SCS CN Runoff Estimation for Vindhya Chal Region using Remote Sensing and GIS

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Abstract For the effective management of watershed accurate understanding of hydrological behavior is needed and is required. Estimation of runoff from storm rainfall is frequently needed for water resource planning and environmental impact analysis. Among the most basic challenges of hydrology are the prediction and quantification of catchment surface runoff. Remote sensing (RS) and Geographic information system (GIS) can be effectively used to manage spatial and non-spatial database that represent the hydrologic characteristics of the watershed. The Land use and Land Cover map, Soil map, Rainfall data are collected from different sources and processed. The weighted Curve numbers were determined based on antecedent moisture condition with an integration of hydrologic soil groups and land use/land cover classes. The study area shows that 40% of area falls under high CN value which interprets in more runoff to the study area. The annual runoff depth for catchment was computed for this un-gauge catchment area. The study reveals that the SCS-CN model can be used to estimate surface runoff depth when adequate hydrological information is not available.

Keywords Geographical Information System (GIS); Hydrological Soil Group (HSG); Land Cover/Land Use (LCLU); SCS CN; Runoff

1. Introduction

Water resources development plays an important role in achieving multifaceted economic and social development of a nation [3]. A watershed is the area covering all the land that contributes runoff water to a common point. It is a natural physiographic or ecological unit composed of interrelated parts and functions [7]. Water scarce regions in different parts of India are subject to various hydrological constraints. The resource poor agricultural communities that depend on rainfed agriculture are the hardest hit. Rainfall patterns in these areas are unpredictable. Therefore, the ability to efficiently harvest the rainfall runoff is of critical importance to maintain agricultural production, in an economically and environmentally sustainable manner. However, implementation of runoff harvesting in an extensive way, without any adverse impacts on downstream hydrological systems, requires a better understanding of the hydrological processes [8]. In India, the availability of accurate information
on runoff is scarcely available in few selected sites. However, quickening of the watershed management program for conservation and development of natural resources management has necessitated the runoff information.

Conventional methods of runoff estimation are expensive, time consuming and difficult process and these methods of runoff measurements are not easy for hilly and inaccessible terrains. Remote sensing technology can augment the conventional methods to a great extent in rainfall-runoff studies [6]. It plays a vital role in acquisition of data in the different aspects of landuse and soil cover, which are essential parameters in the field of watershed runoff estimation. Geographic Information System (GIS) provides a useful approach because it provides a framework for collecting, storing, analyzing, transforming and displaying spatial and non-spatial data for particular purposes [8]. Thus the use of GIS technology as a spatial data management and an analysis tool provides an effective mechanism for hydrologic/hydraulic studies.

In this study the Soil Conservation Service Curve Number (SCS CN) method also known as hydrologic soil group method, was used, for quick runoff estimation [7]. Generally the model is well suited for small watersheds of less than 250km² and it requires details of soil characteristics land use and vegetation condition [10]. Advances in computational power and the growing availability of spatial data from remote sensing techniques have made it possible to use hydrological models like SCS curve number in spatial domain with GIS [5]. The model has been found to perform well without much calibration.

2. Study Area

This study was conducted in the Vindhyachal region. It’s geographically located in Mirzapur district of Uttar Pradesh. It lies between 25°08’5 N to 25°10’03’ N Latitudes and 80°26’30’ E to 82°29’11’ E longitudes. The study area covers 5.75 sq.km (Figure 1). It is situated in the southern part of Uttar Pradesh. The climate of Mirzapur district is tropical monsoonal, with the year divisible into winter (November-February), summer (April-mid June) and rainy (late June-October) seasons. The mean monthly minimum temperature ranges between 13.4° and 30.7°C and the mean monthly maximum between 23.4° and 40.2°C. About 9 months of the year are dry and 3 months are moist. The average rainfall varies between 850 and 1300 mm. About 85% of the annual rainfall occurs during the rainy season from the southwest monsoon. The terrain in Vindhyachal region is hard rocky and the soils are residual, well-drained entisols and alfisols, derived from recent alluvium and Kaimur sandstones (Dhandraul orthoquartzites), sandy to sandy loam in texture and reddish to reddish brown in color [10]. The rainfall data for 35 years starting from 1971 to 2012 has been obtained from IMD, Pune. Figure 2 shows the annual rainfall variation for 35 years. Out of 35 years of annual rainfall, 13 years received more than average rainfall.
3. Methodology

In this study, Survey of India (SOI) toposheet no. ‘63K/8’ of 1:50000 scale was used to extract study area boundary and drainage lines. Remote Sensing data, Resources at LISS IV, of 5.8 meter resolution (acquired on 2nd Oct 2011) was used to delineate landuse and landcover map. Soil map is collected from National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Delhi Regional. Hydrological Soil Group (HSG) map is prepared using soil characteristics and Land Use map. Daily gridded rainfall data of 35 years for the study area is collected from National Climate Centre, IMD, Pune to calculate SCS CN method.

3.1. SCS Curve Number

For the estimation of the amount of direct run-off that will be produced from a given precipitation from a basin, various hydrologic models are available. These models range from complex to simple, having different structures and input data requirements. Amongst these models, Soil Conservation Service (SCS) model is most widely used for the estimation of direct run-off. Figure 2 shows the flow chart of runoff estimation using SCS-CN model and its implementation in GIS. The SCS Method is widely used in the design of major hydraulic structures such as culverts, detention basins, stream relocation and large drainage ditches. To compute the run-off, the first step to be followed is to delineate and measure the drainage area tributary into the study area.
Next, the Curve Number (CN) is determined, which is a dimensionless number run-off index determined based on hydrological soil group, land use, land treatment, hydrologic conditions and antecedent moisture condition (AMC). Each soil type is assigned a hydrologic soil group of A, B, C or D depending on its characteristics of infiltration. The CN values may vary from 1 to 100. Higher values of CN indicate higher run-off. The soil moisture conditions of the basin existing at the time of occurrence of storm would have a great influence on run-off peak that can result from the storm. High rainfall during summer season may not produce high discharge because most of the water enters to the soil under the existing high infiltration capacity rate. During winter and rainy season, low capacity of infiltration takes places due to the wetness prevailing in the soil, due to precipitation occurred in the earlier periods. For different land uses, the value of curve number varies within the area. The weighted curve number is calculated for each polygon of land area.

\[
\text{Weighted Curve Number} = \frac{\sum_{1}^{n} CN_i A_i}{\sum_{1}^{n} A_i}
\]  \hspace{1cm} (1)

Where, \( CN_i \) is the curve number for particular land unit and \( A_i \) is the area of each land use.

The potential maximum soil retention is calculated for each triangular area by using the following formula

\[
S = \frac{25400}{CN} - 254
\]  \hspace{1cm} (2)

In order to account for the water losses occurring due to plant interceptions, infiltration and surface storage which occur prior to run-off, initial abstraction (Ia) is calculated as 0.2 times the potential storage (S) when the rainfall is greater than 0.2 S. Otherwise, there will not be any run-off.

The assumption of SCS curve number is that, for a single storm event, potential maximum soil retention is equal to the ratio of direct run-off to available rainfall. This relationship, after algebraic
manipulation and inclusion of simplifying assumptions, results in the following expression (USDA-SCS, 1985):

$$Q = \frac{(P - 0.25)^2}{P + 0.8}$$

(3)

Where, Q is the direct run-off depth and P is the total rainfall. Using Equation 3, the depth of run-off for different storms is calculated.

4. Data Processing

4.1. Software Used

ArcGIS 9.2 was used for creating, managing and generation of different layer and maps. EADAS Imagine 9.1 was used for generation of landuse landcover (LULC) map.

4.2. Catchment Division

For the convenience of further understanding the Vindhyachal region, is divided into thirty five catchment areas. These small catchments constitute the study area. The largest catchment is 0.88 sqkm and smallest is 0.038 sq.km.

4.3. Land use Map

The Survey of India toposheet covering the Vindhyachal region was selected as the base map and for georeferencing the other maps to bring all spatial data in a single platform. In the present study, the supervised classification was carried out in ‘ERDAS IMAGINE 9.1 software using a georeferenced multispectral image of Resourcesat 2 LISS-IV (acquired on 2nd October, 2011). In this image ten to fifteen training sets for each class were taken. Five landuse landcover (LULC) classes were established here as Open Scrub, Exposed land, Rocky outcrop, Waterbody and Settlement. The landuse landcover map is shown in Figure 3. The distribution of LULC classes is mentioned in Table 1. Accuracy Assessment of the Classified Land use map was done and the overall classification accuracy of the classified landuse map was found to be 84.27% and overall kappa is 0.8222.

Table 1: Landuse / Landcover Classes Present in the Study Area (Year 2011)

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Land use Type</th>
<th>Area (Sq km)</th>
<th>Area in Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Open Scrub</td>
<td>3.4</td>
<td>59.34</td>
</tr>
<tr>
<td>2.</td>
<td>Exposed Land</td>
<td>0.72</td>
<td>12.57</td>
</tr>
<tr>
<td>3.</td>
<td>Rocky Outcrop</td>
<td>1.57</td>
<td>27.40</td>
</tr>
<tr>
<td>4.</td>
<td>Settlement</td>
<td>0.003</td>
<td>0.052</td>
</tr>
<tr>
<td>5.</td>
<td>Water body</td>
<td>0.037</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td><strong>5.73</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
4.4. Soil Map

A soil map of 1:500,000 scales is collected from National Bureau of Soil Survey and Land use Planning, (N.B.S.S. & L.U.P.) Delhi, Regional Centre. This soil map was scanned and georeferenced with respect to Study Area in ERDAS Imagine 9.2. With the help of ArcGIS software vector data layer of Soil map was thus created.

4.5. Slope Map

Hilly areas are significant in terms of rainfall-runoff response. The rapid runoff response from steep slopes results in non-availability of water in peak demand periods, even if the average rainfall is high. Slope is derived from a relief ratio, which is the ratio of the elevation difference between two points to the horizontal straight distance between the two points.

The distribution of slope classes is showed in Table 2. It can be observed from the table that very gentle and gentle slope covers 38.57 and 36.79 percent of land respectively. Whereas, steep and very steep slope covers 3.72 and 1.745 percent respectively. The slope map of the area, as developed in ArcGIS, is shown in Figure 4.

Table 2: Slope Classes Present in the Study Area

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Slope Classes</th>
<th>Area (Sq.km)</th>
<th>Area in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0.0128 – 2.726</td>
<td>2.21</td>
<td>38.57</td>
</tr>
<tr>
<td>2.</td>
<td>2.726 – 5.156</td>
<td>2.11</td>
<td>36.79</td>
</tr>
<tr>
<td>3.</td>
<td>5.156 – 8.879</td>
<td>1.09</td>
<td>19.16</td>
</tr>
<tr>
<td>4.</td>
<td>8.879 – 15.328</td>
<td>0.213</td>
<td>3.72</td>
</tr>
<tr>
<td>5.</td>
<td>15.328 – 26.388</td>
<td>0.100</td>
<td>1.745</td>
</tr>
<tr>
<td>Total</td>
<td>5.73</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
5. Results and Discussion

5.1. Hydrological Soil Map

The hydrologic soil group is an attribute of the soil mapping unit, each soil mapping unit is assigned a particular hydrologic soil group: A, B, C, or D. A hydrologic soil group of ‘B’ is generated in Arc GIS is shown in Figure 5. It is obtained by performing Intersection operation between Soil map and Land use layer in GIS. In this map new polygons has been obtained and with each polygon the soil hydrologic group and landuse are associated. Group B soils have a moderately low runoff potential due to moderate infiltration rates (3.81–7.62 cm/h).

5.2. CN Value

From the standard SCS-CN table the correct curve numbers were assigned for all the combinations. The weighted curve number was determined for the whole study area based on the antecedent
moisture conditions. The calculated CN value for each polygon is for average conditions (i.e. antecedent moisture condition class II). The CN value of each hydrologic soil group and corresponding land use class are given in Table 3. Hydrologic soil groups B lead to low CN value. In terms of land use and hydrologic soil group combination, the lowest CN value was found to be 47 in OpenScrub and the highest CN value was found to be 85 in settlement areas. High CN values in exposed land and rocky outcrop can be explained by low vegetation density, high soil compaction and presence of stony surface and cause low infiltration rate.

About 40% of the Vindhya region, has CN values between 79 and 86, 60% are comes under the CN value of 47, whereas 0.52% is under CN value of 85. These values show that Vindhyachal catchment generates more runoff for a given rainfall in areas having greater CN values. Because by increasing the value of CN in a specific area, the amount of runoff will be increased. Figure 6 showing CN map.

<table>
<thead>
<tr>
<th>Landuse Class</th>
<th>Hydrological Soil Group</th>
<th>Area (Sq.km)</th>
<th>CN Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OpenScrub</td>
<td>B</td>
<td>3.4</td>
<td>47</td>
</tr>
<tr>
<td>Exposed Land</td>
<td>B</td>
<td>0.72</td>
<td>79</td>
</tr>
<tr>
<td>Rocky outcrop</td>
<td>B</td>
<td>1.57</td>
<td>86</td>
</tr>
<tr>
<td>Settlement</td>
<td>B</td>
<td>0.0032</td>
<td>85</td>
</tr>
<tr>
<td>Waterbody</td>
<td>B</td>
<td>0.37</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5.73</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Curve Number and their Respective Landuse Table of the Study Area

Figure 6: CN Map

5.3. Runoff Map

Runoff is calculated using rainfall data from Indian Meteorological Department, Delhi. For that, 25 year rainfall data was obtained from IMD. For this study we have used average annual rainfall of 86.85 cm to calculate runoff using SCS CN method. We have generated runoff for 35 catchments lying in the study area. Figure 7 showing runoff Map generated in Arc GIS.
6. Conclusions

The incorporation of SCS-CN model and GIS facilitates for runoff estimation improves the accuracy of estimated runoff. For un-gauged watersheds accurate prediction of the quantity of runoff from land surface into rivers and streams requires much effort and time. But this information is essential in dealing with watershed development and management problems. Remote sensing technology can augment the conventional method to a great extent in rainfall-runoff studies. In this study SCS CN modified method is implemented in GIS for estimation of runoff of the watershed area.

The manual calculation of CN’s for large areas or many drainage basins can be cumbersome and time consuming, therefore a GIS is an appropriate tool to use for such an application.

References


