Catena 173 (2019) 48–58

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Reverification of antecedent moisture condition dependent runoff curve number formulae using experimental data of Indian watersheds

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ARTICLE INFO

Keywords:
Agricultural field
Curve number
Antecedent moisture condition
Runoff
NEH-4 table
SCS-CN
NRCS-CN

ABSTRACT

The present study evaluates the performance of five existing and three proposed antecedent moisture condition (AMC)-based runoff curve number (CN) conversion formulae utilizing the data of a large number of naturally observed rainfall (P)–runoff (Q) for an agricultural field located at Roorkee, Uttarakhand, India and available published data around the globe. For developing the proposed formulae, CNs were derived for P–Q datasets from 39 watersheds using standard initial abstraction ratio (λ) values as 0.20 and 0.030. The existing formulae outperformed the proposed formulae when tested numerically using the available National Engineering Handbook chapter–4 (NEH–4) tabular AMC-dependent CNs as target values. It might be because the existing formulae were derived from the same datasets used as targeted values (i.e. NEH–4 AMC defining tables). Therefore, when tested on large set of field data, the three proposed formulae performed better than the existing ones, the formula with λ = 0.030 the best of all.

1. Introduction

The Natural Resources Conservation Service curve number (NRCS–CN) formerly known as the Soil Conservation Service curve number (SCS–CN) method is the most popular method to determine the storm event runoff from an ungauged small watershed for a given amount of rainfall (NRCS, 1997; SCS 1972). The main reason that the method has been adopted by most hydrologists is due to its simplicity and applicability to ungauged watersheds with the use of only single parameter known as curve number (CN) which is derived from catchment features such as land use/cover, soil type, and 5–day antecedent rainfall (P_5) (Mishra et al., 2008a). It has been widely used in a number of standard hydrologic models such as Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1980), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1990; Neitsch et al., 2002), Agricultural Non-point Source Model (AGNPS) (Young et al., 1989), Erosion Productivity Impact Calculator (EPIC) (Sharpley and Williams, 1990), Constrained Linear Simulation (CLS) (Natale and Todini, 1977), Storm Water Management (Krysanova et al., 1998), Hydrologic Engineering Center-1 (HEC-1) (HEC, 1981), Agricultural Policy/Environmental eXtender (APEX) (Williams et al., 2012) and Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Smith and Williams, 1980). In addition, the CN method has also been coupled with a number of popular models like universal soil loss equation (USLE) (Lal et al., 2017a; Mishra et al., 2006), Modified Linear Spectral Mixture Analysis (Xu et al., 2016), Xinanjiang runoff model (Lin et al., 2014) and ModClark (Saghafian et al., 2016) for enhancing their ability to improve the runoff, sediment, and environmental river flow estimation.

The general form of the SCS–CN equation is given as (SCS 1972):

$$Q = \begin{cases} \dfrac{(P - I_a)^2}{(P + S - I_a)}, & P > I_a \\ 0 & P \le I_a \end{cases} \tag{1}$$

In Eq. (1), P (mm) is the rainfall, Q (mm) is the direct surface runoff, I_a is the initial abstraction (mm) and S (mm) is the potential maximum retention. Here, I_a is expressed as a function of S (i.e. $I_a = \lambda S$) in which λ is known as the initial abstraction ratio. The existing version of the SCS–CN method recommended a standard value of λ = 0.20 in field applications (SCS 1972, 1985). The research community however pointed out that the standard value of λ = 0.20 is vague and a value of about 0.05 or less is more practical for various parts of world (Fu et al., 2011; Lal et al., 2015; Shi et al., 2009; Zhou and Lei, 2011).

For a given observed rainfall (P)–runoff(Q) data, S can be calculated by solving Eq. (1), as follows (Hawkins, 1993):

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https://doi.org/10.1016/j.catena.2018.09.002
Received 29 March 2017; Received in revised form 18 August 2018; Accepted 2 September 2018

Table 1
AMC dependent curve number conversion formulae.

Model ID	Method	AMC-3	AMC-1
M1	Hawkins et al. (1985)	$CN_3 = \frac{CN_2}{0.427 + 0.00573CN_2}$	$CN_1 = \frac{CN_2}{2.281 - 0.01281CN_2}$
M2	Mishra et al. (2008b)	$CN_3 = \frac{CN_2}{0.430 + 0.0057CN_2}$	$CN_1 = \frac{CN_2}{2.2754 - 0.012754CN_2}$
M3	Chow et al. (1988)	$CN_3 = \frac{23CN_2}{10 + 0.13CN_2}$	$CN_1 = \frac{4.2CN_2}{10 - 0.058CN_2}$
M4	Sobhani (1975)	$CN_3 = \frac{CN_2}{0.4036 + 0.005964CN_2}$	$CN_1 = \frac{CN_2}{2.334 - 0.01334CN_2}$
M5	Arnold et al. (1990)	$CN_3 = CN_2 \exp[0.00673(100 - CN_2)]$	$CN_1 = CN_2 - \frac{20(100 - CN_2)}{[100 - CN_2 + \exp\{2.533 - 0.0636(100 - CN_2)\}]}$
M6	Eq. (8) fitted for CN_1 and CN_3 (λ = 0.2) with 10% and 90% POE, respectively	$CN_3 = \frac{CN_2}{0.50503 + 0.00495CN_2}$ $R^2 = 0.640$	$CN_1 = \frac{CN_2}{1.92192 - 0.00922CN_2}$ $R^2 = 0.472$
M7	Eq. (8) fitted for CN_1 and CN_3 (λ = 0.2) with 12% and 88% POE, respectively	$CN_3 = \frac{CN_2}{0.53072 + 0.00469CN_2}$ $R^2 = 0.641$	$CN_1 = \frac{CN_2}{1.84153 - 0.00842CN_2}$ $R^2 = 0.512$
M8	Eq. (8) fitted for CN_1 and CN_3 (λ = 0.03) with 12% and 88% POE, respectively	$CN_3 = \frac{CN_2}{0.42405 + 0.00576CN_2}$ $R^2 = 0.715$	$CN_1 = \frac{CN_2}{2.42081 - 0.01421CN_2}$ $R^2 = 0.760$

$$S = \frac{(\{2\lambda P + (1-\lambda)Q\} - \sqrt{\{2\lambda P + (1-\lambda)Q\}^2 - 4(\lambda P)^2 + 4\lambda^2 QP})}{2\lambda^2} \quad \text{for } 0 < Q < P \tag{2}$$

Here, S can vary in the range of $0 \le S \le \infty$. Therefore, it can be transformed into CN varying in a more appealing range, $0 \le CN \le 100$, and vice versa:

$$CN = \frac{25400}{S + 254} \tag{3}$$

In Eq. (3), S is in mm and CN is the dimensionless entity.

For ungauged watersheds, CN can be derived using National Engineering Handbook chapter–4 (NEH–4) look–up tables (SCS, 1985) based on soil type, land cover and land management practices. The accuracy of runoff prediction, however, largely depends on accurate estimation of the lumped parameter CN (Ponce and Hawkins, 1996), which varies with antecedent rainfall and associated soil moisture. The watershed moisture condition prior to rainfall is commonly called as antecedent moisture condition (AMC), and P_5 (SCS, 1956, 1971) is often utilized as a predictor to categorize AMC into three levels, namely, AMC-1 (dry), AMC-2 (normal), and AMC-3 (wet). In practice, CNs are first calculated for AMC-2, and then adjusted to AMC-3 or AMC-1 depending on P_5. The findings of Hjelmfelt Jr. et al. (1981) showed that the AMC tables given by NEH (Table 10.1, SCS 1971) described the AMC into three classes, AMC-3, AMC-2, and AMC-1 (or CN_3, CN_2 and CN_1), which account statistically for 90%, 50%, and 10%, respectively, of the cumulative probability that a given rainfall will exceed the runoff depth. This notion is also well tested and supported by various researchers (Haan and Schulze, 1987; Hauser and Jones, 1991). Of late, Grabau et al. (2009) and Hawkins et al. (2015) examined the same AMC tables (i.e. Table 10.1, SCS 1971) and found that the concept of AMC-3 and AMC-1 may be better described as 88^{th} and 12^{th} percentiles instead of 90^{th} and 10^{th} percentiles, respectively. The concept of Grabau et al. (2009) and Hawkins et al. (2015) has, however, not yet been tested using P–Q data around the globe. Notably, AMC-2 status is considered as the reference condition, for which CN values are derived from NEH–4 tables (SCS 1971).

In order to relate the three AMCs, a number of attempts have been made for converting CNs of AMC-2 to AMC-1 or AMC-3 (Arnold et al., 1990; Chow et al., 1988; Hawkins et al., 1985; Mishra et al., 2008b; Sobhani, 1975). Firstly, Sobhani (1975), Hawkins et al. (1985) and Chow et al. (1988) used the tabular NEH–4 (SCS 1956, 1971, 1972) AMC-dependent CN–values for deriving mathematical expressions useful for converting the CN of one AMC to another. Later, Arnold et al. (1990) also developed CN–conversion formulae for using in SWAT model developed by Agricultural Research Service of the United States Department of Agriculture (USDA–ARS). The form of Arnold et al. (1990) formulae is entirely different; the size of data used is however not known, except they are based on NEH–4 table CNs. Of late, Mishra et al. (2008b) also used the same AMC table and provided a new set of mathematical expressions based on Fourier filtration smoothening procedure.

Since AMC plays a significant role in runoff generation and the runoff calculated is highly sensitive to CN, a comprehensive comparative evaluation of the existing formulae and discussion on their validity is required and it is one of the objectives of the paper. Secondly, since all the existing formulae have been derived from the same dataset, their validity is tested by deriving similar formulae from new dataset representing different climatic conditions. Furthermore, a new approach incorporating the effect of λ into AMC formula was also tested utilizing the global data.

2. CN–Conversion formulae

2.1. *Sobhani (1975) formulae*

The Sobhani (1975) formulae for converting the CNs from AMC-2 (CN_2) to AMC-1 (CN_1) or AMC-3 (CN_3) are presented in Table 1. These were developed by analyzing the AMC–dependent CN values as shown in Table 10.1 of NEH–4 (SCS 1971, 1972), in which linear relations were found to exist between the maximum potential retention (S) for AMC-2 and that for AMC-1 or AMC-3. Sobhani (1975) equations are applicable in CN–range (55, 95) as these were developed by considering every 5th CNs (or 9 data-points) in the range (55, 95).

2.2. *Hawkins et al. (1985) formulae*

Hawkins et al. (1985) also used the same above AMC based NEH-4 CN table and derived the following expressions using smoothened CN–data derived from straight line plot on normal probability paper (Mishra et al., 2008b; Ponce and Hawkins, 1996):

$$S_3 = 0.427\,S_2 \quad R^2 = 0.994 \quad \text{Standard Error (SE)} = 2.2352\ \text{mm} \tag{4}$$

$$S_1 = 2.281 S_2 \quad R^2 = 0.999 \quad \text{Standard Error (SE)} = 5.2324\ \text{mm} \tag{5}$$

Similar to the Sobhani (1975) expressions, Eqs. (4) and (5) are also