International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

A State-of-the-Art of the SCS-CN Methodology

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ABSTRACT: Any new development of an alternative (or innovation) to extend, generalize, or to improve a methodology requires an understanding of its state-of-the-art. This understanding entails a critical review of historical development, limitations, advantages, applications, implications, and original intent of the methodology. There exists a significant body of literature published on the Soil Conservation Service-Curve Number (SCS-CN) (presently also known as Natural Resource Conservation Service (NRCS-CN)) model and several recent articles have reviewed the model at length. This paper is an attempt to explore the model further for some of its major discrepancies, such as: (1) implementation of antecedent moisture condition procedure; (2) consideration of 'mean' or 'median' Curve Number (CN) as a representative (quite sensitive) CN for a watershed; (3) initial abstraction (I_a) and potential maximum retention (S) relationship; (4) use of the potential maximum retention (S) parameter in the model; and (5) effect of storm intensity or duration in runoff estimation. Focusing on these issues, this study finally emphasizes the refinement of the methodology by improving its hydrologic algorithms so that its formulation is more realistic and logical in structure.

INTRODUCTION

The march of events that mark the progress of an elemental particle of water from the sea surface into the atmosphere, to the land and back to the sea is known as hydrologic cycle (Meinzer, 1942), a significant component of hydrology. Among the various components of the hydrologic cycle, the process of rainfall–runoff is not only one of the vital components but is also very complex in nature. A systematic and continuous investigation has resulted into numerous types of rainfall–runoff models, a comprehensive review of which is available elsewhere (Singh 1988, 1995; O'Loughlin *et al.*, 1996; Singh and Frevert 2002a, 2002b, 2006).

A multitude of factors, such as availability of data, objective, accuracy, skill, computing facilities, time, resources, etc., govern the selection of a particular model and its application. The search for suitable models for different conditions still continues and thus more and more models are suggested. The Natural Resource Conservation Service—Curve Number (NRCS-CN) model, formerly known as Soil Conservation Service—Curve Number (SCS-CN) model (SCS 1956, 1964, 1969, 1971, 1972, 1985, 1993), is one of the popular models for computing the volume of surface runoff from small to medium-sized agricultural watersheds for a given rainfall event. This model has been the focus of much discussion in agricultural hydrologic literature and is also widely used in continuous modeling schemes (Mishra and Singh, 1999b).

The SCS-CN model converts rainfall to surface runoff (or rainfall-excess) using a single parameter, called Curve Number (CN) which is derived from watershed characteristics and 5 day antecedent rainfall.

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Some of the reasons for its popularity are that: (1) it is simple (Bales and Betson, 1981); (2) it is a familiar procedure that has been used for many years around the world; (3) it is computationally efficient; (4) the required inputs are generally available; and (5) it relates runoff to soil type, land use, and management practices. The use of readily available daily rainfall is particularly an important input to the SCS-CN model. This model however has its own limitations and assumptions, which lead to many questionable arguments on its applications. Since its inception, the SCS-CN model has been improved, extended and modified in various ways. This paper aims to (a) provide a state-of-the-art review of the SCS-CN methodology and (b) highlight some of the major issues of concern. More particularly, it discusses the following: theoretical (analytical) justification, importance of CN and the development of representative CN for a watershed, low rainfall–high CN bias, AMC and its development, the relation of initial abstraction with potential maximum retention, effect of storm duration, source-area concept, SCS-CN application to long-term hydrologic simulation and distributed modelling, use of Remote Sensing (RS) data and Geographical Information System (GIS), and advantages and limitations of the model. The paper finally suggests future studies to improve the model and its scope.

BACKGROUND

The SCS-CN model was developed in 1954 by the U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS) and it is described in the Soil Conservation Service (SCS) National Engineering Handbook, Section 4: Hydrology (NEH-4) (SCS, 1985). In 1994, SCS became Natural Resource Conservation Service (NRCS), and therefore the SCS-CN model is renamed as NRCS-CN model in the current literature. Since model elements, particularly the factors affecting the model parameter CN, can be better described in terms of soil conservation, rather than the conservation of other natural resources, this paper retains the more popular name, i.e., the SCS-CN method.

The SCS-CN model is the product of more than 20 years of rainfall–runoff studies carried out using the data collected from small rural watersheds. Based on annual flood data collected at a number of watersheds with drainage areas of 2.6 sq. km (= 1 sq. mile) or less and with near uniform basin hydrologic soil–cover complex, SCS developed CN tables (Bales and Betson, 1981). It is a simple procedure for estimating streamflow volume (exclusive of base flow) generated by large rainstorms. It is basically a conceptual model that provides a consistent basis for estimating the amount of direct surface runoff under varying soil, land use/land cover, and hydrologic conditions.

Tracing the origin of the SCS-CN methodology, Sherman (1942, 1949) was the first to propose the plotting of direct surface runoff against storm rainfall. Later, Mockus (1949) proposed that the estimates of surface runoff for ungauged watersheds could be based on soil, land use, antecedent rainfall, storm duration, and average annual temperature. He combined these factors into an empirical parameter 'b' characterizing the relationship between rainfall depth P and runoff depth Q (Rallison and Miller, 1981) as,

$$Q = P\,(1 - 10^{-bP}) \qquad \ldots (1)$$

According to Mishra and Singh (1999b, 2003c), Equation (1) forms the basis of the development of the SCS-CN concept. In a separate attempt, Andrews (unpublished report, 1954) developed a graphical procedure for estimating runoff from rainfall utilizing infiltrometer data, depicting several combinations of soil texture, type and amount of cover, and conservation practices, which combined together are referred to as 'soil–cover complex'. The Mockus empirical rainfall–runoff (P–Q) relationship and Andrew's soil–cover complex formed the basis of the conceptual rainfall–runoff relationship incorporated in NEH-4 (Ponce and Hawkins 1996).

In the past three decades, the SCS-CN methodology has been used worldwide by a number of investigators for runoff estimation and has, in turn, attracted intensive and extensive exploration into its formation, rationality, pros and cons as to applicability and extendibility, physical significance, etc. Accordingly, based on the reviews available on its applicability to field data (Hjelmfelt *et al.*, 2001), NEH-4 has been significantly revised several times, and more recently in 1993 (SCS 1993).

REVIEW OF LITERATURE

Theoretical Justification

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

(a) Water Balance Equation,

$$P = I_a + F + Q \quad \dots (2)$$

(b) Proportionality Hypothesis,

$$\frac{Q}{P - I_a} = \frac{F}{S} \quad \dots (3)$$

(c) I_a–S Hypothesis,

$$I_a = \lambda S \quad \dots (4)$$

where P = total rainfall, I_a = initial abstraction, F = cumulative infiltration, Q = direct surface runoff, S = potential maximum retention, and λ = initial abstraction ratio.

Mockus (1949) suggested that the model produced rainfall–runoff curves of the type derivable from the data from natural watersheds. Here, since the concepts (assumptions) of the SCS-CN model are purely empirical, a brief review of the justifications available in literature is in order. The Handbook of Hydrology (Maidment, 1993) states that the assumption of proportionality (Equation 3) seems to be quite arbitrary and has no theoretical or empirical justification (Pilgrim and Cordery, 1993). Mishra and Singh (2003c) described this proportionality in terms of $C = S_r$ concept, where C is the runoff coefficient and S_r is the degree of saturation, and presented severai SCS-CN-inspired models.

According to Chen (1981) and Mishra and Singh (2004a, b), the SCS-CN model is an alternative expression of the infiltration decay curve, and in practice it can be used as one of the parametric infiltration models, or modified forms thereof, to formulate the standard infiltration capacity curve for a given soil–cover–moisture complex. Yu (1998) derived the SCS-CN model theoretically (analytically), assuming an exponential distribution for the spatial variation of infiltration capacity and the temporal variation of rainfall rate. Under these assumptions, runoff will be produced anywhere on a catchment where the time-varying rainfall rate exceeds the spatially variable but time-constant infiltration capacity (making no allowance for any run-on process) (Beven 2002). Mishra and Singh (1999b) derived the SCS-CN model analytically with its basis in the Mockus method (Equation 1). Later, the constrained region for the validity of the Mockus (1949) method, and the existence of watersheds with CN < 50 was pointed out. Further, the underlying assumption on the spatial variability of rainfall employed by the SCS-CN and Mockus methods were critically discussed (Mishra and Singh, 2001).

Recently, Mishra and Singh (2002a, 2003b) revisited the existing SCS-CN model from an analytical perspective and explored the fundamental proportionality concept (Equation 3). Mishra and Singh (2002a) described F (Equation 3) as the dynamic portion of infiltration (F_d) and distinguished it from the static or gravitational infiltration (F_c), while Mishra and Singh (2003b) derived (Equation 3) using the first-order linear hypothesis for the variation of S with rainfall. Further, Mishra and Singh (2003a) explained the physical significance of S using the diffusion term of the linear Fokker–Planck equation for infiltration (Philip, 1974), which relates S to the soil storage and transmission properties.

Determination of Representative CN

For using the existing SCS-CN model in field, determination of its basic parameter-CN-requires information on watershed characteristics, such as land use and treatment classes (agricultural, range, forest, and more recently, urban (SCS, 1986)), Antecedent Moisture Condition (AMC), Hydrologic Soil Group (HSG) (A, B, C and D), and hydrologic condition (poor, fair and good). From error analysis, Hawkins (1975) pointed out that errors in CN may have much more serious consequences than errors of similar magnitude in P, but for a considerable precipitation range (up to about 23 cm). Chen (1981) pointed out that smaller the values of CN, the larger are the effects of the variation of initial abstraction and rainfall on runoff. Further, Bales and Betson (1981) emphasized that CN was significantly related to storm hydrograph model parameters, such as peak flow. Especially, in low runoff and low rainfall situations, errors in runoff calculation near its threshold are severe. According to Knisel and Davis (2000), CN is a sensitive parameter in the simulation of runoff volume in GLEAMS and found that the runoff estimates for small changes in high CN values were more sensitive than equivalent small changes in low CN values. Therefore, it is clearly understood that the accurate CN estimation is quite important in storm runoff calculations. Due to these reasons, numerous approaches are in practice for estimating runoff or representative CN for a watershed, as categorized in Figure 1 based on the CN estimation procedure.

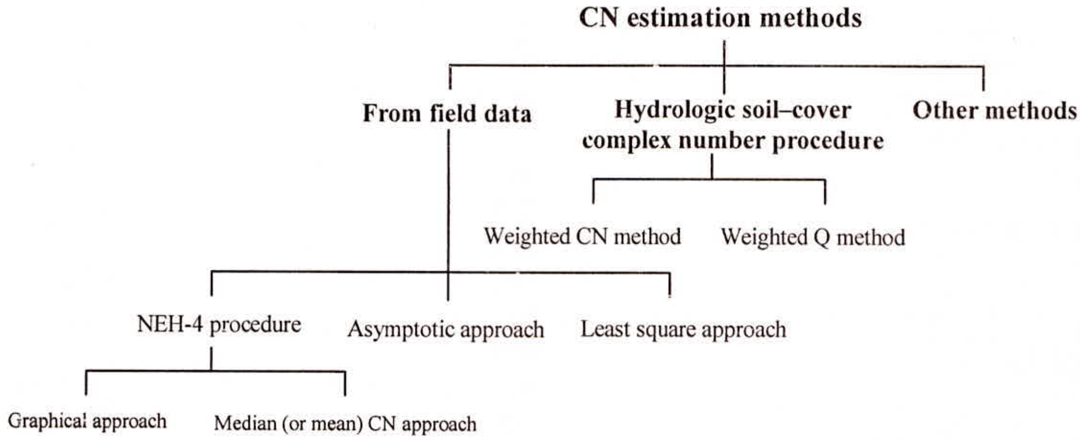

Fig. 1: Classification of CN Estimation Methods

The asymptotic approach is valid only in a frequency matching sense, and therefore, it is applied to return-period runoff estimation. Its use for other than the frequency matching cases is questionable and debatable. The least squares method for derivation of the best-fit CN (or S) is very similar to the asymptotic method (especially for the ordered data) as both use the same data and both are free from the rainfall depth influence. It suggests that little is gained by least squares fitting, except for the natural data case and it may be an unnecessary refinement. The NEH-4 procedure consists of a graphical approach and a median (or mean) CN approach. Although the NEH-4 (SCS, 1972) graphical approach is simple, it is obsolete due to its major drawbacks, such as the requirement of the annual flood event data, its better performance only beyond annual event circumstances, etc. Instead, a simple average (mean) or median CN from a number of storms is practiced. From the observed rainfall–runoff data, CN is determined for each P-Q pair. From the values of CN, either 'median' or 'mean' CN is taken as a representative CN for a watershed. Here, the occurrence of low P - high CN bias is judiciously considered. This is a common method adopted elsewhere. Traditionally, the 'median' or 'mean' CN value is represented as CN_{II}, describes the 'average condition' of the watershed in terms of wetness, and is considered as representative to the considered watershed.

The hydrologic soil-cover complex method uses the available standard CN table of NEH-4 (SCS, 1993) for estimating CN of a watershed based on its land use type and hydrological soil group type. This is used mostly for engaged watersheds. In this approach, the weighted CN method is less time-consuming, but it tends to be less accurate than when compared with the actual (measured) runoff depth. In general, the weighted Q method is superior to the weighted CN method. Two problems arise while using this 'hydrologic soil–cover complex number' approach: (1) the calculation is much more sensitive to the CN value chosen than it is to rainfall depths (Hawkins, 1975; Bondelid *et al.,* 1982); and (2) it is difficult to accurately select the CN values from the available handbook CN tables (Hawkins, 1984). However, this approach has been recently tried with the aid of remote sensing and GIS techniques in distributed watershed modeling. Hawkins (1984) suggested that the determination of CN values from field data is better than that due to hydrologic soil–cover complex number method, for the latter leads to variable, inconsistent, or invalid results.

Due to the SCS-CN model being quite sensitive to CN for accurate runoff estimation, several different approaches have been tried in the past. For example, Bonta (1997) proposed the derived frequency distribution approach for determining watershed CNs from measured data, treating P and Q data as separate frequency distributions. This method gives fewer variable estimates of CN for a wide range of sample sizes than do the asymptotic and median-CN approaches. It is advantageous in a limited P-Q data situation and does not require watershed response type to estimate CN, as needed in the asymptotic method. Mishra and Dwivedi (1998) presented an approach to determine the upper and lower bounds or enveloping CNs, which are useful in high and low flow studies, respectively. McCuen (2002) found the quantity (100-CN) to fit the gamma distribution, which he used for developing the confidence intervals for CNs ranging from 65 to 95, employing method of moments. Later, Bhunya *et al.* (2002, 2003) provided a more reliable procedure for estimation of confidence intervals by employing the method of maximum likelihood, and method of L-moments in addition to method of moments. These methods however require further testing on large datasets.

Antecedent Moisture Condition

The Antecedent Moisture Condition (AMC) plays an important role in the determination of CN for runoff estimation. AMC is defined as the initial moisture condition of the watershed prior to the storm event of interest. The SCS-CN model expresses this parameter as an index based on seasonal limits for the total 5 day antecedent rainfall, and it is classified into three discrete variations, such as AMC I (dry), II (average) or III (wet). Normally, AMC II is taken as the base with reference to which CNs are adjusted to estimate runoff. Depending on the 5 day antecedent rainfall amount, AMC II (CN_{II}) is convertible to AMC I (CN_I) or AMC III (CN_{III}) using any of the relations given by Sobhani (1975), Chow *et al.* (1988), Hawkins *et al.* (1985), Neitsch *et al.* (2002) (Table 1), and also directly from the NEH-4 tables (SCS, 1972) for runoff estimation. Due to the availability of more than one formulation, Mishra *et al.* (2006) critically reviewed these CN conversion formulae. They found the Neitsch *et al.* (2002) formula to yield undesirable negative values of CN_I in the CN_{II} range (1, 19). It is however noted here that the CN-values obtained for most soil–cover–moisture complexes in the field are generally greater than 40 (SCS, 1972). Yet, the occurrence of negative CN-values is conceptually not rational. According to Mishra *et al.* (2006), the Hawkins *et al.* (1985) CN-conversion formula performed better than others. The CN_I or CN_{III} conversions from these formulae deviated by only about 0.1% in the CN_{II} range (50, 100).

Developments in AMC

The AMC procedure due to NEH-4 suffers from three major weaknesses (Hope and Schulze 1981): (1) the relationship between AMC and antecedent rainfall holds for discrete classes, rather than continuous (Hawkins, 1978b); (2) the use of 5 day antecedent rainfall is not based on physical reality, but on subjective judgment; (3) evapotranspiration (ET) and drainage are not considered in the depletion of catchment storage.

As nothing was known on the actual field data that went into the development of the NEH-4 AMC table, and also the methodology adopted, the table can be seen as a convention. Its application actually belongs to administrative hydrology, not scientific hydrology, and therefore, it is 'true' only inside the CN world. It is noted that early editions of NEH-4 show some variation in table from what is now offered. This is due to the smoothening of data of CN_{II} versus CN_I and CN_{II} versus CN_{III} plotted on normal-normal probability paper, published in 1956 edition of NEH-4 (Rallison and Cronshey, 1979). Due to the uncertainty of NEH-4 AMC table values, Williams and LaSeur (1976), Hawkins (1978b), Bales and Betson (1981) reviewed critically the issues of CN adjustment with the watershed moisture status.

Bales and Betson (1981) noticed that if SCS-CN tables were used for determining a hydrologic soil–cover complex number and if the wettest antecedent moisture condition was assumed, runoff volumes would be regularly under-predicted in the regions represented by these data. The runoff volumes would apparently be under-predicted even for higher yield events, for which the SCS-CN methodology best applies. According to Chen (1981), a drastic (discrete) change of AMC over a short period of time may cause a serious error in CN-value and hence in the estimated runoff. Further, Hjelmfelt *et al.* (1981) found that the AMC conversion table described the 90% (AMC I), 50% (AMC II), and 10% (AMC III) cumulative probabilities of exceedance of runoff depth for a given rainfall. Again, Hjelmfelt (1982) tested the association of CN variation with antecedent precipitation and with peak discharge and found good correlation with the former, while it was poor with the latter.

Table 1: Popular AMC Dependent CN-Conversion Formulae

Method	AMC I	AMC III
Sobhani (1975)	$CN_I = \frac{CN_{II}}{2.334 - 0.01334CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.4036 + 0.005964CN_{II}}$
Hawkins et al. (1985)	$CN_I = \frac{CN_{II}}{2.281 - 0.01281CN_{II}}$	$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573CN_{II}}$
Chow et al. (1988)	$CN_I = \frac{4.2CN_{II}}{10 - 0.058CN_{II}}$	$CN_{III} = \frac{23CN_{II}}{10 + 0.13CN_{II}}$
Neitsch et al. (2002)	$CN_I = CN_{II} - \frac{20(100 - CN_{II})}{\{100 - CN_{II} + \exp[2.533 - 0.0636(100 - CN_{II})]\}}$	$CN_{III} = CN_{II}\exp\{0.00673(100 - CN_{II})\}$

Gray *et al.* (1982) assumed four AMC classes with respect to initial infiltration capacities for each soil type, instead of three AMC classes defined by SCS, and performed a regression analysis using average annual precipitation. According to Ponce and Hawkins (1996), the AMC table (SCS, 1972) of NEH-4 does not account for regional differences or scale effects and, therefore, an antecedent period longer than 5 days might be required for large watersheds.

Besides the quality of the measured P-Q data, the accuracy of runoff prediction largely depends on accurate estimation of the lumped parameter CN (Ponce and Hawkins, 1996) which varies with (1) spatial and temporal variability of storm and watershed characteristics, and (2) antecedent rainfall and associated soil moisture. According to Ponce and Hawkins (1996) and McCuen (2002), AMCs are assumed to be the primary cause of the storm to storm variation of CN on any one watershed. It is noted that a watershed would have more than one CN value, indeed a set of CN values (SCS 1985; Hjelmfelt 1991). In response to the aforementioned criticisms of the AMC procedure, the reference to AMC was removed in the CN-portion of NEH-4 (Hawkins, 1996), and the variability incorporated by considering CN as a random variable (Hjelmfelt *et al., 2*001), and in turn, the terminology changed to 'antecedent runoff condition (ARC)' that explains only a part of the CN-variation (Van Mullem *et al., 2*002). Heggen (2001) found that the three-parameter Normalized Antecedent Precipitation Index (NAPI) model outperforms the one-parameter (AMC II) CN model. Recently, using the 5 day antecedent rainfall, Mishra and Singh (2002b) proposed an SCS-CN-based model incorporating non-linear continuous variation of antecedent moisture (M).

Therefore, it is evident that AMC is still one of the major sources of the CN-variability, and the accuracy of runoff computation largely depends on the correctness of the CN value. Contradictorily, in many climates, a more important source of variability is rainfall intensity and its pattern within the storm and this cannot be accounted for by the SCS-CN model. According to Smith (1997), the antecedent moisture for most storms has a far lower variability than does the storm CN. Walker *et al.* (1998) used baseflow, rather than the antecedent rainfall, for quantifying the watershed wetness prior to the storm event of interest. More recently, McCuen (2002) prescribed AMC limits statistically and showed that confidence intervals can be used to assess the variation in CN. According to Woodward *et al.* (2002), a number of other factors (than the ones listed in NEH-4, namely, soil type, land use, hydrologic condition and antecedent moisture) affecting CN, such as stage of crop growth and soil moisture, also explain the individual CN-variation with storms.

Therefore, the best approach to define antecedent condition is to use a model to establish antecedent conditions. A more rational approach, however, should be to adjust the soil moisture status in continuous modelling, such as in SWAT. Ironically, such a description of the variation in CN is also not proper, though it is being widely used. In future, more efforts are required for testing the validity of 5 day antecedent rainfall or soil moisture accounting procedure using field data.

I_a-S Relationship

Initial efforts in the SCS-CN formulation (Plummer and Woodward 2002) did not consider initial abstraction, but as development continued, it was included as a fixed fraction of S (Equation 4). This relationship was justified on the basis of actual measurements on watersheds less than 10 acres in size, despite a considerable scatter in the resulting I_a-S plot (SCS, 1985). NEH-4 (SCS, 1985) reported 50% of data points to lie within $0.095 \leq \lambda \leq 0.38$, leading to a standard value of $\lambda = 0.2$ (Ponce and Hawkins, 1996). Besides the wider variability in the resulting I_a-S plot (SCS, 1985), a simple assumption of $I_a = 0.2S$ has led to the severe criticism and modification since its inception. For example, the Central Unit for Soil Conservation (1972) recommended a λ value of 0.3 for all regions of India, except for the black cotton region for which it is 0.1 under AMC II and III conditions. Aron *et al.* (1977) suggested $\lambda \leq 0.1$ and Golding (1979) provided CN-dependent λ-values for urban watersheds: $\lambda = 0.075$ for $CN \leq 70$, $\lambda = 0.1$ for $70 < CN \leq 80$, and $\lambda = 0.15$ for $80 < CN \leq 90$. Springer *et al.* (1980) found $\lambda = 0.2$ not appropriate for arid and humid watersheds and cautioned against its use for other watersheds. Here, the conclusion of a publication on the NRCS website is worth citing:

> *"....each relationship of I_a to S requires a unique set of runoff curve numbers. Simple revision of the relationship of I_a to S to something other than $I_a = 0.2S$ requires more than a simple change of the runoff equation. There is no linear relationship between the runoff curve numbers for the two I_a conditions. It also requires a new set of runoff curve numbers developed from analysis of small watershed data."*

From these findings, it is probably not justifiable to tweak this relationship as part of the development of a design hydrograph for a site when no calibration data are available. If played with the existing relationship, the standard CN values are no longer valid (Rallison and Miller, 1981). For this reason, Rallison (1980) did not recommend its further refinement. Indeed, a critical examination of I_a-S relationship and a logical refinement is needed for pragmatic applications.

Cazier and Hawkins (1984) suggested $\lambda = 0.0$ which best fitted their dataset, and according to Ramasastri and Seth (1985); Jain and Seth (1997); Jena and Tiwari (2002), λ could vary in the range (0, 0.3). As an alternative, Bosznay (1989) suggested to treat I_a as a random variable. Since, many storm and landscape factors interact to define the initial abstraction (Hjelmfelt, 1991), fixing of λ at 0.2 is tantamount to regionalization based on geologic and climatic settings (Ponce and Hawkins, 1996). Consequently, the number of methods increases when CN is determined from the measured P-Q data and λ is allowed to vary (Bonta, 1997). Walker *et al.* (1998) pointed out that the sources of error associated with I_a-estimates and listed in NEH-4 include the likelihood of some abstracted rainfall to have eventually appeared at the outlet and emphasized further that some of this rainfall might have contributed to quick response in tile-drained watersheds.

Based on their mathematical analysis, Mishra and Singh (1999a, b) found λ to vary from 0 to ∞. They further explained the functional behaviour of the SCS-CN model using I_a as a key descriptor in $C–I_a^*- \lambda$ spectrum, where C is the runoff factor (= Q/P) and I_a^* is the non-dimensional initial abstraction (= I_a/P). Among others (e.g., Bonta 1997, Woodward *et al.*, 2002), Hawkins and Khojeini (2000) and Hawkins *et al.* (2002) examined data-supported values of the I_a/S ratio and suggested accommodations for updating its role employing two techniques, event analysis and model fitting, to determine I_a/S from field data. They found λ to vary from storm to storm or watershed to watershed, and $\lambda = 0.05$ fitted better than did $\lambda = 0.2$. Jena and Tiwari (2002), however, found $\lambda = 0.2$ to be most appropriate for their study area. While describing the origin and derivation of I_a/S in the runoff CN system, Plummer and Woodward (2002) considered λ in the range (0, 0.2), but emphasizing that the refinement was a collaborative effort of Forest Service (FS), ARS, and NRCS. Interestingly, while explaining the SCS-CN proportionality concept (Equation 3) using the volumetric concept of soil–water–air, Mishra and Singh (2003c) described λ as the degree of atmospheric saturation. They also provided a more complete SCS-CN-based initial abstraction model incorporating infiltration, interception, evaporation, and surface depression separately. For infiltration only, $\lambda = f_o t_p/S$ or αt_p, where f_o is the initial infiltration rate, t_p is the time to ponding, and α is the infiltration decay parameter analogous to the Horton (1938) infiltration decay parameter. Michel *et al.* (2005) linked S and S_a (= sum of I_a and soil moisture at the beginning of an event), instead of S and I_a for simplification for continuous modelling.

Storm Duration

The SCS-CN formulation does not contain any expression of time to account for the impact of rainfall intensity or storm duration on the generated runoff. It was not incorporated largely due to the non-availability of reliable data (Cowan, 1957, in Woodward *et al.*, 2002). While attempting to incorporate rainfall intensity or its duration for runoff estimation, Mockus (1949) modified the Sherman (1949) concept of plotting direct surface runoff against storm rainfall by incorporating storm duration as a factor, in addition to soil type, areal extent and location, land use, antecedent rainfall, storm rainfall depth, average annual temperature, and date of storm. Further attempts (Smith, 1978; Hawkins, 1978a in Rallison and Miller 1981) proposed the CN-based infiltration relationship and found CN to vary with storm intensity and storm duration. It is of common experience that CN decreases as storm duration increases. Thus, rainfall intensity or indirectly storm duration is one of the most influencing factors affecting runoff generation. This is, however, in contrast with the concept that the precipitation rate affects only runoff rates, not runoff volume (Steenhuis *et al.*, 1995). Rallison (1980) attributed the runoff variation to varying infiltration rates at the soil surface strongly affected by rainfall impact and, in turn, rainfall intensity. According to Bales and Betson (1981), the peak flow rate is affected by rainfall intensity, storm yield (runoff/rainfall), initial moisture conditions and season, as well as rainfall and runoff volume.

Introducing an additional parameter 'surface detention' to produce a dynamic equation, Chen (1981) included time in the SCS-CN procedure. For simplicity, the effect of surface detention on infiltration was assumed to be negligibly small. During rainfall (of uniform intensity and continuing indefinitely), the cumulative surface detention was found to grow rapidly in the early stages and then very slowly converging to a maximum value. It depends mainly on the roughness characteristics and the slope of the soil surface on which rainwater moves. In general, high-intensity precipitation events occur less frequently than do low-intensity events, and the duration of a high-intensity event is likely to be shorter than that of a low-intensity event. Therefore, Smith (1997) proposed to account for not only rainfall intensity but also its pattern in the SCS-CN model for a particular storm that can produce different runoff hydrographs, depending on rainfall intensity.

These attempts led Yu (1998) to assume a probability distribution of rainfall intensity in time and infiltration rate in space to derive the SCS-CN equation analytically. Mishra *et al.* (2002) proposed an SCS-CN-based runoff rate equation coupled with a routing mechanism to generate the time distribution of runoff volume. These attempts, however, need further refinement for practical situations in which data is a major constraint.

Source Area Concept

Variable source areas or partial areas denote the areas of a watershed actually contributing flow to the stream at any time. They expand during rainfall and contract thereafter around streams (Chow *et al.*, 1988). This concept was not considered in the SCS-CN model before the 1970s. In 1973, using a large set of data from several small western forested watersheds, Hawkins (1973) showed the existence of a strong relationship between CN and storm rainfall. Based on the observation, he later (Hawkins, 1979) allowed CN to vary with rainfall volume on watersheds apparently exhibiting a constant source area. In the design of surface drains, Varshney *et al.* (1983) suggested the use of an areal correction factor in the determination of runoff from the SCS-CN model. Later, Steenhuis *et al.* (1995) found the SCS-CN model to be interpretable using the principles of partial area hydrology and its efficacy to predict the contributing area. In their studies Steenhuis *et al.* (1995) and Gburek *et al.* (2002) assumed surface runoff to be generated from rainfall on the expanding and contracting saturated zones and CN to be considered exclusively for these areas (Garen and Moore 2005). On the other hand, Suwandono *et al.* (1999) used unit hydrograph concept to (a) generate rainfall hyetographs and runoff hydrographs and (b) estimate sediment loss from the source area using the SCS-CN model.

Applications

The SCS-CN model was originally formulated and intended for conservative engineering design of agricultural water management projects. Its application elsewhere should always be accompanied by good discretion and sound engineering judgment. Though the SCS-CN model originated as an empirical, event-based procedure for flood hydrology, it has been adapted and used in various models for simulating the runoff behaviour of ordinary as well as large rainfall events and daily time series as well as events (Garen and Moore, 2005). This model was found to be performing best in agricultural sites, fairly in range sites, and poorly in forest sites.

In 1982, McCuen provided guidelines for using the SCS-CN model for hydrologic analyses. Heggen (1981) and Srinivas *et al.* (1997) illustrated relative runoff estimation by a CN nomograph for $\lambda = 0.2$ and $\lambda = 0.3/0.1$ (Indian catchments), respectively. Based on the experience, the joint working group of NRCS recognized three distinctly different modes of application for CNs (Hjelmfelt *et al.*, 2001; Van Mullem *et al.*, 2002): (1) determination of runoff volume of a given return period from given total event rainfall for that return period; (2) determination of direct runoff for individual events, explaining the variability from event to event, as used in continuous simulation models; and (3) determination of infiltration rates for short time intervals as used with unit hydrograph development of flood hydrographs. Mishra and Singh (2003c) presented an up-to-date account of the SCS-CN model and discussed its potential for practical applications other than those originally intended.

To state a few different applications of SCS-CN model apart from its original applications, Svoboda (1991) used the CN concept to calculate the soil-water content and subsequently, the rainfall contribution to direct runoff and ground water. Pandit and Gopalakrishnan (1996) determined annual storm runoff coefficients (ASRCs) by a continuous simulation technique, based on the SCS-CN model. Hawkins and Ward (1998) found a distinct relationship between cover and CN and the resulting CN values compared with the NEH-4 table values. Recently, Mishra (2000) and Mishra and Singh (2004b) developed an SCS-CN based long-term hydrologic model for simulating daily runoff from two Indian catchments. Putty and Hareesha (2001) used the model for piped catchments of wet mountainous regions of the Western Ghats in South India to simulate subsurface quickflow, source area runoff, and delayed flow. Pandit (2002) used the model for a Continuous Annual Load Simulation Model (CALSIM) to determine annual or average annual pollutant loads from watersheds.

Mishra *et al.* (2003) modified the SCS-CN model (SCS, 1956) by accounting for the static portion of infiltration and the antecedent moisture in its basic proportionality concept (Equation 3) and found that the modified model performed well on the same datasets as used in NEH-4 (SCS, 1971). However, there is scope for further improvement in the results of the modified version using infiltration data. On a large set of rainfall–runoff data of 234 watersheds in USA, ranging from 0.01 to 310.3 km^2, Mishra *et al.* (2004a) evaluated the modified version of the Mishra and Singh (2002b) (MS) model which is based on the SCS-CN model and incorporates the antecedent moisture in direct surface runoff computations. This modified MS model performed better than the existing SCS-CN model. Later, Mishra *et al.* (2005b) proposed a catchment-area-based evaluation of the modified version of the MS model.

Mishra *et al.* (2005a) investigated the general SCS-CN-based MS (Mishra and Singh, 1999b) model and its eight variants for their field applicability using a large set of rainfall–runoff events derived from a number of US watersheds varying in size from 0.3 to 30351.5 ha, grouped into five classes based on rainfall magnitude. According to Mishra *et al.* (2005a), the existing SCS-CN model generally performed significantly poorer than all the general model variants on all datasets with rainfall $\leq$ 50.8 mm, and therefore it was appropriate for high rain events (> 50.8 mm). Using a more rational approach, Michel *et al.* (2005) provided a more complete assessment of the initial condition and delivered a renewed SCS-CN procedure based on continuous soil moisture accounting procedure.

In its special application to metal partitioning in urban pollutant transport system, Mishra *et al.* (2004b) examined the partitioning of 12 metal elements, Zn, Cd, Pb, Ni, Mn, Fe, Cr, Mg, Al, Ca, Cu, and Na, between dissolved and particulate-bound forms using the basic proportionality concept (Equation 3) of the SCS-CN model. The metal partitioning analogue led Mishra *et al.* (2004b) to postulate two parameters, the potential maximum desorption, Ψ, and the partitioning CN (or PCN), analogous to the SCS-CN model parameters S and CN, respectively. Further, Mishra *et al.* (2004b) found that the PCN-based ranking of metals generally agreed with that available in literature. Later, Mishra *et al.* (2004c) extended the PCN-based metal partitioning in urban snowmelt, rainfall–runoff, and river flow environments.

Distributed Modelling, Remote Sensing and GIS

The SCS-CN model was originally developed as spatially and temporally lumped model for conversion of storm rainfall depth to direct runoff volume. Its incorporation in the infiltration-capacity-equivalent form (Aron *et al.* 1977; Hawkins 1978a, 1980; Chen 1981; Mishra and Singh 2002a, b) extends the method to the domain of distributed modelling. In the present age of growing computing prowess, the distributed procedure may be well coupled with the SCS-CN model on the scale of hydrological response units (Beven 2002). The land use, which is an important characteristic of runoff process and affects infiltration, erosion, and evapotranspiration can be derived from remote sensing data and subsequently gives a way to distributed modeling.

A few investigators utilized the aerial photographs and satellite data along with others to estimate the CN values (e.g., Ragan and Jackson 1980; Pandey and Sahu 2002). Owing to its pixel format, RS data can be easily merged with the Geographical Information System (GIS), which enhances the possibility of data integration, synthesis, and analysis. Although, accuracy associated with practical uses of RS data varies, the applicability of remotely sensed data is not limited by the degree of accuracy (Rango *et al.*, 1983).

In their studies, Mohd and Mansor (1999), Sharma and Dubey (2001), Nagaraj *et al.* (2002), and Jena and Tiwari (2002) found the GIS-derived SCS-CN results consistent with and preferable to those due to conventional methods. Utilizing GIS and distributing the basin into a number of square cells, the U.S. Army Corps of Engineers integrated the spatially distributed data with the SCS-CN model for runoff computation. In this approach, soil and land use information is derived for each cell for rainfall-excess computation.

Most works overlay the land use and HSG maps, label CNs to each polygon, and take area-weighted CNs to describe the behaviour of a hydrologic basin (e.g., Pal and Agarwal 1999; Suresh Babu *et al.*, 2002; Saravanan and Suresh Babu 2005). With aid of GIS, Pandit *et al.* (1999) modified the potential maximum retention (S) for slope. For runoff estimation, Tripathi *et al.* (2002) proposed a best-fit empirical model considering watershed's geomorphological and CN parameters. Halley *et al.* (2002) extended ArcView GIS for CN estimation from land use and HSG maps.

The most difficult part of the RS and GIS use is acquiring and inputting data into GIS. Notably, GIS is advantageous if the study area is large and runoff is modeled repetitively, for example, for alternative land use/land cover scenarios. However, in developing countries, such as India, these state-of-the-art techniques need to be exploited extensively in hydrological applications.

Advantages and Limitations

The SCS-CN model is so simple that it can be used with little skill and/or with little experience in hydrology, perhaps one of the main reasons of its popularity. The model is advantageous for the following reasons (Bales and Betson 1981; Ponce and Hawkins 1996; Beven 2002):

- It is a simple, predictable, and stable conceptual model;
- Its calculations are straightforward and intuitively logical;
- It relies on only one parameter (CN);
- The required input is generally available;
- The methodology is well established and accepted;
- It is the only agency methodology whose features are readily grasped and reasonably well-documented environmental inputs (soil, land use/treatment, surface condition and AMC);
- It responds well to major runoff-producing watershed properties (soil, land use/treatment, surface condition and AMC);
- The technique is applicable to ungauged basins;
- The model does best in agricultural sites, for which it was originally intended, and extended to urban and forest sites;
- The model is featured in most of the hydrologic computer models in current use;
- Its application to RS-GIS-based distributed watershed modeling is relatively easy;
- As the model was formulated on the basis of small catchment measurements, not on the point scale measurement, it is likely to be revisited in future for point scale process.

The model however also has limitations as follows (Chen 1981; Bales and Betson 1981; Ponce and Hawkins 1996; Willeke 1997; Smith 1997; Mani *et al.,* 2002):

- The successful model application is mainly limited by the considered watershed size and, to a lesser extent, by the magnitude of runoff events. Actual distributions of rainfall and infiltration rates would rather indicate the model applicability to the onsidered watershed (Yu, 1998);
- In the absence of clear guidelines, it is assumed that the model can be applied to small- and mid-size catchments. Its application to large catchments (say > 100 sq. miles or 250 sq. km) should be viewed with caution;
- Model predictions were never intended to match the response of individual storms, these were rather to predict an average trend;
- The SCS-CN methodology does not account for rainfall intensity and its pattern within the storm, an important source of variability;
- The CN derived for a watershed inherently considers particular storms (for example, annual series) from which it was derived;
- Being an event-based model by origin, it is not intended to be applicable to continuous simulation;
- The model applicability is restricted to modeling storm losses only. Barring appropriate modifications, the model should not be used to model the long-term hydrologic response of a catchment;
- The model does not account for interflow and groundwater flow;
- Because no information has been published on the range of return periods of the annual floods used to develop the tabulated CN values, some questions still remain as to the size of the event (either rainfall or runoff duration) for which methodology is suited;
- Since the model was originally developed using regional data, some caution is recommended for its use in other geographic or climatic settings. The fixing of the initial abstraction ratio (λ) at 0.2 pre-empts regionalization based on geologic and climatic setting;
- The method lacks clear guidance on how to vary antecedent condition. The model may be very sensitive to CN and antecedent conditions, for lower CNs and/or rainfall depths. The available discrete relationship between CN and AMC is not realistic;
- The model does best in agricultural sites, for which it was originally intended and extended to urban sites. Its accuracy however varies with varying biomes.

SPECIFIC ISSUES

The SCS-CN model has been used as one of the runoff estimation methods in most simulation models developed by the United States Department of Agriculture (USDA) for hydrology, soil erosion and non-point source water quality (Hawkins 1993; SCS 1993; Ponce and Hawkins 1996; Mishra and Singh 2003c; Garen and Moore 2005). In spite of its success, several issues exist in the conventional SCS-CN model. According to Garen and Moore (2005), though the SCS-CN model originated as an empirical, event-based procedure for flood hydrology, the method has been adapted and used in models for simulating the runoff behaviour of ordinary as well as large rainfalls and daily time series as well as events. The use of SCS-CN model in this manner, however, is beset with a number of problems, issues, and misinterpretations that undermine its utility in providing a realistic and accurate representation of the water quantity in the flow paths, and source areas upon which erosion and water quality predictions depend.

Garen and Moore (2005) pointed out a number of discrepancies about the SCS-CN procedure and these have led either to a misinterpretation of its results or its usage well beyond its realm of applicability. From literature, the following issues can be identified: (1) Implementation of AMC procedure, (2) consideration of 'mean' or 'median' CN as a representative CN of a watershed in the model for which CN is a sensitive parameter, (3) I_a–S relationship, (4) potential maximum retention (S) parameter usage in the model, and (5) effect of storm intensity or duration in runoff estimation.

AMC Procedure

The procedure adopted in the SCS-CN model to consider AMC in runoff estimation lacks continuous relationship and uses 5 day antecedent rainfall based on subjective judgment. It is conceivable that for a given watershed, more than 10% variation in CN may arise solely from differences in AMC, or in extreme situations, from changing land conditions over time. In the conventional SCS-CN model, the representative CN is estimated without considering the actual AMC, and later in runoff estimation, this estimated CN is for AMC I, II, or III. It is to point out that, based on 5 day antecedent rainfall, AMC can be considered while estimating the representative CN. It is evident that a misjudgment in AMC or a drastic change in AMC over a short period of time, as in the conventional SCS-CN model, causes a serious error in CN estimation, and hence, in estimation of direct surface runoff. Further, the three discrete AMCs of the existing SCS-CN methodology ignore the continuously depletive nature of soil moisture. Stepping from one AMC to another commonly shifts the CN in multiple digits and changes the estimated Q by significant fractions. Therefore, it obviously needs a continuous relation for either continuous variation of AMC in the CN adjustments or incorporation of AMC directly in SCS-CN equation for improved model performance. The Mishra and Singh (2002b) model that modified the SCS-CN model for this purpose is either applicable in continuous simulation or lacks the consistency in the usage of parameter S, which is explained in what follows.

Mean Vs Median CN

In the conventional SCS-CN application, 'median' or 'mean' CN is often used as a representative CN for a watershed and it subsequently leads to an ambiguity if both are equivalent or better. Here, it is important to select the better one as the model results are quite sensitive to CN variations. Though many adopt the 'median' as representative CN_{II}, a few claim the 'mean' to be equivalent or even superior to the 'median' value. For example, Schneider and McCuen (2005) found that the bias in the mean CN is significantly less than the median CN if used as the estimator on simulated dataset. At the same time, Bonta (1997) pointed out that the determination of CN by using an average S (or CN) should be avoided because it gives more variable estimates than the median does and also gives poor CN estimates of measured data for the 'violent' watershed type. Therefore, a proper justification is needed to use either 'mean' or 'median' CN based on pragmatic application to large datasets.

I_a–S Relationship

I_a–S relationship was empirically derived from the observed P, Q, and I_a data, and S was computed from the existing SCS-CN methodology utilizing these data. The wide scatter of points shown in I_a–S plot of SCS-CN methodology (SCS, 1956), λ was fixed, for simplicity reasons, at 0.2 assuming a linear relationship ($I_a = \lambda S$) and it is debatable, as described above. In addition, a variety of field conditions, including precipitation varying in space and time, seasonal variations of plant covers, drastically variable antecedent soil moisture conditions, etc., the universal application of equation $I_a = 0.2S$ in the SCS-CN methodology does not represent the real ground situation, and therefore may not be acceptable (Chen, 1981). The significance of λ in runoff estimation using the SCS-CN model is therefore analyzed. Further, in reality I_a is such a variable that varies from watershed to watershed, storm to storm, and region to region, due to its dependency on AMC and S.

Parameter 'S'

According to the existing SCS-CN method, the extent of runoff contribution of a storage element depends on its capacity or alternatively, the magnitude of S (Mishra and Singh 2003c). Since parameter S in the existing SCS-CN model can vary in the range of $0 \leq S \leq \infty$, it is mapped on to a dimensionless CN, varying in a more appealing range $0 \leq CN \leq 100$. This parameter S is defined as post-initial potential maximum retention and is taken as constant for a particular storm because it is the potentially maximum retentive value that can occur under the existing conditions if storm continues indefinitely (SCS, 1972). On the other hand, the SCS-CN model assumes a (mean) constant S (or CN) for a watershed, which is storm invariant for a given AMC (SCS, 1972).

Further this 'potential maximum retention', S is characterized as invariant between homogeneous watersheds of similar land use pattern, irrespective of their location and region. Contradictorily, Rietz and Hawkins (2000) found a significant difference (at 5% level) between the CN values (or S) of the same land use between different watersheds within the same region and also in all watersheds within the region. Accordingly, it is evident that there exists an intrinsic parameter to account for these variations, that is, from watershed to watershed, storm to storm, and region to region. At the same time, it is required to maintain a single 'potential maximum retention' parameter for a watershed that is storm invariant accordingly, if SCS-CN model is considered for application. Therefore, modifications of SCS-CN formulation are required for enhanced performance.

Consideration of Storm Intensity or Duration in SCS-CN Structure

The SCS-CN model limits the calculation of direct surface runoff depth and does not explicitly consider temporal variations of rainfall intensity. This forms a major drawback of the model. However, the temporal distribution of rainfall is introduced at a later stage in the SCS-CN application, i.e., while generating runoff hydrograph by convolution or other means. Though a few investigators, as indicated in the literature review, considered the rainfall intensity in SCS-CN model formulation, these data (rainfall intensity, infiltration etc.) are as such not readily available. Further, the applicability is restricted to the continuous domain and the incorporation of intensity is indirectly considered apart from the original SCS-CN equation. Thus, it follows that a research gap still exists to account properly for either storm intensity or duration of rainfall directly in SCS-CN formulation.

EPILOGUE

This paper provides a commentary on the state of the art of SCS-CN methodology from various aspects. In spite of its success, the SCS-CN model has severe structural inconsistencies as described earlier in this paper. This is primarily due to the incomprehension over the usage of essential parameter (S or CN), applicability of initial condition, incorrect use of the underlying AMC procedure either in discrete modelling or continuous modeling, etc. Though it is extensively revisited, revised, and modified to enhance its performance for an intended application and also to introduce into other, perhaps, newer applications. There is still scope for refinement in many of the unnoticed aspects (or issues) as explained in the paper. It is possible to amend the model with a change of parameter and a sounder understanding of the underlying procedures for enhanced performance in its applications. Recently, some efforts have been made to consider these issues and to improve the model for enhanced performance. Thus, there exists a scope to enhance the performance of the SCS-CN model based on these specific issues mentioned in this paper with deeper perceptions.

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