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Rainfall runoff simulation by using SCS-CN model in Shipra river basin of Madhya Pradesh, India

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Abstract

Rainfall Runoff computation of any basin plays an important role in water resources planning and management. Here we have developed conceptual models the SCS-CN model to study the hydrological behavior of the river. The models were evaluated on the basis of coefficient of determination (R^2), coefficient of correlation (r), Nash-Sutcliffe Efficiency and Root Mean Square Error. The estimated or simulated values were compared with the observed data which showed good consistency. The SCS-CN model showed Nash-Sutcliffe efficiency is 72%, coefficient of determination R^2 values 0.616, coefficient of correlation is 0.78 and Root Mean Square Error is 83.09 which were satisfactorily close to the observed values. The study of the model indicates that the SCS-CN model is suitable for the hydrological study of the Shipra river basin of Madhya Pradesh in India.

Keywords: rainfall runoff modeling, curve number, antecedent moisture condition

Introduction

Water is the natural important resource which needs preservation, control and management. The water resources can be managed by implementing and improving the engineering practices. In water resources planning and development process, it is essential to measure available water resources in the river system. In India the river gauging network is not adequate and data availability is very poor. In such circumstances the rainfall is transformed to generate the runoff by developing relationship between rainfall and runoff or by using suitable rainfall runoff model. A rainfall runoff model is a mathematical model that describes catchment and gives relationship between precipitation and runoff. Specifically, a rainfall runoff model produces the surface runoff hydrograph when precipitation is given as an input (Das, 2012) [4]. Important need of rainfall runoff modelling for practical problem in water resources assessment, design of engineering channels, flood forecasting, predicting population incidents and many more purposes. Modelling existing catchments for which input-output data exist, runoff estimation on ungauged basins and prediction of effects of catchment change. A rainfall runoff model is helpful in computation of discharge from a basin (Das, 2012) [4]. In most of the locations we have the rainfall data but the discharge or the runoff data is not available or is available in gaps. Modelling gives information to hold up the decision making of water management policies (Chander, 2014) [2]. The widely known rainfall-runoff models identified are the rational method (Mcpherson, 1969) [12], SCS-CN method (Maidment, 1993) [11], and Green-Ampt method (Green and Ampt, 1911) [8]. Many researchers conducted number of rainfall runoff modeling using different models and techniques. Watershed as a series of identical reservoirs and prepared a conceptual rainfall runoff models by routing a unit inflow through the reservoirs (Nash, 1958) [16]. Pathak *et al.*, (1984) [18] developed a model to predict runoff volume from small watershed to simulate daily, monthly and annual runoff volume quite accurately. Kumar and Rastogi (1989) [19] developed a mathematical model of the instantaneous unit hydrograph based on time area histogram for a small watershed at Pantnagar. Mishra and Singh (1998) have worked on SCS-CN method. Das (2004) [5] developed a hydrological model for estimation of runoff in a small watershed.

The rainfall runoff modeling has an important role in water resources planning of the region for simulation of long term runoff using rainfall and catchment characteristics as an input. Researchers have always tried to develop and compare various rainfall runoff models to identify suitable model for the river basin of their interest so that it can be applied effectively in the region. In this paper, rainfall runoff model i.e. SCS-CN model has been developed and based on performance criteria such as Root Mean Square Error (RMSE), Efficiency Index (EI)

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and correlation coefficient (R^2) on Shipra river basin located in Madhya Pradesh, India. The SCS-CN is widely used as a simple method for predicting direct runoff volume for a given rainfall event. The basic data required to apply SCS-CN method is the rainfall, soil retention or soil storage, soil group/type which depends on the infiltration rate, initial abstraction and curve number.

The main objective of this study was to develop rainfall runoff model for estimating runoff simulation using SCS-CN model for Shipra river basin of Madhya Pradesh in India.

Materials and Methods

Experimental site

The Shipra river of Madhya Pradesh, India traverses a total course of about 190 km through four districts namely Dewas, Indore, Ujjain, and Ratlam before joining Chambal River near Kalu-Khera village. The majority of the Shipra basin area falls in Indore and Ujjain districts however a small part of it is being found come under Ratlam and Dewas districts. Shipra River has been extended between 76°06'20" and 75°55'60" North Latitude and 22°09'00" and 23°07'20" East Longitude and covers an area of 5679 sq. km. It is one of the sacred rivers in Hinduism. The holy city of Ujjain is situated on its right bank. The Shipra also known as the Kshipra, originates from Kakribardi hills in Vindhya Range north of Dhar and flows north across the Malwa Plateau to join the Chambal River. After every 12 years, the Kumbh Mela (also called Simhastha) takes place at Ujjain on the city's elaborate riverside Ghats, besides yearly celebrations of the river goddess Kshipra. There are hundreds of Hindu shrines along the banks of the river Shipra. Over the years the river has lost its perennial nature and now runs dry for a period of 5 to 6 months per year. The water of the Shipra is used for drinking, industrial use and lift irrigation purposes. It is reported that there is a normal practice of pumping water from the river for

providing irrigation to surrounding agricultural fields. The present study has been carried out at National Institute of Hydrology (NIH), Regional Centre, Bhopal, India. Thus data collected by NIH from various State and Central agencies was used in the study for analysis. The daily rainfall data collected from Indian Meteorology Department (IMD), Pune and State Water Data Centre, Water Resources Department, Govt. of Madhya Pradesh, Bhopal, India was used in the study. The meteorological data of Indore observatory collected from IMD, Pune like relative humidity, wind speed, sunshine hours, mean and maximum temperature etc. was used in the study. The daily rainfall data and gauge-discharge data of Ujjain site on Shipra river for the period from 1996 to 2006 was used in the study for calibration and validation of rainfall runoff model. This data was collected by NIH, Regional Centre, Bhopal from Chambal Division, Central Water Commission, Jaipur. Both the model was developed to carry out rainfall-runoff modeling in Shipra river basin at Ujjain G/d site having catchment area 2102 Km² using daily rainfall data of five rain gauge stations namely Indore, Ujjain, Dewas, Mhow and Sanwer to apply in the model. As present study has been carried out as a part of NIH, Regional Centre, Bhopal in India. Shipra river basin as well as location of stations for which the present study has been carried out is shown in *Figure 1*. The GPS coordinates and elevation of study area is shown in Table 1.

Table 1: Geographical location of Study Area

Stations	Latitude	Longitude	Elevation
Indore	22.7196° N	75.8577° E	550 m
Ujjain	23.1823900° N	75.7764300° E	494 m
Dewas	22.9623° N	76.0508° E	535 m
Mhow	22.5524° N	75.7565° E	556 m
Sanwer	22.976303°N	75.827553° E	32000 m

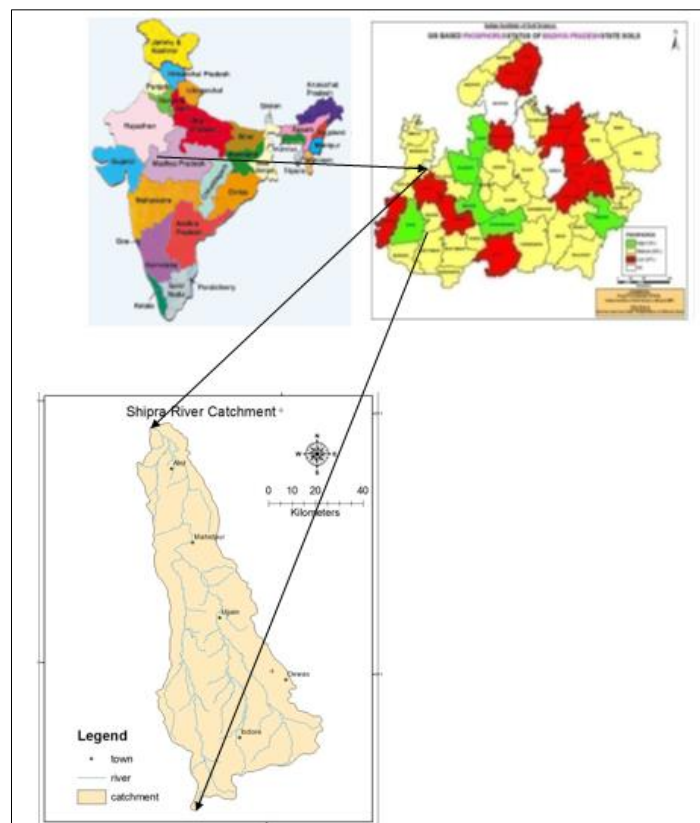


Fig 1: Index map of Shipra river basin

SCS-CN Method

Soil Conservation Service Curve Number (SCS-CN) method developed by Soil Conservation Services (SCS) of USA, 1969 is a simple, predictable and stable conceptual method for estimation of direct runoff depth based on storm rainfall depth. It relies on only one parameter, CN. In this method, runoff depth is a function of total rainfall depth and an abstraction parameter referred to as runoff curve number or simply curve number and is usually represented by CN (Mishra and Singh, 2003) [13]. Pandey and Sahu (2002) [17] pointed out that the land use/land cover is an important parameter input of the SCS-CN model. Currently, it is a well established method, having been widely accepted for use in USA and many other countries.

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 runoff (Q) to maximum potential runoff (P-I_a) is equal to the ratio of the actual infiltration (F) to the potential maximum retention (S). The second hypothesis relates the initial abstraction (I_a) is some fraction of the potential maximum retention (S). Thus, the SCS-CN method consisted of the following equations (Subramanya K, 1994) [20].

The SCS-CN model calculates direct runoff depth (Q) using the following equation:

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \text{ for } P > I_a \text{ (Eq.1)}$$

Where, P= total precipitation (mm), I_a = initial abstraction (mm), and S= potential maximum retention (mm).

$$Q=0, \text{ for } P \leq I_a.$$

The initial abstraction is related to S by the equation:

$$I_a = \lambda S \text{ (Eq.2)}$$

Where, λ is an initial abstraction ratio. The values of λ vary in the range of 0.1 and 0.3. The value of λ has been developed for black soil region for Indian conditions as 0.3 for AMC-I and 0.1 for AMC-II & III (Hand book of Hydrology, Mini. of Agriculture, 1972). On the basis of extensive measurements in small size catchments (US Soil Conservation Service, 1985) adopted λ=0.2 as a standard value. In practice, the Curve Number (CN) is used to compute S in mm as,

$$S = \frac{25400}{CN} - 254 \text{ (Eq.3)}$$

Soils

As per National Engineering Handbook (NEH) developed by USDA (1986) soils are classified in four Groups A, B, C and D based upon the infiltration and other characteristics. The description of each of the hydrologic soil groups is given in Table 2.

Table 2: Hydrological soil groups

Hydrological Soil Group	Soil textures	Runoff potential	Water transmission	Final infiltration
Group A	Deep, well drained sands and gravels	Low	High rate	>7.5
Group B	Moderately deep, well drained with Moderate	Moderate	Moderate rate	3.8–7.5
Group C	Clay loams, shallow sandy loam, soils with moderate to fine textures	Moderate	Moderate rate	1.3–3.8
Group D	Clay soils that swell significantly when wet	High	Low rate	<1.3

Antecedent Moisture Condition (AMC)

AMC indicates the moisture content of soil at the beginning of the rainfall event. The AMC is an attempt to account for the variation in curve number in an area under consideration from time to time. Three levels of AMC were documented by SCS AMC I, AMC II & AMC III. The limits of these three AMC classes are based on rainfall magnitude of previous five days and season (dormant season and growing season). AMC for determination of curve number is given in Table 2.

Table 2: Antecedent moisture conditions (AMC) for determining the values of CN

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

Land use

For determination of composite curve number (CN), soil type and land use information is essential. To obtain the spatial information of soil type and land cover, the output of a case study carried out by Mishra A (2014) [14] on Shipra basin was referred and applied as an input in present study. The said study was carried out for assessment of surface water yield using SWAT hydrological model where author prepared soil map and land use maps using remote sensing data and GIS software. The same information was used in the present study

for estimation of CN as required in SCS model. The study concluded that major soil type observed in Shipra basin was clay and land type was mainly irrigated agricultural land. As the soil in Shipra basin is mainly of clay type, all soils in the Shipra basin belong to soil group D. Once the hydrologic soil group has been determined, the curve number of the site is determined by land use and hydrologic condition to the soil group.

Computation of average curve number

Theissen polygons are established for each identified raingauge station. For each theissen cell, area weighted CN (AMC II) and also CN (AMC I) and CN (AMC III) were determined.

CN for AMC I is calculated as:

$$CN_I = CN_{II} / (2.281 - 0.01281CN_{II}) \text{ (Eq.4)}$$

CN for AMC III is calculated as:

$$CN_{III} = CN_{II} / (0.427 - 0.00573CN_{II}) \text{ (Eq.5)}$$

SCS- CN for hydrologic soil cover complex under AMC II condition for the study area is given in Table 3. Jena *et al.*, (2012) used area weighted composite curve number for various conditions of land use and hydrologic soil conditions are computed as follows:

$$CN = (CN_1 \times A_1) + (CN_2 \times A_2) + \dots \dots \dots (CN_n \times A_n) / A \text{ (Eq.6)}$$

Where A₁, A₂, A₃, ..., represent areas of polygon having CN

values $CN_1, CN_2, CN_3, \dots, CN_n$ respectively and A is the total area.

Table 3: Weighted curve number (AMC II) for the study area

Type of Cultivated Land	Hydrologic condition	Hydrologic Soil Group	Curve Number	% Area	% Area* CN	Weighted CN
Contoured	Good	D	86	40	34.40	82.6
Bunded	Good	D	79	40	31.60	
Bunded	Poor	D	83	20	16.60	

Accuracy Criteria

Accuracy of the model can be examined on the basis of coefficient of determination (R^2), Efficiency Index (EI) and Root Mean Square Error (RMSE). The use of the coefficient of determination is to test the goodness of fit of the model and to assess how well a model explains and predicts future outcomes. It is expressed as a value between zero and one. The coefficient of determination (R^2) of the model was calculated by using the following equation:

$$R^2 = \frac{\sum_{i=1}^n (q_o - \bar{q}_o)(q_s - \bar{q}_s)}{\sqrt{[\sum_{i=1}^n (q_o - \bar{q}_o)^2][\sum_{i=1}^n (q_s - \bar{q}_s)^2]}} \quad (Eq.7)$$

Where, q_o = observed flow, \bar{q}_o = mean value of observed flow, q_s = simulated flow and n = number of data points.

The reliability of the model was evaluated on the basis of Efficiency Index (EI) as described by the Nash and Sutcliffe. EI depends upon the error present in the model like missing data or inconsistency in the data and it is directly proportional to errors present in the input information of the model. The value of efficiency index lies between 0 to 1. The efficiency index equal to 1 indicates the best performance of the model. The efficiency index was calculated by using the following relationship:

$$EI = \frac{[\sum_{i=1}^n (q_o - \bar{q}_o)^2 - \sum_{i=1}^n (q_o - q_s)^2]}{\sum_{i=1}^n (q_o - \bar{q}_o)^2} \quad (Eq.8)$$

Where, q_o = observed flow, \bar{q}_o = mean value of observed flow, q_s = simulated flow and n = number of data points.

Root Mean Square Error (RMSE) was used by Fleming (1975) was another technique applied to assess the reliability of MIKE11. This technique can be taken to be a measure of absolute error between the observed and simulated discharges. It is defined by

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (q_o - q_s)^2} \quad (Eq.9)$$

Where, q_o = observed flow, q_s = simulated flow and n = number of data points.

Results and Discussion

Both the model was developed to carry out rainfall-runoff modeling in Shipra river basin at Ujjain G/d site having catchment area 2102 Km² using daily rainfall data of five rain gauge stations whose weights play a main role in calculating the rainfall weights to apply in the model. The Thiessen polygon of study area was prepared in Arc GIS tool by considering five rain gauge stations namely Indore, Ujjain, Dewas, Sanwer and Mhow. It is shown in following Figure 2 and Figure 3. Among five rain gauge stations, Indore and Ujjain are the most influencing station covering maximum area. The weights of rain gauge stations are given in Table 4.



Fig 2: Catchment area of Ujjain up to G/D site

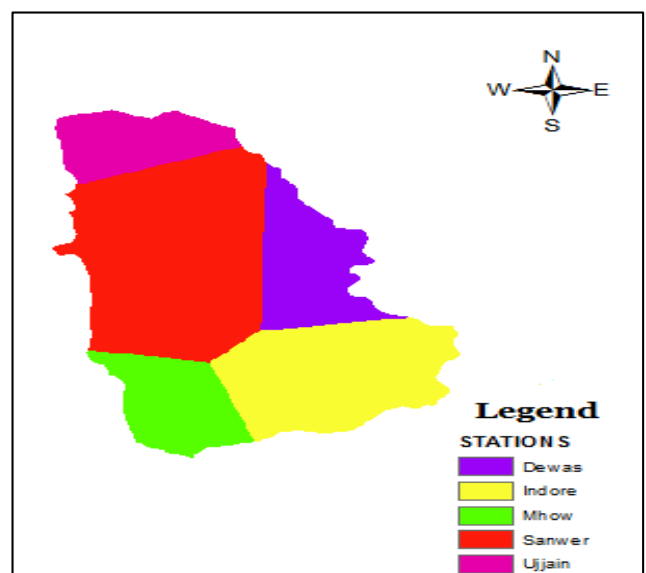


Fig 3: Thiessen Map

Table 4: Thiessen weights for raingauge stations

Station	Raingauge Station	Weights
1	Ujjain	0.12
2	Indore	0.31
3	Dewas	0.23
4	Sanwer	0.25
5	Mhow	0.90

Before starting the model development, the reliability of rainfall data was tested by plotting the annual rainfall against the annual runoff as shown in Figure 4. The correlation coefficient was obtained as 0.781, showing good correlation between rainfall and observed runoff. A straight line graph thus obtained, shown the linear relation between rainfall and observed runoff and concluded that the data was consistent to be used further in rainfall-runoff modeling.

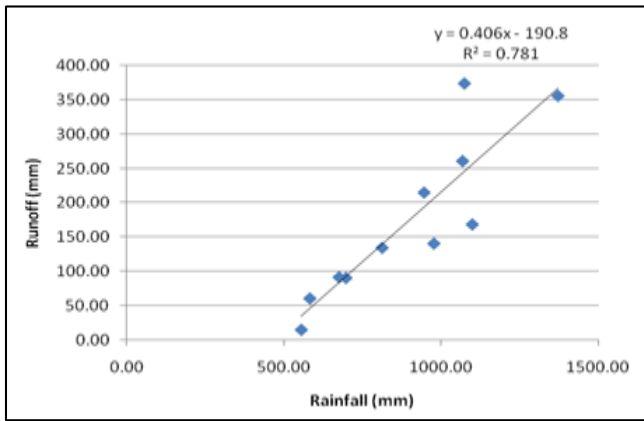


Fig 4: Linear relation between rainfall and runoff for the 1996 to 2006

SCS-CN model

The SCS-CN model was a setup to carry out rainfall-runoff modeling in Shipra river basin at Ujjain G/d site having catchment area 2102 km². In the SCS-CN model, the daily rainfall values were used as inputs to compute daily runoff.

For various curve numbers, the runoff estimated for different AMC conditions. The individual composite curve number was computed for all study area for AMC II condition. Using equation (5) the daily runoff depth were computed. From the equation (1) daily runoff, monthly and annual values can be derived. The runoff depths are computed for each rainfall event for the years 1996-2006 is shown in *Table 5* and the relationship between rainfall-runoff is shown in *Figure 5*.

Table 5: Runoff Values (1996-2006)

Year	Rainfall (mm)	Estimated Runoff (mm)
1996	1075.19	319.4697
1997	1069.53	215.3062
1998	946.98	165.9087
1999	985.12	160.6527
2000	556.34	63.68513
2001	583.59	116.436
2002	736.41	124.5204
2003	1100.32	247.4099
2004	813.48	174.2698
2005	676.33	220.3154
2006	1372.99	442.932

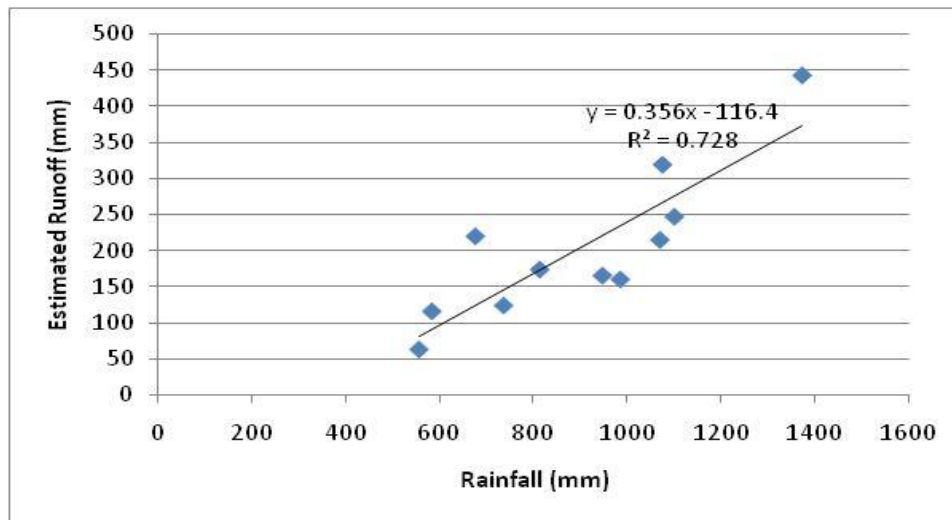


Fig 5: Rainfall-Runoff relationship for the year 1996 to 2006

Accuracy Criteria

SCS-CN models is important to evaluate which model is best suitable for particular basin. Most efficient model gives us better result and help in the efficient planning and management of water resources. Cheap, efficient and less time consuming, simple, highly trusted and does not require hydrologist suggestion in best chosen for the proper distribution and management of water resource planning and development. The value of accuracy criteria for SCS-CN model is shown in *Table 6*.

Table 6: SCS-CN rainfall runoff model for total period

	SCS-CN model
Coefficient of determination (R ²)	0.616
Coefficient of correlation (r)	0.78
Nash Sutcliffe Efficiency (%)	72%
Root Mean Square Error	83.09

The performance of SCS-CN model was evaluated based on Accuracy criteria such as coefficient of determination (R²), Coefficient of correlation (r), Nash Sutcliffe Efficiency and Root Mean Square Error. The SCS-CN showed Nash-

Sutcliffe efficiency is 72%, coefficient of determination R² values 0.616, coefficient of correlation is 0.78 and Root Mean Square Error is 83.09 for the period of 1996 to 2006 in *Table 8* which were satisfactorily close to the observed values.

Conclusion

In this study the runoff is estimated to Shipra River Catchment of Madhya Pradesh, India by SCS-CN model. The SCS-CN method developed by Soil Conservation Services (SCS) of USA, for calculating runoff for ungauged catchments gives runoff by considering all the parameters which influences runoff namely soil type, land use pattern and antecedent soil moisture conditions. SCS-CN is covering a large area i.e. the estimated discharge value coming out to be much higher than the observed value, so for designing purpose it is economical. The estimated or the simulated discharge from the SCS-CN model was compared with the observed discharge to test their performance in Shipra basin. The models were also evaluated on the basis of performance criteria such a Coefficient of Determination (R²), Coefficient of correlation (r), Efficiency Index (EI), Root Mean Square of Error (RMSE). The SCS-CN model shows Efficiency Index

72% and coefficient of determination R^2 value 0.616 which were satisfactorily close to the observed values. From this study it is inferred the SCS-CN model is economical to calculate runoff to ungauged catchments.

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