Remote Sensing and GIS Applications for Estimation of Runoff in an Ungauged Watershed

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Abstract

The basic concept of Integrated Water Resources Management (IWRM) is to integrate not only the stakeholders but also various sources of supply is put together to fulfil the demands. Precipitation is the main source of water in the river basins, which is not uniform over space and time. The surface water management requires the storage structures to be created on the rivers and rivulets at surplus locations during surplus periods. Knowledge of availability of total water and peak flow are the major design criteria of any water resource structure. Estimation of peak flow and total volume of water becomes a difficult task for the ungauged catchments. For the purpose of computation of peak flow and total runoff estimation, an attempt has been made to compute the total volumetric runoff through the water balance of Bina river watershed using the Thornthwaite and Mather model. Also, the SCS-CN method developed by soil conservation services (SCS) has been adopted for accomplishment of the above stated objective. The input parameters to the SCS-CN model and Water Balance model, i.e. landuse, soil texture, and hydro-meteorological data have been computed with the help of remote sensing and GIS techniques. Three years rainfall and runoff data from the year 2006 to 2008 have been used for evaluation of the model performance. The model efficiency has been checked with the observed runoff data available for Bina river watershed for short duration. The runoff computed by SCS-CN model has been found more accurate than those of the runoff estimated by the Thornthwaite and Mather model. Both the methods provide volumetric runoff, however the SCS-CN can be utilised to compute peak discharge by convolution of the estimated rainfall excess with SCS Unit Hydrograph (SCS-UH) of the desired watershed.

Introduction

Water Management is the key to mitigate the water scarcity situation. Most of the Indian River basins have plenty of water flow during the monsoon months go out without utilization, while after monsoon season the tributaries often become dry and flow in major rivers dwindles to mere channels. The maximum part of the rain water flows without use because of inadequate water harvesting structures and management plans. One has to create adequate structures for storage, diversion and conveyance of water and operate them to meet various demands in a sustainable manner. The main source of water, the rainfall, is not uniform over space and time, therefore construction of water storage structures on the rivers and rivulets at surplus locations in the river basins are required for storage of surplus flow during the monsoon periods. The major design criteria of any water resource structure include total water capacity and peak discharge to be passed without damaging the storage structure. Generally the flows occurring in these rivers vary over the time of a year according to the hydro-meteorological conditions. In Indian scenario most of the river catchments are ungauged and estimation of peak flow and total volume of water becomes a difficult task.

The basic principle in hydrological modelling is that the model is used to calculate river flow based on meteorological data, which are available in a basin or in its vicinity. Hydrological models include subroutines for the most significant hydrological processes, such as precipitation at different locations, soil moisture dynamics, evapotranspiration, recharge of groundwater, runoff generation and routing in reservoirs and rivers. Most runoff models are based on the water balance, using precipitation as a driving variable and calculating the quantities directed as runoff, R, from the water balance Eq. 1.

$$R = P - E - \Delta S \tag{1}$$

where, P is precipitation, E is evapotranspiration, and ΔS represents various storage terms.

Objectives of the Study

Owing to the fact, the present study is aimed to choose a suitable hydrological model for estimation of runoff in ungauged catchment of Bina river watershed, a major tributary of Betwa River in Bundelkhand region of Madhya Pradesh. For the purpose of computation of peak flow and total runoff estimation, the SCS-CN method, developed by soil conservation services (SCS) of USA in 1969, has been adopted for accomplishment of the above stated objective. Also, the total volumetric runoff is to be computed through the water balance of Bina river watershed using the Thornthwaite and Mather model. The output of the study shall be useful for finalising the design storage capacity of reservoir and design flood estimation for spillway design.

Study Area

Bina river is a major tributary of River Betwa in Bundelkhand region of Madhya Pradesh, which originate from Begumganj block of Raisen district and enters Sagar district at Rahatgarh block and traverse through Khurai and Bina tehsil before confluence with river Betwa near Basoda town in Vidisha district. Presently, domestic water supplies to Rahatgarh, Khurai and Bina town; railways requirement at Bina Railway Junction and industrial supplies for Bina Refinery and proposed JP power project is met from this river beside limited irrigation from the river by direct pumping. “Bina Complex- Irrigation and Multipurpose Project” has been proposed. Under this project, four dams are proposed, the Madia dam and Chakarpur dam-cum-pickup weir on Bina river and one each on Dehra and Dhasan rivers, which are the tributaries of river Betwa. The Index map showing the watershed upto Rahatgarh is shown in Figure 1.

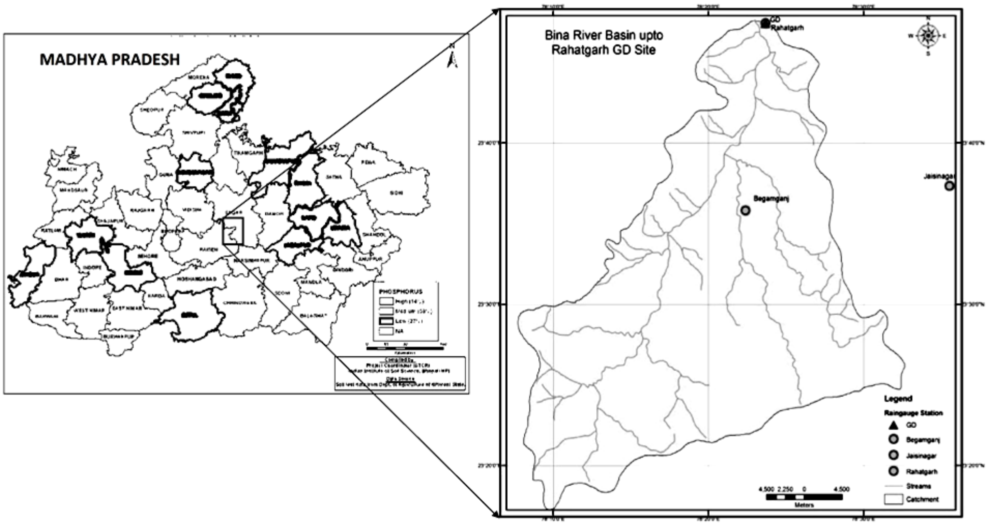

Figure 1: Index Map Showing Bina River Watershed upto Rahatgarh Town

The study area is located partly in Sagar, Vidisa and Raisen districts of Madhya Pradesh. Various maps of Bina Basin are shown below. The geographical area of the Bina basin up to Rahatgarh Gauge-Discharge is about 1139 Km^2. Bina river basin which traverses through the fertile plains of Madhya Pradesh, is one of the important tributary of Betwa River, which is one of the important basin of Yamuna River. Bina river basin is situated at 24° 10’ to 24° 42’ N latitudes and 78° 09’ to 78° 23’ E longitudes. The catchment area is highly undulating and covered by forests, barren lands and localized rain-fed agriculture. The drainage density is more in the upper catchment as compared to the lower part of the Bina river basin, the later is mostly gently sloping to plain topography mostly covered with agricultural fields. The streams are dry after the monsoon months despite enough rainfall; the average annual rainfall in recent years over the basin is 1016.37 mm and 980.35 mm during monsoon months, i.e. June to October. Therefore groundwater is exploited for domestic and agricultural uses during Rabi season causing depletion of the water table in most of the area.

Methodology

In the present study an attempt has been made to study the water balance of Bina river watershed which is a tributary of Betwa basin in Madhya Pradesh, using the Thornthwaite and Mather model using landuse, soil texture, and hydro-meteorological data as input parameters with the help of remote sensing and GIS techniques. Thornthwaite (1948) correlated mean monthly temperature with evapotranspiration as determined from water balance for valleys where sufficient moisture water was available to maintain active transpiration. The relationship developed for computation of potential evapotranspiration (PET) is given in Eq. 2.

Thornthwaite Equation

$$\mathbf{PET} = \mathbf{16}\left(\frac{\mathbf{L}}{\mathbf{12}}\right)\left(\frac{\mathbf{N}}{\mathbf{30}}\right)\left(\frac{\mathbf{10T_a}}{\mathbf{I}}\right)^{\propto} \tag{2}$$

Where,

$\boldsymbol{PET}$ is the estimated potential evapotranspira-tion (mm/month)

$\boldsymbol{T_a}$ is the average daily temperature (degrees Celsius; if this is negative, use 0) of the month being calculated

$\boldsymbol{T_a}$ is the number of days in the month being calculated

$\boldsymbol{L}$ is the average day length (hours) of the month being calculated

$$\alpha = (6.75\ \mathrm{X}\ 10^{-7})\mathrm{I}^3 - (7.71 * 10^{-5})\mathrm{I}^2 - (1.792 * 10^{-2})\mathrm{I} + 0.49239$$

$\boldsymbol{I} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{12}}\left(\frac{\boldsymbol{T_{ai}}}{\boldsymbol{5}}\right)^{\boldsymbol{1.514}}$ is a heat index which depends on the monthly mean temperatures.

In the next step (P – PET) was computed, which is an estimation of the quantitative water excess (+) or deficit (–) with P as precipitation. Then the accumulated values of (P – PET), i.e. the accumulated potential water loss (APWL) for each month, were calculated. Then the actual storage of soil moisture (STOR) for each month was calculated by equation:

$$\mathrm{STOR} = \mathrm{AWC} \times \mathbf{e}^{\mathbf{(APWL\ /\ AWC)}} \tag{3}$$

Where, AWC is available water capacity (i.e. the moisture storage capacity) of the soil.

The actual evapotranspiration (AET), surplus and deficits are computed based on the soil moisture storage in the root zone as suggested by Thornthwaite and Mather (1957). Finally, the available moisture for surface runoff is computed by taking the total monthly rainfall in the river basin.

SCS-CN Model

The Soil Conservation Service (SCS) model developed by USDA (United States Department of Agriculture) computes direct surface runoff through an empirical equation that requires the rainfall and a watershed parameter popularly known as the Runoff Curve Number or simply the Curve Number (CN). The CN is a representation of complex land use/ land cover and soil conditions in a catchment and is determined either from the tables, charts etc. available in the literature or on the basis of experience of soils, land use and hydrological characteristics such as the soil moisture etc. The CN is used is estimating the potential retention or maximum potential losses to runoff.

The direct runoff depth (Q) is calculated using the following equation:

$$\boldsymbol{Q} = \frac{(\boldsymbol{P}-\boldsymbol{I_a})^2}{(\boldsymbol{P}-\boldsymbol{I_a}+\boldsymbol{S})} \quad \text{for } P > I_a \qquad (4)$$

Where, P= total precipitation (mm), I_a = initial abstraction (mm), and S= potential maximum retention (mm). This is valid for P > I_a, that means runoff begins after precipitation exceeds initial abstraction, Q = 0 otherwise.

To simplify the Equation 4, a linear relationship between initial abstraction (I_a) and potential maximum retention (S) was suggested by USDA in 1986 in their publication (Technical Release 55)

$$\boldsymbol{I_a} = \boldsymbol{\lambda S} \qquad (5)$$

Where, λ is an initial abstraction ratio. The values of λ varies in the range of 0 and 0.3, which have been recorded in a number of studies carried out for various geologic and climatic regions in the United States and other countries (Ramasastri and Seth, 1985). In general, the value of λ is taken as 0.20, however for Indian conditions it is taken for black soil region as 0.3 for AMC-I and 0.1 for AMC-II & III (Hand book of Hydrology, Mini. of Agriculture, 1972). In practice, the runoff Curve Number (CN) is used to compute S in mm as,

$$\boldsymbol{S} = \frac{\mathbf{25400}}{\boldsymbol{CN}} - \mathbf{254} \qquad (6)$$

CN values range from 0 to 100.

The watersheds with higher CN value yield higher runoff volume for a given rainfall. The underlying difference between S and CN is that the former is a dimensional quantity (L) whereas the latter is a non-dimensional quantity (Mishra and Singh, 2003).

Results

The water balance study was conducted in the Bina river watershed up Rahatgarh town. An attempt has been made to create a digital database, mainly of watershed area, soils and land use/land cover to assess the water balance of the Bina basin using toposheet and satellite remote sensing data in GIS environment to generate output in tabular form for water balance computations. The inputs to the SCS-CN model are Curve Number and rainfall. The curve number is function of the soil-cover complex and antecedent moisture condition (AMC). Thornthwaite and Mather equation for computation of available water capacity (AWC) also require landuse class and textural soil class as input in terms of rooting depth and moisture holding capacity respectively.

The input parameters to the SCS-CN model and Water Balance model, i.e. landuse, soil texture, and hydro-meteorological data have been computed with the help of remote sensing and GIS techniques. The Integrated Land and Water Information System (ILWIS) Geographic Information System (GIS) has been used for data analysis, integration and overlay. The climatic information, viz. minimum, maximum and mean temperature, sun sign hours, etc. have been collected from the India Meteorological Department (IMD), Pune and the daily rainfall and river discharge data have been collected from the Madhya Pradesh State Water Data Centre, Bhopal. The soils map obtained from National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Nagpur in hardcopy was digitised and stored in raster format. The soil map of the study area is shown in Figure 2.

The ILWIS GIS software has the capability of Digital Image Processing (DIP) capabilities also. The landuse map was prepared by applying Maximum Likelihood Classifier (MLC) digital classification of multi-date LISS-IV Satellite data aquired from the National Remote Sensing Centre (NRSC), Hyderabad. The land use map of Bina river watershed is given in Figure 3.

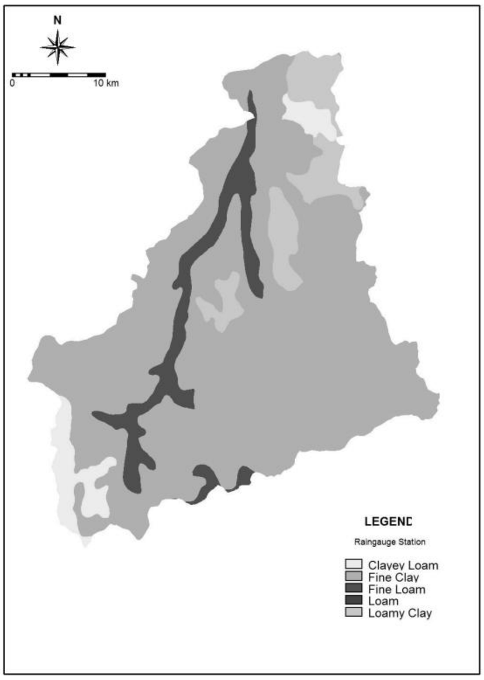

Figure 2: Map Showing Textural Soil Class in Bina River Watershed

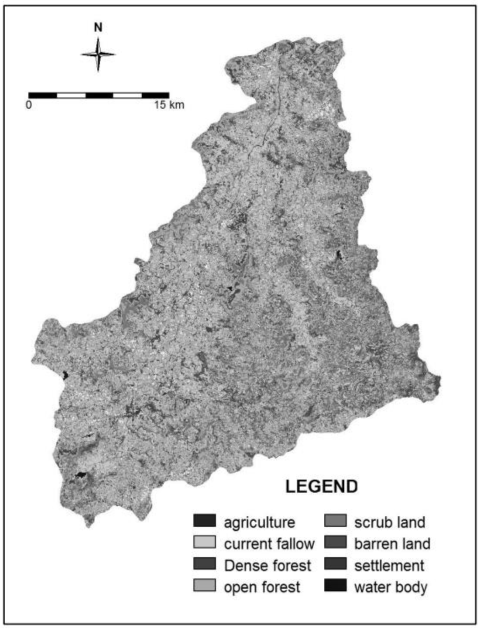

Figure 3: Land Use Map of Bina River Watershed

The average values of Curve Number (CN), maximum potential retention (S) and initial abstraction (I_a) computed for Bina sub-basin has been given in Table 1.

Table 1: SCS-CN Model Parameters

Initial Condition	CN Value	S (mm)	$Ia=\lambda \cdot S$ (mm)
AMC-I	69.44	111.8	22.36
AMC-II	83.46	50.3	10.07
AMC-III	93.99	16.2	3.25

Three years daily rainfall and observed runoff data for the year 2006 to 2008 have been used for computation of direct surface runoff and evaluation of the model performance. The direct runoff was computed by using Eq. 6 on daily basis and summed up to get the total monthly volumetric discharge in million cubic meters (MCM). The SCS-CN model computes the direct surface runoff, which does not include the base flow contribution of the watershed. It is therefore assumed that about 15% volume of the total direct runoff during the previous month will be the base flow contribution for the current month. The total monthly rainfall and direct runoff is given in Table 2.

The basic assumption made in the Thornthwaite & Mather method is that the surplus and deficit moisture in the soils in root zone control the actual evapotranspiration. If the available moisture > PET, than the AET equals the PET, otherwise the AET is limited to the available moisture, i.e. AET < PET. The available moisture (rainfall), the PET and AET have been computed by using the equations suggested by Thornthwaite and Mather method. The surplus moisture is responsible for runoff in the river basin, which flows either as direct runoff or base flow. In the present study, these computations have been made in MS Excel sheets and compiled to get the monthly volumetric runoff in MCM. The results are compared in Table 3.

The Nash-Sutcliffe efficiency of the runoff estimated by SCS-CN model varies between 0.69 to 0.87 and between 0.58 to 0.71 for the Thornthwaite & Mather. The efficiency of both the models are given in Table 4.

Table 2: Computation of Direct Runoff by SCS-CN Model

Year	Month	June	July	Aug	Sept	Oct	Total
2006	Rainfall (mm)	10.14	272.53	433.08	239.38	2.88	958.00
	Runoff (MCM)	0.00	111.55	297.44	210.06	25.19	644.24
2007	Rainfall (mm)	100.81	378.64	201.54	174.06	0.00	855.05
	Runoff (MCM)	44.55	241.81	113.48	57.50	6.87	464.21
2008	Rainfall (mm)	0.00	308.43	215.18	144.80	19.29	687.70
	Runoff (MCM)	0.00	176.99	131.12	52.90	5.58	366.59

Table 3: Comparison of Runoff by Thornthwaite & Mather Model and SCS-CN Model with Observed values in (MCM)

Year	Month	June	July	Aug	Sept	Oct	Total
2006	Observed	27.39	201.46	232.77	152.35	51.90	665.87
	Th.&Mather	0.00	159.36	274.28	204.62	89.70	727.96
	SCS-CN	0.00	111.55	297.44	210.06	25.19	644.24
2007	Observed	9.74	170.92	128.11	111.35	58.87	479.00
	Th.&Mather	0.00	119.56	203.17	136.26	52.66	511.65
	SCS-CN	44.55	241.81	113.48	57.50	6.87	464.21
2008	Observed	52.75	114.51	171.32	55.89	34.69	429.16
	Th.&Mather	51.06	137.84	176.53	99.38	9.62	474.43
	SCS-CN	0.00	176.99	131.12	52.90	5.58	366.59

Table 4: Calculated Model Efficiency Coefficients for the year 2006-2008

Model	Year	2006	2007	2008
SCS-CN	Nash-Sutcliffe Coefficient (E)	0.71	0.58	0.61
	Relative Volume Error (RVE)	-3.2 %	-3.1 %	-14.6 %
Thornthwaite & Mather	Nash-Sutcliffe Coefficient (E)	0.86	0.69	0.87
	Relative Volume Error (RVE)	9.3 %	6.8 %	10.5 %

Conclusions

The result obtained from SCS Method has also been compared with the observed flow on monthly basis. The soil conservation service – curve Number (SCS-CN) Method of rainfall-runoff modelling for an un-gauged catchment gives best estimation of surface runoff. The monthly water balance of Bina river basin has been carried out by wring the Thornthwaite and mather model based on the land use, soil texture and climatic condition. The following conclusions can be drawn from the present study.

i. Both the methods provide best results in the Bina river basin.
ii. The Thornthwaite & Mather method was used for computation of surplus water for surface runoff on monthly basis, where as the SCS-CN model was applied for daily runoff estimation.
iii. Both the models provide results with good correlation, however the RVE of the results of SCS-CN model is found to be better than that of the Thornthwaite & Mather method.

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