difficult process. ESRI software's Arc view, Arc Info and Arc GIS 9.1 versions are helpful to compute the watershed parameters like slope map, drainage map, contour map, TIN and DEM etc. And also Remote Sensing technology and Geographical Information Systems (GIS) can augment the conventional methods to a great extent in rainfall runoff studies. In the present study a small agricultural watershed rainfall-runoff model was chosen. The advantage of formulating this model for the watershed is that it enables to generate the runoff. Once the model is formulated, calibrated and validated, the same can be applied to any watershed to estimate the runoff, even if the sub catchment is ungauged. Keeping these points in view, the rainfall-runoff model, Overland Time of Concentration Model has been formulated and developed. It contains three modules namely Time of Concentration, Rainfall and Soil Moisture module for the estimation of daily runoff. Pamena – I Watershed, Chevella Mandal, Rangareddy District, Andhra Pradesh, India has been considered for the study. It is concluded that the developed OTC model is a fairly good model and it is comparable with the standard models considered in the present study viz., SCS-CN and TR-55 Models.

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INTRODUCTION

Watershed modeling is a comprehensive program to determine runoffs using standard techniques. Model flood control structures such as detention basins with various outlet structures, use actual or synthetic rainfall distributions. Watershed modeling includes rainfall maps for the entire area to calculate intensity duration frequency relationships. The rainfall-runoff process in a watershed is a complex and complicated phenomenon governed by large number of known and unknown physiographic factors that vary both in space and time (10). The rain falling on a catchment undergoes number of transformations and abstractions through various component processes such as interception, detention, transpiration, overland flow, infiltration, interflow, percolation, sub-base flow, base flow etc., and emerges as runoff at the catchment outlet. Application of mathematical modeling techniques to the constituent processes involved in the physical processes of runoff generation has led to better understanding of the processes and their interaction (1).

A number of investigators have attempted to develop rainfall runoff relationships that could apply to any region or watershed under any set of conditions (11). However, these methods must be used with caution because of the variable factors that affect the calculation of runoff from a known volume of rainfall. The SCS (SCS 1964, 1975, 1986) (9) represent a useful set of rainfall runoff curves that also include land cover, soil type and initial losses (abstraction) in determining direct runoff. A number of unit hydrograph methods, Snyder's method, Time of Concentration and the SCS methods are most often used based on their simplicity and relative accuracy under a variety of watershed conditions.

STUDY AREA

Pamena – I Watershed which is the part of Pamena village falls under the agro-climatic zone V of Andhra Pradesh which is designated as North Telangana agro climatic zone. The village is 6 km away from Chevella located on Shabad road and in the southern part of Ranga Reddy district.(Source: Action plan for Watershed Development Program in Pamena – I Watershed, Chevella Mandal, Ranga Reddy District, A.P.). The village lies between longitudes 78º 06'–78º 09' and latitudes 17º 15'30''–17º 17'30'' falling in Survey of India toposheet no.56 K/3. Pamena-I Watershed has a geographical area of 500 ha. The study area on satellite imagery of Indian Remote Sensing (IRS) - 1D, Linear Imaging Self-scanning Sensor (LISS)-III & PAN (Panchromatic) merged map is shown in Fig. 1. The distribution of rainfall is unequal and major part of annual rainfall occurs in a few months due to South West monsoon. Early withdrawal of monsoon results in crop failures and makes agriculture a gamble.

Rainfall: The rainfall is the source of all water in the form of rain. The watershed mainly experiences the southwest monsoon. The rainfall in the non-monsoon period is insignificant. The average annual rainfall in the basin is 855.00 mm. The south-west monsoon sets in by middle of June. During the monsoon season, heavy to moderate rains alternate with breaks when there is little or no rain. The strength of the monsoon current increases from June to July and remains more or less steady in August and begins to weaken in the month of September.

The daily data of rainfall has been collected for the period 1996 to 2005 and the total annual rainfall recorded as 877.6, 741.10, 1050.10, 678.40, 869.40, 840.00, 643.00, 1041.60, 768.00, 1040.60 mm respectively. In this watershed, highest rainfall of 1050.10 mm is recorded in 1998 and lowest of 643 mm in 2002. The watershed experiences predominantly southwest monsoon. The period of June to November has been considered as monsoon period, and December to May has been considered as non-monsoon for hydrological purpose.

Soils: The soils of Pamena –I watershed mainly consist of 48% of black loamy soils, and 44% of black clayey soils with small sandy patches spread over here and there. (Directorate of Census Operations, A.P. 2004 -2005).The soil map with black loamy soils and black clayey soils is shown in Fig. 2. Due to severe runoff, the soil is cut to great depths causing severe erosion problem as well as loss of nutrients. The excessive rate of erosion is also attributed to the unscientific agricultural practices (2). In spite of erosion and low fertility, the farmers are practicing cultivation of cotton, sunflower etc. instead of cover crops which is aggravating soil erosion.

COMPUTATION OF WATERSHED PARAMETERS USING ESRI SOFTWARE'S ARC VIEW, ARC INFO AND ARC GIS 9.1 VERSIONS

Drainage Map: Drainage pattern of the Pamena – I watershed was digitized from projected toposheets. Now, the already prepared polygon coverage was overlaid on the drainage map to compute the stream length and drainage density in each sub area of the Pamena – I watershed in **ESRI environment.** The stream length, perimeter and drainage density were presented in Table 1. Highest and lowest elevations of the study area i.e. Pamena – I watershed were also listed in Table 1.

Slope Map: The slope function in **Arc Editor** calculates the maximum rate of change between each cell and its neighbours. Every cell has a slope value in the output raster. The lower slope value indicates a flatter terrain and the higher the slope value, the steeper the terrain. The output slope raster can be calculated either in percent of slope or degree of slope.

Contour Map: Contours are lines that connect points of equal elevation. The equal elevation points were located from toposheet number 56 K/3, on a scale of 1: 50, 000 collected from Survey of India (SOI), Hyderabad. The collected toposheets were scanned and registered with tic points and rectified. Further, the rectified maps were projected. All individual projected maps were finally merged as a single layer. The contours were digitized with an interval of 5 m. The contour attribute table contains an elevation attribute for each contour line. The contour map was prepared using **Arc Map of Arc GIS 9.1**. Contour map is a useful surface representation because it enables to simultaneously visualize flat and steep areas, ridges, valleys in the study area.

Digital Elevation Model (DEM) Map: A DEM is a raster representation of a continuous surface, usually referring to the surface of the earth. The DEM is used to refer specifically to a regular grid of spot heights. It is the simplest and most common form of digital representation of topography (6). The Digital Elevation Model of Pamena–I watershed was generated from the contour map using surface analysis tool of spatial analyst in **Arc View** and is shown in Fig. 3

Triangulated Irregular Network (TIN) Map: A Triangulated Irregular Network (TIN) is a digital data structure used in a Geographic Information System (GIS) for the representation of a surface A TIN is a vector based representation of the physical land surface, made up of irregularly distributed nodes and lines with three dimensional co-ordinates (x, y, and z) that are arranged in a network of non-overlapping triangles (7). TIN's are often derived from the elevation data of a rasterized Digital Elevation Model (DEM). The Triangulated Irregular Network (TIN) map was prepared using **Arc Editor** and it is shown in Fig. 4.

METHODOLOGY

Soil Conservation Service (SCS) Curve Number Method: The runoff curve number method is a procedure for computing hydrologic abstraction from storm rainfall developed by the USDA Soil Conservation Service (12). In this method, runoff depth (i.e., effective rainfall depth) is a function of total rainfall depth and an abstraction parameter referred to as runoff curve number or CN. The curve number lies in the range 1 to 100, being a function of runoff producing catchment properties viz. hydrologic soil type, land use and treatment, ground surface condition, and Antecedent Moisture Condition(AMC). The runoff curve number method is developed based on 24-h rainfall – runoff data.

For a storm event, the depth of effective rainfall or direct runoff (P_e) is less than or equal to the depth of total rainfall (P). After runoff begins, the depth of water retained in the catchment (F_a) is less than or equal to the potential maximum retention (S). There is some amount of rainfall I_a (initial abstraction before ponding) for which no runoff will occur, so the potential runoff is ($P – I_a$).

The hypothesis of the SCS method is based on the assumption of proportionality between retention and runoff.

$$\frac{F_a}{S} = \frac{Q}{(P - I_a)} \qquad \text{--------------------- (1)}$$

This states that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff. This assumption underscores the conceptual basis of the runoff curve number method. From the continuity principle $P = P_e + I_a + F_a$ ---------------------- (2)

Where, P = Total Rainfall in mm; P_e = Rainfall excess in mm; I_a = Initial abstraction in mm

F_a = Continuing abstraction in mm; S = potential maximum retention in mm

The actual retention, when the initial abstraction is considered, is

$$F_a = (P-I_a) - P_e \quad \text{---------------------------} \quad (3)$$

Replacing F_a in Eq. (1) by Eq. (3) leads to Solving for P_e

$$\frac{(P-I_a)-P_e}{S} = \frac{P_e}{(P-I_a)} \quad \text{----------------} \quad (4)$$

$$P_e = \frac{(P-I_a)^2}{(P-I_a)+S} \quad \text{----------------} \quad (5)$$

The initial abstraction is a function of land use, treatment and condition, interception, infiltration, depression storage and antecedent soil moisture (5). SCS did an empirical analysis for the development of its rainfall – runoff relation, and they found the following formula to be the best for estimating I_a:

$$I_a = 0.2S \quad \text{--- -------------} \quad (6)$$

It is found that the above equation is not correct under all circumstances Louis Berger International, Inc., and Water and Power Consultancy Services (India) Ltd., found the following equations better suited than Eq.(6) for Indian conditions. According to them, for all regions including black soil area with AMC - I.

$$I_a = 0.3S \quad \text{--------------} \quad (7)$$

And for regions with black soils and with AMC II and III, it is given by

$$I_a = 0.1S \quad \text{---------------} \quad (8)$$

If Eq.(7) is substituted in Eq.(5), it leads to

$$P_e = \frac{(P-0.3S)^2}{(P+0.7S)} \quad \text{--------------} \quad (9)$$

and with Eq. (8), it results in

$$P_e = \frac{(P-0.1S)^2}{(P+0.9S)} \quad \text{-------------} \quad (10)$$

The empirical studies conducted by SCS further indicated that S can be estimated by

$$S = \frac{25400}{CN} - 254 \quad \text{--------------} \quad (11)$$

Study area has been classified for Land Use / Land Cover into four classes viz., Built up Area**,** Double Cropped Land**,** Fallow Land and Land with/without Scrub. In each sub area NDVI values are generated in ERDAS 8.7. Area under each class has been calculated from the attribute table and listed in Table 2. The classified thematic map was converted from raster to vector format for further analysis. The Land Use/ Land Cover thematic map and soil map were interpreted in command tools of ARC/INFO (3). The areas of different Land use class and soil combinations were obtained in the attributes selection menu by using logical expression and accordingly different CN values were assigned. Then weighted CN for each sub area in the study area was worked out using the following equation.

$$\text{Weighted Curve Number} = \frac{\sum (CN_i * A_i)}{A} \quad \text{--------------------} \quad (12)$$

Where CN_i = Curve number from 1 to 100

A_i = Area with curve number CN_i.
A = Area of each sub area

The weighted curve number is calculated from the classification of land use / land cover i.e. from table 2 and their corresponding areas are taken to substitute in the equation 12.

Weighted Curve Number = (85X0.06) + (75X2.95) + (1.75X61) + (0.24X61) / 5.0
= 69.55

The calculated weighted curve number is used for the calculation of recharge capacity of study area using the equation 11.

Technical Release - 55 (TR – 55) Model: The model structure, input parameters required for the estimation of daily runoff viz., define the area, specify the flow of runoff to a reach (water path), rain fall data, runoff curve**,** time of concentration and procedure for the estimation of daily runoff were explained in the following sub sections.

Model structure: Technical Release-55 (TR-55) presents simplified procedures for estimating runoff and peak discharges in small watersheds. In selecting the appropriate procedure, consider the scope and complexity of the problem, the available data, and the acceptable level of error. While this TR -55 gives special emphasis to urban and urbanizing watersheds, the procedures apply to any small watershed in which certain limitations are met. The TR – 55 Model is a Hydrologic model for small watersheds specifically for rainfall – runoff. (USDA, Urban Hydrology for Small Watersheds Natural Resources Conservation Service, Conservation Engineering Division, Technical Release– 55, June1986) (8). TR-55 creates a theoretic rain storm in the computer and assesses how much water runs into the river.

One critical parameter in this model is Time of Concentration (t_c), which is the time, it takes for runoff to travel to a point of interest from the hydraulically most distant point. Normally rainfall duration equal to or greater than t_c is used. Therefore, the rainfall distributions were designed to contain the intensity of any duration of rainfall for the frequency of the event chosen. That is, if the 10-year frequency, 24-hour rainfall is used, the most intense hour will approximate the 10-year, 1-hour rainfall volume.

Overland Time of Concentration – Runoff Model: Despite the importance of overland time of concentration on the design discharge, the assessment covers nine formulas published between 1946 and 1993, which are intended for overland flow only that is subjected to uniform rain. The assessment compares the estimation from the formulas with experimental values that are derived under the same conditions for two surfaces: concrete and grass. The assessment shows that formulas which do not account for the rainfall intensity are only valid for a limited range of rainfall intensities. The formulas that account for the rainfall intensity generally show better agreement with the experimental data. Finally, the assessment gives two rankings of the formulas for the two surfaces in accordance to their accuracy as compared to the experimental data.

The formula that has the best accuracy for both surfaces is the Chen and Wong formula. In the overland time of concentration calculation, we require inputs for the longest watercourse length in the watershed (L), the average slope of that watercourse (S), and a coefficient representing the type of groundcover. Usually L and S can be obtained from topographic maps. The coefficient is determined from photographs of the watershed or field reconnaissance. The calculation computes the time of concentration and average velocity in the longest watercourse. Once the model is validated at a watershed level, it can be applied to ungauged sub basins to calculate runoff.

Keeping these points in view, Overland Time of Concentration (OTC) Runoff Model has been formulated and developed. It contains five modules namely Rainfall, Time of Concentration (t_c), Wilting Point, Accumulated Potential Water Loss (APWL) and Soil Moisture for the estimation of daily runoff.

RESULTS AND ANALYSIS

Yearly runoff estimated from the three models viz. SCS-CN, TR-55 and OTC model have been compared and represented graphically in Fig. 5. Average yearly rainfall and runoff in mm over the Pamena–I watershed was estimated from SCS-CN, TR-55 and OTC model were given in Table 3 and these values compared with yearly observed runoff in the same table. Monthly runoffs estimated from SCS-CN, TR-55 and OTC model were quite close and some times OTC model over estimated than the remaining two models while TR-55 model under estimated than the other models. In most of the months, the runoff estimated from SCS-CN model and OTC model data closely resembled each other.

The yearly runoff estimated from three models viz. SCS-CN, TR-55 and OTC model have been compared with yearly observed runoff and shown in Fig. 6. The figure shows that the yearly runoff values estimated from the SCS-CN method were generally high. The OTC model yielded runoff higher than that from TR-55 model, but it is lower than the SCS-CN method for the duration of 2000 to 2005 expect in the year 2003. The yearly observed runoffs are less compared to three models.

From this analysis, it can be concluded that good correlation was found in all models viz. SCS-CN method, TR-55 model and OTC model (4) .However it is higher in the case of SCS-CN method followed by TR-55 model and OTC model. Mean Square Error (MSE) in mm is estimated for daily, monthly and yearly runoff calculated from each of the three different models namely SCS-CN method, TR-55 model and OTC model and the corresponding observed runoff for the Pamena –I watershed. MSE was found to be low in the case of OTC model compared to that from SCS-CN and TR-55 model on yearly basis, but it is high compared to SCS-CN method and TR-55 method on monthly basis and this MSE is low compared to that from TR-55 method on daily basis. Statistical evaluation criteria between observed runoff and estimated runoff using SCS-CN, TR-55 and OTC models were given in Table 4.

CONCLUSIONS

(i) GIS and Remote Sensing techniques have proved to be boon, which helps in quick and accurate analysis of watershed area due to quick, flexible and efficient data handling capability of GIS and use of satellite imageries, which represent the existing site conditions.

(ii) The developed model that was based on the time area rainfall – runoff analysis and applied in a small-forested watershed gave satisfactory results especially for the ascendant curve of the simulated flood hydrographs. However, a combination of the model's application with the determination of the transportation of sediment would improve its application.

(iii) Rainfall intensity is considered in this study and duration is taken as major parameter to calculate runoff and this model can be used for homogeneous or heterogeneous watersheds because it is applicable to single or more watershed areas.

(iv) It is mainly depends on convolution process and it does not discuss various curve numbers.

(v) In this OTC model, when rainfall exceeds the infiltration rate at the surface, excess water begins to accumulate as surface storage in small depressions governed by surface topography.

(vi) As depression storage begins to fill overland flow or runoff begins to occur on portions of watershed and the flow quickly concentrate to small rivulets. In this model, t_c is the time it takes a kinematic wave to travel from the hydrologically most distant part of the basin to the point of interest.

(viii) All the hydrological parameters which are spatially and temporally variable were found to be more accurately estimated through RS and GIS.

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TABLE 1 WATERSHED PARAMETERS DERIVED FROM GIS

Name of the area	Highest elevation in m	Lowest elevation in m	Area in Sq. Km.	Perimeter in Km	Stream Length in Km	Drainage Density
Pamena –I watershed	640	595	5.0	1.5	10.75	0.09

TABLE 2 LAND USE / LAND COVER DETAILS OF THE STUDY AREA

S. No.	Classification	Area (Sq. Km.)	Percentage
1	Built up Area	0.06	1.2
2	Double Cropped Land	2.95	59.0
3	Fallow Land	1.75	35.0
4	Land with/without Scrub	0.24	4.8
	Total	5.00	100.00

TABLE 3 COMPARISON OF YEARLY RAINFALL AND ESTIMATED YEARLY RUNOFF IN MM FROM SCS-CN, TR-55 AND OTC METHODS WITH OBSERVED RUNOFF

Year	Rainfall	SCS-CN Runoff	TR-55 Runoff	OTC Runoff	Observed Runoff
1996	877	490	448	428	385
1997	741	266	244	273	205
1998	1050	654	615	580	576
1999	678	337	309	388	279
2000	869	512	498	510	461

2001	840	476	463	458	376
2002	643	289	253	264	251
2003	1042	635	624	697	589
2004	768	385	358	373	321
2005	1041	636	585	571	538

TABLE 4 STATISTICAL EVALUATION CRITERIA BETWEEN OBSERVED RUNOFF AND ESTIMATED RUNOFF USING SCS-CN, TR -55 AND OTC MODELS

	DAILY			MONTHLY			YEARLY		
Statistical Parameter	**SCS-CN**	**TR-55**	**OTC**	**SCS-CN**	**TR-55**	**OTC**	**SCS-CN**	**TR-55**	**OTC**
Nash Coefficient of Efficiency (NCE) in %	72	75	73	92	96	94	99	99	99
Coefficient of Correlation (CC) in	91	93	83	90	98	86	79	81	82
Volumetric Error (VE) in mm	0.09	0.19	0.20	0.02	0.01	0.15	0.26	0.23	0.21
Mean Square Error (MSE) in mm	3.55	4.01	3.73	0.39	0.06	0.55	0.27	0.24	0.23

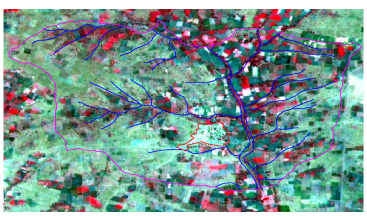

FIG. 1 STUDY AREA ON SATELLITE IMAGERY

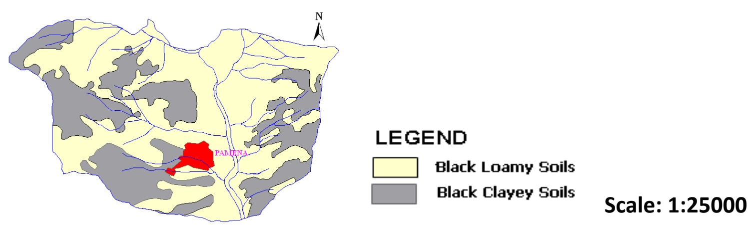

FIG. 2 SOIL MAP

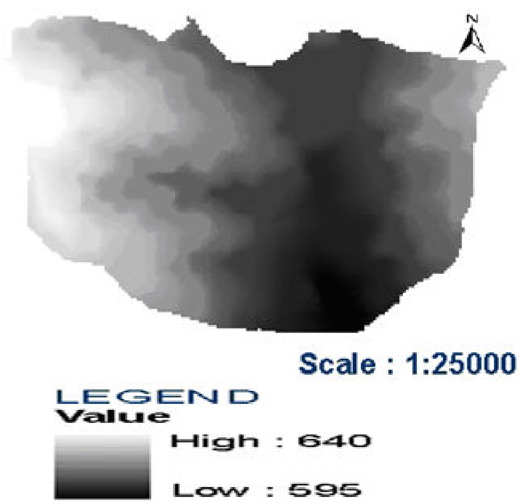

FIG.3 DIGITAL ELEVATION MODEL (DEM) MAP

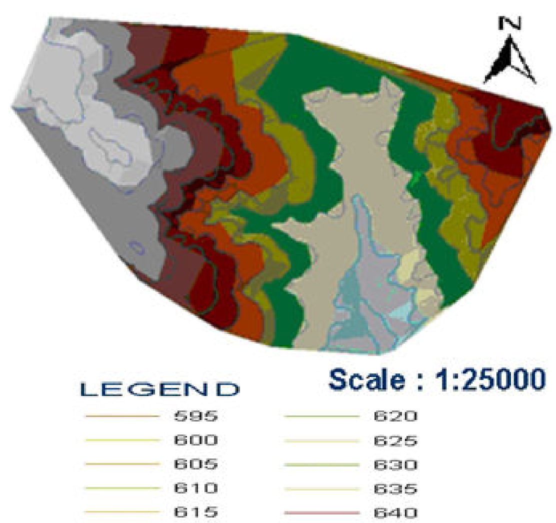

FIG. 4 TRIANGULATED IRREGULAR NETWORK (TIN) MAP

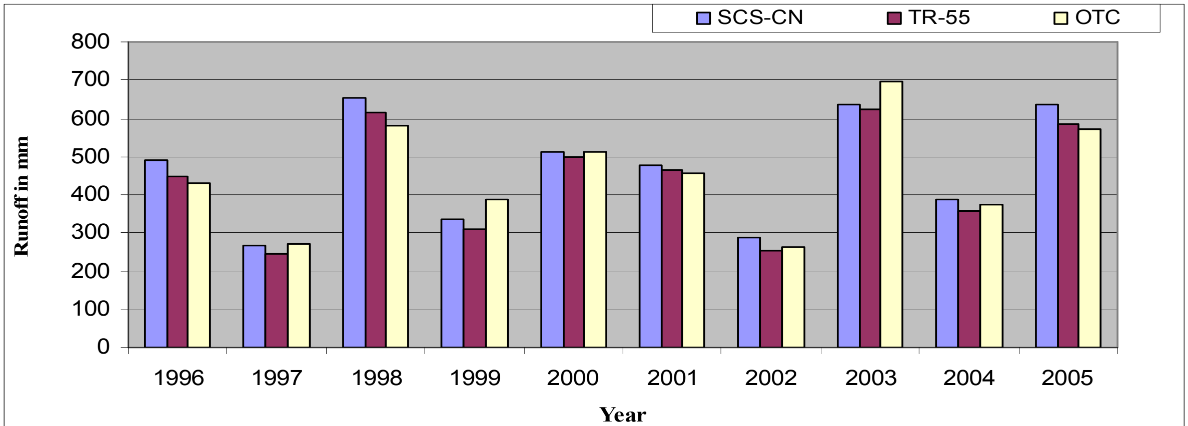

Fig. 5 Comparison of estimated yearly Runoff from SCS-CN, TR-55 and OTC models

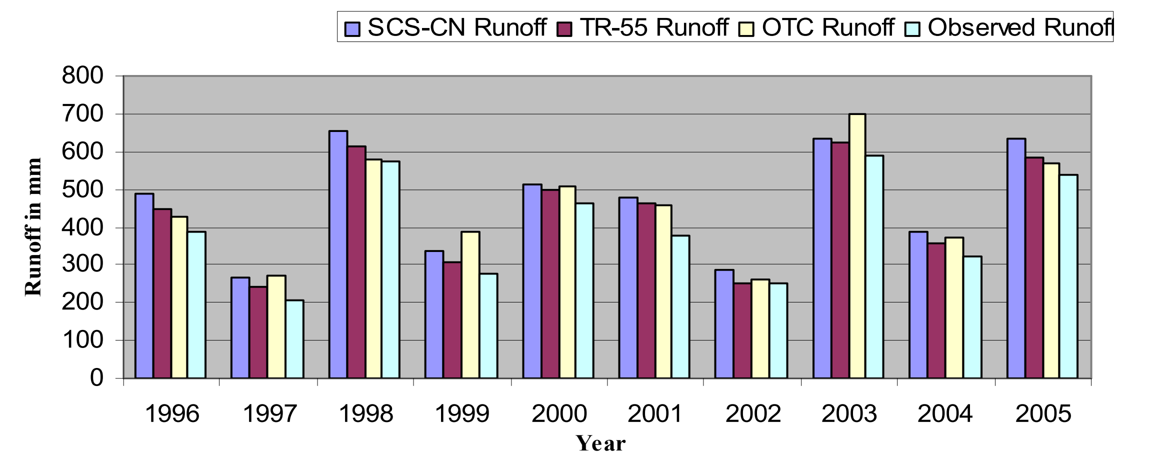

Fig. 6 Comparison of estimated SCS-CN, TR-55 and OTC runoffs with yearly observed runoff