Runoff Curve Number: Has It Reached Maturity?

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Abstract: The conceptual and empirical foundations of the runoff curve number method are reviewed. The method is a conceptual model of hydrologic abstraction of storm rainfall. Its objective is to estimate direct runoff depth from storm rainfall depth, based on a parameter referred to as the "curve number." The method does not take into account the spatial and temporal variability of infiltration and other abstractive losses; rather, it aggregates them into a calculation of the total depth loss for a given storm event and drainage area. The method describes average trends, which precludes it from being perfectly predictive. The observed variability in curve numbers, beyond that which can be attributed to soil type, land use/treatment, and surface condition, is embodied in the concept of antecedent condition. The method is widely used in the United States and other countries. Perceived advantages of the method are (1) its simplicity; (2) its predictability; (3) its stability; (4) its reliance on only one parameter; and (5) its responsiveness to major runoff-producing watershed properties (soil type, land use/treatment, surface condition, and antecedent condition). Perceived disadvantages are (1) its marked sensitivity to curve number; (2) the absence of clear guidance on how to vary antecedent condition; (3) the method's varying accuracy for different biomes; (4) the absence of an explicit provision for spatial scale effects; and (5) the fixing of the initial abstraction ratio at 0.2, preempting a regionalization based on geologic and climatic setting.

INTRODUCTION

The runoff curve number method for the estimation of direct runoff from storm rainfall is well established in hydrologic engineering and environmental impact analyses. Its popularity is rooted in its convenience, its simplicity, its authoritative origins, and its responsiveness to four readily grasped catchment properties: soil type, land use/treatment, surface condition, and antecedent condition.

The method was developed in 1954 by the USDA Soil Conservation Service (Rallison 1980), and is described in the Soil Conservation Service (SCS) National Engineering Handbook Section 4: Hydrology (NEH-4) (*SCS* 1985). The first version of the handbook containing the method was published in 1954. Subsequent revisions followed in 1956, 1964, 1965, 1971, 1972, 1985, and 1993. Since its inception, the method had the full support of a federal agency and, moreover, it filled a strategic technological niche. Thus, it quickly became established in hydrologic practice, with numerous applications in the United States and other countries. Experience with the runoff curve number continues to increase to this date (Bosznay 1989; Hjelmfelt 1991; Hawkins 1993; Steenhuis et al. 1995).

The method's credibility and acceptance has suffered, however, due to its origin as agency methodology, which effectively isolated it from the rigors of peer review. Other than the information contained in NEH-4, which was not intended to be exhaustive (Rallison and Cronshey 1979), no complete account of the method's foundations is available to date, despite some recent noteworthy attempts (Rallison 1980; Chen 1982; Miller and Cronshey 1989).

In the four decades that have elapsed since the method's inception, the increased availability of computers has led to the use of complex hydrologic models, many of which incorporate the curve number method. Thus, the question naturally arises: What is the status of the curve number method in a postulated hierarchy of hydrologic abstraction models? (Miller and Cronshey 1989; Rallison and Miller 1982). Has it matured into general acceptance and usage? Or, as some of its critics suggest, is it now obsolete, a remnant of outdated technology, and in need of overhaul or outright replacement? (Smith and Eggert 1978; Van Mullem 1989).

An effective overhaul of the method would require a clearer understanding of its properties than is currently available (Woodward 1991; Woodward and Gburek 1992). An outright replacement, if one were to be developed, is likely to forego part or all of the extensive data on hydrologic soil groups and land use/treatment classes that has been assembled for most of the United States (Miller and Cronshey 1989). More than 4,000 soils in the United States have been given a hydrologic soil group (Rallison 1980). Moreover, a replacement or overhaul could not avoid relying on many of those same features that are now part of the curve number method. Therefore, it has become necessary to examine the curve number method, to shed additional light on its foundations, and to delineate its strengths and weaknesses, so that the method may continue to be used by practitioners without fear of an impending demise. Thus, the objectives of this paper are the following:

1. To critically examine the curve number method
2. To clarify its conceptual and empirical basis
3. To delineate its capabilities, limitations, and uses
4. To identify areas of research in runoff curve number methodology

Over the years, the conceptual basis of the curve number method has been the object of both support and criticism. A conceptual model shares the simplicity of empirical models and the wider applicability of the more rigorous physically based models (Dooge 1977). Being conceptual, the runoff curve number method is simple, and this is at the root of its popularity. On the other hand, it is precisely for this reason that the runoff curve number method has not fared well among the supporters of alternative models, which include the physically based models (Smith 1976). If experience is any indication, the choice between physically based and conceptual models of hydrologic abstraction is a difficult one, particularly with regard to infiltration (Branson et al. 1981; Savabi et al. 1990; Hjelmfelt 1991).

Branson et al. (1962, 1981), among others, have argued that the simpler conceptual models are not necessarily inferior to the more complex physically based models. The latter may do a good job of describing the physical processes, but this

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is usually at the expense of the chemical and biological aspects. In many instances, processes such as surface crusting, clay shrinkage and swelling, entrapped gases, root structure and decay, and soil macro- and microfauna may be of such importance as to largely invalidate a strictly physical approach to infiltration modeling (Le Bissonnais and Singer 1993).

LUMPED VERSUS DISTRIBUTED MODELS

The curve number method is an infiltration loss model, although it may also account for interception and surface storage losses through its initial abstraction feature. As originally developed, the method is not intended to account for evaporation and evapotranspiration (long-term losses).

An infiltration loss model can be either lumped or distributed. The lumped model aggregates spatial and temporal variations into a calculation of the total infiltration depth for a given storm depth and drainage area. The distributed model describes instantaneous and/or local infiltration rates, from which a total infiltration depth is eventually obtained by suitable integration in time and space. The curve number method was originally developed as a lumped model (spatial and temporal), used to convert storm rainfall depth into direct runoff volume. To this date, it is used primarily as a temporally lumped model in the manner specified by the NEH-4 handbook (*SCS* 1985). However, a few investigators, notably Smith (1976), Aron et al. (1977), Chen (1975, 1976, 1982), and Hawkins (1978a, 1980) have developed infiltration-capacity-equivalent formulas based directly or indirectly on the curve number method. This effectively extends the method to the domain of distributed modeling, although the instances of this type of use appear to be relatively few. Existing infiltration formulas such as Green and Ampt (1911), Horton (1933), and Philip (1957) describe instantaneous and/or local infiltration rates, and thus are directly suited for distributed modeling.

The relative advantages of distributed modeling versus lumped modeling are not easily determined. With regard to infiltration capacities, the spatial and temporal variability that prevails in almost all practical settings does not usually favor the distributed approach, unless the nature of this variability can be specifically incorporated into the model, which is not a small task (Miller and Cronshey 1989). Disregarding this variability, or not accounting for it in a realistic way, amounts in a real sense to lumping. Therefore, the lumped models owe their existence to our inability to properly account for the intrinsic variability of natural phenomena. What this means in practice is that a lumped model is not necessarily bad. Rather, that it is a practical way to substitute for the more complex distributed process while attempting to preserve the main features of the prototype.

A measurement of infiltration rate, or infiltration capacity, as accurate as it may be, can only describe the rate at the point of measure (Miller and Cronshey 1989). Extrapolation to a larger area is tantamount to lumping. In fact, a lumped infiltration depth is a statement of a spatially and temporally averaged infiltration rate (however small the sample plot), with all the advantages and disadvantages that this implies. The advantage is that the method preserves the average features of the phenomena. The disadvantage is that the method does not specifically describe the spatial and/or temporal variability. Nevertheless, a few interpretations of the curve number method in terms of the spatial distribution of loss depths have been developed (Hawkins 1982; Hawkins and Cundy 1982).

In practice, an acceptable amount of lumping is a function of problem scale. For small-scale problems, for example, plots measured in square feet or acres (square meters or hectares), an attempt to ascertain the spatial and temporal variability of infiltration capacity may be justified by detailed field measurements. However, as the scale increases to hundreds of hectares and tens of square kilometers, the practical inability to collect increasing amounts of infiltration data makes lumping an absolute necessity in infiltration modeling. Sooner or later, a certain amount of spatial averaging has to be introduced. Furthermore, considering that spatial averaging is implicit in the nature of rainfall data at any scale, a strong case is made for lumping as a de facto modeling tactic.

CONVERSION OF RAINFALL TO RUNOFF

The conversion of rainfall to runoff is the centerpiece of surface water modeling. An elementary expression of conservation of mass is

$$Q = P - L \tag{1}$$

where Q = runoff; P = rainfall; and L = abstractive losses, or hydrologic abstractions.

The quantification of hydrologic abstractions can be a complex task. These fall into five categories:

1. Interception storage in a rural setting, by vegetation foliage, stems, and litter and in an urban setting, by cultural features of the landscape
2. Surface storage in ponds, puddles, and other usually small temporary storage locations
3. Infiltration to the subsurface to feed and replenish soil moisture, interflow, and ground-water flow
4. Evaporation from water bodies such as lakes, reservoirs, streams, and rivers as well as from moisture on bare ground
5. Evapotranspiration from all types of vegetation

Of these five types of hydrologic abstractions, infiltration is the most important for storm analysis (short term). Evaporation and evapotranspiration are the most important for seasonal or annual yield evaluations (long term). The remaining two losses (interception and surface storage) are usually of secondary importance.

The curve number method is an infiltration loss model; therefore, its applicability is restricted to modeling storm losses. Barring appropriate modifications, the method should not be used to model the long-term hydrologic response of a catchment. Nevertheless, it is recognized that the method has been used in several long-term hydrologic simulation models developed in the past two decades (Williams and LaSeur 1976; Huber et al. 1976; Knisel 1980; Soni and Mishra 1985), with varying degrees of success (Woodward and Gburek 1992). Since the curve number method (as developed by SCS) does not model evaporation and evapotranspiration, its use in long-term hydrologic simulation should be restricted to modeling the storm losses and associated surface runoff (Boughton 1989).

Ponce and Shetty (1995) have recently developed a conceptual model of a catchment's annual water balance. The model accomplishes the sequential separation of (1) annual precipitation into surface runoff and wetting; and (2) wetting into baseflow and vaporization. Ponce and Shetty's model draws on a concept similar to that of the runoff curve number. However, for a given site, the value of the annual retention parameter bears no resemblance to that of the conventional curve number method.

MODES OF SURFACE RUNOFF GENERATION

To clarify the basis of the curve number method, we review here the processes of surface runoff generation. Surface runoff is generated by a variety of surface and near-surface flow processes, of which some of the most important are

1. Hortonian overland flow
2. Saturation overland flow
3. Throughflow processes
4. Partial-area runoff
5. Direct channel interception
6. Surface phenomena, such as crust development, hydrophobic soil layers, and frozen ground

Hortonian overland flow describes the process that takes place when rainfall rate exceeds infiltration capacity, usually at the beginning of a storm (or season), when the soil profile is likely to be on the dry side. The rate difference (rainfall rate minus infiltration capacity) is the effective rainfall rate that is converted to surface runoff.

Saturation overland flow describes the process that takes place after the soil profile has become saturated, either from antecedent rainfall events or from a sufficient volume of rainfall within the same event. At this point, any additional rainfall, regardless of intensity, will be converted into surface runoff. Saturation overland flow usually occurs during an infrequent storm, or toward the end of a particularly wet season, when the soil is likely to be already wet from prior storms.

Throughflow prevails in heavily vegetated areas with thick soil covers containing less permeable layers, overlying relatively impermeable unweathered bedrock (Kirkby and Chorley 1967). Strictly speaking, throughflow is not direct (surface) runoff, since the flow takes place primarily as interflow, or lateral flow immediately below the ground surface. Throughflow's relatively quick response, however, is in the same time frame as surface runoff and, thus, it is generally regarded as a mode of surface runoff generation.

The concept of partial-area runoff developed from the recognition that runoff estimates were improved by assuming that only rainfall on a small and fairly constant part of each drainage basin is able to contribute to direct runoff (Kirkby and Chorley 1967). Thus, partial-area runoff can be interpreted as a combination of throughflow in the upper hillslopes and saturation overland flow in the lower hillslopes (Chorley 1978; Branson et al. 1981; Hawkins 1981).

Direct channel interception refers to the runoff that originates from rainfall falling directly into the channels. This mode of surface runoff generation may be important in dense channel networks and certain humid bases, where direct channel interception may be the primary source of streamflow (Hawkins 1973).

Surface phenomena includes processes such as crust development, hydrophobic soil layers, and frozen ground, which render the soil surface impermeable, promoting surface runoff. For instance, a surface crust may develop following splash erosion in a denuded watershed, adversely affected by human activities or a natural hazard such as fire. Under a specific set of circumstances, including soil type and texture, the silt entrained by splash erosion may deposit on the surface and create a thin crust that eventually reduces the infiltration rate to a negligible level. Thus, any additional rainfall will be converted to surface runoff. This mode of surface runoff generation is typical of semiarid environments, where large amounts of surface runoff may take place even though the underlying soil profile, below a relatively thin veneer, remains substantially dry ("Influences" 1940; Le Bissonnais and Singer 1993).

HISTORICAL BACKGROUND

The origins of the curve number methodology can be traced back to the thousands of infiltrometer tests carried out by SCS in the late 1930s and early 1940s. The intent was to develop basic data to evaluate the effects of watershed treatment and soil conservation measures on the rainfall-runoff process. A major catalyst for the development and implementation of the runoff curve number methodology was the passage of the Watershed Protection and Flood Prevention Act of August 1954. Studies associated with small watershed project planning were expected to require a substantial improvement in hydrologic computation within SCS (Rallison 1980).

Sherman (1942, 1949) had proposed plotting direct runoff versus storm rainfall. Building on this idea, Mockus (1949) proposed that estimates of surface runoff for ungauged watersheds could be based on information on soils, land use, antecedent rainfall, storm duration, and average annual temperature. Furthermore, he combined these factors into an empirical parameter b characterizing the relationship between rainfall depth P and runoff depth Q (Rallison 1980).

$$Q = P(1 - 10^{-bP}) \tag{2}$$

Andrews (unpublished report, 1954), using infiltrometer 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 association was referred to as a "soil-cover complex" (Miller and Cronshey 1989).

Mockus' empirical P-Q rainfall-runoff relationship [(2)] and Andrews' soil-cover complex were the basics of the conceptual rainfall-runoff relationship incorporated into the forerunner version of NEH-4 (*Hydrology* 1954). The method, since referred to as the runoff curve number, had the following significant features:

1. The runoff depth Q is bounded in the range $0 \leq Q \leq P$, assuring its stability.
2. As rainfall depth P grows unbounded ($P \rightarrow \infty$), the actual retention ($P - Q$) asymptotically approaches a constant value S. This constant value, referred to in NEH-4 as "potential maximum retention," and here simply as "potential retention," characterizes the watershed's potential for abstracting and retaining storm moisture and, therefore, its direct runoff potential.
3. A runoff equation relates Q to P, and a curve parameter CN, in turn, relates to S.
4. Estimates of CN are based on: (1) hydrologic soil group; (2) land use and treatment classes; (3) hydrologic surface condition; and (4) antecedent moisture condition.

RUNOFF CURVE NUMBER EQUATION

The method assumes a proportionality between retention and runoff, such that

$$\frac{F}{S} = \frac{Q}{P} \tag{3}$$

where $F = P - Q$ = actual retention; S = potential retention; Q = actual runoff; and P = potential runoff, that is, total rainfall. The values of P, Q, and S are given in depth dimensions. While the original method was developed in U.S. customary units (in.), an appropriate conversion to SI units (cm) is possible (Ponce 1989). Rainfall P is the total depth of storm rainfall. Runoff Q is the total depth of direct runoff resulting from storm rainfall P. Potential retention S is the maximum depth of storm rainfall that could potentially be abstracted by a given site.

In a typical case, a certain amount of rainfall, referred to as "initial abstraction," is abstracted as interception, infiltration, and surface storage before runoff begins. In the curve number method, this initial abstraction I_a is subtracted from rainfall P in (3) to yield

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \tag{4}$$

Solving for Q in (4) yields

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

which is valid for $P > I_a$, that is, after runoff begins; and $Q = 0$ otherwise. With initial abstraction included in (4), the actual retention $P - Q$ asymptotically approaches a constant value $S + I_a$ as rainfall grows unbounded.

Eq. (5) has two parameters: S and I_a. To remove the necessity for an independent estimation of initial abstraction, a linear relationship between I_a and S was suggested [*SCS* (1985), and earlier versions]

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

where λ = initial abstraction ratio.

Eq. (6) was justified on the basis of measurements in watersheds less than 10 acres in size (*SCS* 1985). While there was considerable scatter in the data, NEH-4 reported that 50% of the data points lay within the limits $0.095 \le \lambda \le 0.38$ [*SCS* (1985), and earlier versions]. This led SCS to adopt a standard value of the initial abstraction ratio $\lambda = 0.2$. However, values varying in the range $0.0 \le \lambda \le 0.3$ have been documented in a number of studies encompassing various geographical locations in the United States and other countries ("Estimation" 1972; Springer et al. 1980; Cazier and Hawkins 1984; Ramasastri and Seth 1985; Bosznay 1989).

With $\lambda = 0.2$ in (6), (5) becomes

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{7}$$

subject to $P > 0.2S$; and $Q = 0$ otherwise.

Eq. (7) now contains only one parameter, potential retention S, which varies in the range $0 \le S \le \infty$. For convenience in practical applications, S is mapped into a dimensionless parameter CN, the curve number, which varies in the more appealing range $100 \ge \text{CN} \ge 0$. The chosen mapping equation is

$$S = \frac{1{,}000}{\text{CN}} - 10 \tag{8}$$

where 1,000 and 10 are arbitrarily chosen constants having the same units as S (in.). Likewise

$$\text{CN} = \frac{1{,}000}{S + 10} \tag{9}$$

A CN = 100 represents a condition of zero potential retention ($S = 0$), that is, an impermeable watershed. Conversely, a CN = 0 represents a theoretical upper bound to the potential retention ($S = \infty$), that is, an infinitely abstracting watershed.

Substituting (8) into (7), the equation relating direct runoff Q to storm rainfall P is obtained, with CN as the curve number, or curve parameter

$$Q = \frac{[\text{CN}(P + 2) - 200]^2}{\text{CN}[\text{CN}(P - 8) + 800]} \tag{10}$$

subject to $P > (200/\text{CN}) - 2$; and $Q = 0$ otherwise.

Eq. (5) can be expanded to yield (Chen 1976; Hawkins 1978b)

$$Q = P - I_a - S + \frac{S^2}{P - I_a + S} \tag{11}$$

This equation reveals that as potential runoff grows unbounded ($P - I_a \rightarrow \infty$), actual retention, excluding initial abstraction ($P - I_a - Q$), asymptotically approaches potential retention S. This is the basic tenet of the curve number method, that is, the asymptotic behavior of actual retention toward potential retention for sufficiently large values of potential runoff. Note that this behavior properly simulates the saturation overland flow mode of runoff generation. In this connection, Chen (1975, 1976, 1982) has derived an infiltration equation based on the curve number method, and related it to the Holtan infiltration equation, which explicitly accounts for available soil storage (Holtan et al. 1975).

In practice, there are some situations where the storm rainfall-runoff relationship does not follow (11) strictly. In these cases, fitting a curve number from data may prove to be a challenge (Hawkins 1993). Alternative rainfall-runoff models such as

$$Q = b(P - I_a) \tag{12}$$

have been formulated (Fogel and Duckstein 1970; Hawkins 1992), but the problem remains to determine the empirical coefficient b, preferably as a function of runoff-producing properties. An apparent drawback of (12) is that as potential runoff grows unbounded ($P - I_a \rightarrow \infty$), actual retention also grows unbounded ($P - I_a - Q \rightarrow \infty$), simulating the capacity for infinite storage, that is, infinite potential retention. This same feature is shared by the classical infiltration formulas of Green and Ampt, Horton, and Phillip, a situation that has led to their being described as "bottomless," that is, able to simulate the Hortonian overland flow mode of runoff generation. On the other hand, the curve number method has a finite value of storage S for all curve numbers, excluding the special case of CN = 0, which in only a theoretical limit, and not used in practice.

The humble empirical beginnings of the curve number method in no way detract from its distinctive conceptual basis. Indeed, it is only under a conceptual modeling framework that we are able to discern *why* the retention and runoff ratios ought to be equal (Eq. 3). Equality of these ratios leads to a conceptual model where the curve number is the only parameter describing the process. In turn, this parameter is a surrogate for potential retention, a measure of available subsurface storage, that is, of the ability of a given site to abstract storm rainfall.

ANTECEDENT MOISTURE/RUNOFF CONDITION

A conceptual model works in the mean, implying that there is room for some variability. Early development of the runoff curve number method confirmed that this variability was indeed real, and that the same watershed could have more than one curve number, indeed, a set of curve numbers (*SCS* 1985; Hjelmfelt 1991). Among the likely sources of this variability are

1. The effect of the spatial variability of storm and watershed properties
2. The effect of the temporal variability of the storm, that is, the storm intensity
3. The quality of the measured data, that is, the P-Q sets
4. The effect of antecedent rainfall and associated soil moisture

The latter was recognized very early as the primary or tractable source of the variability, and thus, the concept of antecedent moisture condition (AMC) originated (*SCS* 1985).

More recently, the same concept has been referred to as the antecedent runoff condition (ARC) to denote a shift of emphasis from soil moisture to runoff ("Urban" 1986).

The original-handbook runoff curve numbers were developed from recorded rainfall-runoff data, where hydrologic soil group, land use/treatment class, and surface condition were known. Daily rainfall-runoff data corresponding to the annual flood series at a site were used in the method's development (Rallison and Cronshey 1979). The data was plotted as rainfall P in the abscissas and direct runoff Q in the ordinates. 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 CN values of NEH-4 tables represent the average of median site CN values with the indicated soil, cover, and surface condition. The average condition was taken to mean average response, which was then extended to imply average soil moisture condition (Miller and Cronshey 1989). The natural scatter of points around the median CN 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. While the theoretical bounds of curve number are CN = 0 (Q = 0) and CN = 100 ($Q = P$), the enveloping CN values reduce the limits to practical values based on site experience. These enveloping CN values are considered as the practical upper and lower limits of expected CN variability for the given soil-cover complex combination. Thus, antecedent moisture condition was used as a parameter to represent the experienced variability (Rallison and Cronshey 1979).

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 and other applicable tables (*SCS* 1985). The low value is the dry curve number, of AMC 1 (lowest runoff potential). The high value is the wet curve number, of AMC 3 (highest runoff potential).

NEH-4 contains a conversion table (Table 10.1) listing corresponding AMC 1 and AMC 3 CN values for given AMC 2 CN values. The original values of this table, reported in the 1956 edition of NEH-4, were based on unsmoothed data. The values in the present AMC conversion table [in *SCS* (1985)] have been smoothed by fitting straight lines on normal probability paper. Capitalizing on this fact, Sobhani (1975) and Hawkins et al. (1985) developed correlations between the dry or wet potential retentions S_1 and S_3 and the average potential retention S_2. Hawkins et al. (1985) reported that

$$S_1 = 2.281S_2 \quad (13)$$

with r^2 = 0.999, and S_e = 0.206 in., and

$$S_3 = 0.427S_2 \quad (14)$$

with r^2 = 0.994, and S_e = 0.088 in.

These equations are applicable in the range 55 ≤ CN ≤ 95, which encompasses most estimated or experienced curve numbers.

Substitution of (13) and (14) into (8) leads to

$$CN_1 = \frac{CN_2}{2.281 - 0.01281CN_2} \quad (15)$$

with r^2 = 0.996, and S_e = 1.0CN, and

$$CN_3 = \frac{CN_2}{0.427 + 0.00573CN_2} \quad (16)$$

with r^2 = 0.994, and S_e = 0.7CN.

The one-to-one relationship between CN and S [(8) and (9)] renders the latter intrinsically related to antecedent moisture. Thus, 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. In other words, potential retention and its corresponding curve number are intended to reflect not only the capacity of a given site to abstract and retain storm rainfall, but also (1) the recent history of antecedent rainfall, or lack of it, which may have caused the soil moisture to depart from an average level; (2) seasonal variations in runoff properties; and (3) unusual storm conditions.

In this role, site moisture per se acts as a surrogate for all other sources of variability, beyond that which could be attributed to soil, land use/treatment, and surface condition. Hjelmfelt et al. (1982) found that the AMC conversion table described the 90% (AMC 1), 50% (AMC 2), and 10% (AMC 3) cumulative probabilities of exceedence of runoff depth for a given rainfall. In other words, they found that AMC 2 represented the central tendency, while AMC 1 and AMC 3 accounted for dispersion in the data. A similar analysis was performed by Gray et al. (1982) using data from Indiana, Kentucky, and Tennessee, and by Hawkins (1983), using data from Arizona and Utah. Hawkins et al. (1985) interpreted the AMC categories as "error bands" or envelopes indicating the experienced variability in rainfall-runoff data.

What level of AMC should be used in a given case? For this purpose, NEH-4 (*SCS* 1985) shows the appropriate AMC level based on the total 5-day antecedent rainfall, for dormant and growing season (Table 4.2: "Seasonal Rainfall Limits for AMC"). This table was developed using data from an unspecified location, and subsequently was adopted for general use (Miller and Cronshey 1989). Unfortunately, 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. Echoing this concern, SCS has recently deleted Table 4.2 from the new version of Chapter 4, NEH-4, released in 1993.

In practice, a determination of AMC is left to the user, who must evaluate whether a certain design situation warrants either AMC 1, AMC 2, or AMC 3. It is understood that AMC 2 represents a typical design situation. A choice of AMC 1 results in lesser runoff volume, whereas greater runoff results from a choice of AMC 3. Design manuals specify the AMC choice as a function of return period, with AMC level increasing with return period. For example, the *Hydrology Manual* (1986) of Orange County, California, specifies AMC 1 for 2- and 5-yr storms, AMC 2 for 10-, 25-, and 50-yr storms, and AMC 3 for 100-yr storms. Likewise, the *Hydrology Manual* (1985) of San Diego County, California, specifies AMC values varying between 1.5 and 3.0 (in increments of 0.5) for a range of design frequencies (5–150 yr) and four climate regions: coast, foothills, mountains, and desert. While SCS does not endorse the use of fractional AMC levels (Rallison and Cronshey 1979), the practice exists and should be acknowledged.

RUNOFF CURVE NUMBERS EVALUATED FROM DATA

Since the method's inception, several investigators have attempted to determine runoff curve numbers from small watershed rainfall-runoff data. The objective has been either to verify the CN values given in the standard tables, or to extend the methodology to soil-cover complexes and geographic locations not covered in the NEH-4 handbook. An established procedure solves for S in (7), leading to (Hawkins 1973; 1979)

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \quad (17)$$

For a given P and Q pair, the potential retention S is calculated with this equation, and the corresponding CN is calculated using (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 P and its corresponding runoff volume Q (both in inches) for the annual floods at a site (Rallison and Cronshey 1979; Springer et al. 1980). This procedure has the advantage that it results in a considerable range in rainfall and runoff values. Perceived disadvantages are that (1) this type of data is not readily available; (2) the return periods of corresponding rainfall and runoff events are not necessarily the same; and (3) there is only one data point per year of measurement.

In the absence of a long annual flood series, particularly in semiarid regions, some investigators have chosen to use less selective criteria for candidate storm events, including events of return period less than 1 yr (Woodward 1973; Hawkins 1984). This choice results in considerably more data for analysis, as well as slightly different CN values compared to those obtained using an annual flood series (Springer et al. 1980). The choice of frequency for candidate storm events is the subject of continuing research (Woodward and Gburek 1992).

Another approach to determine curve numbers from data is the frequency-matching method (Hjelmfelt 1980). The storm rainfall and direct runoff depths are sorted separately, and then realigned on a rank-order basis to form seemingly desirable P-Q pairs of equal return period. However, the individual runoff values are not necessarily associated with the causative rainfall values (Hawkins 1993).

OTHER EXPRESSIONS OF THE CURVE NUMBER EQUATION

The SCS runoff curve number has been applied in many countries throughout the world. Therefore, its expression in SI units is necessary. Likewise, geographic and other differences may dictate that the initial abstraction ratio λ be relaxed to the range validated by local experience, say $0.0 \le \lambda \le 0.3$.

In SI units, (10) converts to

$$Q = \frac{R\{\mathrm{CN}[(P/R) + 2] - 200\}^2}{\mathrm{CN}\{\mathrm{CN}[(P/R) - 8] + 800\}} \tag{18}$$

where P (cm) is divided by $R = 2.54$ (cm/in.), and the result of the computation is multiplied by R, to give Q in cm. Being dimensionless, the curve number CN remains the same in both U.S. customary and SI units. Eq. (18) is subject to the restriction that $P > R[(200/\mathrm{CN}) - 2]$; and $Q = 0$ otherwise.

To obtain the runoff curve number equation for a variable λ, (6) and (8) are substituted into (5) to yield (Ponce 1989)

$$Q = \frac{[\mathrm{CN}(P + 10\lambda) - 1{,}000\lambda]^2}{\mathrm{CN}\{\mathrm{CN}[P - 10(1 - \lambda)] + 1{,}000(1 - \lambda)\}} \tag{19}$$

which is subject to the restriction that $P > (1{,}000\lambda/\mathrm{CN}) - 10\lambda$; and $Q = 0$ otherwise.

Eq. (17) is applicable only for the standard value of initial abstraction $\lambda = 0.2$. For $\lambda = 0$

$$S = (P/Q)(P - Q) \tag{20}$$

In general, for $\lambda > 0$ (Chen 1982)

$$S = (\lambda^{-1})\{P + (0.5\lambda^{-1})[(1 - \lambda)Q - [(1 - \lambda)^2Q^2 + 4\lambda PQ]^{1/2}]\} \tag{21}$$

CRITIQUE OF RUNOFF CURVE NUMBER

There is a growing body of literature on the curve number method (Bosznay 1989; Hjelmfelt 1991; Hawkins 1993; Steenhuis et al. 1995). It will suffice here to enumerate the method's advantages and disadvantages. 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, supported by empirical data.
2. It relies on only one parameter, the runoff curve number CN, which varies as a function of four major runoff-producing watershed properties:
   - Hydrologic soil group: A, B, C, and D
   - Land use and treatment classes: agricultural, range, forest, and, more recently, urban ("Urban" 1986)
   - Hydrologic surface condition of native pasture: poor, fair, and good
   - Antecedent moisture condition, a surrogate for other sources of variability, including soil moisture: 1, 2, and 3
3. It is the only agency methodology that features readily grasped and reasonably well-documented environmental inputs (soil, land use/treatment, surface condition, and antecedent moisture condition).
4. It is a well established method, having been widely accepted for use in the United States and other countries.

While it is theoretically possible for the curve numbers to span the range 0–100, practical design values validated by experience are more likely to be in the range 40–98, with few exceptions (Van Mullem 1989). This is a significant advantage, because it restricts the method's only parameter to a relatively narrow range. Viewed in this light, it is seen that estimating a design CN is indeed an empirical exercise within a conceptual modeling framework. Such an exercise is not unlike that of estimating Chezy's C or Manning's n in open-channel flow (Hawkins 1975).

Perceived disadvantages are

1. The method was originally developed using regional data, mostly from the midwestern United States, and has since been extended by way of practice to the entire United States and other countries. Some caution is recommended for its use in other geographic or climatic regions. Local studies and related experience should be substituted for the U.S. nationwide CN tables where appropriate.
2. In some instances, particularly for the lower curve numbers and/or rainfall depths, the method may be very sensitive to curve number and antecedent condition (Hawkins 1975; Bondelid et al. 1982; Ponce 1989). This is not necessarily a weak point, since it may be a reflection of the natural variability. There is, however, a lack of clear guidance on how to vary antecedent condition.
3. The method does best in agricultural sites, for which it was originally intended. Its applicability has since been extended to urban sites ("Urban" 1986). The method rates fairly in applications to range sites, and generally does poorly in applications to forest sites (Hawkins 1984, 1993). The implication here is that the runoff curve number (as developed by SCS) is better suited for storm rainfall-runoff estimates in streams with negligible baseflow, that is, those for which the ratio of direct runoff to total runoff is close to one. Typically, this is the case of streams of first and second order in subhumid and humid regions, and of ephemeral streams in arid and semiarid regions.
4. The method has no explicit provision for spatial scale effects. For example, Simanton et al. (1973) have shown that curve numbers for areas less than 560 acres (227

ha) in southeastern Arizona tend to decrease with increasing watershed size, reflecting the substantial role of channel transmission losses in this semiarid region. In the absence of clear guidelines, the runoff curve number is assumed to apply to small and midsize catchments, comparable in size to those that would normally fall within SCS scope. Without catchment subdivision and associated channel routing, its application to large catchments (say, greater than 100 sq mi, or 250 sq km) should be viewed with caution.
5. The method fixes the initial abstraction ratio at $\lambda = 0.2$. At first this appears to be an advantage, since it effectively reduces the number of parameters to one. In general, however, λ could be interpreted as a regional parameter to enhance the method's responsiveness to a diversity of geologic and climatic settings (Bosznay 1989; Ramasastri and Seth 1985). Additional research is needed to shed light on this issue.

RUNOFF CURVE NUMBER: HAS IT REACHED MATURITY?

Having reviewed its foundations, its conceptual/empirical basis, and its range of applicability, we now address the central issue of this paper: Has the runoff curve number method reached its maturity? Maturity implies usefulness, acceptance with faults acknowledged, understanding of its capabilities, and continued growth with possible eventual refinements.

We believe the method has now reached maturity on these counts:

1. The method is widely understood and accepted for what it is: a conceptual model supported with empirical data to estimate direct runoff volume from infrequent storm rainfall depth, lumped to circumvent the often cumbersome description of spatial and temporal variability of infiltration and other losses.
2. It is the method of choice by practicing engineers and hydrologists for soil and water conservation planning and design, and flood control design. The method is featured in most of the hydrologic computer models in current use, in the United States and abroad. Its practicality as a design method is beyond doubt.
3. A replacement method, if one is developed, would have to clearly prove its superiority. None of the existing point infiltration formulas, such as those of Horton, Philip, or Green and Ampt, are beyond reproach. An apparent limitation is that they allow an infinite amount of soil moisture storage. More importantly, however, is the criticism that none of these methods can claim a holistic approach, that is, one that accounts for the physical, chemical, and biological aspects of the phenomena, and that includes all relevant hydrologic processes. In many instances, the biological aspects of infiltration may be subject to such spatial diversity (the effect of vegetative subsurface features such as roots and root decay, and soil macro- and microfauna) as to defy description by even the most complex of models.

SUMMARY

The runoff curve number method owes its popularity among hydrology practitioners to its simplicity, predictability, and stability, and to its support by a major U.S. federal agency. In the four decades that have elapsed since its inception, questions have arisen as to its nature and beginnings. Its adoption and use throughout the United States and other countries, far beyond the scope intended by its original developers, have demanded that the method be subject to close scrutiny.

The method is a conceptual model of hydrologic abstraction of storm rainfall, supported by empirical data. Its objective is to estimate direct runoff volume from storm rainfall depth, based on a curve number CN. The curve number, which varies in the convenient range $100 \geq CN \geq 0$, is a surrogate for potential retention, a conceptual parameter varying in the range $0 \leq S \leq \infty$. The method does not take into account the spatial and temporal variability of infiltration and other abstractive losses; rather, it aggregates these into a calculation of the total depth loss for a given storm event and drainage area. The method works in the mean, by describing average trends, which precludes it from being perfectly predictive. The observed variability in curve numbers, beyond that which can be attributed to soil type, land use/treatment, and surface condition, is embodied in the concept of antecedent condition.

The advantages of the method are (1) its simplicity; (2) its predictability; (3) its stability; (4) its reliance on only one parameter; and (5) its responsiveness to major runoff-producing watershed properties. Perceived disadvantages are (1) its marked sensitivity to the choice of curve number; (2) the absence of clear guidance on how to vary antecedent moisture; (3) the method's varying accuracy for different biomes; (4) the absence of an explicit provision for spatial scale effects; and (5) the fixing of the initial abstraction ratio at $\lambda = 0.2$, preempting a regionalization based on geologic and climatic setting.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

b = exponent in eq. (2), coefficient in eq. (12);

CN = runoff curve number;
CN_1 = dry curve number (AMC 1);
CN_2 = average curve number (AMC 2);
CN_3 = wet curve number (AMC 3);
F = actual retention;
I_a = initial abstraction;
L = abstractive losses;
P = rainfall, potential runoff;
$P - Q$ = actual retention;
Q = runoff, actual runoff;
R = unit conversion factor;
r = correlation coefficient;
S = potential retention;
S_1 = dry potential retention;
S_2 = average potential retention;
S_3 = wet potential retention;
S_e = standard error of estimate; and
λ = initial abstraction ratio.