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Runoff Curve Number and Computation of Design Flood Hydrograph using SCS

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1.0 Introduction

Water is one of the most important natural resources of a country, which controls the human developmental activities. Planning and execution of water resources projects require runoff estimates from storm events. Generally, in a river basin, number of raingauges are always more than the number of stream gauges which results in a longer rainfall records than the streamflow records. This leads to a situation in which it will be necessary to evolve some methodology to calculate runoff from the available rainfall records. A review of the literature reveals that there are many methods available to derive runoff from the rainfall records. In the absence of direct measurement of runoff, rainfall-runoff relationships, developed for a hydrologically homogeneous region can be used for the estimation of yields.

One of the simplest rainfall-runoff model is the linear model correlating runoff to rainfall. But important runoff producing mechanisms such as rainfall intensity, infiltration rate, antecedent moisture condition, etc., are not reflected in this type of model. There is a wide variety of other models where effect of these factors have been taken into account. SCS runoff curve number method is one of those models which has wide acceptance in many hydrologic applications.

In 1954, the USDA Soil Conservation Service (SCS) proposed the curve number method to determine outflow hydrographs for use in small structural design and appraisal of land use changes. This procedure is based on a non-linear rainfall-runoff relation that uses a land condition factor called 'the curve number' to calculate depth of rainfall excess, and uses a triangular unit hydrograph to route rainfall excess to produce an outflow hydrograph. The curve number is a function of hydrologic soil type, land use and treatment, ground surface condition, and antecedent moisture. This method has been described in the SCS National Engineering Handbook, Section 4: Hydrology (NEH-4). It is a well established method in hydrological engineering and environmental impact analysis. Its popularity is rooted in its convenience, simplicity, authoritative origin, and responsiveness to four major catchment properties; soil type, land use/ land treatment, surface condition, and antecedent moisture condition.

The curve numbers (CN) associated with the soil cover complexes are median values, roughly representing average conditions on a watershed. These values are evolved based on the data from research watersheds, where experiments were conducted to determine the runoff for different soil and cover conditions.

The fundamental hypotheses of the SCS CN method are as follows;
(i) Runoff starts after an initial abstraction has been satisfied. This abstraction mainly consists of interception, surface storage, and infiltration, and
(ii) The ratio of actual retention of rainfall to the potential maximum retention S is equal to the ratio of direct runoff to rainfall minus initial abstraction.

The method is based on proportionality between retention and runoff in the following form;

$$F/S = Q/P \tag{1}$$

where, F is actual retention (P - Q); and S = potential retention.

Potential retention is a measure of the ability of a given site to abstract and retain storm rainfall, provided the level of antecedent moisture has been factored into the analysis. This relation states that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff. For practical applications, the above equation can be improved by incorporating an initial abstraction. The initial abstraction consists mainly of interception, infiltration, and surface storage, all of which occur before runoff begins. Then the above equation can be rewritten as:

$$(P - Ia - Q)/S = Q/(P - Ia)\text{, or}$$

$$Q = (P - Ia)^2/(P - Ia + S) \tag{2}$$

where, Q is the runoff volume uniformly distributed over the drainage basin, and P is the mean precipitation over the drainage basin.

The initial abstraction Ia can be expressed as a function of S, and SCS have recommended, Ia = 0.2 S from their field experiences. Physically, this means that for a given storm, 20 % of the potential maximum retention is the initial abstraction before runoff begins. Presumably, 0.8 S represents other retention losses including interception, infiltration, evapo-transpiration, and depression storage, occurring after runoff begins.

Therefore, SCS rainfall-runoff relation becomes:

$$Q = (P - 0.2S)^2/(P + 0.8S) \tag{3}$$

Evidently, this is a one-parameter model with S as the parameter. This parameter depends upon characteristics of the soil-vegetation-land use (SVL) complex and antecedent soil moisture condition on a watershed.

SCS developed three antecedent moisture conditions and labeled them as AMC-I, II, and III. AMC-I represents dry condition of soil, AMC-III represents saturated soil and AMC-II is the average condition.

The watershed storage index S, is conveniently expressed in terms of a dimensionless index, runoff curve number as:

$CN = 1000/(10 + S)$, where S is in inches

or $CN = 25400/(254 + S)$, where S is in mms. (4)

Curve numbers are dimensionless, and can vary from 0 (no runoff) to 100 (all rainfall becomes runoff). Design estimates of CN based on soil, and land use are given in SCS National Engineering Handbook, Section IV (NEH-4).

Even though this methodology has been developed for small agricultural watersheds in USA, its simplicity attracted many researchers in India and other countries. This method has been subjected to large number of improvements and changes, to suit the conditions prevalent in the user country. The runoff curve number for different hydrologic soil cover complexes for Indian conditions are given in Handbook of Hydrology (1972), Soil Conservation Division, Ministry of Agriculture, Govt. of India.

Vandersypen et al. (1972) developed the following relationship between initial abstraction and potential maximum retention, for Indian conditions.

For black soil region (AMC I) and for all other regions, Ia = 0.3 S.

Therefore the SCS rainfall-runoff relationship becomes:

$$Q = (P - 0.3S)^2/(P + 0.7S) \qquad (5)$$

and for black soil region (AMC-II and III), Ia = 0.1 S and the rainfall-runoff equation becomes:

$$Q = (P - 0.1S)^2/(P + 0.9S) \qquad (6)$$

This equation is used with the assumption that the cracks, which are typical of black soil, when dry are filled.

So, for an event rainfall and curve number estimated from the SCS tables, the corresponding runoff can be calculated using equation (4) and (2). It is found that the calculated runoff values are sensitive to the CN values than to the observed rainfall values (Hawkins, 1975). Also it is found that selection of CN is difficult, for soil and land use/land cover types which are not mentioned in the SCS tables. So, the curve number values estimated using the conventional SCS method has to be verified using local real data on rainfall and runoff, for better application of SCS methodology.

For the generation of Hydrograph using SCS method, peak runoff rate and time to peak are to be calculated as follows;

$$Q_p = 0.146\ A\ Q\ /T_p$$

where, Q_p is the peak discharge rate in cumecs, A is the watershed area in sq. kms. Q is the effective runoff in mms., and T_p is the time to peak in hours.

$$T_p = \Delta D/\ 2 + L_t$$

Where, ΔD is the duration of unit excess rainfall in hours, $\Delta D = 0.133\ T_c$; and L_t is the watershed lag time, $L_t = l^{0.8}\ (S+1)^{0.7}\ /\ 1900\ Y^{0.5}$, where, l is the hydraulic length of watershed in feet, S is the potential retention of the watershed in inches and Y is the average watershed slope (%); T_c is the time of concentration, $T_c = L_t/0.6$. T_c can also be calculated by Kirpich formula. Lag time is the time from the centroid of rainfall to the peak of the hydrograph. Time of concentration is the time taken by the water to flow from the farthest point to the basin outlet.

Ordinates of the unit hydrograph were estimated by multiplying T_p and Q_p with time ratio (t/T_p) and discharge ratio (Q/Q_p) of SCS dimensionless unit hydrograph as shown in Table1. This dimensionless unit hydrograph is developed by Victor Mockus from a large number of unit hydrographs of watersheds varying size and geographical locations. The dimensionless curvilinear unit hydrograph has 37.5 % of the total volume in the raising side, which is represented by one unit of time and one unit of discharge. This hydrograph has a point of inflection approximately 1.70 times the time-to-peak and the time to peak 0.2 of the time-of-base. This can also be represented by an equivalent triangular hydrograph.

Table 1. Ordinates of Dimensionless Unit Hydrograph

Sl. No.	Time Ratio (t/T_p)	Discharge ratio (q/q_p)
1	0.00	0.00
2	0.10	0.03
3	0.20	0.10
4	0.30	0.19
5	0.40	0.31
6	0.50	0.47
7	0.60	0.66
8	0.70	0.82
9	0.80	0.93
10	0.90	0.99
11	1.00	1.00
12	1.20	0.93
13	1.40	0.78
14	1.60	0.56
15	1.80	0.46
16	2.00	0.33
17	2.20	0.20
18	2.40	0.15
19	2.60	0.11
20	2.80	0.08
21	3.00	0.06
22	3.20	0.04
23	3.40	0.03
24	3.60	0.02
25	3.80	0.02
26	4.00	0.01
27	4.50	0.005
28	5.00	0.00

2.0 SCS Curve Number Method

The SCS curve number method is an infiltration loss model, although it may also account for interception and surface storage losses through its initial abstraction feature. This method is not intended to account for long term losses such as evaporation and evapo-transpiration.

The curve number methodology was originated as the result of a large number of infiltration tests carried out by SCS in late 1930s and 1940s. These tests were conducted to evaluate the effects of watershed treatment and soil conservation measures on the rainfall-runoff process. Sherman (1942, 1949) had proposed plotting direct runoff versus storm rainfall. Based on this idea, Mockus (1949), suggested that surface runoff estimates for ungauged watersheds could be made using the information on soils, land use, antecedent rainfall, storm duration, and average annual temperature. He combined all these factors into an empirical parameter 'b' characterising the relationship between rainfall depth P and runoff depth Q; $Q = P(1 - 10^{-bP})$ (Rallison, 1980). Andrews (1954), using infiltration data from Texas, Oklahoma, Arkansas, and Louisiana, developed a graphical procedure for estimating runoff from rainfall for several combinations of soil texture, type and amount of cover, and conservation practices. The combination was referred to as 'soil-cover complex' (Miler and Croshney, 1989).

Mockus' empirical rainfall-runoff relationship and Andrews' soil-cover complex were the basics of the conceptual rainfall-runoff relationship put forward by SCS, which is known as curve number method.

The SCS rainfall-runoff relationship, $Q = (P - Ia)^2/(P - Ia + S)$, has two parameters; S and Ia. To remove the necessity for an independent estimation of initial abstraction, a linear relationship between Ia and S was suggested by SCS; $Ia = \lambda\ S$, where λ is the initial abstraction ratio. From the experiments conducted in watersheds less than 10 acres in size, it is found that 50 % of the data points were lying within the limits of $0.095 \leq \lambda \leq 0.38$. From this analysis, SCS adopted a standard value for initial abstraction ratio as 0.2. However, values varying in the range of 0.0 - 0.3 have been documented in a number of studies encompassing various geographical locations.

The major factors that influence CN value are the hydrologic soil group, land use/treatment class, hydrologic condition, and antecedent moisture condition.

The SCS has classified all soils into four hydrologic soil groups (A, B, C, and D) according to their infiltration rate, which is obtained for bare soil after prolonged wetting. Among these, the group A is having the lowest runoff potential and high infiltration rates and group D soils are having highest runoff potential with lowest infiltration rates.

Treatment is a cover type modifier used in the SCS table to describe the effect on CN of the management of cultivated agricultural lands. It includes mechanical practices, such as contouring and terracing, and management practices, such as crop rotations and reduced or no tillage.

Hydrologic condition indicates the effect of cover type and treatment on infiltration and runoff and is generally estimated from density of plant and residue cover on sample areas. A good hydrologic condition indicates that the soil usually has a low runoff potential for the given hydrologic soil group, cover type, and treatment.

Antecedent moisture condition is an index of runoff potential for a storm event. The AMC is an attempt to account for the variation in CN at a site from storm to storm.

The NEH-4 runoff curve numbers were developed from recorded rainfall-runoff data, where hydrologic soil group, land use/treatment class, and surface condition were known. The P-Q data was plotted and the CN corresponding to the curve that separated half of the plotted data from the other half was taken as the median curve number for the given site. The natural scatter of points around the median curve number was interpreted as a measure of the natural variability of soil moisture and associated rainfall-runoff relation.

To account for this variability, the P-Q plots were used to define enveloping or near-enveloping CN values for each site. These enveloping curve number values are considered as the practical upper and lower limits of expected CN variability for the given combination of soil cover complex. Thus, antecedent moisture condition was used as a parameter to represent the experienced variability. The curve number lying in the middle of the distribution is the median curve number, corresponding to AMC 2 (average runoff potential). This is the standard curve number given in the SCS tables. The low value is the dry curve number, of AMC 1 (lowest runoff potential) and the high value is the wet curve number, of AMC 3 (highest runoff potential).

To decide about the level of AMC to be used in a given case, NEH-4 has given a table based on total 5-day antecedent rainfall, for dormant and growing season. However, the table does not account for regional differences or scale effects. An antecedent period longer than 5 days would probably be required for larger watersheds. By considering this, SCS has deleted the table in the new version of Chapter 4, NEH, released in 1993. So in practice, the determination of AMC is left to the user, who must evaluate whether a certain design situation warrants, AMC 1, AMC 2, or AMC 3.

Ponce (1996), enumerated the advantages and disadvantages of the method as:
The advantages are:

1. It is a simple, predictable, and stable conceptual method for the estimation of direct runoff depth based on storm rainfall depth.

2. It relies on only one parameter, the runoff curve number, which varies as a function of four major runoff producing watershed properties; hydrologic soil group, land use and treatment class, hydrologic surface condition, and antecedent moisture condition.

3. It is the only methodology that features readily grasped and reasonably well documented inputs.

4. It is a well established method, having been widely accepted for use in various countries.

The disadvantages are:

1. The method was originally developed using regional data, mostly from the midwestern USA. So some caution is necessary when it is applied to other geographic or climatic regions.

2. For lower curve numbers and/or rainfall depths, the method is very sensitive to curve number and antecedent moisture condition.

3. The method is best suited for agricultural sites, for which it was originally intended, and has since been extended to urban sites. The method rates fairly in applications to range sites, and generally does poorly in application to forest sites. The implication here is that the method is best suited for storm rainfall-runoff estimates in streams with negligible baseflow, ie., those for which the ratio of direct runoff to total runoff is close to one.

4. The method has no explicit provision for spatial scale effects. Without catchment subdivision and associated channel routing, its application to large catchments (greater than 250 sq. km.) should be viewed with caution.

5. The method fixes the initial abstraction ratio at 0.2. In general, however, this ratio could be interpreted as a regional parameter.

3.0 Curve Number from Rainfall-Runoff Data

Curve numbers given in the SCS tables (NEH-4) were derived from analysis of data from small experimental watersheds in USA. So, use of the same tables in our conditions, will lead to erroneous estimation of curve numbers and in turn runoff depths. Hence, it is advantageous to have some alternate method for the estimation of runoff curve number. The objective is either to verify the curve number values given in the standard SCS tables, or, to extend the methodology to soil cover complexes and geographic locations not covered by the NEH-4. Because of the sensitivity of the method to CN values and the unreliability of CN estimates from standard tables, reassurance and safe reference should be taken from local real data situations, ie., by determining curve number for local watersheds from recorded storm rainfall-runoff.

Since the method's inception, several investigators have attempted to determine runoff curve numbers from small watershed rainfall-runoff data, which can be used for homogeneous regions. An established procedure to estimate CN values from rainfall-runoff data is to solve for S from SCS rainfall-runoff equation, which results in:

$$S = 5(P + 2Q - \sqrt{4Q^2 + 5PQ})\text{, for Ia} = 0.2\text{ S} \qquad (7)$$

For a given P and Q pair, the potential retention S can be calculated using the above equation, and the corresponding CN can be calculated using, $CN = 1000/(10 + S)$.

For areas where Ia = 0.1 S or 0.3 S, the expressions for the calculation of S from the observed rainfall-runoff pairs are as follows;

for Ia = 0.1 S,

$$S = 5(2P + 9Q - \sqrt{81Q^2 + 40PQ}) \qquad (8)$$

for Ia = 0.3 S,

$$S = 0.56(6P + 7Q - \sqrt{49Q^2 + 120PQ}) \qquad (9)$$

There are several ways to select the P-Q pairs for analysis. The standard method, referred to as the annual flood series, is to select daily rainfall and its corresponding runoff volume for the annual floods at a site. When the annual flood series is not available for a larger period, it is possible to select storm event data. This incorporates rainfall-runoff events with return period less than one year. This procedure has the advantage that it results in a considerable range of rainfall and runoff values for analysis.

Another approach is the frequency matching method. The storm rainfall and direct runoff depths are sorted separately, and then realigned on a rank basis to form desirable P-Q pairs of equal return period. The individual runoff values are not necessarily associated with the original rainfalls. For all return periods, the CN is taken to be consistent. Thus, when treating rainfall and runoff data, the N-year return period rainfall should be paired with N-year return period runoff. Here, the CN method may be seen as a transformation between a rainfall-depth distribution and a runoff depth distribution.

When curve numbers are calculated from real storm data, a secondary relationship emerges between CN and the storm rainfall depth. Different watersheds with varying rainfall-runoff relationship show different types of variation of curve number values with increasing precipitation values. The first variation is the Complacent behaviour, in which the observed CN values decline steadily with increasing rainfall depth and show no appreciable tendency to achieve a stable value. In this case, curve number cannot be safely determined from data, because no constant value is clearly approached.

The second variation is the standard behaviour, which is the most common scenario. Here, observed CN declines with increasing storm size and approaches and/or maintain a near constant value with increasingly larger storm. The runoff itself may arise from a variety of source process, including overland flow and rapid subsurface flow.

The third variation is violent behaviour, in which the distinguishing feature is that the observed curve numbers rise suddenly and later asymptotically approach a constant value. There is often accompanying complacent behaviour at lower rainfalls. From a source-process standpoint, this could be a threshold phenomenon at some critical rainfall depth value.

In most of the cases, these calculated CNs approach a constant value with increasing rainfall. This asymptotic constant value CN_∞ is used to identify the curve number for a watershed. The equation;

$$CN(P) = CN_\infty + (100 - CN_\infty)\exp(-kP) \qquad (10)$$

has been found to fit (P-CN) data set, where CN_∞ is the constant curve number value as $P \to \infty$ and k is a fitting constant. This equation may be fitted by a least square procedure to calculate CN_∞ and k. Although, this is an entirely curve fitting approach, it has been found to be appropriate for a wide array of watershed data sets.

This asymptotic constant value is used in identifying the CN for a watershed. Thus, where no constant value is approached, as in complacent situations, no CN_∞ can be determined. The problem is then reduced to an objective determination of that asymptote for the standard and violent situations.

4.0 Remarks

In practical use, application of the SCS method is simple and direct. Problems are caused by different researchers obtaining different answers as a result of choice of different procedures, especially for estimating time of concentration and in choosing the curve number CN.

Confusion has resulted from application of the method as a deterministic model for estimating the flood resulting from a particular rainfall, and as a probablistic model to estimate design flood. The method has been tested extensively in the deterministic sense with generally poor results. Testing of SCS method as a probablistic model concluded that the CN values required to reproduce flood peaks estimated by frequency analyses of recorded flows depended on the method of estimating time of concentration and the average recurrence interval of the design flood.

All of the above results cast some doubt on the accuracy and validity of the SCS method. Care is required in its application, and there is a need for checking of the method against observed flood data in each region where the method is applied.

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