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Estimation and comparision of curve numbers based on dynamic land use land cover change, observed rainfall-runoff data and land slope

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SUMMARY

The CN represents runoff potential is estimated using three different methods for three watersheds namely Barureva, Sher and Umar watershed located in Narmada basin. Among three watersheds, Sher watershed has gauging site for the runoff measurements. The CN computed from the observed rainfall-runoff events is termed as $CN_{(PQ)}$, land use and land cover (LULC) is termed as $CN_{(LU)}$ and the CN based on land slope is termed as $SACN_2$.

The estimated annual $CN_{(PQ)}$ varies from 69 to 87 over the 26 years data period with median 74 and average 75. The range of $CN_{(PQ)}$ from 70 to 79 are most significant values and these truly represent the AMC II condition for the Sher watershed. The annual $CN_{(LU)}$ was computed for all three watersheds using GIS and the years are 1973, 1989 and 2000. Satellite imagery of MSS, TM and ETM+ sensors are available for these years and obtained from the Global Land Cover Facility Data Center of Maryland University USA. The computed $CN_{(LU)}$ values show rising trend with the time and this trend is attributed to expansion of agriculture area in all watersheds. The predicted values of $CN_{(LU)}$ with time (year) can be used to predict runoff potential under the effect of change in LULC. Comparison of $CN_{(LU)}$ and $CN_{(PQ)}$ values shows close agreement and it also validates the classification of LULC. The estimation of slope adjusted $SA\text{-}CN_2$ shows the significant difference over conventional CN for the hilly forest lands. For the micro watershed planning, SCS-CN method should be modified to incorporate the effect of change in land use and land cover along with effect of land slope.

1. Introduction

Rainfall generated runoff in a watershed is an important input in design of hydraulic structures and erosion control measures. On long term basis, change in runoff volume and its time distribution indicates dynamic changes occurring in a watershed. Poor land use planning and land management practices may adversely impact surface runoff quantities and quality through the reduction of land use and land cover (LULC) and increase in imperviousness of surface areas (Harr et al., 1975; Minner, 1998; Beighley and Moglen, 2002; Tong and Chen, 2002; Booth et al., 2002). Urbanization, deforestation, changes in agricultural practices, open grazing, etc. are part of LULC change. Thus, a hydrologic model that uses LULC as input is useful to quantify the effect of LULC changes on runoff. One such widely used model is the Soil Conservation Service Curve Number (SCS-CN) method. It computes the surface runoff volume for a given rainfall event from small agricultural, forest, and urban watersheds (SCS, 1956 and 1986). The method is simple to use and requires basic descriptive inputs that are converted to numeric values for estimation of direct runoff volume (Bonta, 1997). "Curve number" indicates runoff potential of land area and it is the function of hydrologic soil group, antecedent rainfall, land use pattern, density of plant cover and conservation practices followed in the land area.

The SCS-CN method is widely used by engineers, hydrologists and watershed managers as a simple watershed model, and as the runoff estimating component in more complex watershed models. In words of Ponce and Hawkins (1996) "The SCS-CN method is a conceptual model of hydrologic abstraction of storm rainfall, supported by empirical data. Its objective is to estimate direct runoff volume from storm rainfall depth, based on a curve number CN". Despite widespread use of SCS-CN methodology, realistic estimation of parameter CN has been a topic of discussion among hydrologists and water resources community (Hawkins, 1978; Hjemfelt, 1980; Rallison, 1980; McCuen, 2002; Simanton

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et al., 1996; Steenhuis et al., 1995; Bonta, 1997; Ponce and Hawkins, 1996; Sahu et al., 2007; Mishra and Singh, 2006).

Geographic Information System (GIS), which has been designed to restore, manipulate, retrieve and display spatial and non-spatial data, is an important tool in analysis of parameters such as land use, land cover, soils, topographical and hydrological conditions. Remote sensing along with GIS application help to collect, analyze and interpret the multidisciplinary data rapidly on large scale and is very much helpful for watershed planning. Estimation of runoff potential from ungauged watersheds using conventional methods requires much time and efforts. Conventional methods of runoff measurements are not easy for inaccessible terrain and not economical for a large number of small watersheds. Remote sensing and GIS can augment the conventional method to a great extent in rainfall-runoff modelling (Ragan and Jackson, 1980; Slack and Welch, 1980; Tiwari et al., 1991; Pandey and Sahu, 2002; Patil et al., 2008). They effectively utilized the satellite data to estimate the USDA soil conservation Services (SCS) Runoff Curve Number (CN) for Indian Watersheds.

Recent studies (Sharda et al., 1993; Schumann et al., 2000; Saxena et al., 2000; Shrimali et al., 2001; Reddy et al., 2004; Strager et al., 2010; Makhamreh, 2011; Magesh et al., 2012) illustrate that Remote Sensing (RS) and Geographic Information System (GIS) techniques are of great use in characterization and prioritization of watershed areas. Land use land cover is the category in which RS has made its largest impact and comes closest to maximizing technological capabilities (Garbrecht et al., 2001; Pandey et al., 2002). Keeping in view, RS and GIS can be successfully utilized to improve accuracy in estimation of Curve Number for a watershed from its land use data and digitized soil map (Still and Shih, 1985; White, 1988; Kumar et al., 1997; Melesse and Shih, 2002; Pandey and Sahu, 2002; Cheng et al., 2006).

Thus, the present study deals with the application of SCS-CN method coupled with GIS and Remote Sensing for runoff potential with the following objectives: (i) to develop year wise series of curve numbers (CN_{PQ}) using observed rainfall (P) and runoff (Q) events of period greater than 1-day; (ii) to develop a versatile regression model for estimation of curve numbers (CN_{LU}) using land use land cover and hydrological soil cover data and compare and validate with observed CN_{PQ}; (iii) to predict runoff potential using SCS-CN method based on versatile CN regression model on the basis of LULC changes; and finally (iv) to test the performance of SCS-CN method based on versatile CN regression model for runoff estimation using observed data.

2. SCS-CN method

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of actual amount of direct surface runoff Q to the total rainfall P (or maximum potential surface runoff) to the ratio of actual infiltration (F) to the amount of the potential maximum retention S. The second hypothesis relates the initial abstraction (I_a) to the potential maximum retention (S). The popular form of SCS-CN method is expressed as:

$$\begin{aligned} Q &= \tfrac{(P-Ia)^2}{(P-Ia+S)} \quad \text{for } P \geq Ia \\ &= 0 \quad \text{otherwise} \end{aligned} \tag{1}$$

where P is total rainfall; I_a is initial abstraction; F is cumulative infiltration excluding I_a; Q is direct runoff; and S is potential maximum retention.In general λ is taken as 0.2; the Eq. (1) reduces to

$$\begin{aligned} Q &= \tfrac{(P-0.2S)^2}{(P+0.8S)} \quad \text{for } P \geq 0.2S \\ &= 0, \quad \text{for } P \leqslant 0.2S \end{aligned} \tag{2}$$

The parameter S of the SCS-CN method depends on soil type, land use, hydrologic condition, and antecedent moisture condition (AMC). Analytically, parameter S is obtained from Eq. (2) as (Hawkins, 1993):

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \tag{3}$$

Since parameter S can vary in the range of $0 \leqslant S \leqslant \infty$, it is mapped onto a dimensionless curve number CN, varying in a more appealing range $0 \leqslant \text{CN} \leqslant 100$, as:

$$\text{CN} = \frac{25400}{(254 + S)} \tag{4}$$

where S is in mm. The difference between S and CN is that the former is a dimensional quantity (L) whereas the later is non-dimensional. CN = 100 represents a condition of zero potential maximum retention ($S = 0$), that is, an impermeable watershed. Conversely, CN = 0 represents a theoretical upper bound to potential maximum retention ($S = \infty$), that is an infinitely abstracting watershed. However, the practical design values validated by experience lie in the range of 40 to 98 (Van Mullem, 1989).

2.1. Estimation of CN from observed rainfall (P)-runoff (Q) data: [CN_{PQ}]

The study area consist of three adjacent watersheds namely Barureva, Sher and Umar conjoin together to form an important southern sub-basin of Narmada basin, MP, India. The gauging site at Belkheri (Fig. 1) monitors the discharge of Sher watershed of area 1488 km^2. The daily discharge data for a period of 26 years starting from 1977 to 2002 and corresponding daily rainfall data measured at three major stations, namely Narsinghpur, Harai and Lakhnadon is used in the present analysis. Thiessen polygon method was used for areal averaging of daily rainfall data measured at the three stations. The number of events selected in a year depends upon the amount of rainfall and its daily distribution in watershed. A simple straight line method was adopted for base flow separation (Fig. 2). It was found that the year 1997 observed highest number of flood events (13), while only 2 events were available in year 1989 due to unavailability of daily rainfall data. The duration for the selected events varies from 3 to 13 days as shown in Fig. 2. Same procedure was adopted for the rest of the observed P–Q events used in the estimation of CN analysis.

Procedure adopted for CN_{PQ} estimation for P–Q event occurring from 13th to 21st July, 1986 (Fig. 2) is outlined here as: (i) estimate base flow using Straight Line method (=0.412 mm); (ii) estimate direct runoff depth by deducting base flow from total runoff depth. For the selected event direct runoff depth = 26.61 mm and corresponding rainfall = 84.58 mm; (iii) use Hawkins formula (Eq. (3)) to estimate S = 95.61 mm; and (iv) use (Eq. (4)) to estimate CN_{PQ} for selected event; CN_{PQ} = 72.65.

Same procedure was followed for rest of the observed P–Q events in each year to estimate event based CN_{PQ}. Finally, for AMCII condition, the median value criteria given by Bonta (1993) and Mishra et al. (2005) was applied to get the annual CN_{PQ} values shown in Fig. 3.

2.2. CN from land use and land cover (LULC) and soil cover: [CN_{LU}]

The CN_{LU} is a dimensionless runoff index based on hydrologic soil group (HSG), land use, land treatment, hydrologic conditions and antecedent moisture condition (AMC) which counts on previous 5 days rainfall total. It is termed as 'CN_{LU}' to distinguish from 'CN_{PQ}'. In present study, land use land cover maps of three different years (1972, 1989 and 2000) have been derived from satellite