Regionalization of Parameters of Rainfall-Runoff Model for Large Ungauged Catchments

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ABSTRACT
Predicting accurately inflows into the reservoirs in order to operate the dam Gates to safely release the floods in Indian rivers has been a difficult task for the project engineers. Generally, the flood water is released after the reservoir level reaches the danger zone, causing man-made flood problem in the downstream of the reservoir. One of the major constraints in developing forecast model is the scarcity of climatic data and raingauge network. With these limitations, the SCS-CN method developed by USDA is suitable for predicting inflow into the reservoirs by using the single model parameter "the Curve Number" and rainfall as input to the model. In this study, the hydro-meteorological data observed in Wainganga sub-basin of the Godavari river basin in Madhya Pradesh has been used to develop of the SCS-CN based rainfall-runoff model. In the SCS runoff model, the total rainfall is separated into three components, viz. the initial abstraction, actual retention after runoff begins and actual runoff. The SCS model computes the runoff per storm basis. In India, generally the rainfall is recorded on daily basis, i.e. during last 24 hours. However, in reality there may be multiple storms of shorter durations in a day or any storm may continue for more than one day during the monsoon months. The observed rainfall and runoff data have been used for development and validation of the flow model under different watershed conditions, AMC-I, AMC-II and AMC-III. The Direct Runoff computed from the model has been used for comparison with the observed flow to check the efficiency of the Rainfall-Runoff model. The results show good correlation between the observed runoff and model runoff.

Keywords
SCS-CN method, Wainganga river, Sanjay Sarovar Reservoir, Rainfall-Runoff modeling, Ungauged catchment.

1. INTRODUCTION
Floods are the most important natural hazard in the Mediterranean area, and warning systems providing forecasts in many sensitive risky points are needed. Nevertheless, some particularities of this area (meteorology, morphology, urbanization degree) make the anticipation of floods difficult. Particularly, high variability of rainfall exists both in time and space, and river basins have in general small response times. Therefore, hydrometeorological models taking into account the rainfall variability should play an important role in inflow forecasting systems in Mediterranean basins. The India Meteorological Department, responsible for observation of climatic data including rainfall in India, mainly collects rainfall data on daily basis. Only few automatic weather stations equipped with Automatic Rain Gauges are installed to record hourly rainfall.

Initially the Soil Conservation Service (now Natural Resources Conservation Service, NRCS) of USDA has developed SCS-CN method to estimate direct surface runoff produced from small agricultural watersheds. The SCS-CN method was applied worldwide for all kind of watersheds as the method requires minimum parameters to estimate the runoff, which is available for most of the watersheds. Remote sensing collects multi-spectral, multi-resolution, multi-temporal data, and turns them into useful information. This technique has been used extensively and is recognized as powerful and effective tools for landuse mapping and analyzing its spatial distribution. Geographical Information System (GIS) technology provides a flexible environment for entering, analyzing, and displaying digital data from various sources, for identifying urban features, detecting changes, and developing database. The remote sensing and GIS techniques together provide the complete input data reuired for the SCS-CN rainfall-runoff modeling.

Though each of the hydrological models have their own merits and demerits, the Soil Conservation Service Curve Number method is simple, well acclaimed and produces better results (Stuebe and Johnston, 1990; Ponce and Hawkins,1996; Mishra and Singh, 2003, Hundecha and Bárdossy, 2004, Michel et al., 2005; Mishra et al., 2008; Schneider and McCuen, 2005). Many researchers have utilized the Geographic Information System technique to estimate runoff Curve Number values throughout the world. Pandey and Sahu (2002) pointed out that the land use/land cover is an important parameter input of the SCS-CN model. Nayak and Jaiswal (2003) found that there was a good correlation between the measured and estimated runoff depth using GIS and CN in Central India. They concluded that GIS is an efficient tool for the preparation of most of the input data required by the SCS curve number model. Zhan and Huang (2004) described the development and application of the ArcCN Runoff tool, an extension of esri ArcGIS software which can be applied to determine curve numbers and calculate runoff or infiltration for a storm event within a watershed. Zhan and Huang also suggested that the implementation of a precipitation time series and the consideration of factors such as dry and wet antecedent moisture conditions (for CN parameters) would improve the predictions of the ArcCN Runoff tool. Other studies have examined the effects of the landuse change on rainfall-runoff and runoff sediment using statistical methods. Nayak and Narulkar (2011, 2013) have applied the SCS-CN method in various formats, lumped parameters, distributed parameters and modified value of Curve Number. They found that the modified SCS-CN model fits best for the large forested watersheds in Narmada river basin in India.

2. METHODOLOGY

2.1 SCS-CN Model

The runoff curve number method is a procedure for hydrologic abstraction developed by the USDA Soil Conservation Service. In this method, direct runoff depth (i.e. effective rainfall) 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 SCS-CN. The method uses a simple hypothesis given by Mockus (1949) which equates the ratio of actual retention after runoff begins (P-Q) and potential maximum retention after runoff begins (S) with the ratio of actual runoff (Q) and actual rainfall (P). Some fraction of rainfall is retained as initial abstraction, and then the amount of rainfall available for runoff is ($P - I_a$) instead of P.

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

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

Where, P= total precipitation (mm), I_a = initial abstraction (mm), and S= potential maximum retention (mm). In practice, the runoff Curve Number (CN) is used to compute S in mm as,

$$S=\frac{25400}{CN}-254 \qquad (2)$$

In order to make the equation 1 linear, I_a is defined as,

$$I_a=\lambda.S \qquad (3)$$

Where, λ is an initial abstraction ratio. The values of λ varies 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, 0.2 for AMC-II and 0.1 for AMC-III.

The antecedent moisture condition (AMC) is the index of the soil condition with respect to runoff potential before the storm. The antecedent moisture condition is divided in three categories by NEH-4 based on the crop season and 5-days antecedent precipitation (USDA, 1986) as follows:

AMC I: Dormant season antecedent precipitation < 12 mm, growing season antecedent precipitation < 36 mm.

AMC II: Dormant season antecedent precipitation between 12 and 28 mm, growing season antecedent precipitation between 36 and 53 mm.

AMC III: Dormant season antecedent precipitation > 28 mm, growing season antecedent soil moisture > 53 mm.

To derive the average CN values for AMC I, II & III mathematically from the rainfall-runoff data of gauged watershed, Hawkins (1993) suggested S (or CN) computation using the following equation, which can be derived from Eq. (1).

$$Q=\frac{(P-\lambda S)^2}{P+(1-\lambda)S} \qquad (4)$$

Solving the equation 4 for S,

$$S=\frac{1}{\lambda}\left[P+\frac{(1-\lambda)}{2\lambda}-\sqrt{Q\left\{\left(\frac{1-\lambda}{2\lambda}\right)^2Q+\frac{1}{\lambda}P\right\}}\right] \qquad (5)$$

Combining Eq.(5) with Eq.(2), value of CN can be computed directly from observed rainfall and direct runoff data:

$$CN=\frac{25400}{254+\frac{1}{\lambda}\left[P+\frac{(1-\lambda)}{2\lambda}-\sqrt{Q\left\{\left(\frac{1-\lambda}{2\lambda}\right)^2Q+\frac{1}{\lambda}P\right\}}\right]} \qquad (6)$$

2.2 Evaluation of Model Performance

It is clear from the above equation 6, that the curve number for a catchment may be computed by using the inverse formula of the SCS-CN method, if the rainfall and corresponding runoff is known. There may be slight deviations in the computed CN values for a number of storms. The median value of the curve number has been taken as the average curve number for the watershed. Now, using equation 1, the direct runoff has been calculated for the observed rainfall and the computed curve number. The computed runoff is then compared with the observed runoff to evaluate the model.

2.2.1 Root Mean Square Error

The accuracy of rainfall-runoff model can be evaluated on basis of the Root Mean Square Error (RMSE), which is defined with respect to the estimated runoff, Q_{model} and observed runoff, Q_{obs} as follows:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(Q_{obs,i}-Q_{model,i}\right)^2}{N}} \qquad (7)$$

where Q_{obs} is observed values and Q_{model} is modeled values at time i, and N is total number of observations of considered rainfall events. The calculated RMSE values have units of runoff, mm.

2.2.2 Nash-Sutcliffe coefficient

The Nash-Sutcliffe model efficiency coefficient (E) is commonly used to assess the predictive power of hydrological discharge models. It is defined as:

$$E=1-\frac{\sum_{i=1}^{n}\left(Q_{obs,i}-Q_{model,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i}-\overline{Q}_{obs}\right)^2} \qquad (8)$$

where $Q_{obs,i}$ is observed values; $Q_{model,i}$ is modelled values at time *i* and $\overline{Q}_{obs}$ is the average observed discharge for whole time period. Nash-Sutcliffe efficiencies can range from -∞ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match between model and observations. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (-∞ < E < 0) occurs when the observed mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate the model is.

3. STUDY AREA

The upper Wainganga sub-basin upto Sanjay Sarovar Reservoir of Godavari river basin in Madhya Pradesh, India has been selected to validate the SCS-CN method for large ungauged catchments in central India. The Wainganga river originates about 12 Km from Mundara village of Seoni district in the southern slopes of the Satpura Range of Madhya Pradesh, India and flows south through Madhya Pradesh and Maharashtra in a very meandering course of nearly 580 kms. before joining the Godavari river. The Sanjay Sarovar dam has been constructed near Bhimgarh village across river Wainganga. The Sanjay Sarovar Reservoir (SSR) has a catchment area of 2008 sq.km with 1225 mm average annual rainfall. The study area comprises of highly undulating topography mostly covered with open forests and scrubs and the gently sloping foot hills. The plain area is mostly covered with agriculture landuse. The study area as shown in Figure 1 is located between 21°24' to 22°28' N latitudes and 79°03' to 79°40' E longitudes. The catchment area falls in the Seoni district in Madhya Pradesh. Survey of India toposheet No. 53 N covers the study area.

Figure 1. Base map showing the study area

4. DATA USED

4.1 Procurement of Maps

The Survey of India toposheets covering the Sanjay Sarovar Reservoir catchment area was selected and imported into the ILWIS GIS platform to prepare the base map. The location of SSR, RG stations, major roads, drainage network and watershed boundary have been marked on the base map (Figure 1). The soils map procured from NBSS&LUP, Nagpur was digitized and imported in the ILWIS platform. Different types soil classes in the study area (soil map) have been further assigned to suitable hydrologic soil group to facilitate the antecedent moisture condition criteria for determination of curve numbers. The soils of the study area are mostly black cotton soil with moderate infiltration capacity defined as Hydrological Soil Group C.

4.2 Rainfall and Discharge data

The Real Time Data Acquisition System (RTDAS) has been installed in the Wainganga basin under Hydrology Project-II. Toal four rainguage stations are located in Wainganga sub-basin upto Sanjay Sarovar Reservoir, namely Amarwara, Chaurai, Chhapara and Seoni. The daily rainfall data for these stations were obtained from the State Water Data Centre, WRD, Bhopal. The daily rainfall recorded by each raingauge station has been assigned the weights computed by the Thiessen polygon method according to the coverage in percent of total geographical area as 26.4, 13.4, 29.0 and 31.2 percent respectively to compute the weighted average rainfall of the sub-basin. The average rainfall in the SSR catchment was computed based on the Thiessen weights assigned to each RG station using MS Excel sheet. Computation of average rainfall (from June 22, 2005 to July 18, 2005) is shown at Table 1. The average rainfall (P) has been used for computation of Curve Number.

Table 1. Computation of weighted average rainfall

Date	Rain Gauge Station (Thiessen Wt.)				Ave. Rainfall (mm)
	Amar-wara (0.26)	Chha-para (0.29)	Chaurai (0.14)	Seoni (0.31)	
6/22/2005	29.0	0.0	0.0	24.0	15.14
6/23/2005	0.0	0.0	12.0	0.0	1.61
6/24/2005	26.2	1.2	19.0	0.0	9.79
6/25/2005	67.6	12.7	46.8	40.0	40.26
6/26/2005	109.0	45.8	81.2	94.0	82.25
6/27/2005	13.4	0.0	30.2	10.0	10.70
6/28/2005	0.0	10.2	3.8	28.0	12.22
6/29/2005	5.0	0.0	0.0	3.2	2.32
6/30/2005	0.0	1.2	2.0	0.0	0.62
7/1/2005	0.0	1.1	19.2	27.0	11.32
7/2/2005	9.0	1.1	10.3	16.0	9.07
7/3/2005	2.6	0.0	6.8	11.0	5.03
7/4/2005	54.2	48.3	26.8	24.0	39.39
7/5/2005	70.4	66.1	31.3	23.0	49.11
7/6/2005	19.6	30.5	6.4	4.0	16.12
7/7/2005	0.0	5.1	0.0	0.0	1.48
7/8/2005	17.0	5.1	30.2	21.0	16.56
7/9/2005	71.4	7.7	71.2	0.0	30.58
7/10/2005	45.0	24.4	24.6	13.0	26.29
7/11/2005	1.8	0.0	4.0	0.0	1.01
7/12/2005	14.8	20.4	102.8	79.0	48.26
7/13/2005	15.0	0.0	21.6	0.0	6.84
7/14/2005	6.4	17.8	3.2	0.0	7.28
7/15/2005	1.0	12.7	0.0	3.0	4.89
7/16/2005	9.8	12.6	9.2	8.0	9.97
7/17/2005	7.2	2.6	8.6	7.0	5.99
7/18/2005	0.0	0.0	0.0	0.0	0.00

The Thiessen polygon map and location of raingauge stations prepared using ILWIS GIS platform are given at Figure 2.

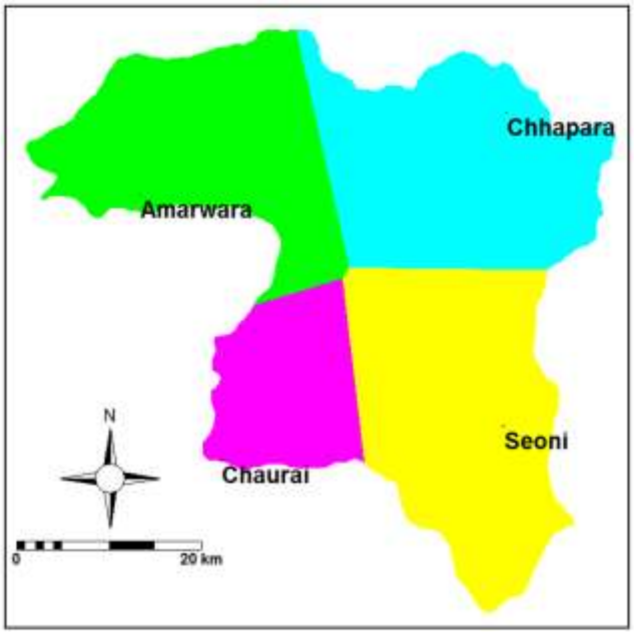

Figure 2. Raingauge stations and Thiessen polygon map

The daily water levels of the Sanjay Sarovar reservoir have been obtained from the State Water Data Centre, WRD, Bhopal for computation of daily inflow volume into the reservoir. The inflow into the SSR have been computed using water balance of the reservoir by adding the total outflow, canal supply, domestic supply and change in storage in the reservoir (Table 2). After getting the series of daily inflow into the reservoir, the base flow has been deducted to get the inflow due to rainfall, viz. direct runoff from the catchment (Q).

Table 2: Computation of inflow into SSR (MCM)

Date	Level	Capacity	Change in storage	Spillway discharge	Domestic supply	Canal offtake
7/26/05	516.00	353.63	5.22	0	0.317	60.734
7/27/05	516.40	370.52	16.89	0	0.317	195.803
7/28/05	516.90	391.63	21.11	0	0.317	244.646
7/29/05	516.80	387.41	-4.22	316.9	0.317	268.375
7/30/05	516.70	383.18	-4.23	78.67	0.317	30.029
7/31/05	517.05	398.17	14.99	20.51	0.317	194.322
8/1/05	517.70	428.34	30.17	812.98	0.317	1162.487
8/2/05	517.15	402.82	-25.52	401.95	0.317	106.897
8/3/05	517.00	395.85	-6.97	132.28	0.317	51.926
8/4/05	517.15	402.82	6.97	82.41	0.317	163.398
8/5/05	517.40	414.42	11.6	105.83	0.317	240.406
8/6/05	517.05	398.17	-16.25	552.3	0.317	364.538
8/7/05	517.00	395.85	-2.32	229.92	0.317	203.385
8/8/05	517.00	395.85	0	160.39	0.317	160.707
8/9/05	517.00	395.85	0	91.52	0.317	91.837
8/10/05	517.00	395.85	0	57.84	0.317	58.157

The observed inflow in volumetric unit, MCM has been converted into the equivalent depth of direct runoff (mm) by dividing the same with the catchment area. The observed and computed direct runoff have been compared to evaluate the model efficiency.

5. RESULTS

In the present study, an attempt has been made to use the NRCS-CN based rainfall-runoff equation to calculate the average Curve Number from known value of direct runoff produced by the rainfall occurred in the catchment area of Sanjay Sarovar Reservoir. The antecedent moisture condition of the watershed was assigned as AMC-I, AMC-II and AMC-III based on the values of previous five days' accumulated rainfall. The observed values of the depth of rainfall (mm) and depth of direct runoff (mm) have been used in Equation 6 to compute the average Curve Number for the SSR catchment for the three different antecedent moisture conditions. Calculations of CN for some of the events are shown at Table 3. Similar calculations have been carried out in MS Excel worksheet for the rainfall events during the year 2005 to 2008.

Table 3: Calculation of SCS Curve Number

Date	AMC	λ	P (mm)	Q (mm)	CN
30-6-07	I	0.3	35.43	0.916	74.53
2-7-07	III	0.1	10.26	2.077	91.78
3-7-07	III	0.1	12.28	2.157	89.32
6-7-07	I	0.3	29.76	1.011	78.51
8-7-07	II	0.2	97.29	50.960	81.33
9-7-07	III	0.1	36.11	13.742	85.77
26-7-07	III	0.1	25.44	5.555	82.75
28-7-07	II	0.2	39.04	7.534	79.74
30-7-07	III	0.1	2.24	0.110	95.89
31-7-07	III	0.1	16.75	2.399	84.16
1-8-07	III	0.1	18.52	6.423	91.29
2-8-07	III	0.1	13.12	4.084	92.90
3-8-07	III	0.1	19.61	5.143	88.01
4-8-07	III	0.1	16.23	7.750	94.90
5-8-07	III	0.1	18.96	9.598	94.62
7-8-07	III	0.1	46.26	17.512	82.37
8-8-07	III	0.1	37.77	22.574	92.45
20-8-07	I	0.3	39.07	3.408	77.91
24-8-07	I	0.3	18.62	0.000	80.36
25-8-07	II	0.2	52.98	18.002	82.06
26-8-07	III	0.1	29.92	16.207	92.65
28-8-07	III	0.1	12.68	3.154	91.52

The values of Curve Number obtained have been plotted for AMC-I, AMC-II and AMC-III and shown at Figure 3. The line shows the best fit for the three AMC conditions. Further, the median value of the computed SCS-CN has been considered as average value for the SSR catchment for different watershed conditions. The average curve number for the SSR catchment have been computed as 79.82, 83.40 and 89.31 for AMC-I. AMC-II and AMC-III respectively. In order to validate the computed Curve Numbers for different conditions, the direct runoff have been computed by taking the computed CN and rainfall is input to the equation 1. The values of R^2, RMSE and Nash-sutcliffe efficiency (N-S) have been computed as given at Table 4.

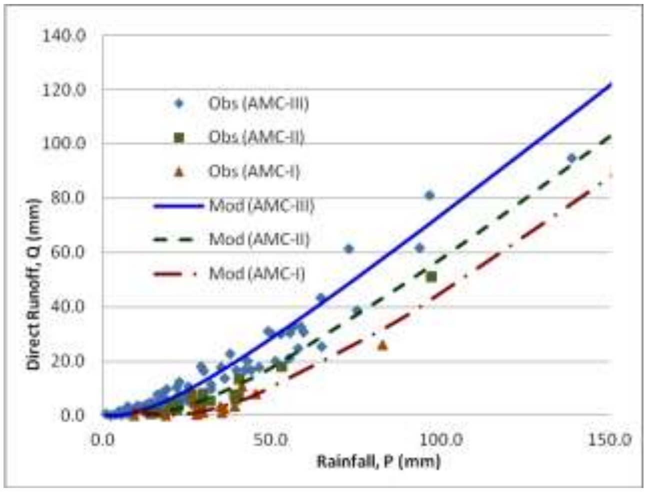

Figure 3: SCS-CN plotted for different atershed conditions

As seen from the Table 4, the SCS-CN parameter (Curve Number) computed by the inverse formula (Equation 6) for the Wainganga basin gives best results and may be applied for the similar ungauged catchments in Central India. The runoff from the watershed computed using SCS-CN method is in volumetric unit and hence, it may be used for the reservoir operation purpose but may not fit for flood forecasting or estimation of short duration flood hydrographs.

Table 4: Evaluation of SCS-CN model

Evaluation criteria	Watershed condition		
	AMC-I	AMC-II	AMC-III
R^2	0.888	0.968	0.976
RMSE	2.50	2.29	4.81
N-S	0.84	0.95	0.97

6. CONCLUSIONS

The Gauge and Discharge observation may not be possible at all desired/vulnerable locations for purpose of design and operation of water resources systems. In such cases hydrological modeling for ungauged catchments, which require minimum parameters are of great use for the estimation of relevant hydrological processes. The conclusions that may be drawn are:

1. Most of the input data required by the SCS curve number model are easily available in India,
2. The runoff estimated using SCS curve number model are comparable with the runoff measured by the conventional method, and
3. The analysis can be extended further to compute the initial abstraction ratio and accurate curve number, where sufficient hydrological, soil and landuse data are available for longer duration.

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