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PAST, PRESENT, AND FUTURE SCS RUNOFF PROCEDURE

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ABSTRACT

The Soil Conservation Service (SCS) runoff equation, which came into common use in the mid-1950's, is the product of more than 20 years of studies of rainfall-runoff relationships from small rural watershed areas. The procedure, which is basically empirical, was developed to provide a consistent basis for estimating the amount of runoff under varying land use and soil types. It was initially used by SCS in project planning for the small watershed program (Public Law 83-566). Because of its simplicity, however, its use has spread through the spectrum of hydrologic application by federal, state, and private hydrologists. The procedure is generally reliable when used in situations for which it was designed, but it is not adequate for solving all types of hydrologic problems. After more than two decades of field use, it is time to reexamine the SCS runoff procedure to determine whether it can be improved or whether a new procedure should be developed.

INTRODUCTION

In 1954 the Soil Conservation Service (SCS) developed a unique procedure for estimating direct runoff from storm rainfall. This procedure was the end product of a major field investigation effort and the work of numerous early investigators (Mockus 1949, Sherman 1949, Andrews 1954, Ogrosky 1956). A major catalyst for getting this procedure to the field was the passage of the Watershed Protection and Flood Prevention Act (Public Law 83-566) in August 1954. Studies associated with small watershed project planning were expected to require a quantum jump in hydrologic computations within SCS and the solution of new types of hydrologic problems.

The procedure, which is frequently referred to as the curve number technique, has proven to be a very useful tool for evaluating effects of changes in land use and treatment on direct runoff. At present, it is the procedure most frequently used within SCS to estimate direct runoff from ungaged areas.

During the past 10 years, the curve number procedure has increasingly been applied to hydrologic problems it was not originally intended to solve. Although its use for a variety of problems is not necessarily inappropriate, the original authors certainly did not foresee its widespread application to the entire spectrum of hydrologic problems encountered on ungaged areas.

HISTORICAL BACKGROUND

Experimental Watersheds

The need for hydrologic data in the design of conservation practices became acute in the mid-1930's, when SCS was established and charged with setting up demonstration conservation projects and overseeing the design and construction of soil and water conservation practices. As a result of this need, experimental watersheds were established at a number of locations to obtain data on rainfall, runoff, and associated factors. Many of these were elaborate studies involving watershed areas of several square miles.

With the passage of the Flood Control Act of 1936 (Public Law 74-738), the Department of Agriculture was authorized to carry out surveys and investigations of watersheds to install measures for retarding runoff and waterflow and preventing soil erosion. A classic hydrologic problem, which was encountered early, was the evaluation of the effect of watershed treatment and/or conservation measures on the rainfall-runoff process.

According to Andrews (1954), data from the experimental watersheds were meager and covered only a small fraction of the conditions encountered in any watershed. To obtain the basic data necessary to evaluate the effects of the proposed conservation measures, infiltrometer studies were made.

Infiltrometer Studies

Thousands of infiltrometer runs were made during the late 1930's and early 1940's with the vast majority using the sprinkling-type infiltrometer. The type F infiltrometer was found most satisfactory (Sharp et al. 1940); but because the plots used were 6 feet wide and multiples of 12 feet long, the equipment was cumbersome and its operation somewhat expensive. As an economy measure, a type FA infiltrometer was devised for a plot measuring 12 by 30 inches and was used extensively.

Using primarily the data from infiltrometer plots and small watersheds, three private consultants--W. W. Horner, R. E. Horton, and R. K. Sherman--were employed by SCS to aid in developing a rational method for estimating the runoff from any given plot of land under various cover conditions. Horner (1940) credited Horton (1933, 1939) with much of the pioneering work of characterizing infiltration capacity curves while he (Horner) concentrated on the development of infiltration capacity from small watershed data. The result of these studies was a series of rainfall retention rate curves that were used, together with precipitation-excess and time-of-excess curves, to obtain the volume of runoff from any given physical land unit. Because this method required the availability of a recording raingage, its use was seriously limited in many areas.

Other methods of estimating runoff, devised during the early 1940's, used infiltration data as background material. Andrews (1954) grouped the infiltrometer data from Texas, Oklahoma, Arkansas, and Louisiana and found that texture class was the only soil characteristic that was consistent within each group. From these data he developed a graphical procedure for estimating runoff from rainfall for combinations of soil texture, type and amount of cover, and conservation practices. This association was referred to as a soil-cover complex.

Rainfall-Runoff Relationship

L. K. Sherman (1949) was one of the first to propose plotting direct runoff versus storm rainfall. Building on this idea, Mockus (1949) proposed that surface runoff could be estimated from the following information:

1. Soils: types, areal extents, and locations.
2. Land use: kinds, areal extents, and locations.
3. Antecedent rainfall.
4. Duration of a storm and associated rainfall amount.
5. Average annual temperature and date of storm.

Mockus (1949) combined these parameters into an index value, b, which was solved from the equation:

$$b = \frac{0.0374\ (10)^{0.229M}\ C^{1.061}}{T^{1.990}\ D^{1.333}\ (10)^{2.271(S/D)}} \qquad (1)$$

where

M = 5-day antecedent rainfall, inches
C = cover practice index
T = seasonal index, which is a function of date and temperature (°F)
D = duration of storm, hours
S = soils index, inches per hour

Resulting b values were used as the second independent variable (P being the initial independent variable) in a graph of P vs. Q, in which

$$Q = P[1-(10)^{-bP}] \qquad (2)$$

where

Q = direct runoff, inches
P = storm rainfall, inches

It also follows that the slope, b, in equation 2 is related to watershed and storm characteristics, and that it will be possible to predict Q for any storm on any watershed when these characteristics are known for that watershed and storm (Mockus 1949).

Mockus (1949) summarized the results of testing equations 1 and 2 as follows:

> Better results were obtained for large storms than for small storms, for short storms than for long storms, and for mixed-cover rather than single-cover watersheds. Breaking long storms into parts containing the more intense periods and adding the computed Q values improved the estimates for long storms. There was difficulty in defining amounts and durations of storms for large watersheds. [Large was defined as anything larger than several hundred acres.]

SCS RUNOFF EQUATION

By the early 1950's it was apparent that SCS needed a procedure that, with the kinds of data that were available, could be applied nationally. The models of Sherman (1949) and others were for gaged watersheds, and they were freehand determinations of the rainfall-runoff relation. The rainfall-runoff relations developed by Andrews (1949) and Mockus (1949) were somewhat generalized; it was desirable--but not necessary--to have a stream gage on the problem watershed.

The work of Andrews and Mockus is the basis for the generalized SCS rainfall-runoff relation, which can be expressed as follows: when accumulated natural runoff is plotted versus accumulated natural rainfall, runoff starts after some rainfall has accumulated and becomes asymptotic to a line of 45° slope. Figure 1 shows a typical relationship. When data from infiltrometer runs are used, the resulting curve is similar but it is generally asymptotic to a line of less than 45° slope, because of lateral flow below the infiltration plot.

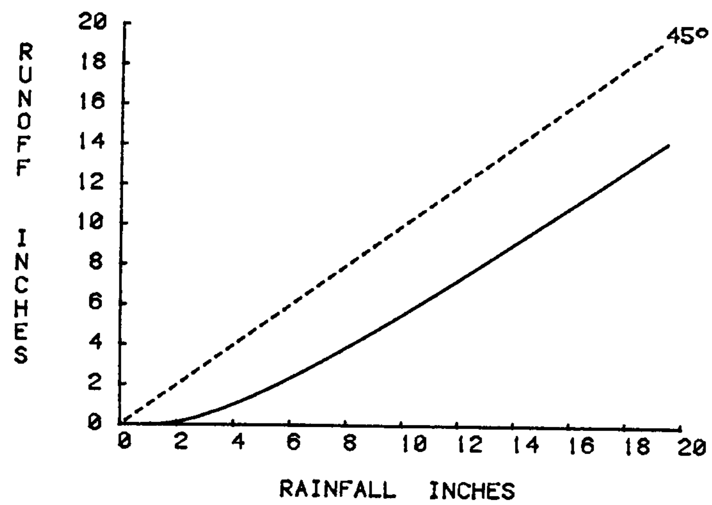

Figure 1. Accumulated Rainfall and Runoff.

Development of Runoff Equation

Analysis of storm event rainfall and runoff records indicates that there is a threshold which must be exceeded before runoff occurs; that is, the rainfall magnitude must be sufficient to satisfy interception, depression storage, and the infiltration quantity before the start of runoff. The rainfall required to satisfy the above volumes is termed the initial abstraction, I_a. After runoff begins, additional loss occurs mainly in the form of infiltration. The total actual retention for the event after start of runoff is given the symbol F.

After runoff begins, F increases with increasing rainfall up to some maximum retention, S. Runoff, Q, also increases as the rainfall, P, increases. Figure 2 shows the relationship among these variables. The ratio of actual retention F to maximum retention S is assumed to be equal to the ratio of runoff to rainfall minus initial abstration. The assumed relationship in mathematical form is

$$Q/(P-I_a) = F/S \qquad (3)$$

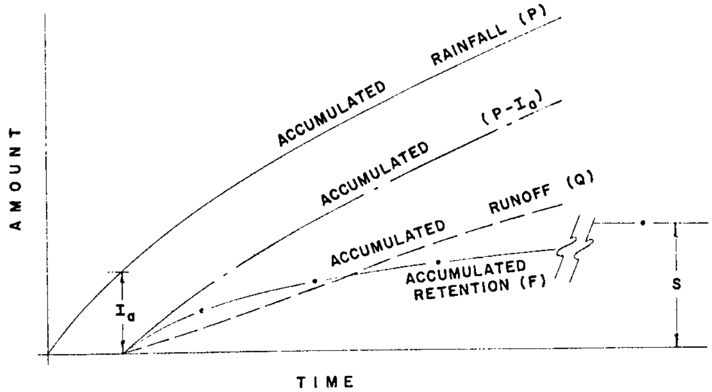

Figure 2. Schematic Curves Showing the Relation Expressed by Equation 3.

In the limit, as $P \to \infty$ $F \to S$ and the ratio $F/S \to 1$. The ratio of $Q/(P-I_a)$ also approaches 1 although it can never actually reach 1, but for all practical purposes the two ratios approach 1 as $P \to \infty$. When $P = I_a$, $F = 0$ and the ratio of $F/S = 0$. As P becomes greater than I_a the ratio of F/S is still near zero and the $Q/(P-I_a)$ ratio is also near zero. Since the relationship holds at the two end points, it is assumed to hold for all intermediate points. After runoff begins, all rainfall becomes runoff or actual retention. That is,

$$(P-I_a) = F + Q \tag{4}$$

Solving equations 3 and 4 for Q when $P > I_a$ yields

$$Q = (P-I_a)^2/((P-Ia)+S) \tag{5}$$

and when $P \leq I_a$, $Q = 0$

To eliminate the necessity of estimating both variables (I_a and S) in equation 5, field data (SCS 1956) were used to estimate I_a in terms of S.

The field data indicated the empirical relationship:

$$I_a = 0.2S \tag{6}$$

which, when substituted for I_a in equation 5, results in the more familiar equation:

$$Q = (P-0.2S)^2/(P+0.8S) \text{ for } P > 0.2S \tag{7}$$

Equation 7 has an advantage over many that have been proposed: it is easier to use because it requires only one parameter (S) related to storm and watershed characteristics. S is related to a runoff curve number by the relationship:

$$CN = 1000/(S+10) \tag{8}$$

Significance of S

Mockus (1964) discussed the significance and limitations of S. S is limited by either the rate of infiltration at the soil surface or the amount of water storage available in the soil profile, whichever gives the smaller S value. The magnitudes of S for various soil cover combinations were estimated by plotting storm rainfall and runoff, estimating a curve number and determining the values from the relationship expressed in equation 5, solved for S. Since infiltration rates at the soil surface are strongly influenced by rainfall impact, they are strongly affected by the rainfall intensity. In practice, rainfall intensity was neglected, since little information was available in rural areas when the procedure was initially developed.

DEVELOPMENT OF CURVE NUMBERS

To the extent possible, curve numbers were developed from gaged watershed data where soils, cover, and hydrologic conditions were known (SCS 1972). Daily rainfall and runoff volumes were used for the annual floods at a site (SCS 1973).

Data were plotted as rainfall versus runoff (P versus Q) on arithmetic cross section paper. A grid of plotted curve numbers for $I_a = 0.2S$ was laid over the cross-section paper, and the median CN was selected (see fig. 3). The curve numbers represent the averages of median site values for hydrologic soil groups, cover, and hydrologic conditions. Not all soils, cover types, and hydrologic conditions were represented from watershed data. To complete the information contained in SCS National Handbook, Section 4, Hydrology (NEH-4 1972), the data were interpolated (Mockus 1964).

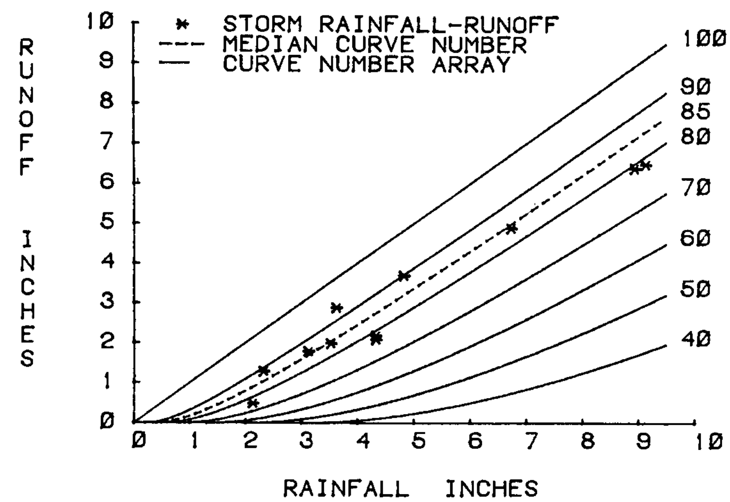

Figure 3. Median Curve Number Development.

To explain the rationale used to develop individual curve numbers, Mockus (1964) wrote: "The CN associated with the soil-cover complexes are median values, roughly representing average conditions on a watershed. We took the average condition to mean average soil moisture condition because we had to ignore rainfall intensity." The sample variability in CN can be due to infiltration, evapotranspiration, soil moisture, lag time, rainfall intensity, temperature, etc. Antecedent moisture condition (AMC) was used to represent this variability. The AMC I is the lower enveloping CN, AMC II the median CN, and AMC III the upper enveloping CN (Mockus 1964).

In justifying the development of the runoff equation, Mockus wrote (1964):

> 1. The runoff equation is based on the hypothesis expressed by [equation 3]...We justify [equation 3] on the grounds that it produces rainfall-runoff curves of a type found on natural watersheds.
> 2. Other equations will also produce rainfall-runoff curves like those from [equation 3] but these other equations have three or more parameters to be determined in advance, and this is difficult to do with ordinarily obtainable data.
> 3. Actually the CN's have been verified experimentally since they are based on data from research watersheds where the experiment was to determine the runoff for different soil and cover conditions.
> 4. The particular CN's used by the SCS are not the only ones that can be developed for use with [equation 7]. By using other storm or watershed characteristics, other kinds of CN's can be obtained. The practical value of the results will depend on how well the chosen characteristics can be represented by the data ordinarily at hand. We could have gone on to develop a very complicated set of CN's, but they would have been unusable.
> 5. The research watersheds from which data were used are located in various parts of the United States, so that our CN's applies throughout the country.

Limits of Application

Mockus (1964) noted several characteristics of equation 7 that limit the types of problems for which it should be used. The equation does not contain any expression for time. It is for estimating runoff from individual storms. In practice, the amount of daily rainfall is used; total runoff from a storm of greater duration is calculated as the sum of daily increments. For a continuous storm--one with no breaks in the rainfall--equation 7 can be used to calculate the accumulated runoff. For a discontinuous storm, which has intervals of no rain, there is some recovery of infiltration rates during the intervals. If the period does not exceed an hour or so, it can be ignored and the estimate will be reasonably accurate. When the rainless periods are over an hour, a new higher CN is usually selected on the basis of the change in antecedent moisture for the next period of rain.

The relationship between I_a and S was determined from natural rainfall and runoff data from experimental watersheds (SCS 1956). Further refinement of I_a is possible but not recommended, because under typical field conditions very little is known of the magnitudes of interception, infiltration, and surface storage.

Discussing the limits of application of the SCS runoff procedures, Kent (1966) states:

> The procedures are primarily for establishing safe limits in design, and for comparing the effectiveness of alternative systems of measures within a watershed project. They are not used to recreate specific features of an actual storm.
>
> [Equation 7] was developed for conditions usually encountered in small watersheds in which only daily rainfall and watershed data are ordinarily available. It was developed from data and for situations where total rainfall amount of one or more storms occurring in a calendar day is known but without knowing their distribution with respect to time.

Cowan (1957) summarizes the reasons why time was not incorporated:

> Time was not incorporated in the method for estimating runoff for two important, practical reasons. First, sufficient reliable data were not available to define curves of infiltration capacity versus time for a wide range in soil, land use, and cover conditions. Second, if time had been incorporated in the method, it would have required a determination of the time distribution of rainfall in storms for which runoff was to be estimated. In the majority of cases, rainfall records on the watersheds with which we deal do not permit reliable determinations of the time distribution of individual storms.

CONCERNS ABOUT APPLICATION OF THE CURVE NUMBER PROCEDURE

Several investigators (Jackson 1975, Abbott 1976, Jackson 1976, Smith 1978, Hawkins, 1978a, and 1978b) have expressed concern that the curve number procedure does not always reproduce measured runoff from specific storm rainfall. In some instances lack of agreement occurs if an "average condition" CN is applied to a specific storm event. The CN for a storm event, however, can be anywhere within the enveloping CN range for the soil cover complex or even beyond the range. Reich and Jackson (1971) found that S values (inversely related to CN) had to be extended in both directions to reproduce 210 floods on 15 watersheds smaller than 20 square miles. SCS established the enveloping CN range as a generalization of observed values, but CN values beyond the limits are not excluded. Variation in reproduction of specific events by the CN procedure can also be explained by inaccurate separation of direct storm runoff from total runoff.

Three CN values--for the upper and lower enveloping values as well as the median--are published in NEH-4 (SCS 1972) for many soil-cover complexes, but NEH-4 provides no guidance for selecting other CN values throughout the expected range. If users keep in mind how these points were established, it will be apparent that it may not be meaningful to define rigidly some relationships for interpolating values along the range.

Smith (1978) and Hawkins (1978a) have also found that infiltration relationships, when calculated by the curve number procedure, vary with storm intensity. Other hydrologists have found that curve numbers apparently vary by storm duration, becoming smaller as storm duration increases.

There are other concerns regarding use of the procedure. Data for developing reliable curve numbers are not equally available throughout the United States. Information on rainfall, runoff, and soil is deficient for many range and forest areas, particularly in the Western States and, as a consequence, there are many soil cover complexes that are either unclassified or lack data for verification. The sparseness of rainfall-runoff data in urban or urbanizing areas has forced reliance on interpretive values with little "hard" data available for verification. The curve number procedure does not work well in areas of karst topography, or in any area where a large proportion of flow is subsurface, rather than direct runoff. Several investigators (Hawkins 1979, Simanton et al. 1973) have noted problems with the curve number approach for situations where only a portion of the watershed area may be contributing due to watershed characteristics, or there is significant variability of rainfall intensity over the watershed. There is nothing inherent in the procedure to preclude its use for evaluation of effects of changes induced by mining and wildfire and grazing management systems. Many of these conditions are not adequately covered, primarily due to lack of rainfall, runoff, and watershed data suitable for analysis.

In the absence of measurements of rainfall, runoff for small watersheds, considerable hope has been attached to the opportunity to gather data by use of a sprinkling infiltrometer. These data, while useful for a specific site, have not proven to have the transferability that is essential to make a procedure national in scope.

THE SCS RUNOFF EQUATION AND THE FUTURE

The SCS runoff equation has been in use for more than 25 years. It has provided a uniform basis for estimating the effects of land treatment and land use changes on volumes of runoff under the wide range of climatic conditions found in the world. More than 4,000 soils have been given a hydrologic grouping (SCS 1972).

The CN procedure continues to be most satisfactory when used for the type of hydrologic problems that it was developed to solve--evaluating effects of land use changes and conservation practices on direct runoff. Since it was not developed to reproduce individual historical runoff events, only limited success has been achieved by those using it for that purpose. Better success has been had by developing frequency curves of rainfall and runoff estimated from curve numbers. For situations in which continuous simulation of the hydrologic process is required, the lack of a time parameter in the curve number procedure is a significant restraint.

An alternative method for estimating runoff, based upon the development of infiltration curves, appears to offer the best opportunity for developing a more detailed procedure. The infiltration concept has been available for nearly 50 years; however, because of an inability to obtain quantitative information on the many factors that affect infiltration, its use as a tool for evaluating the effect of land use changes has been limited.

Musgrave (1955) reviewed the major factors that affect infiltration. These include:

1. Surface condition (of soil) and amount of protection against the impact of rain.

2. Internal characteristics of the soil mass, including pore size, depth or thickness of the permeable portion, degree of swelling of clay and colloids, content of organic matter, and degree of aggregation.
3. Moisture content and degree of saturation.
4. Duration of rainfall or application of water.
5. Season of the year and temperature of soil and water.

The continuing role of the Soil Conservation Service is to provide technical assistance for the application of soil and water conservation measures on the land. This requires that an infiltration-based model have the capability to reflect changes in infiltration resulting from changes in soil characteristics that are due to conservation management practices.

An infiltration model that appears to have this capability uses the Green and Ampt infiltration equation. Following Mein and Larson (1971) the Green and Ampt rate equation is:

$$f = K\ (1 + n\psi_f/F)$$

where

f = Infiltration rate (cm/hr)
K = Hydraulic conductivity (cm/hr)
n = Available porosity
ψ_f = Wetting front capillary pressure head (cm)
F = Infiltration amount (cm)

Brakensiek et al. (1980) have derived Green and Ampt infiltration equation parameters for ten soil texture classes and have indicated that the result can be used in sensitivity studies of the influence of soil variability on watershed hydrologic outputs. The Green and Ampt equation appears to have wide applicability to modeling the infiltration process.

At present SCS is better able to quantify many of the soil parameters that affect infiltration. An increasing amount of detailed data on soil characteristics is now available including saturated hydraulic conductivity, bulk density, and moisture content.

Two additional items that require attention before a workable field procedure can be developed using infiltration curves include:

1. Prediction of the effects of management practices, tillage, rotation, and the other practices on soil parameters such as bulk density and hydraulic conductivity.

2. Development of a technique for estimating spatial variability of soil parameters. Measurement of soil parameters represents a point measurement, which can be useful for prediction only if it is made applicable for a significant area.

Future SCS runoff procedures will very likely include a hierarchy of processes. At the lowest level may be a simplified curve number approach, ranging upward to an infiltration based storm runoff model where a detailed analysis is required.

Whether an infiltration based storm runoff model suitable for field use can be developed in the near future depends on (1) the amount of usable data available from research stations to determine the effects of management practices on soil parameters, (2) success in identifying soil parameters for developing infiltration relationships, and (3) the capability to handle the inherent spatial variability of soil parameters and the effects of tillage practices on infiltration rates.

SUMMARY

The CN technique was developed in SCS to solve an immediate problem--to predict the effects of proposed changes in land use and treatment on direct runoff. Several similar procedures preceded it during the 20 years before 1955 when the procedure was first described in an SCS handbook. Since 1955, however, the procedure has increasingly been used in applications that its authors had not intended. This has generated substantial criticism regarding its perceived shortcomings.

Although the procedure adequately solves the types of problems for which it was developed, its wide use in the engineering profession for a myriad of other types of problems makes it mandatory that SCS and others thoroughly examine opportunities for improvement. Certain new data are available, particularly for soils, that may eliminate much of the subjective portion of the procedure. The Green and Ampt infiltration equation is being examined by the U.S. Department of Agriculture, Agricultural Research Service, for application with parameters of saturated hydraulic conductivity, porosity, wetting front tension, and antecedent soil moisture. It may be difficult to determine changes in these parameters that reflect the runoff effects of changes in land use and treatment. Through present studies it is hoped to strengthen the curve number approach and develop a hierarchy of procedures for estimating runoff from rainfall.

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