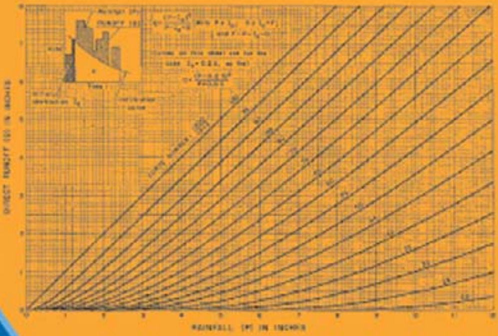

Curve Number Hydrology

State of the Practice

Richard H. Hawkins
Timothy J. Ward
Donald E. Woodward
Joseph A. Van Mullem

CURVE NUMBER HYDROLOGY

STATE OF THE PRACTICE

PREPARED BY
The ASCE/EWRI Curve Number Hydrology Task Committee

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Preface

“Art is the lie that enables us to realize the truth.”
—Picasso

Acknowledgments

This report has benefitted from numerous individuals during its development. The Curve Number Hydrology Task Committee membership has varied since its creation, but early membership included (in addition to the authors of the report) Richard H. Berich, Allen Hjelmfelt, Jr., Richard H. McCuen, Norman Miller, Jit Pagano, Victor Miguel Ponce, Kenneth G. Renard, and Zhida Song-James. Several of these individuals represented the Surface Water Technical Committee and/or the Watershed Management Technical Committee of the EWRI/ASCE.

The authors acknowledge the many contributions that were freely given, and the significant roles by the following, in generating this report, and to a larger extent to the ongoing creation and evolution of the Curve Number “method” itself: James V. Bonta, Cheng-lung Chen, Mark M. Dripchak, Allen T. Hjelmfelt, Jr, Rollin H. Hotchkiss, Ruiyun Jiang, Paul A. Lawrence, Richard H. McCuen, S.K. Mishra, Victor Miguel Ponce, Robert E. Rallison, Kenneth G. Renard, P. DeAnne Rietz, J. Marvin Rosa, Roland Schulze, J. Roger Simanton, Maria J. Simas, Vijay P. Singh, Ghassem Sobhani, Everett P. Springer, and Kevin E. VerWeire. The authors also wish to thank James V. Bonta, Paul DeBarry, Allen T. Hjelmfelt, Jr., Claudia Hoeft, Rollin H. Hotchkiss, Richard H. McCuen, and Kenneth G. Renard for their reviews of an early draft of this report. Their time and critical comments are greatly appreciated.

Thanks are also due to the Arizona Agricultural Experiment Station, which supported one of the authors (Hawkins) over the duration of this work.

Very special recognition must go posthumously to Victor Mockus (August 8, 1913–May 22, 1997). While generally unappreciated in the applied hydrology community, it was his creative genius that brought the Curve Number method together from the different components.

Limitations and Apologies

Given the finite time, energy, and intellectual resources available for this work, the viewpoint and reporting here is unavoidably slanted to North American experiences and use. Recent years have seen an explosion of Curve Number (CN) applications and technical papers. Much of this mushrooming has been contemporary with the creation of this report, and universal up-to-date coverage is simply not possible.

International adaptation of the CN method has grown. An admirable CN subculture has evolved in India under the leaderships of S.K. Mishra and V.P. Singh and many co-workers. A similar well-developed technology has evolved in South Africa pioneered by Professor Roland E. Schulze. Although these were originally incubated in the USA, they have been further developed to meet specific user needs and technical expectations in their own social and technical environments. While only limited technical coverage is given to the international CN community in this report, the ongoing efforts and contributions are worthy of note.

The CN procedure is no longer a simple American agency method. Examples of interest, participation, in and adaptation to other international settings are provided by Boughton (1989) [Australia]; Reich (1962) [South Africa]; Ghile (2004) [Eritria]; Colombo and Sarfatti (2005?) [Italy and Eritrea]; Gebremeskel et al. (2005), and Perrone and Matramootoo (1998) [Canada]; Ignar et al. (1995), Ignar (1988, 1993), Banasik *et al* (1994) [Poland]; Kuntner(2002) [Switzerland]; Sobhani (1976)[Iran]; Al-Udani (1984) [Yemen]; Michel et al. (2005) [France]; Ponce et al.(2005) [Mexico]; Sartori et al. (2004) [Brazil]; Wang et al. (2006) [China]; Auersald and Haider(1996), Zaiss (1989), and Sartor (1996) [Germany]; Choi et al. (2002) [South Korea]; and Calvo et al. (2006) [Panama]. These examples are by no means exhaustive.

Much of the international interest is prompted by the wide array of associated agricultural and water quality models which have incorporated elements of the CN method for runoff generation and soil moisture management. These models seem to have achieved a life and user group of their own, and the CN components are used as a fixed background technology. This too is treated only in a recognition mode in this report. Investigations in this area do contribute markedly to the growing application of the procedure internationally, however.

With this as a background, the authors regret any misinterpretations, or any omissions of significant contributions: and such are by innocence or natural ignorance, and not by intent.

Richard H. Hawkins
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February 2008

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I. INTRODUCTION

PURPOSE AND CHARGE

In response to a growing awareness of the role and limitations of the Curve Number (CN) method in engineering and environmental impact applications, the Task Committee was formed in late 1997, under the joint auspices of the Watershed Management Technical Committee and the Surface Water Technical Committee in the Water Resources Engineering Division (now Environmental and Water Resources Institute, or EWRI) of the American Society of Civil Engineers.

The Curve Number method was developed in the 1950s by the U.S.D.A. Soil Conservation Service, or “SCS” (Now the Natural Resources Conservation Service, or “NRCS”). It has been in use for about 50 years, and is a popular, ubiquitous, and enduring means of estimating storm runoff from rainfall events. Since its inception a good deal has been learned about the CN method and its origins, new applications and developments have emerged, and insights to general rainfall-runoff hydrology have been gained through exercising it. However, there is no single available document that capsulate this current status and understanding. Such is needed by those who apply it, teach it, or study it. Accordingly, the Task Committee was charged in 1997 with "... collating, soliciting, and reviewing materials, and preparing a report on the state of the practice in Curve Number hydrology for rainfall-runoff estimation, not to include the associated hydrograph generation techniques." This essentially asks "What do we know about the Curve Number method now that we didn't know 50 years ago?"

It should be noted that the charge specifically excluded the triangular unit hydrograph techniques released at the same time by SCS. This was a separate contribution often mistakenly taken as a component of a single inclusive CN method. More properly, when taken together, the CN methodology and the triangular unit hydrographs are sometimes simply called the "SCS Methods".

Although very much an agency method, limited summary and background in non-agency sources can be found in Reich (1962), Ogrosky and Mockus (1964), Rallison (1980), Rallison and Miller (1981), McCuen (1982), Boughton (1989), Ponce and Hawkins (1996), Rawls et al. (1992), and Pilgrim and Cordery (1992). A compact review is also give by Thompson (2002). While there was very little in the open or technically-reviewed journal literature on the method for about the first ten years of its use, the method is now featured in most relevant hydrology texts, and has become a standard fixture in the surface water hydrology. A recent book by Mishra and Singh (2003) has elaborated in some detail on the method and its derivations. McCuen’s (1982) “Guide to Hydrologic Analysis Using SCS Methods” has been widely used. An interesting summary is given by Bevan (2000).

In addition, the CN method plays an unusual role as essentially the only member of its genre. The examples, provocations, terminology, and handles can be used to express, explore, and define rainfall-runoff concerns that exceed the CN method.

This report is primarily a synthesis of literature on the evolution and growth of the method since its inception. Changes in understanding and awareness have occurred by the following means: 1) Analysis of the equation(s) and tables via mathematical or computational exercises, or a pencil-and-paper approach with hydrologic inferences; 2) Data analysis, testing, and experiences with the method with measured rainfall and direct runoff observations and other field data. This has led to testing the validity and generality of handbook values; 3) Imaginative interpretations, extensions, or forcing to meet new needs. The CN method fits the niche well and has been extended to other situations. This is evident in the continuous modeling applications discussed in this report; and 4) Institutional policy decisions and revelations related mainly to technical leadership by NRCS. Most of the user community looks to NRCS for primary leadership with the method.

AUTHORITY, SOURCES, AND LEADERSHIP

With the passage of the Small Watershed and Flood Control Act of 1954 (PL-566) and its assignment to the SCS, the need for a uniform procedure for runoff volume estimation from small watersheds based on available data, applicable nationwide, and incorporating soils and land condition expressions was apparent. To meet this need, the CN procedure was developed under the leadership of the SCS, with the assistance of the Agricultural Research Service (ARS), and the US Forest Service (USFS). It has become well-known, and is used world-wide as a single event runoff model in planning and design for a wide range of land types from agricultural to urban, and in both engineering and land management scenarios. Application has been extended by the user community to a number of other situations, including the estimation of daily rainfall-runoff in continuous models.

As the authoring agency and sole source for institutional documentation and background, NRCS is regarded by default as the method's keeper and is cast into the leadership role in CN technology. In that role, there is a potential and responsibility to meet the user community needs for illuminating technical advice, and for service to emerging or unappreciated issues. This is especially cogent given its ubiquitous application and world-wide popularity. In addition, NRCS is the sole source for the Hydrologic Soils Groups classifications, upon which the method depends, and is the primary unquestioned authority for explicit CN values and tables. For much of the user community, the CN method is what the NRCS says it is, as shown in National Engineering Handbook Section 4,"Hydrology" (NEH4) and its successors. This nurturing association has had a large influence on the method's popularity and application.

From the outset the primary source reference has been the NRCS "National Engineering Handbook, Section 4, Hydrology", or simply "NEH4" (USDA, SCS, 1969). The first release was in 1954, and it has been through numerous updates, (e.g., USDA, SCS 1976, 1985, 1986, 1988, and 1993). The main concepts have remained constant, however. As a technical manual to meet agency needs, NEH4 emerged in fiat mode as a completed document.

Unfortunately, there was no external or public review and little specific documentation on the origins of much of it (Willeke, 1997; Pilgrim and Cordery, 1992). Furthermore, although widely used, there was little information on it in the open literature for about ten years following its release. The current incarnation of NEH4 is NEH 630 (USDA, NRCS 2003). The terms are used somewhat interchangeably here depending upon the temporal context, or in general as NEH4/630.

While there is no formal CN assistance line, the agency has historically responded to technical queries on an *ad hoc* basis. However, neither NRCS nor its manuals assume the role of hydrology police. NEH4/630 is a guide, and not a specifications manual or hydrology code. Outside of NRCS, the imprimatur offered by agency endorsement and origins is suggestive only; not an enforceable authority. NRCS obligations and attentions are primarily to application to programs within the agency.

Nevertheless, in fulfilling the keeper role, a series of updates and changes have been offered, often with the issuance of current handbook versions. These include extension to urban lands with TR55 "Urban Hydrology for Small Watersheds" (USDA, SCS 1986), abandonment of specific AMC (Antecedent Moisture Class) classes (USDA, NRCS 1993), and issuance of CNs for additional land uses (USDA SCS, 1973). Updating has also occurred in professional journals, although without the appearance of NRCS concurrence or participation. Substantial internal review was initiated in about 1990 with several professional papers and presentations (Woodward 1991; Plummer and Woodward 1998, 1999).

It is the nature of responsible professional engineering to apply creative judgment and experience to specific situations to meet client needs. The key technical niche that the method fills, along with its transparent simplicity, has invited applications to new roles well beyond original intent and data foundation. It is also the nature of professional practice that the changes are not always adopted promptly in local jurisdictions or general application. Awareness and incorporation into current practice is not instantaneous. Users then assume the responsibility for consequences of misuse or archaic application.

In 1990, an agency-university CN work group was formed and was active in examining and enhancing the method. Many of the issues covered in this report sprang from this group. Examples are studies on seasonal and regional CN variations (Price, 1998, Rietz, 1999), and – as will be shown later in this report – revaluation of the Ia/S ratio (Jiang, 2001). In this latter regard, as a result of such studies, the group has recommended the adoption of $I_a/S=0.05$ in place of its current value of $I_a/S=0.2$, and subsequent redefinition of the CN tables. These enhancements do not appear in contemporary (2008) versions of NEH 630.

RAINFALL-RUNOFF

Need: Direct runoff from rainfall is one of the more fundamental concepts in hydrology, serving as a point of departure for flood peak estimation and structure design. As a hydrologic event, rainfall-runoff is a common occurrence, and much public and professional awareness of hydrology is built on experience with it. In addition, via the role of land use and condition, it is also a fundamental problem of environmental impact and water quality modeling.

The CN method arose in the mid-1950's to meet the planning and design needs of the SCS in implementing Public Law 566. This nation-wide effort required consistent and objective methodologies, a basis in agriculture and soils, responses attributable to land management, and realism with respect to the limited data situations at that time. Because there was little technology available, it was necessary to create a new method on short notice for such purpose.

Method: Reduced to thumbnail basics, the method calculates an event's direct runoff depth (Q) arising from a rainfall of depth (P) and a storage index S (also a depth) by the hyperbolic equation

$$Q = (P-0.2S)^2/(P+0.8S) \qquad P \geq 0.2S,\ Q=0 \text{ otherwise} \qquad [1]$$

The storage index S, a measure of the watersheds hydrologic response potential, is transformed to $CN=1000/(10+S)$ (with S in inches), or a "Curve Number", for which the method is named. Conceptually, CN can vary from 0 to 100, corresponding to $S=\infty$ and $S=0$ respectively.

Using the method requires selection of a Curve Number from tables or experience, based on soils land use, hydrologic condition, and initial moisture status. Accordingly, NEH4 provided CN tables for a variety of expected soils and land use conditions. (e.g., see Table 2 in this report.) Soils were classed by textural series into four “Hydrologic Soil Groups”, “A” through “D,” from the more porous and deep, to the harder, finer, and shallower respectively. A variation in event CN to accommodate observed runoff variability through antecedent moisture was also given, though current interpretation was as general “error bands.” In the above, the P, Q, and S were expressed in inches, though metric forms are now also used.

The calculation is intended for the "direct runoff" hydrograph that is associated with individual rainfall events. The usual interpretation is, and NEH4 suggests, an infiltration process, or overland flow. However, the expression is general, and rainfall excess may arise from infiltration excess (overland flow), quick flow (rapid return flow on porous sites), variable source area saturation, or direct channel interception. It is not intended for use with snowmelt, sleet, hail, dew, or fog drip. The "P" should be taken only as rainfall, and not the more inclusive "Precipitation" suggested by the symbol “P.”

Furthermore, through selection of CN, land condition effects are expressible. Thus, it is also a tool of environmental impact assessment, fitting into the land treatment goals of its PL566 origins.

Roles: Since its inception, the CN model has filled a waiting technology gap, and has been used and extended to a variety of opportune applications. As a general simplistic rainfall-runoff event model, it has no serious competitors. Despite its many shortcomings, widespread use makes it difficult to ignore. Its appeal is that it is holistic, unpretentious, simple, and seemingly conceptually clear and transparent. Also, its offering of authoritative origins and coefficients promotes acceptance.

It is important to note that it is not a flood peak or hydrograph method, but provides only rainfall and runoff depth, and that in the notion of rainfall excess. Cumulative runoff with time (and thus cumulative losses) with rainstorm time can be - and are - easily calculated, and serve as a basis for subsequent hydrograph calculation. However, it should be noted the equations include no time dimension. Nevertheless, it is quickly assumed that Q(P)=Q(P(t)), following time-distributed storm rainfalls. While this is a giant conceptual leap from independent event rainfall-runoff data, it is the primary application in event hydrograph models. In a strict technical sense, this Q(P(t)) should be more properly seen as "rainfall excess".

II. CURVE NUMBER METHOD

DEVELOPMENT

The original equation was created via the following steps, drawing from the basic water budget form in depth units as

$$P = Q + F \qquad [2]$$

or, rainfall (P) is runoff (Q) plus losses (F). No initial losses or abstraction is assumed at this stage. The development from this basic equation [2] can be traced as follows:

1. Available small watershed total event P:Q data was plotted for inspection, and it was noted that: a) the general trend of runoff began at Q=0 when P=0; b) the general forms were concave upwards; c) the plot seemed to bend towards a constant P-Q (or F) as P grew larger; and d) that there was a good deal of scatter or variation around this central concave-upwards trend. Only points of $0 \le Q \le P$ were used. This is illustrated by Figure 1

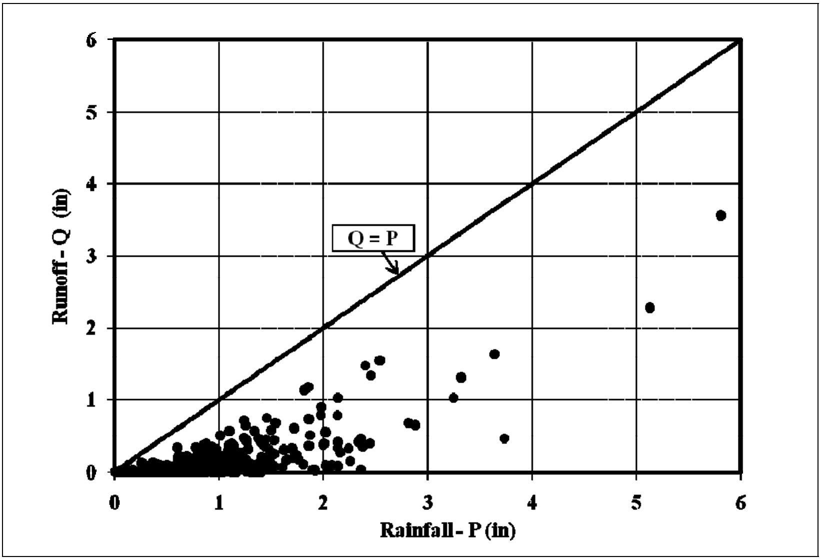


Figure 1. Rainfall and runoff depths for 482 events from 1939 to 1967 for watershed 44002, Hastings, Nebraska. The drainage area is 411 acres [data from USDA, ARS]. Note the Q=P line and that all data points are $0 \le Q \le P$.

2. From the notion of a limiting loss, the definition of S (maximum potential losses to runoff) was made

$$S = \lim_{P\to\infty}(P-Q) = \lim_{P\to\infty}(F) \qquad [3]$$

3. It was then reasoned that to explain the runoff fraction Q/P, the variables F, S, and P must be somehow included. The following was a simple reasonable assumption

$$Q/P = F/S = \text{Actual losses/Potential losses, or} \qquad [4]$$
$$Q = PF/S$$

Insofar as this equality is true at the extremes of $P=0$ and $P\to\infty$, its validity in the interval was asserted.

4. Substituting $F=P-Q$ into equation 4 and solving for Q results in

$$Q = P^2/(P+S) \qquad [5]$$

This is the first basic form of the runoff equation, and contains both rainfall (P) and surrogate land condition measures (S).

5. However, internal agency review suggested, despite the data plots seeming to originate at 0,0, for individual events some amount of rainfall was required before runoff begins. This was recognized and called "Initial abstraction", or I_a. To correct for this I_a effect, all P in the above equations was replaced by $P-I_a$, so that

$$Q = (P-I_a)^2/(P-I_a+S) \qquad P\geq I_a,\ Q=0 \text{ otherwise} \qquad [6a]$$

The quantity $P-I_a$ is called the *effective rainfall*, or P_e, and equations [2]-[5] might more properly use P_e in place of P. For example, equations [1] or [5] would be

$$Q = P_e^2/(P_e+S) \qquad [6b]$$

However, the definition of S was left formally unchanged, resulting in some later confusion (Chen 1981a, b, c). S now becomes the maximum potential difference between P_e and Q, or the maximum possible value of (P-Q) following satisfaction of I_a.

6**.** To simplify the equation to the single parameter S, further studies were conducted, and $I_a= 0.2S$ was found as a median relationship (see Figure 1). This was substituted to give

$$Q = (P-0.2S)^2/(P+0.8S) \qquad P\geq 0.2S,\ Q = 0 \text{ otherwise} \qquad [7]$$

This is the equation as now widely used. It is important to preserve the Q=0 threshold in equations [6] and [7] as an integral part of the method. Unfortunately, the details of the data sources and analysis methods that lead to Figure 2 and $I_a=0.2S$ have not survived.

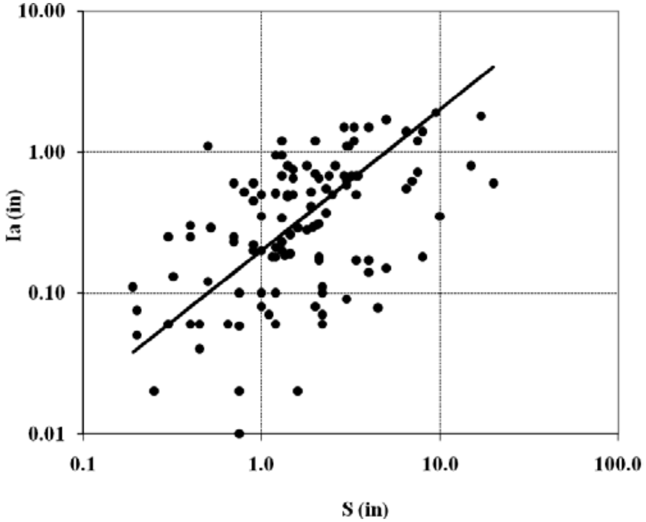


Figure 2. Relationship of I_a to S, from NEH4 Table 10.2. The plotted line is $I_a=0.2S$, and defines the median. Half of the 112 points plotted are above the line shown.

7. At this point the index S was transformed to CN by the arbitrary identity

$$CN = 1000/(10+S) \qquad \text{[S is in inches]} \qquad [8]$$

This was done to have a soils/land/cover coefficient with a direct positive relationship to calculated Q, and that varied conveniently from 0 to100. The 10 and the 1000, while in inches, have no intrinsic meaning, and CN is dimensionless. Several of these steps and assumptions will be discussed in greater detail later in this report.

In summary, the development invoked four assumptions and/or assertions:

1. S exists and is defined as $\lim_{P\to\infty}(P-Q) = \lim_{P\to\infty}(F)$ [3]
2. $Q/P=F/S$ [4]
3. I_a exists and is 0.2S [9]
4. $CN = 1000/(10+S)$ [8]

A plot of Q vs. P for various CNs is shown in Figure 3. This is the central icon in the CN method. Other approaches for deriving the runoff equation are presented elsewhere in this report. In accordance with the customs of the day, the original work was done with English units, or inches. Equations [2]-[7] are dimensionally homogenous, and perform in any consistent set of units.

However, the transformation of S in inches to CN included the requirement of the 10 and 1000. In metric expression, a correct form is

$$CN=25400/[254+S] \qquad [10]$$

where S is in mm and the P and Q in equation [7] should be in mm as well.

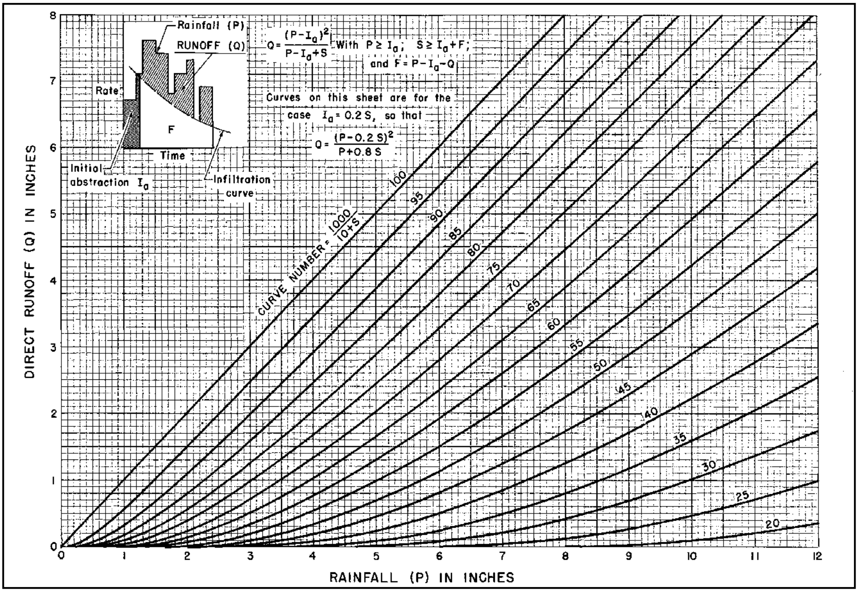


Figure 3. Rainfall and direct runoff depth for different CNs. Source:NEH4/630, Fig 10.1.

CURVE NUMBERS AND LAND USES

As presented above, application of the CN runoff equation (i.e., Equation 7) requires S, which is calculated from a CN. The conceptualization of CN as a measure of watershed response hydrology based on soils, cover, and land use was an additional major step. It also required an explanation for the runoff variability seen in the data.

Handbook tables: The handbook CN tables for agricultural watersheds were developed from rainfall-runoff data from small instrumented USDA watersheds, located mainly the Eastern, Midwestern, and Southern US. It was assumed that each was represented by a single hydrologic soil group (Rallison, 1980). A list of selected site-sources is shown in Table 1.

Tables and charts for CN as a function of land use and soils were given in NEH-4 and ensuing agency releases for a number of different land types. A popular reference table for CNs is given as Table 2.

Table 1. Research watersheds used in the determination of NEH4 Curve Numbers

State	Location	State	Location
Arizona	Safford	New Mexico	Albuquerque
Arkansas	Bentonville	New Mexico	Mexican Spgs.
California	Santa Paula	New York	Bath
California	Watsonville	Ohio	Coshocton
Colorado	Colorado Springs	Ohio	Hamilton
Georgia	Americus	Oklahoma	Muskogee
Idaho	Emmett	Oregon	Newberg
Illinois	Edwardsville	Texas	Garland
Maryland	Hagerstown	Texas	Vega
Montana	Culbertson	Texas	Waco
Nebraska	Hastings	Virginia	Danville
New Jersey	Freehold	Wisconsin	Fennimore

Source: Rallison (1980)

Illuminating details on the original data sets and the analyses performed have not survived. Furthermore, the basic data from only a few of the above locations are still available. The CN table entries are thought to have reflected best estimates and incorporated current agricultural policy implicit in PL 566. CN fitting seems to have been done graphically superimposing annual event P and Q values on Figure 2, and selecting the median CN value indicated. Because of the nature of these site-sources, the method is most applicable to agricultural conditions.

CNs for forested lands were developed by the US Forest Service, while SCS developed woodland or woodlot runoff CNs. The methods for making these assignments or the data sets used are unknown. For urban lands (USDA, SCS 1986), CNs were developed by weighting representative CNs for impervious land types and open spaces in good condition. The CNs for rangeland watersheds were developed by SCS. Current editions of NEH4/630 contain a variety of CN tables and charts for an array of additional soils and land uses, but contain little source information. Local tables and charts have been offered (but not documented) and are common as well.

Table 2. Runoff Curve Numbers for Hydrologic Soil-Cover Complexes, ARC II, and I_a /S= 0.2

Land use	Treatment or practice	Hydrologic condition	Hydrologic Soil Group			
			A	B	C	D
Fallow	Straight row	---	77	86	91	94
Row Crops	"	Poor	72	81	88	91
	"	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
"		Good	65	75	84	86
	" and terraced	Poor	66	74	80	82
	" " "	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	" and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded	Straight row	Poor	66	77	85	89
legumes 1/	" "	Good	58	72	81	85
or rotation	Contoured	Poor	64	75	83	85
	"	Good	63	73	80	83
	" and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	"	Fair	25	59	75	83
	"	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads	----		59	74	82	86
Roads (dirt) 2/	----		72	82	87	89
(hard surface) 2/	----		74	84	90	92

1 Close-drilled or broadcast 2 Including right-of-way. Source: Table 9.1, NEH4

Soils: CNs are strongly related to soils. NEH4 introduced the concept of Hydrologic Soil Groups (HSGs), which play a prominent role in the methodology. Briefly, all surveyed soils are placed into one of four groups, A, B, C, or D, with A being the most porous, deepest, and least runoff-prone, and D the shallowest, finest textures, and most runoff-prone. For poorly-drained sites, a "/D" is appended. Specific classifications for surveyed soil series are made by USDA soils scientists on the basis of correlation and precedent. Brief and general descriptions given for the four groups are listed below, and taken from NEH4 Chapter 7. Current NEH4 editions and state NRCS engineering and soils offices carry the latest lists of hydrologic soils classifications.

> **Group A** soils have low runoff potential and high infiltration rates even when thoroughly wetted They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 0.30 in/hr).
>
> **Group B** soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15 –0.30 in/hr).
>
> **Group C** soils have low infiltration rates when thoroughly wetted, and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05 to 0.15in/hr).
>
> **Group D** soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a high permanent water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-0.05 in/hr).

A later SCS publication, TR55 (USDA, SCS 1975, 1986) give simpler criteria based solely on texture, taken from an earlier paper by Brakensiek and Rawls (1983):

Table 3. Hydrologic Soil Groups (HSG) based on texture

Texture	HSG
Sand, loamy sand, sandy loam	A
Silt loam or loam	B
Sandy clay loam	C
Clay loam, silty clay loam, sandy clay, silty clay, or clay	D

The silt textural classification is missing from Table 3, but when the above information plotted on a textural triangle, silt is clearly an extension of the B category.

Inspection of handbook CN tables (e.g., NEH630 or TR55) for watersheds without mechanical treatments results in Table 4 with approximate ranges of CN by HSG.

The HSG concept springs from studies done by Musgrave (1955). Several alternative associated infiltration metrics have also been proposed by other sources (see Table 9, part III), and the absolute values for transmission rates shown are well below most encountered in infiltration work.

For work outside the USA, soils groupings are not defined, but are presumed by default to be applicable. There are no independent objective instructions or professional protocols for determining HSGs, and known correlations with United Nations FAO soil classifications are not known.

Table 4. Minimum, central, and maximum handbook CNs for HSGs

HSG	Minimum	Central	Maximum
A	25	51 - 68	77
B	48	62 - 77	86
C	65	70 - 84	91
D	73	77 - 88	94

Notes: Minimums from “woods”, or “weed-grass mixture with brush the major element” in good condition. Taken from Table 2, or from TR55, Table 2-2c. Maximums for fallow, bare soil, from TR55, Table 2-2b. Central is a smoothed general cluster range from a number of listings.

<u>CN adjustments between Hydrologic Soil Groups</u>: Translation of CNs between the different HSGs originated with a graphical relationship called the “Curve Number Aligner.” Developed by Victor Mockus, it has no original source reference. It was first presented in the open literature in graphical form by Enderlin and Markowitz (1962) who derived it from the HSG and CN entries in NEH4 Table 9.1(Table 2 here). Algebraic representation of it is given in the series of equations in Table 5.

Table 5. Curve Number aligner equations

$$CN(A) = CN(A) \quad [11a]$$
$$CN(B) = 37.8 + 0.622*CN(A) \quad [11b]$$
$$CN(C) = 58.9 + 0.411*CN(A) \quad [11c]$$
$$CN(D) = 67.2 + 0.328*CN(A) \quad [11d]$$

For example, if woods in poor conditions for an A hydrologic soil group has a CN of 45, then - using equations [11b] and [11c] - woods in poor conditions in a B hydrologic soil group would have a CN of 66, and in a C soil a CN of 77. Therefore, if the land-use CN for one hydrologic soil group and cover was known, then the CNs for the other hydrologic soil groups and same cover could be determined. These were assumed to be for AMC II (see below).

These converge to 100, 100, and are completely defined by their intercepts. Using “0” subscript here, the intercepts are CN(A,0)=0, CN(B,0)=37.8, CN(C,0)=58.9, and CN(D,0) = 67.2, and the slope is (1 - intercept/100). In addition, the system of equations allows for solution with any HSG as the reference independent variable.

Several other observations can be taken from Table 5. First, comparing the intercepts suggest greater hydrologic similarities between C and D soils than between A and B. Second, they also fix the lower limits of CN for the A, B, C groups, which occurs when CN(A)=0. Thus B soils are limited in CNs from 37.8 to 100, C soils from 58.9 to 100, and D soils from 67.2 to 100. From this information, the possible CN range for A soils is 0 to 100. These algebraic expressions suggest a much wider range than practical: More realistic limits and ranges are seen in Table 4. For example, CNs for A soils do not vary from 0 to 100.

Antecedent moisture: The observed spread of direct runoff around the central trend was acknowledged, and assumed to be an antecedent moisture condition effect, or "AMC". Three different conditions were stated: AMC I, II, and III, corresponding to low, average (or median), and high direct runoffs. Two different expressions of this concept were given in NEH4. First, NEH4's Table 10.1 gave CNs for AMC I and III, based on the AMC II Curve Number, which is taken as the characterizing standard condition. Its source or derivation was not stated, and entries were not consistent at lower CNs between editions in some of the early versions. An abbreviated copy of Table 10.1 is given as Table 6 here.

Table 6. CN-AMC relationships

CN(II)	CN(I)	CN(III)	S(II)	Ia(II)
100	100	100	0	0
95	87	98	0.526	0.11
90	78	96	1.11	0.22
85	70	94	1.76	0.35
80	63	91	2.50	0.50
75	57	88	3.33	0.67
70	51	85	4.28	0.86
65	45	82	5.38	1.08
60	40	78	6.67	1.33
55	35	74	8.18	1.64
50	31	70	10.00	2.00
45	26	55	12.2	2.44
40	22	60	15.0	3.00
35	18	55	18.6	3.72
30	15	50	23.3	4.66
25	12	43	30.0	6.00
20	9	37	40.0	8.00
15	6	30	56.7	11.34
10	4	22	90.0	18.00
5	2	13	190.0	38.00
0	0	0	∞	∞

Source: condensed from NEH4 Table 10.1. S(II), Ia in inches.

Second, specific prior 5-day rainfall values for the 3 AMC classes by season were given in early versions of NEH4 and are shown in Table 7 here for historical reference only: **application is discouraged**, and it is no longer endorsed by NRCS (Shaw, 1993).

Table 7. Antecedent Moisture Classes defined by 5-day prior rainfall

Condition	------ 5-Day prior rainfall (in) ------	
	Dormant Season	Growing Season
I	<0.50	<1.4
II	0.50-1.10	1.40-2.1
III	>1.10	>2.1

Source: Table 4.2 (discontinued) NEH4, Ch 4. For historical and information purposes only. No longer endorsed or supported by NRCS; DO NOT USE.

While this issue will be discussed in more detail in this report, a subsequent review found that the rainfall-based table (i.e., Table 7) applied only to certain selected small watersheds in Texas, and is not representative of conditions across the entire United States. It was also recognized that many additional storm and watershed factors may also impact the direct runoff. In addition to prior rainfall, these could include such as stage of plant growth, rainfall intensity, and storm duration and distribution. As will be discussed subsequently, a current interpretation of the classes is as general "error bands" from all known and unknown sources of departure from the central trend of the CN equation (i.e., equation [1].) Another application – to be discussed later - is as soil physics profile reference points; i.e., wilting point and field capacity.

Subsequent handbook versions (USDA, SCS, 1993) deleted Table 4.2 (i.e., Table 7 here), and the terminology changed to Antecedent *Runoff* Condition ("A***R***C"). Thus the absolute average conditions could be different, for example, in Arizona and New York. That is, ARC II varies from place to place, and is a function of local climate, soil, vegetation, and land use.

With this, ARC II is also reaffirmed as the average conditions when local annual flooding occurs, leading to the central trend (the runoff equation) of rainfall-runoff for all possible conditions. Thus, in general, the Table CNs are for ARC II, and are the proper basis for design situations.

The components of the CN method are summarized in Table 8. Several of the "Current Status and comments" items will be developed later in this report.

Table 8. Summary of the components of the Curve Number Method

Item	Source	Current status and comments
A. **Equation**	$Q=(P-0.2S)^2/(P+0.8S)$ See below	Fits many, but not all PQ data sets as $P\to\infty$. Shape correct. Widely used
$S = \lim_{P\to\infty} (P-Q)$	Existence assumed in NEH4	Few examples in data of P-Q →constant
Q/P=F/S	Original with NEH4	See above. Selective affirmation as $P\to\infty$
$I_a = 0.2S$	NEH4, but unknown data sources and analyses	Current suggested improvement is $Ia\approx0.05S$
CN=1000/(10+S)	Transformation/definition	Current usage. S in inches
B. HSG	Prior SCS work Questionable	Lacks objective criteria. consistency. Infiltration criteria unrealistic Contemporary revisions by NRCS
C. CN Tables	Mostly undocumented	Still used authoritatively. Sources largely unknown
CN Charts	Mostly undocumented	Sources largely unknown
CN Aligner	Unknown, SCS ca 1958?	Unknown, Manifested in CN tables
D. AMC and Conversions		Currently "ARC"
CN I-II-III Conversions	Unknown. Only known source is NEH4, Table10.1	Assumed to be error bands in event hydrology. Also used in continuous Models as soil physics thresholds
AMC-climate	Unknown, undocumented Thought to have originated in Texas	Dropped from NEH4 in 1993, and use is discouraged, but still in popular use

APPLICATION

Modes of Application: The reasoning used in model development is drawn from observations of full rainfall and runoff depths on individual storm events. However, as first pointed out by Hjelmfelt (1983) its application as enunciated in NEH4 and in current usage covers three (3) distinct different modes, or usages. All three are shown by example in NEH4, though not identified or categorized as such.

1. The *first* role is to give the return period direct runoff from the same return period rainfall depth. This is the traditional engineering application, where user interest is in transforming the rainfall frequency event to the runoff frequency event. For example: the 100-year return period runoff is estimated from the 100-year rainfall and the CN as

$$Q_{rp} = (P_{rp}-0.2S)^2/(P_{rp}+0.8S) \qquad \text{for } P_{rp} \geq 0.2S \qquad [12a]$$
$$Q_{rp} = 0 \qquad \text{for } P_{rp} \leq 0.2S \qquad [12b]$$

where the subscript "rp" signifies return period. If this was the sole pragmatic application, the AMC and Ia features might have been omitted from the original development. This notion is exploited in determining CN from field data, by performing calibration analyses on rank-ordered P and Q data points.

2. The *second* role is to explain rainfall-runoff for individual events, wherein the procedure approximates a physical model with a central trend and an unexplained component. From the basic equation

$$Q = (P-0.2S)^2/(P+0.8S) \pm \in(Q) \qquad \text{for } P \geq 0.2S \text{ and } Q>0 \qquad [13a]$$
$$Q = 0 \qquad \text{for } P \leq 0.2S \qquad [13b]$$

where $\in$ is the "error", or unexplained contribution caused by all the influences that affect runoff variability, including error in the model or the data. This attempt to minimally mimic field observations was the original justification for including I_a and for creating the AMC bands (shown here as $\pm \in(Q)$) and soil moisture connections, and subsequently the ARC. The latter is intended to explain event to event variability. In addition to antecedent moisture, such deterministic influences included storm duration, intensity distribution, and seasonal variations.

Early interpretations attributed all the variation to only soil moisture, and represent soil moisture by 5-day antecedent rainfall. Alternatively, the random component might be with S so that

$$Q = [P-0.2(S\pm\in(S))]^2/[P+0.8(S\pm\in(S))] \qquad \text{for } P \geq 0.2(S\pm\in(S)) \qquad [14a]$$
$$Q = 0 \qquad \text{for } P \leq 0.2(S\pm\in(S)) \qquad [14b]$$

This tactic is applied when inserted as the direct runoff component in continuous models, where the storage index S is made a function of current accounting for site moisture. Such approaches are treated in some detail subsequently in this report

3. The *third* role is to infer processes; namely infiltration ["loss"] and soil moisture-CN relations. Its use as an infiltration (or watershed "loss") device for short time intervals inside of hydrologic models is widespread, such as HEC-1 (USACE, 1987), TR20 (USDA, SCS 1982), and in many continuous simulation models. It operates by taking runoff differences

over finite times during the progress of a rainstorm. This may follow on the heels of the first application above. This is

$$\Delta Q_t = (P_{t+\Delta t} - 0.2S)^2/(P_{t+\Delta t} + 0.8S) - (P_t - 0.2S)^2/(P_t + 0.8S) \qquad \text{for } P_{t+\Delta t}>0.2S \qquad [15]$$

Here “t” is rainstorm time. The ΔQ so generated is used as a rainfall excess pulse for input to unit hydrographs for the Δt used. Insofar as ΔP-ΔQ=ΔF, this may be taken as an “infiltration” equation. This interpretation is well-developed, but questionable, and will be discussed in more detail later.

Also, as will be discussed later, the CN method is also used in a variety of continuous simulation models as technique of soil moisture and CN management, drawing on the assumed equivalence - or some relationship - between the potential soil moisture storage and “S”, or 1000/CN – 10. This approach was first pioneered by Williams and LeSeur (1976)

It should be noted that the second role above, i.e., as an abbreviated, compact model of deterministic rainfall and runoff is the vision shared by most users for the CN method. The return period matching (the first role described in the above section) and inferred process interpretations (the third role above) are not widely recognized or appreciated, although they are widely used. Prominent examples of this limited awareness in interpretation can be seen in Bevan (2000) and Mishra and Singh (1999). Furthermore, differences in the aims and assumptions of the three applications are usually at the root of most critiques of the method.

Drainage area: There is no direct stated NRCS guidance in NEH4/630 limiting watershed size in application of the CN method. The one oblique piece of advice in NEH4/630 is “These [drainage units] should be no greater than 20 square miles and should have a homogeneous drainage pattern.”

The drainage areas of the 199 watersheds in 24 locations from which the first CN tables were constructed (see Table 1 here, omitting Culbertson, Montana) vary from 0.24 to 46,080 acres (0.1 to 18650 ha), with the middle 60% between 3 and 300 acres (1.2 to 121 ha) with a median of 19.7 acres (8 ha). Though specific watersheds used are not known, soils homogeneity was a major criterion in the original selections. Because of an awareness of spatial variability of soils and land use properties, this was and is a concern when computational simplicity encourages the lumped parameter (weighted CN) form. This difficulty has been allayed in many later computer-based applications which allow weighted runoff calculation for distributed smaller CN source areas, or hydrologic resource units (HRUs).

Various local and modeling applications references suggest drainage area limits from about 5 mi^2 to about 100 mi^2. In Texas, application for peak discharge is recommended “… from 1 to 2000 acres.” (0.4 to 809 ha) based on concentration time considerations. (USDA SCS, 1990) Ponce (1989) suggests application for mid-sized catchments, or roughly 100-5000 km^2. Pilgrim and Cordery (1992) mention its application to “Small to medium … drainage basins.” Singh (1989) comments that “the method can be applied to large watersheds with multiple land uses.” Boughton (1989) mentions application to “catchment sizes from 0.25 ha to 1000 km^2”, the latter is supported by Williams and LaSeur

(1976). These upper ranges approximate the statutory upper limit for PL566 watersheds of 250,000 acres (ca 390.6 mi^2 or 1012km^2).

In regions of more uniform rainfall, it can be applied at the river basin scale with favorable results. For example, analysis of basin-wide rainfall-runoff data (Singh, 1971) from Salt Creek, Illinois (334 mi^2 or 865 km^2) gives a CN value (71) consistent with handbook expectations. It has been usefully and rationally applied on a 414 km^2 basin in Panama (Calvo et al., 2006), and the (69.1 km^2) Little Vermillion River in Illinois (Walker et al., 2005). A conspicuous example of river basin application appears in NEH4: Amicalola Creek, Georgia, shows CN definition on drainage areas of 84.7square miles (219.4 km^2).

In an extension of the CN method to large watersheds, Hong et al. (2007) have estimated global runoff from major river basins around the world. Their study applied the CN method to river basins using satellite rainfall data and other remote sensing information in a simple rainfall-runoff simulation in order to obtain an approximation of runoff. River basins modeled included the Amazon, Mississippi, and Yangtze, each with areas exceeding 1 million km^2. They report that the global-averaged CN is 72.803.

In summary, it should be noted that this question is general to rainfall-runoff hydrology, and not unique to the CN method. There seem to be no hard criterion for drainage area limitations. Although “smaller might inherently appear to be better,” the additional effort of modeling many small areas and then combining outputs does not always improve the answer.

The above paragraphs raise the issues of time of concentration, rainfall homogeneity, and soils/cover homogeneity as related to drainage area, subject matters not covered in NEH4. The choices hang on professional user judgment, data availability, storm extent, and land heterogeneity.

<u>Storm size limitations</u>: No lower or upper limits of storm applications were stated in the original development. This issue is discussed later in this report.

<u>Annual events</u>: Handbook Curve Numbers were originally developed by analysis of the largest annual rainfall flood event and its associated rainfall (Rallison, 1980). However, in the interests of data use efficiency, and by default application, most subsequent analyses and applications have ignored that constraint. In fitting CNs to data using only annual peak events, similar but slightly different CNs are obtained when using an assemblage of all large events.

SUMMARY

The Curve Number Method was developed for specific agency needs as a lumped one-parameter non-linear rainfall-runoff depth equation. Given a rainfall depth, P, the CN method’s accuracy depends on the selection of the proper CN, which in turn requires an understanding of the watershed characteristics of soils, cover, land use, and (perhaps) prior moisture status. These watershed characteristics, although intuitively correct, were developed without peer review from then-existing concepts and data. As originally presented, no mention was made of distributed forms or application beyond the limited original intent.

As will be shown in the following sections, the method filled a waiting technical niche, later to be absorbed and further opportunistically extended to fit applications well beyond the original intent. In addition, critical examination of the method gave alternative perspectives and allowed for reviews previously unavailable, resulting in adjustments and better understanding. This improved understanding pertains to the rainfall-runoff process in general, as well as the Curve Number method in particular.

III. FINDINGS and DEVELOPMENTS

Following the initial offering in NEH4 in the 1950s, and spurred by years of application by SCS/NRCS and others, a plethora of refinements, developments, alternative understandings, additional exposition, enlargements, and creative spin-offs have gradually evolved. Much of this was in response to new opportunities and needs that arrived with computers, remote sensing, GIS, and greatly increased environmental focus in soil and water management and general land planning. Other insightful work examined the method in a more critical vein, providing some of the open technical review originally absent.

Insofar as the Curve Number method boldly defined a series of component processes that were – and are – widely accepted and repeated on an intuitive or approximate basis, several of them have become widely used and taken as general hydrologic standards. For example the concept of the hydrologic soil groupings (HSG) is used internationally as an underlying notion in generating storm flow, and in erosion models as well. While the profound function of soils was appreciated prior to NEH4, the CN method gave it identity and substance.

STRUCTURE OF THE BASIC EQUATION

The algebraic expression of the relationship offers a tempting avenue of analysis. A thorough early analysis and mathematical treatment was given in several papers by Chen (1981a, 1981b, 1981c), and numerous others have followed.

Dimensionless expressions: Dimensionless variables are common in science, and find high expression in hydraulics and fluid mechanics. They are used to reduce the number of variables, make the underling relationships more visible, and expose dimensional consistency. The CN equation is dimensionally homogeneous, allowing standardization of P and Q on the storage index S, so that $Q_*=Q/S$, $P_*=P/S$, $I_{a*}=I_a/S$ (or, as will be used subsequently, $I_a/S=\lambda$), and $F_* = F/S$. This expresses the equation in relative values based on the characteristics of the watershed measure "S". The runoff equation then becomes

$$Q_* = (P_*-0.2)^2/(P_*+0.8) \quad P_*\geq 0.2, \qquad Q_*=0 \text{ otherwise} \qquad [16]$$

Because of its simplicity, this form presented here in equation [16] will subsequently be used where possible. Specific expressions can be easily made by re-substituting the definitions in the above paragraph. An interesting alternative to this is given by Mishra and Singh (1999), who standardize Q and S on the storm characteristic P. As shown in Figure 4, the family of P-CN-Q curves in Figure 3 can then be simplified to a single curve indicted by equation [16] which preserves the familiar runoff function form.

General forms: The runoff equation can be generalized at each step as follows:

Effective rainfall form: $Q = P_e^2/(P_e+S)$ $P_e \geq 0$ [5a]
Initial Abstraction form: $Q = (P-I_a)^2/(P-I_a+S)$ $P \geq I_a$, $Q=0$ otherwise [6]
NEH4 form: $Q = (P-0.2S)^2/(P+0.8S)$ $P \geq 0.2S$ $Q=0$ otherwise [7]
Lambda (λ) form $Q = (P-\lambda S)^2/(P+(1-\lambda S))$ $P \geq \lambda S$, $Q=0$ otherwise [8]

In the above, λ (lambda) is a generalization of I_a/S and will be discussed later. The dimensionless forms of the above are given in Appendix II. Infiltration forms of the CN equation are extensive and are covered separately later in this report.

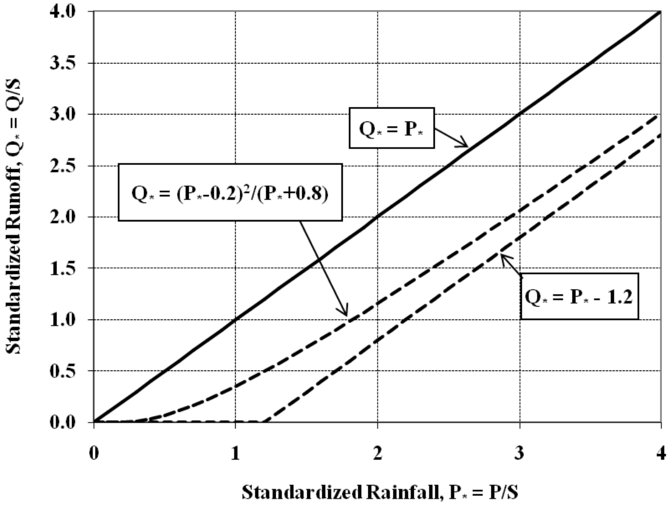


Figure 4. Dimensionless CN direct runoff equation. Standardized on the storage index S, for the case of $I_a/S=0.2$. The function asymptotically approaches $Q_*=P_* -1.2$.

Water budget forms: An alternative form of the runoff equation can be found by expanding the numerator in [1] and/or [16] and carrying out the synthetic division, resulting in

$$Q_* = P_* - 0.2 - [1 - 1/(P_*+0.8)] \qquad [17]$$
$$Q = P - 0.2S - [S - S^2/(P+0.8S)]$$

By matching term by term in [17]

$$Q_* = P_* - I_{a*} - F_* \qquad [18]$$

It is apparent from the above that

$$F_* = 1 - 1/(P_*+0.8) = P_{e*}/(P_{e*}+1) \quad [19a]$$
$$F = S - S^2/(P+0.8S) = S(P-0.2S)/(P+0.8S) = P_eS/(P_e+S) \quad [19b]$$

At this point, it is opportune to note from [17] above the limit of all losses as P→∞ is 1.2S. This was (and is) a seldom-appreciated departure from the original assumption that this would be S, resulting from the introduction of I_a=0.2S. Several of the early editions of NEH4 and summaries (e.g., Ogrosky and Mockus, 1964) carried the original misconception. The problem was first elaborated by Chen (1981a, b, c), who discussed the misconception of inclusion of I_a in S, rather than in addition to it.

Water budget allocations: An additional water budget form can be shown by beginning with $P=I_a + Q + F$, or $1=Q/P + I_a/P + F/P$. The runoff ratio $C=Q/P=Q_*/P_*$, sometimes labeled the "runoff coefficient" is easily shown to be

$$C = Q/P = (P-0.2S)^2/[P(P+0.8S)] = (P_*-0.2)^2/[(P_*(P_*+0.8)] \quad [20a]$$
or $$C = Q/P = 1-(S/P)[1.2-S/(P+0.8S)] = 1 - 1.2/P_* - (P_* - 0.2)/(P_* + 0.8) \quad [20b]$$

Similarly,

$$I_a/P = 0.2/P_* \quad [21]$$
$$F/P = F_*/P_* = (P_*-0.2)/[P_*(P_*+0.8)] \quad [22]$$

and since $1 = Q/P + I_a/P + F/P$, the above three equations specify the component disposition of a rainstorm in terms of P_*. This says that the fractional distribution of the storm to the three components Q, I_a, and F is fixed by P_*.

As shown in Figure 5, the three different components achieve their maximum share of the rainfall at different levels of P/S. As also shown in Table 9, I_a dominates up to P/S=0.45, F dominates from 0.45 to 1.20, and Q becomes the major component of the event water budget above P/S=1.20.

Solutions: Direct solutions for each of the pertinent variables P, Q, S, CN and λ are possible. Direct solution of the NEH4 form, i.e., Equation [7], is solved via the quadratic equation or

$$S = 5[P+2Q-\sqrt{(4Q^2+5PQ)}] \quad [23]$$
$$CN = 200/[2+(P+2Q-\sqrt{(4Q^2+5PQ)})] \quad [24]$$

This permits determination of an "observed" or "realized" CN from any P:Q pair with $0 \leq Q \leq P$. In the quadratic solution for [23] the negative root is selected because it leads to Q=0 at P_e=0, and S=0 at P=Q. A table giving the complete solutions for all variables in dimensionless and direct form is given in Appendix I.

Other derivations and partial area interpretations: A number of attempts have been made to derive the CN equation (i.e., eq [5]) from more fundamental hydrologic behavior assumptions. A majority of these arise from partial area considerations. A limited summary of these is given by Yu (1998). As a part of a larger modeling system, and drawing on work by Moore (1985), the CN equation form was derived by Schaake et al. (1996) assuming an exponential distribution (in space) of both event loss potential and rainfall depth.

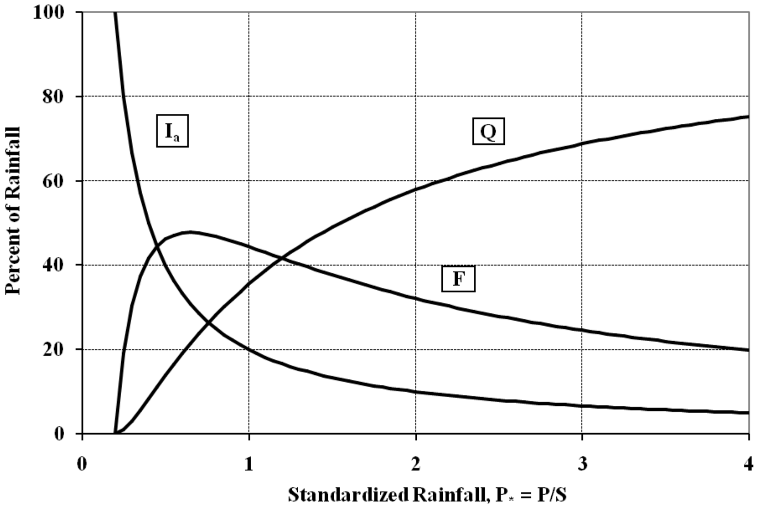


Figure 5. Allocation of rainfall into water budget components within the CN equation. The ratio of $I_a/S=0.2$, and the three ordinates sum to 100%.

Table 9. Characteristic rainfall disposition fractions

Component	Dominance Range (P_*)	P_* at Maximum	Maximum value (% of rainfall)
Ia/P	0 - 0.45	≤ 0.20	100
F/P	0.45 - 1.20	0.6742	48.6
Q/P	1.20 → ∞	→ ∞	→100

A similar independent derivation was made by Yu (1998), but based on rainfall and runoff rates again with exponential distributions. These three approaches apply spatial distributions to both rainfall and watershed properties.

A less sophisticated distributed model varying only watershed loss properties was given by Hawkins (1982). If the individual upland runoff cells perform as $Q=P-F$ for $P\geq F$ and $Q=0$ for $P\leq F$, then the Curve Number equation will be designated by a probability density distribution of

$$g(F) = (2/S)(F/S+0.8)^{-3} \qquad [26a]$$

and in continuous distribution form as

$$G(F) = 1-(F/S+0.8)^{-2} \qquad [26b]$$

when the expression [(P-F) g(F) dF] is integrated from F=0.2S to F=P. The mean value of g(F) is 1.2S, the median is 0.6142S, and the higher moments are indeterminate. This latter function is expressed graphically in the surface runoff component in the Australian water balance model (Boughton, 1987, 2004), a continuous model with several source components.

Steenhuis et al. (1995) also came to the same conclusions and a form of equation 26b, and provided an elegant rationale for equating the slope of the P:Q function (i.e., eq 26b at P=F) to the fractional source area. Nachabe (2006) showed a similar correspondence, connecting Topmodel (Bevan and Kirkby, 1979) to the CN equations via spatially varied soil moisture deficits. Similarly, Lyon et al. (2004) interpreted the CN equation to give source areas (VSA) fractions, and identified likely distributed saturated elements for three watersheds. The results checked well with results from an independent soil moisture routing model.

The CN P:Q relationship can also result from infiltration excess accounting when a constant loss rate ϕ is superimposed on a storm with an intensity-duration described by

$$i(t) = i_o[5/\sqrt{(1+24t/T)} - 1] \qquad [25]$$

where T is the storm duration, and i_o is the maximum intensity, fixed at 6P/T, and $T=1.2S/\phi$. It should be noted that this relationship between S and ϕ does specify a storm duration and distribution (Hawkins 1978).

<u>Other identities</u>: Other identities have been developed as discussed in the following.

CN_o and P_o: The Curve Number at which rainfall excess (direct runoff) begins for a given rainfall depth is called CN_o, and is easily shown to be

$$CN_o = 100/(1+P/2) \qquad [27]$$

For any CN defined by P and Q where $0\leq Q\leq P$, $CN_o\leq CN\leq 100$. Similarly, the rainfall at which the runoff is initiated for a given CN is P_o, and from the above is shown to be

$$P_o = 2[(100/CN)-1] \qquad [28]$$

Rational equation form: The CN equation has been expressed in terms of the runoff coefficient Q/P, closely akin to the rational coefficient. With the basic structure of the rational equation being $q = Ci$, the runoff depth equivalent is $Q=CP$. Substituting CP into equation [23] leads quickly to

$$S = 5P[1+2C-\sqrt{(4C^2+5C)}] = 5Pf(C) \qquad [29a]$$

and $$CN = 100/(1+Pf(C)/2) \qquad [29b]$$

where f(C) is the expression inside the brackets in equation [29a]. Using a fixed C and equations [29] and [29b] leads to a declining CN with rainfall depth P (Hawkins 1973). Though not prevalent, this behavior is not uncommon in many forested watersheds. Also, it can also be easily shown that

$$C = 1-\sqrt{(1-dQ/dP)} \qquad [30a]$$

or $$dQ/dP = 2C - C^2 \quad = C(2-C) \qquad [30b]$$

These equations are Curve Number-specific. It should be noted that dQ/dP might be considered the fractional contributing source area at rainfall depth P.

Alternate assumptions: An alternative equation can be derived by assuming that the original proportion (i.e., $Q/P=F/S$, an unsupported assertion) - had been in the derivative form, then a different but also acceptable runoff equation is found. That is, starting with

$$F/S=dQ/dP \qquad [31]$$

and introducing $P_e=P-I_a$ leads upon solution

$$Q = P_e - S[1-\mathbf{exp}(-P_e/S)] \;\text{ or }\; Q_* = P_{e*} - [1-\mathbf{exp}(-P_{e*})]\,. \qquad [32]$$

This formulation also produces a concave-upward relationship, asymptotically approaching a constant loss, $S + I_a$. Limited fitting experiences suggest that it fits data as well or better than equation [7].

Modified CN equation: Mishra and Singh (1999) derived the CN equation from an expansion of the Mockus equation, $Q= P[1-10^{-bP}]$, and established a Modified CN equation of the form

$$Q = P_e^2/(aP_e+S) = (1/a)[\, P_e^2/(P_e+S/a)] \qquad [33]$$

It should be noted that equation [33] is similar to equation [1] with the addition of 1/a and with "S" being redefined as S/a - and the limiting dQ/dP becomes 1/a as $P_e\rightarrow\infty$. This is a useful modification, insofar as it overcomes difficulties in fitting some data sets to the traditional form which dictate that $dQ/dP\rightarrow 1$ as P_e-Q approaches S. This form also allows a more realistic interpretation of non-zero infiltration velocity characteristics. It has been applied successfully in India.

SENSITIVITY

It has been found that runoff depth Q as calculated by equation [7] is more sensitive to the input CN than to rainfall depth P. This was first shown via a numerical experiment using arbitrary P and CN error levels of ±10%. The conclusion is valid up to a storm depth of about 9 inches (ca 230 mm). Especially large errors are found close to the threshold of runoff, 0.2S. Considering that most design storms are less than 9 inches, the finding has general application (Hawkins, 1975). A similar investigation by Bondelid et al. (1982) using TR55 (USDA, SCS 1986) came to similar conclusions and extended the findings to derived flood peaks. Even in more complex event models with channel routing, such as HEC-1, CN has been found to dominate in importance over rainfall depth and Manning's *n* (Hawkins, 1997).

Figure 6 shows comparisons for a typical small urban watershed of 110 acres in Tucson, Arizona. Upon contemplation, this may be an uncomfortable conclusion, insofar as rainfall is widely measured, appreciated, studied, and analyzed, but CN ground truth is

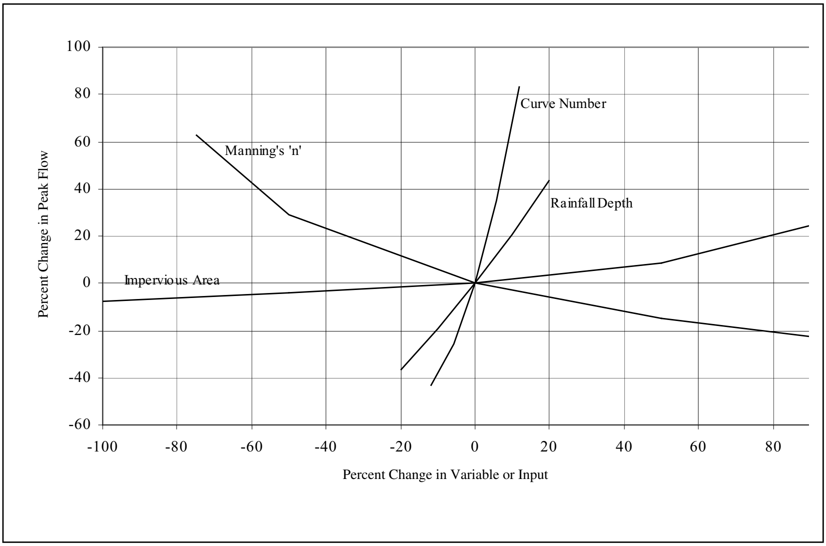


Figure 6. Peak flow sensitivity comparisons for an urban runoff model based on HEC-1. Base values of CN=85, imperviousness=20%, Manning's roughness factor = 0.10 for impervious, 0.20 for pervious, and 0.020 for channels, P=3.6 inches for a 3-hour storm, and a drainage area of 110 acres. In this figure, sensitivity is represented by slope, or $\Delta q_p/\Delta$variable.

rare. Data reality in this subject matter is the reverse of the method's needs.

INFILTRATION

Insofar as CN can be taken as a measure of watershed loss potential, it is naturally compared with infiltration capacities or depths, an alternative measure of loss ability closely linked to soil properties, profile, and structure. This notion is encouraged by the infiltration (i.e., percolation) rates associated with the four Hydrologic Soil Groups (see Tables 3 and 4), which are also closely tied to CN. Thus, it is tempting to draw equivalences between the two ideas. Recognition of the notion seems to have begun with Chen (1975), and Aron et al. (1977).

Infiltration forms: Although the original runoff equation contains no time dimension, time can be superimposed by assuming P as P(t), and Q as Q(t), and F=F(t). Placing these in the time domain is a major unstated and unsubstantiated assumption in the development and use of the method. Since F(t) is the infiltrated depth, taking derivatives of [18] with respect to time gives

$$dF/dt = f(t) = (dP/dt)(P(t)/S+0.8)^{-2} = i(t)[P(t)/S+0.8]^{-2} \qquad [34]$$

or alternatively, through substitution

$$f(t) = i(t)[1-F(t)/S]^{2} \qquad [35]$$
$$f(t) = i(t)[1-Q(t)/P_e(t)]^{2} \qquad [36]$$

where i(t) is the instantaneous storm intensity, F(t) is the cumulative infiltrated depth, P(t) is the cumulative rainfall depth, $P_e(t)$ is the cumulative effective rainfall (or $P(t)-I_a$) depth, and f(t) is the instantaneous infiltration capacity. Eq [34] is first attributable to Chen (1975). Note that equations 34-36 all compute f(t) as a function of i(t), indicating that infiltration capacity is a positive function of instantaneous intensity, a unique feature of the CN equation that finds some basis in fact. That the derived equation contains f as a function of t, and/or of F(t), is in keeping with other infiltration equations, including Philip (1954), Horton (1939, 1940), and Green-Ampt (1911).

An easily-derived more general form (Hawkins, 2001) applies for *any* runoff function which draws directly from $P_e = Q + F$, i.e.,

$$f(t) = i(t)[1-dQ(t)/dP_e(t)] \qquad [37a]$$

or

$$q(t) = i(t)[dQ(t)/dP_e(t)] \qquad [37b]$$

With some algebra, Equations 34-36 can be shown to be equivalent to [37].

Alternative origins: Using the alternative assumption in the derivation beginning with F/S=dQ/dP, leads to three different equations that parallel [34]–[36]. These are given for their curiosity value here

$$f(t) = i(t)\mathbf{e}^{-P(t)/S} \quad [38]$$
$$f(t) = i(t)[1-F(t)/S] \quad [39]$$
$$f(t) = i(t)[1-dQ(t)/dP(t)] \quad [40]$$

These are also consistent with [37]; the third above is identical in form.

Basic conflicts: The Curve Number method and the infiltration capacity notion are incompatible in three basic ways: (1) the absence of a time dimension; (2) the lack of a non-zero equilibrium infiltration velocity; and (3) the role of rainfall intensity.

Time: A fundamental difference is that the CN equation contains no time dimension, while infiltration rate and capacity, or f(t), expressions are in length/time, such as mm/hr. Thus, to relate CN to f(t), some time measure must be either introduced or inferred.

Constant rates: Severe structural differences exist. Virtually all of the popular or physically-based infiltration equations feature a fixed steady-state rate or capacity. For example, with the popular Green and Ampt (1911) equation, $f(F(t))=K_s(1+n\psi/F(t))$, the steady-state rate is K_s; with Horton's (1939, 1940) equation, $f(t)=f_c+(f_o-f_c)\mathbf{exp}(-kt)$, this stable loss rate is f_c. However, with the CN equation the stable ultimate loss rate is zero. As shown previously (see eqs [22]-[24]), as P grows, the loss rate dF/dt approaches 0: it is not a fixed positive rate like f_c or K_s. Thus, with traditional infiltration expressions, and given a sufficient supply, the ultimate possible infiltrated depth is infinite, while with the CN equation it is limited to I_a+S, which is approached asymptotically as P increases.

Intensity response: In addition, as seen in equations 22-25, the CN-modeled infiltration rate is intensity sensitive, a curious feature, which is neither intuitive nor seen in other current infiltration models. However, this does match field observations on plots and watersheds, but it is thought to arise from spatial variation of point infiltration properties (Hawkins, 1982, Paige et al., 2000, 2002) and not a direct connection of rainfall rate to infiltration rate.

Equivalences: Despite these difficulties, attempts have been made to draw the two ideas together. Beginning with the ultimate definition of CN on P and Q (see equations 20-21), Q can be alternatively calculated from infiltration expressions and specific storm rainfall patterns as

$$Q = \mathbf{\Sigma}[i(t)-f(t))]\Delta t \quad \text{for } i(t)\geq f(t) \quad [41]$$
$$P = \mathbf{\Sigma} i(t)\Delta t \quad [42]$$

As should be obvious from the above, the distribution, depth, and duration of an event are important in conceptualizing the runoff Q, as they are in the infiltration expression, f(t), selected for application. However, this approach has been followed by Morel-Seyoux and Verdin (1981, 1983), Van Mullem(1991, 1997), Nearing et al. (1996), Risse et al. (1995), and Hawkins (1978, 1980). The latter showed that the specific storm intensity distribution was unimportant for P/S values over about 3.0, and that all converged on the dimensionless form for a uniform rainfall distribution of

$$\Phi/i(t) = [P(t)/S+0.8]^{-1} \quad [43]$$

where Φ is the post-I_a constant loss rate, and i(t) is the momentary intensity. It also maintains the rainfall budget (I_a, F, and Q) allocations were as described in equations [19]-[21] and shown in Figure 5. Note that this conveys CN (as “S”), and – in keeping with prior infiltration realizations – that f(t) is a function of intensity i(t).

It has been suggested that CN for unlisted soils and cover situations or sites might be found by using equations [41] and [42] combined with extended natural break-point rainfall databases and spatially distributed infiltration equations. Accordingly, Pierson et al. (1995) simulated such using rainfall data from Hawaii and from southern Idaho, combined with a distributed version of Green-Ampt infiltration function. For the same infiltration assumptions, the CN values thus derived showed distinct differences (~ 30 CN) between the two locations, pointing out the importance of the event rainfall characteristics in computing runoff from an infiltration excess process.

In summary, it is possible - but questionable - to create equivalences between CN and infiltration capacity measures via equations [41] and [42]. Such results are quite dependent on storm duration, depth, and distribution, which are characteristic functions of local climate**.**

SOIL GROUPS

The hydrologic properties of the soils, expressed as Hydrologic Soil Groups (“HSG”) are a fundamental underpinning of the CN method, and are unique to their NRCS source. Group assignments are made for soil series as a part of ongoing soil surveys by NRCS soils scientists. In the past, classifications were presented in NEH4 for over 11,000 US soil series. This is no longer done, but the HSG assignments are available online via their soils series. Descriptions can be found at http://ortho.ftw.nrcs.usda.gov/cgi-bin/osdnamequery.cgi. Updates are found at ftp//ftp.wcc.nrcs.usda.gov/downloads/hydrology_hydraulics/neh630/. Unfortunately, there seem to be no open, completely objective written protocols for making these assignments, thus limiting application to US conditions. For example, there are no known translations to United Nations FAO soils groupings. However, extensions to several international settings have occurred.

For example, to meet South African needs, Schmidt and Schulze (1987) added three intermediate classes, AB, BC, and CD, and developed CN tables for local conditions over their entire soils spectrum. The system is used in the continuous simulation model ACRU (Schulze, 1992). This approach was preceded by a system of hydrologic soils classification drawing equivalences between US and South African conditions (Schulze et al., 1984)**.**

The dominating soils property associated with the HSGs is infiltration capacity, and a variety of connections have been suggested, as shown in Table 10 below. The current USDA stance is shown as the Musgrave (1955) entry. The ultimate source reference for these matters seems to be the USDA - NRCS Soil Survey Manual (USDA, SCS 1993). The Hydrologic Soil Groups are described in its Chapter 3 with its Table 3.9.

Table 10. Hydrologic Soil Groups and infiltration capacities (bare soils)

	-------Breakpoints - in/hr-----			Comments and Remarks
Source	D/C	C/B	B/A	
Musgrave (1955)	0.05	0.15	0.30	0.45 max
Miller et al. (1973)	0.08	0.15	0.30	0.02 min, 0.45max
Estgate (1977)	0.19	0.39	1.18	
USDA,SCS (1972)	0.20	0.80	5.00	
USFS (1970(?))	0.50	1.25	3.00	
Leven and Stender (1967)	0.80	2.50	5.00	
Musgrave (1964)	[0.22]	[0.47]	[1.00]	Relative rates, 1.22 max
USDA, SCS (1993)	0.08	0.79	7.79	K_s, sat. hyd. cond.
Terstrip and Stall (1974)	D=0.10	C=0.25	B=0.50	A = 1.00
Chen (1975)	D=0.17	C=0.75	B=2.0	A = 13.0 Lab rainfall simulations

Source: Hawkins (1980). Chen's results from Chen (1975). USDA, SCS (1993) is from Soil Survey Manual. USDA K_s values above are also given by Boulding (1994)

It is notable that this more current definition includes both an infiltration capacity measure (saturated hydraulic conductivity, or Ks) and a depth description. Linking hydraulic conductivities to the velocity adjectives given here to a directly prior table in the manual leads to the values shown in Table 11.

Chen's (1975) work is one of the few of its kind known. He examined steady-state infiltration rates with laboratory rainfall simulations (at 10 in/hr) on four constructed sub-soils from 8 to 12 inches deep, created on the basis of texture to approximate the four HSGs. He also varied bulk density. For his entry in Table 6 the bulk density was 90 lb/ft^3.

Table 11. Criteria for placement of hydrologic soil groups

Hydrologic Soil Group	Criteria
A	Saturated hydraulic conductivity is *very high* or in the upper half of high and internal free water occurrence is *very deep*
B	Saturated hydraulic conductivity is in the lower half of *high* or in the upper half of *moderately high* and free water occurrence is *deep* or *very deep.*
C	Saturated hydraulic conductivity is in the lower half of *moderately high* or in the upper half of *moderately* low and internal free water occurrence is deeper than *shallow.*
D	Saturated hydraulic conductivity is below the upper half of *moderately low,* and/or internal free water occurrence is *shallow* or *very shallow* and *transitory* through *permanent.*

Wood and Blackburn (1984) examined expected versus observed runoffs from rainfall simulation plots at 12 locations in the semiarid western US, and attributed poor correspondence to the inadequacy of existing handbook HSG information when applied to rangeland conditions. While later perspective – as discussed in this report – suggests additional complications in applying simulator results and infiltration interpretations to this end, the authors do suggest "…that the hydrologic soil groups classification system provides a poor basis for estimating infiltration rates on rangeland and that modifying them may accentuate the prediction errors. These hydrologic soil groups should be abandoned or greatly modified … and criteria should be developed which make use of surface soil conditions."

Nielsen and Hjelmfelt (1998) examined the classification consistency. Using fuzzy logic software, the trained systems – based on 1828 soils phases and series – then assigned soils to HSG's based on numeric output. Their results are shown in Table 12. This table compares current HSG classification against an objective system based on numerical expressions of the soil's known properties.

Table 12. Correlation frequency between assigned and Fuzzy Modeled Hydrologic Soil Groups

Current HSG	Number of soils	Fuzzy Logic HSG Assignment Frequency A	B	C	D	A/D	B/D	C/D
A	155	0.90	0.06	0.00	0.01	0.01	0.00	0.00
B	821	0.25	0.54	0.17	0.02	0.01	0.00	0.00
C	405	0.04	0.25	0.34	0.31	0.00	0.03	0.04
D	404	0.02	0.05	0.05	0.64	0.06	0.10	0.08
A/D	1	0.00	0.00	0.00	0.00	0.00	1.00	0.00
B/D	29	0.10	0.07	0.07	0.00	0.10	0.55	0.10
C/D	13	0.00	0.08	0.08	0.39	0.00	0.31	0.15

Source: Nielsen and Hjelmfelt (1998). Rounding effects in row totals.

From the table, it is obvious that the A and the D soils (i.e., the extremes) agree most consistently with objective classification done with fuzzy logic software. The authors describe this as a "poor correlation between the assigned and modeled groups B and C", which covers over 2/3 of the soils used in the analysis. The uncertainty further exacerbates the dependence of CN on HSG (see Aligner equations in section II), and the sensitive role that CN plays in calculating Q.

INITIAL ABSTRACTION

The existence of an initial abstraction, or the rainfall required to initiate direct runoff, is obvious in field data, and is deeply rooted in the process interpretation of CN method. Expressing I_a as a simple fraction of the storage index S greatly simplifies the equation and its application, regardless of hydrologic reality.

However, the background for the expression $I_a=0.2S$ is somewhat vague. NEH4 shows but a single log-log plot (Figure 10.2 in NEH4, shown as Figure 2 in this report) of I_a and S with a line of $I_a=0.2S$ separating the data (112 points) into two equal size samples. The data plot shows considerable scatter: up to about 2 orders of magnitude. Little information is provided on the technique for determining I_a and S, the number or kinds of watersheds, or the numbers or sizes of the storm events used to determine this relationship. In addition, the limited explanation in NEH4 suggests a circular beginning assumption of $I_a=0.2S$. Analysis of the 112 points (scaled from the figure) shows a poor fit between I_a and S, and that the direct least squares zero-intercept relationship is

$$I_a = 0.111S \qquad r = 0.4528,\ Se = 0.46 \text{ inches} \qquad [44]$$

In the above equation, r is the simple correlation between I_a and S and Se is the standard error of the estimate. The Se value of 0.46 inches is very large compared to the average for the 112 points of 0.48 inches, i.e., the zero-intercept line was equivalent to just selecting the mean value of I_a. In addition, the original versions of NEH4 suggested that

I_a was included in S. This was a widely held notion that was refuted by calculation and algebraic demonstration in the 1970s and 1980s (Chen, 1981).

Investigations of I_a/S: Several investigators have probed the overall I_a/S relationship. Early work by Chen (1976) questioned the universality of the ratio, and first suggested the use of the symbol λ ("lambda") as a generalization for the I_a/S. Cazier and Hawkins (1984) using least squares fitting with published data from 109 small river basins in the US, found that $\lambda=0$ was a much more common value, with an average value of $\lambda=0.0006$.

The availability of larger data sets and improved analysis methods inevitably led to detailed re-examinations of the original $I_a=0.2S$ assumption. Hawkins and Khojeini (2000) studied data from 97 small watersheds and found group median values for λ to vary from 0 to 0.0966 for ordered data, and $\lambda=0$ for all cases with natural data ("natural" and "ordered" refer to data configurations, and are described later in this report). The most comprehensive study was done by Jiang (2001) who used two different methods - event analysis (working with individual storms) and model fitting (2-way, λ and S least squares fitting the equation to groups of events for watersheds) - to evaluate λ. For data from 307 watersheds and plots covering 28,301 events, the summary model fitting results are shown in Table 13.

Table 13. Values of the Initial Abstraction ratio $\lambda = I_a/S$ from model fitting

			Natural Data				**Ordered Data**			
Data Source	Number Watersheds	Number Events	Max	Mean	Median	Min	Max	Mean	Median	Min
ARS	134	12499	0.5766	0.0555	0.0001	0	0.9682	0.1491	0.0736	0
USLE	137	11140	0.996	0.0997	0	0	0.9266	0.1581	0.061	0
Others	36	4392	0.4727	0.04	0	0	0.9793	0.0992	0.0044	0
Total	307	28031	0.996	0.0734	0	0	0.9793	0.1472	0.0618	0

As expected, the found λ values varied from event to event and location to location. In addition most (90%) of the λ values were found to be less than the customary value of 0.20. Drawing from these results, a rounded value of $\lambda=0.05$ seems more appropriate for general application. When used with the original data sets, it produced a better fit (lower RMS errors) in 252 of the 307 cases, or about 5 times out of 6.

Effects of alternative λ: With $\lambda=0.05$, the original equation becomes

$$Q = (P-0.05S_{0.05})2/(P+0.95S_{0.05}) \quad P>0.05S_{0.05},\ Q = 0 \text{ otherwise} \qquad [45]$$

The above shows the 0.05 subscript to indicate that $\lambda=0.05$ is assumed, and to distinguish it from the unsubscripted S value where $\lambda=0.20$. A large majority of the algebraic and statistical relationships described in this report rest on the assumption of $I_a = 0.2S$, and must be considered separately for the case of $I_a=0.05S$.

Conjugate CNs: Insofar as all existing handbook Curve Number tables assume $\lambda=0.20$, a change in table values is required if any other value - such as 0.05 - is used. Subsequent least squares P:Q fitting studies by Jiang (2001), and Hawkins et al. (2001), and Hawkins et al. (2003) on the 307 watersheds using both systems found a close empirical relationship

$$S_{0.05}=1.33S_{0.20}^{1.15} \qquad [46]$$

with S in inches. The above is a version rounded to two decimal places that combines similar results with both ordered and natural data, and with r^2 in excess of 0.993. Thus, CNs in existing tables using $\lambda=0.20$ can be converted to equivalent CNs for the assumption of $\lambda=0.05$. Substituting the above equation into the definition of CN =1000/[10+S(in)] leads to

$$CN_{0.05} = 100/\{1.879[(100/CN_{0.20}) -1]^{1.15} + 1\} \qquad [47]$$

A sample of CNs under the two systems, or "conjugate" CNs, is given in Table 14.

However, a rainfall that will create the same runoff can be calculated by the two differing I_a/S assumptions and the conjugate CNs. This rainfall depth "break point" where both λ assumptions give the same runoff for a given P is shown in Table 14 as P_{crit}. At rainfalls greater than P_{crit}, the $\lambda=0.20$ assumption will give greater calculated runoffs for the given $CN_{0.20}$ than will be calculated for the same rainfall and $CN_{0.05}$

Table 14. Conjugate Curve Numbers, I_a, and P_{crit}

For $\lambda=0.20$			For $\lambda=0.05$			P_{crit} (in)
$CN_{0.20}$	$S_{0.20}$	I_a(in)	$CN_{0.05}$	$S_{0.05}$(in)	I_a (in)	
100.0	0	0	100.00	0	0	-----
95.0	0.526	0.105	94.02	0.636	0.032	2.44
90.0	1.111	0.222	86.95	1.501	0.075	1.72
85.0	1.765	0.353	79.64	2.556	0.127	1.95
80.0	2.500	0.500	72.39	3.815	0.192	2.27
70.0	4.286	0.832	58.51	7.091	0.354	3.05
65.0	5.385	1.077	52.03	9.219	0.461	4.51
60.0	6.667	1.333	45.90	11.785	0.584	4.04
55.0	8.182	1.636	40.14	14.915	0.742	4.64
50.0	10.000	2.000	34.74	18.787	0.939	5.35
45.0	12.222	2.444	29.71	23.663	1.183	6.15
40.0	15.000	3.000	25.03	29.947	1.497	7.13
35.0	18.571	3.714	20.71	38.285	1.914	8.35

Effects on hydrographs: In the above table it should be noted from the differences in S values are especially severe at lower CNs. Also, from the I_a values, the numerical values of CN are lower with the λ=0.05, but the runoff begins at a lower rainfall thresholds. In general, higher runoffs (and higher peaks) are calculated for low P and low CN (or low P/S) settings with λ=0.05. This is representative of well-forested watersheds. At high P/S, less runoff results with λ=0.05, and modeled peaks flows are lower, a condition representative of urbanized watersheds.

SOIL MOISTURE REPESENTATION and AMC/ARC

The original NEH4 exposition of the CN method contained the AMC notion in two forms, both seemingly independent. First, as a climatic definition presented in the since-discontinued NEH4 Table 4.2, or Table 7 here, indicating AMC status (I, II, or III) based on 5-day prior rainfall depths and season. Second as an undocumented table (Table 10.1 in NEH4, shown as Table 6 here) that gave the I, II, and III equivalents. This was linked to explaining the observed variation in direct runoff between events.

Prior 5-day rainfall depths: The cumulative 5-day rainfall depth is a characterizing climatic description of a site. A number of subsequent papers (including Gray et al.; 1982, Hawkins 1983) examined this and found that for most stations – and using the Table 4.2 criteria – the apparent dominant rainfall-defined status was in AMCI. This invited local interpretations and selection of AMCI CN from soils and cover data, with consequent reduction in design peaks and volumes. From this realization, in 1993 the SCS dropped the Table 4.2 definitions from updated NEH4 (Shaw, 1993). Furthermore, CN at AMC II status was defined as the reference CN, as that occurring with the annual floods, and as the basis for standard practice in design. Despite this, the climate-based AMC conditions find continued application, usually in continuous daily time-step models, a topic covered elsewhere in this report.

AMC conversion values: The correspondence between CN at the three AMC status levels was stated in NEH4 Table 10.1 (Table 6 in this report) without explanatory background or hydrologic reference: the original data sources and the derivation technique have not been located. However, in attempts to formulate the relationships, the table offerings have been re-expressed algebraically, as shown in Table 15. The first three of these equations are essentially identical: [50] reduces very nearly to [49] and [50] upon simplification. Equations [48] and [49] are known to arise from direct simple linear fits on the storage term “S” of the CNs offered in NEH4 Table10.1. Specifically, [53a] and [53b] are fit to 45 points from CN=50 to CN=95, giving (Hawkins et al., 1985)

$$S(I) = 2.281S(II) \qquad r^2 = 0.999,\ Se=0.206in \qquad [53a]$$

$$S(III) = 0.427S(II) \qquad r^2 = 0.994,\ Se=0.088\ in \qquad [53b]$$

It should be noted that the coefficients in the above are very nearly reciprocals, or $0.427 \cong 1/2.281$.

Table 15. Algebraic expressions of NEH4 Table10.1

Source	Equation	
Sobhani (1975)	$CN(I) = CN(II)/[2.334-0.01334CN(II)]$	[48a]
	$CN(III) = CN(II)/[0.4036+0.0059CN(II)]$	[48b]
Hawkins et al. (1985)	$CN(I) = CN(II)/[2.281-0.01381CN(II)]$	[49a]
	$CN(III) = CNII./[0.427+0.00573CN(II)]$	[49b]
Chow et al. (1988)	$CN(I) = 4.2CN(II)/[(10-0.058CN(II)]$	[50a]
	$CN(III) = 23CN(II)/[10+0.13CN(II)]$	[50b]
Arnold et al. (1990)	$CN(I) = CN(II) - F(CN(II)$	[51a]
	$CN(III) = CN(II)*\mathbf{exp}[0.00673(100-CN(II)]$	[51b]
where $F(CN(II)) = 20(100-CN(II))/ [100-CN(II))+\mathbf{exp}(2.533-0.0636(100-CN(II)]$		
Double normal	$CN(I) = 100(F^{-1}(CN_{II}/100) - 0.51)$	[52a]
	$CN(III) = 100(F^{-1}(CN_{II}/100) + 0.51)$	[52b]
where F( ) = Normal probability integral; $F^{-1}( )$ = inverse of F()		

Double normal plotting: The ultimate practical fitting of the Table 10.1 AMC relations can be found by plotting CN I, II, and III on the Y-axis on double normal-probability paper, against CNII (X-axis), with the CNs shown as "probability" in percent (Figure 7). This pragmatic exercise leads to three equally spaced and tightly-fitting parallel straight lines. This is consistent with the reciprocal coefficients mentioned above, and suggests a smoothing procedure on limited data to create the original relationship. Fit to the "data" in NEH4/630 Table 10.1 the expressions are shown as Equations [54] below

$CN_{I} ..= 100(F^{-1}(CN_{II}/100) - 0.51)$ $Se = 0.27CN$ [54a]
$CN_{III} = 100(F^{-1}(CN_{II}/100) + 0.51)$ $Se = 0.28CN$ [54b]

where F( ) = Normal probability integral, and $F^{-1}( )$ = inverse of F( ). For example, if $CN_{II}=75$, then $F^{-1}(0.75) = 0.675$, $0.675-0.51 = 0.165$, $F(0.165) = 0.565$, and $100*(F(0.165)) = 56.5 = CN_{I}$. As a check, Table 10.1 says the CN should be 57. This presentation of the double normal plotting is the first documented statement in the open literature of the relationships. It should be restated here that condition II is the basis for design of structures and conservation measures insofar as it represents an "average" watershed condition when flooding occurs.

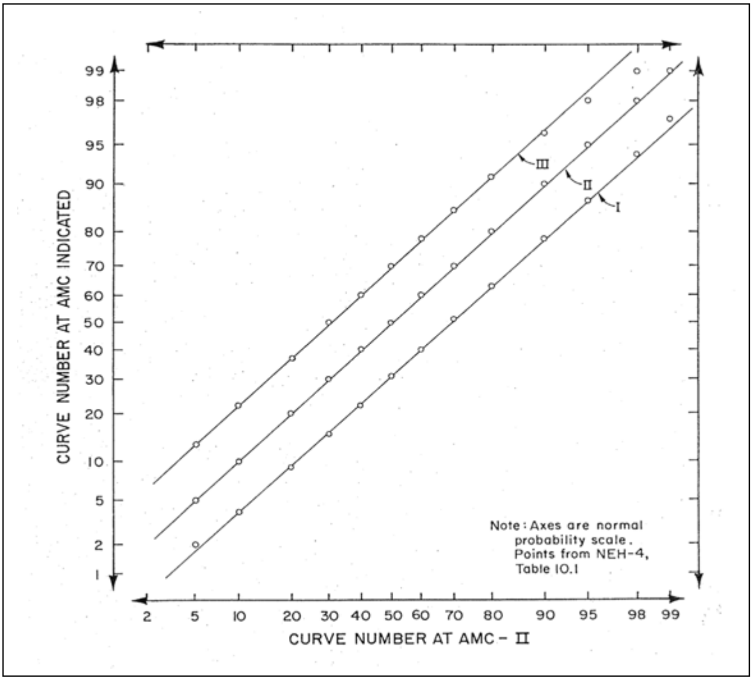


Figure 7. Representation of the handbook AMC I, AMC II, AMC III relationships with double probability plotting.

AMC and ARC as "error bands": The "AMC" concept was converted to an "error bands" concept via findings by Hjelmfelt et al. (1982) of error probabilities associated with the table values of AMC I and AMC III. AMCIII was shown to approximate the direct runoff for a given rainfall for which 90 percent of the runoffs were less; while AMCI approximated the direct runoff for the same rainfall for which 10 percent of the runoffs were less. Reinforcing examples for this notion are given in later papers by Haan and Schulze (1987), and by Hauser and Jones (1991), and Hjelmfelt (1991). Current work by Grabau et al. (2008, in review) further affirms the concept, but refines AMC I and III probabilities as about 12 and 88 percent respectively, leading to about 75 percent of the runoff events falling between ARC I and ARCIII. Figure 8 shows the findings and the plotted points.

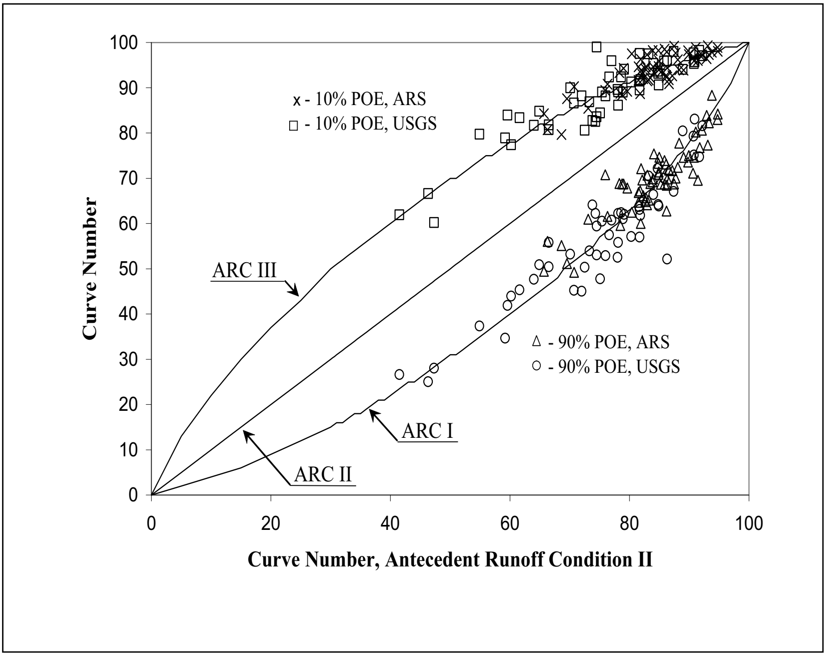


Figure 8. Distribution of CN(I) and CN(III) with 10% and 90% Probability of Exceedance (POE). Figure based on annual peak rate series for selected Agricultural Research Service (ARS) and U.S. Geological Survey (USGS) watersheds (from Grabau et al., 2008, in review).

Except for application in continuous daily models, in which CN hangs on soil moisture accounting (see next section), this "error band" concept predominates currently. In light of the above realizations, the "AMC" notion was dropped in favor of an *Antecedent Runoff Condition*, or A*R*C, acknowledging that runoff inconsistency between storms may result from many factors, and not solely from site moisture differences.

CURVE NUMBERS AND SOIL MOISTURE MODELING

The curve number event runoff equation and the ARC-CN relationships offered in NEH4 Table 10.1 (e.g., Table 2 here) have found application as a hydrologic interpretation of soil profile and site characteristics in ecologic models. Insofar as this is a major extension of the method not covered in the original formulation in NEH4 there is a lack of handbook authority or precedent to guide or support it.

Continuous models with the CN method as a soil moisture manager are sometimes used to determine watershed yield, it is also popular as the hydrology underpinning for upland water quality models. Such approaches also find wide application in continuous hydrologic simulation, usually in planning agricultural or wildland management. This application is widespread, but only defining and cursory coverage is given here. A full critical review is needed but is well beyond the scope of this report.

An abbreviated and selected listing of such continuous models include SWAT (Arnold et al., 1994), SWRRB (Arnold, et al., 1990, Williams et al.,1985), EPIC (Williams et al., 1984), GLEAMS (Leonard et al., 1987), CREAMS (Knisel (ed), 1980), NLEAP (Shaffer et al., 1991)AGNPS(Young et al., 1989, Cronshey and Theurer, 1998) , ARDBSN (Stone et al., 1986), SPUR (Carlson et al., 1995), PRZM (Carsel et al., 1984), ACRU(Schulze, 1992), RUSLE2 (Foster et al., 2003), SPAW (Saxton, 1993), and TVA-HYSIM (Betson et al., 1980)

Essentially all of the current works are technical descendents of the pioneering paper by Williams and LaSeur (1976). Later additions by Arnold et al. (1990) provided the essentials found in many contemporary versions. The most popular module appears to be the one incorporated in SWAT (Nietsch et al., 2002). A more recent procedure along similar lines with successful application is given by Mishra and Singh (2004). An alternative with some enhancements was given shortly following the Williams and LaSeur (1976) paper by Hawkins (1977, 1978). It was applied to the continuous daily model ACRU (Schulze, 1982, 1992) in South Africa (which uses $I_a/S=0.10$, however).

A critique of both of these approaches - based on mass conservation considerations - is given by Mishra and Singh (2004), who suggest a corrected and improved method. Their approach incorporated in a river basin model applied to conditions in India. Michel et al., 2005) present a critical review of these procedures and highlight several inconsistencies when used in continuous models, and derive a procedure to deal more realistically with event rainfall-runoff over a wider variety of initial conditions.

The soil water balance modeling strategy springs from the notion that CN - and thus S (or 1.2S) – is a continuous function of soil moisture with time. Thus, it gives physical meaning to S as the maximum possible post-I_a difference between rainfall and runoff, and is a time-variable measure for site water storage potential. While variations in details abound, a basic representation of the general method is as follows:

1. CN values - assumed to be condition II - are selected from handbook tables or charts for the soils and land use conditions under study.

2. From this, conditions I and III are established using the handbook relationships in NEH4 Table 10.1. (or Table 6 in this report). In some versions, the storage indices (S) corresponding to ARC I and ARC III may be taken to be site wilting point and field capacity respectively.

3. Direct runoff (Q) is generated from the daily rainfall P and the daily CN, the latter defined by allocating the soil moisture with conditions I and III as the limiting cases.

4. Total losses to runoff (P-Q) are counted as additions to site moisture. Site moisture losses from evapotranspiration and drainage/percolation are calculated by various subprocess models.

5. The CN for the next day is calculated from the residual soil moisture content following the above accounting, limited by the wilting point (or ARC I), and by a special case under very wet conditions in excess of field capacity.

Within this general structure, the CN status may be either continuous (a range of soil water contents between AMC I and III) or discrete (I, II, or III). Variants also exist in time step selection, parameter identification, associated processes, GIS application, and accounting intervals.

While these models use the CN runoff equation as a central core, much of the subsequent model operation and logic are beyond the scope of this report. In some cases the primary role of the CN logic is in managing soil moisture, coupled with other processes such as snowmelt, and very little (or no) direct surface runoff is generated. (See Ahl et al., 2006; Ahl and Woods, 2006).

It is worth noting that the Curve Number relationships that began as humble annual peak flow data plots are now interpreted as measures of soil physics: Conditions I and III, originally seen as extremes of rainfall-runoff response, are asserted to be the profile's wilting point and field capacity.

Furthermore, the handbook CNs - many of which were interpolated by such as the Curve Number Aligner or administratively selected as agricultural policy – are, by user necessity, applied with the same confidence that might be accorded to atomic weights of elements. These in turn hang on the accuracy of the Hydrologic Soil Group determinations, a matter illuminated elsewhere in this report.

Even though operated on daily time steps, goodness-of-fit accounting and comparisons are usually on a monthly or an annual basis. Also, while widely used, there is a distinct shortage of critical or comparative examination of model performance at the daily scale, or on the varieties of CNs calculated/produced in the model operation. The soils-and-cover defined CNs from handbook tables become a generic site measure, and not necessarily the CN when flood events occur. In addition, the effects of using the initial abstraction ratio λ (=I_a/S) of 0.05 - as shown by recent studies - on the outcome of such models is not known.

OTHER CN EFFECTS

Soil moisture effects on direct runoff: The above begs the question of actual effects of prior rain or start-of-storm soil moisture on event runoff, either in the P:Q or CN context. The literature is surprisingly sparse and mixed on the topic, despite the intuitive sense and basis in physics. Hawkins and Cate (1998) were able to show a consistent positive effect of prior 5-day rainfall in only 11 of 25 cases for small rain-fed agricultural watersheds, and very mixed effects from intensity and storm distribution factors. A later study (Hawkins and VerWeire, 2005) with a larger sample (43 watersheds) reaffirms the above general findings, and points out the complex role of storm intensity, which seems to be *less* important than prior rainfall.

Montgomery and Clopper (1983) used a 15-day API (Antecedent Precipitation Index) in place of the NEH4-recommended 5-day prior rainfall and showed substantial effects on the "S" value derived by least squares fitting on 6 small agricultural watersheds. In addition, Jacobs et al. (2003), using remotely sensed watershed-wide soil moisture status, were able to isolate a soil moisture signal in CN (and thus Q) for a series of small watersheds in central Oklahoma. This suggests that prior studies were limited by lack of sufficiently representative soil moisture data.

For the 6910 ha Little Vermillion watershed in central Illinois, Walker *et al.*(2005) found CNs to be a positive function of base flow prior to the event, and suggest that – given the local setting of flat slopes, deep soils, and a humid climate – the baseflow could be acting as a surrogate for soil moisture. A similar baseflow-CN effect was found by Calvo et al. (2006) for the Rio Chagres in Panama.

Storm effects - Intensity, distribution and duration: As a simple event model, the method contains no accounting for storm descriptors other than the total storm depth P. Early versions of NEH4 suggest that CN itself is also a function of storm depth, but this is not a widely used current feature of the method. Chapter 21 of NEH4 does suggest smaller CNs for 10-day storms when used in designing flood control structures.

However, as described elsewhere in this report (Calibration Methods), CN as a function of P is quite evident in data analysis; it occurs in nearly all cases studied with reasonable sample sizes. It should be noted that these storm characteristics are often closely interrelated; by fundamental definition, intensity is depth per unit time, and the influences of specific factors are difficult to isolate. Woodward (1973) found a relationship between observed CN and the 1-and 24-hour storm depths in a number of semiarid watersheds. Van Mullem (1997) showed a distinct negative relationship between data-defined CNs and storm durations for sites in Ohio, Nebraska, and Arizona. He also detected a positive relationship between CN and storm intensity. On the other hand, Hawkins and VerWeire (2005) found consistent negative relationships between storm intensity measures and deviations from predicted CN runoff. These anomalies and differences might be reconciled by the interrelationships between storm duration, depth, and intensity.

While the distribution and temporal sequences of storm intensity bursts has no effect on the total storm runoff depth Q with the CN method, it does strongly affect the calculated interval runoffs (i.e., rainfall excesses), and thus the modeled outflow hydrographs derived from it.

CN and direct runoff variation: The above leads naturally into the independent quantification of natural observed variation of Q given P. Such would promote the opportunity to generate large samples of random data and evaluate the probabilities of extreme natural events. Insofar as variation in Q is variation in CN, this problem directs attention to CN scatter around CN(II).

As previously described, work by Hjelmfelt et al. (1982) suggested that the variation of Q or CN is described by the handbook AMC I and III values, and that these values correspond to the 10% and 90% conditional cumulative distribution of Q given P, with AMC II occupying the median (50%) position. This was also demonstrated by Hauser and Moore (1991). Using this information, Hawkins et al. (1985) showed I_a/S to be lognormally distributed, and thus calculated runoff varies accordingly. However, the conditional distribution of direct runoff Q given P has not been determined. It is known that a probability mass of Q(P) exists on the P-axis (Q=0), and that the cumulative frequency is 1.00 at Q=P.

McCuen (2002) assumed a gamma distribution of (100-CN) to describe found-CN variety for a number of watersheds in Maryland and provided CN confidence intervals from this sample**.** For several different locations, Reitz (1999) showed asymptotic watershed CNs at a location to be uniformly distributed (a “block” distribution) with a typical range of about 10 CNs for similar sites and locally identical HSGs and land uses. Yulianti and Lence (1999) assumed a normal distribution for 100/CN, and applied that assumption in simulating data for a hydrologic engineering design problem.

Seasonal effects: Month-to-month variation in Curve Numbers has been found, and seasonal cycles shown in some cases. Price (1998) found distinct seasonal patterns for CN from a number of moist forested watersheds, but diminishing cyclic effects for rain-fed agricultural watersheds, rangelands, urban, and desert watersheds. Where these regular cyclic patterns exist, the extremes of seasonal variation are averaged to define an overall CN. However, heavy cover extremes in some agricultural settings, such as sugar cane, may minimize event runoff to the point of not being able to identify seasonal effects.

Slope effects: There is no independent effect of land slope on CN stated in NEH4/630, and no subsequent enlarging literature. However, in the SWAT (Nietsch et al., 2002), EPIC (Williams, 1995), and SWRRB (Arnold and Williams, 1995) models, it is taken to be

$$CN_{IIa} = (1/3)(CN_{III}-CN_{II})[1-2\mathbf{exp}(-13.86\alpha)] + CN_{II} \qquad [55]$$

The subscripts II and III indicate the ARC, the “a” subscript indicates the slope-corrected CN_{II}, and α is the land slope as a decimal fraction. The effect is positive: CN_{II} increases as slope increases. However the magnitude is relatively slight: at the standard reference slope (assumed to be 5% for table CN) the effect is about +0.25 CN per unit of slope percent at CN_{II}=90, and +0.93 CN per unit of slope percent at CN_{II}=50. No goodness-of-fit information is given for equation [55] above in the source documents, and a 5% reference slope is not found in NEH4/630.

In contrast, Garg et al. (2003) observed a negative relationship between slope and CN (calibrated via the AGNPS model (Young et al. 1989)) over a narrow range (2 CN) for 5 watersheds in south-central Oklahoma. The fitted area-weighted CN dropped about 1.3 units for each percent of watershed slope. In addition, a recent study by VerWeire et al. (2005) found a distinct negative relationship between data-determined asymptotic CNs and GIS-determined average land slope. For 27 small rangeland, forested, and agricultural watersheds, the relationship was

$$CN = 82.2 - 172.86 slope \qquad r^2 = 0.4945 \qquad [56]$$

with slope expressed as a decimal fraction. Both of these findings are counter-intuitive. However, the similarity of the CN-slope gradients (-1.3 and -1.73 CN per percent slope) in these two studies might be noted. The conclusions seem to be in conflict with the adjustments made in the SWAT, EPIC, and SWRRB models. Both of these studies used GIS techniques, and the results may be sensitive to pixel size.

Land use effects: In keeping with the original intent of the method, data-defined CNs have been used to detect the effects of land use or cover changes on direct runoff. However, Simanton et al. (1977) used the CN approach to appraise the hydrologic effects of a brush-to-grass conversion in southern Arizona, and found the technique to be inadequate. They were able to detect effects using linear fits. With much larger data sets and improved methods, Reitz (1999), and Rietz and Hawkins (2000) show several examples for a number of locations of differences in CN between row-crops, pasture, and meadow, with meadows dominating the lower CNs. Effects of natural cover variation on CN were shown by Hawkins and Ward (1998) from a plot of rainfall-runoff data in southeastern New Mexico, and the results agree in general form with CN-cover graphs found in NEH4. The effects of grazing exclusion or inclusion, and of type conversions (brush to grass, or mesquite removal) on CN were shown by Rietz (1999), and by Reitz and Hawkins (2000).

Effects of drainage area: Rainstorm extent becomes a factor in some situations. This is known to be a problem with thunderstorm-driven runoff in the southwestern deserts, where storm cells are often on the order of a square mile, thus do not cover larger watersheds (Osborn et al., 1980, Osborn, 1983). This was demonstrated by Simanton et al. (1996) who found that data-defined CNs decreased with increasing drainage area for Walnut Gulch, Arizona, presumably because of compromises to average watershed storm rainfall that occurred with larger drainage areas, as well as channel transmission losses. The found relationship was $CN=84.7-0.022A$, with A in acres, and $r^2=0.50$. The study covered 18 small watersheds up to 785 acres. As an aside, this situation, with representative return period rainfall depths, leads to a drainage area of about 500-700 acres giving maximum volumetric water yields.

Regional/Climatic variations: With familiarity that came with repeated usage, the difference in identically defined CN (same soils and land use) between regions has become evident. This was studied by Reitz (Rietz, 1999, Reitz and Hawkins, 2000) who found CN variation between locations for forests, rangelands, brush, and meadows, but surprisingly consistent event CNs for small grains and row crops.

Some insights to the effects of different rainfall regimes on CN may be seen in the work by Pierson et al. (1995), who generated CNs from P and Q by modeling infiltration excess with spatially distributed Green-Ampt properties and breakpoint rainfall data from two different locations, Laupahoehoe, Hawaii and Nancy's Gulch, Idaho. With identical infiltration assumptions, the CN behavior (as a function of the mean infiltration capacity) was strikingly different, with the longer storms and lower intensities for Hawaii giving much lower CNs. This was essentially a measure of the "climate" effects of CN as expressed through storm intensities and durations. Extending the results to real-world situations suggests that variations in rainfall patterns alone may produce different CNs between locations.

An array of studies has institutionalized CN adjustments from east to west Texas, and its close association with annual rainfall. (See Hailey and McGill, 1983; USDA, SCS (1990), Thompson (2002), Sandrana (2004a)). Thompson's work performed an asymptotic analysis (see following section on Calibration Methods) of gage records for events of $P/S>0.46$, and CNs were found to drop from near-handbook expectations in northeast Texas to about 24 CNs below handbook values in locations in west and central Texas. These adjustments have been institutionalized based on regional clusters and climate, and are currently used by the Texas Department of Transportation (Sandrana 2004a, 2004b). Previous work referenced above by Hailey and McGill (1983) and USDA, SCS (1990) along this line has been in USDA application in Texas since 1993.

A similar approach has been established in Kansas, with the western half of the state assigned reduced CNs on a stepped system by counties, and on differences in CN under runoff conditions I and II. This is restricted to non-irrigated conservation practices; all other applications use ARC(II).

Counter-observations are made by Osterkamp and Friedman (2000), who suggest that crusted surfaces and lack of soil development and vegetation in the semi-arid west have produced larger flood peaks, even in the face of lower return period rainfalls. They use the observed trends in found CN from 34 research watersheds/locations in the west to support this contention.

CALIBRATION METHODS

Needs and opportunities: Knowing that the calculated runoff Q is more sensitive to CN than to the rainfall depth P, and that the handbook CN values are given as guides only, enlightened practice should seek CNs from local data for local situations. Four (4) methods are described in some detail here: The NEH4 method, or the median CN for annual flood data; Least squares fitting to P:Q data; Asymptotic fitting; which recognizes the drift of CN with rainfall P, and Frequency curve fittings. In addition two other methods have been used: Continuous model calibration; and Sprinkling infiltrometer procedures.

NEH4 treats only the median annual peak CN. The remaining methods raise several issues that include: 1) minimum storm size; 2) non-CN response behavior, or the unsuspected variation of data-defined CN with rainfall depth P; 3) frequency matching (or ordered P:Q data); and 4) the defining population represented by the CN procedure, which questions using all events, or only the annual floods.

NEH4 Method: The single example in NEH4 for CN definition from data is its Figure 5.6, for the station Amicalola Creek near Dawsonville, Georgia, drainage area of 87.4 mi^2. This data was taken from an assembly of river basin scale annual peak rainfall-runoff data prepared for the SCS by the U.S. Geological Survey (Dalrymple, 1965). Plotting the P and Q values (in inches) on the P:Q – CN family plot (Figure 3 in this report) a median value of CN was selected by inspection, choosing the CN that divided the plotted data into two equal groups. It should be noted that this was done graphically, using annual flood peak event data (P and Q) only, for a watershed of river basin scale, and the median CN as the identifying value. Insofar as the data was for annual flood events, the median CN thus determined is for the 2-yr return period. As an interesting aside, the example suggests that such procedures and the Dalrymple (1965) data source were followed to create the CN tables found in NEH4.

The annual peak - median method described above has the appeal of simplicity and the precedents from NEH4 and NEH630. However, on the face of it, any group of simple P:Q pairs from instrumented watersheds should translate into watershed-defining CNs, even without requiring the annual series constraint. Supporting background for this is given by Rallison and Cronshey (1979). Other early attempts were equally direct, but usually departed from the NEH4 annual series example described above.

Accordingly, a number of investigators (e.g., Curtis et al., 1983; Hawkins, 1984) used simple means or median of P:Q-defined CNs from extended data sets (i.e., not constrained to the annual series), with use of the solution given by equation

$$S = 5[P+2Q-\sqrt{(4Q2+5PQ)}] \qquad \text{for } I_a/S = 0.2 \qquad [57]$$

gradually coming into common usage.

Median selection is the method shown in NEH4 and in the current version of NEH630. Defining CN on a mean or median avoids several problems. With the growing availability and analysis of electronically accessible rainfall-runoff data from instrumented watersheds, an awareness of a number of additional issues and options came to the fore in dealing with rainfall-runoff. These are (1) the use of ordered (or ranked, or frequency-matched) data, as promoted by Hjelmfelt (1980, 1983); (2) a variety of CN-P responses not known when the original CN work was done in the 1950s; and (3) alternatives to the use of annual series and thus small data sets.

Data considerations: There are a number of factors to be considered in data analyses as described in the following sections.

Frequency matching and ordered data: Frequency matching the data points was introduced to CN analysis by Hjelmfelt (Hjelmfelt et al., 1982; Hjelmfelt 1983). This idea recognizes that a major use of the CN method is to estimate the return period runoff depth from the same return period rainfall depth; for example, the 100-year flood is estimated from the 100-year rainfall. In keeping with this, the return periods of the P and the Q should be matched in CN determination. In practice this is done by independently re-ordering the event P and Q values, and then re-matching by rank order into new (and mostly mismatched) P:Q pairs. While these new "ordered" pairs may not be as occurred in nature, each event component (P and Q) has the same calculated (i.e., plotting position) return period.

This puts the CN equation in the role of a function that transforms a rainfall frequency curve to a runoff frequency curve. Precedent for this tactic is found in the works of Schaake et al. (1967) who applied it in determining rational coefficients in an urban setting. This method per se - as applied to CNs - is treated later in this section. Thus, P:Q data has two forms; natural (paired as it occurred), and ordered (or re-matched as described here).

Rainfall depth effects: In essentially all cases – using both natural and ordered data sets - a residual relationship between the data-defined CN and the causative rainfall depth P is apparent. The data-defined CNs are not independent of the rainfall depth itself, and a distinct bias to high CNs at small rainfalls is evident. While this is evident upon closer examination in NEH4 examples and in the data used by Hjelmfelt et al. (1982), the phenomenon was first shown and demonstrated by Sneller (1985). It may be attributed to a mixture of data censoring, partial area effects, and to basic error in the model or the data. Data censoring results from the common practice of excluding from the data sets all rainfall events without direct runoff, thus assuring $P \geq 0.2S$, and $100/(1+P/2) < CN < 100$. On the other hand, to the extent that any CNs are manifested at low rainfalls (for which there are many storms), they would – by definition – define high CNs. Additionally, partial area runoff, as from direct channel interception or from other impervious areas, can reproduce the declining CN action as well.

Springing from the above, several distinct CN-P response patterns have been observed, described, and labeled (Hawkins 1990, 1993). The dominating behaviors are:

> Standard: Characterized by a declining CN with increasing P, but approaching a constant or near-stable value asymptotically at higher rainfalls. This is the most common case, and is found in most agricultural, urban, and rangeland settings where rainfall excess is thought to arise from infiltration processes. CN can be determined from such data. Because of sample size limitations from small data sets, not all show a well-defined fixed stable CN, but indicate an approach to it.
>
> Complacent: This condition is also characterized by declining CN with increasing P, but *without* approaching a fixed equilibrium value in the period of record. This can be caused by small constant source areas as may arise from direct channel rainfall. It is commonly found with well-forested watersheds with baseflow. CN fitting is inappropriate in such situations. Such data are more aptly fit to $Q=CP$, with C values usually in the range of 0.005-0.070, rather than to the CN equation (Hawkins, 1973). Complacent behavior is apparently also widely found in urban watersheds, as clearly illustrated by Pitt (1999). This is especially cogent in the case of smaller storms which carry the bulk of urban non-point pollution.
>
> Violent: This pattern is characterized by Complacent behavior with declining CNs at the lower rainfalls, but with a sudden change to a much higher runoff response at

some threshold elevated rainfall depth. Typically, such threshold depths are in the range of 1.5 to 2.5 inches, and a higher near-constant CN is approached with increasing rainfall, typically in the 85-95 range.

These behaviors or responses to rainfall are illustrated by Figures 9 to 11.

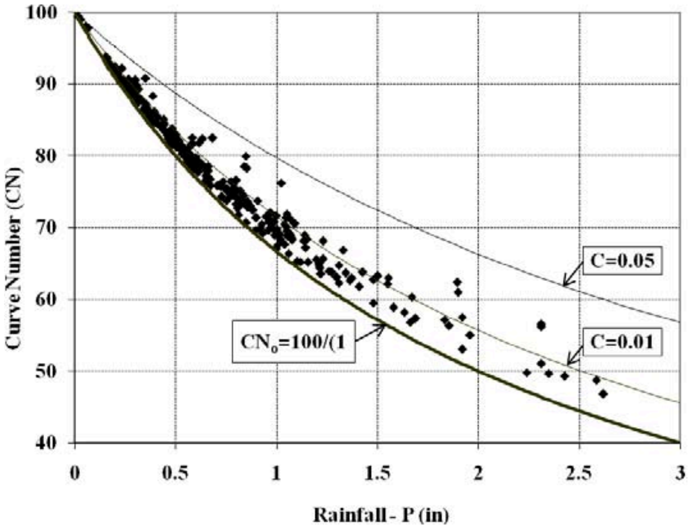
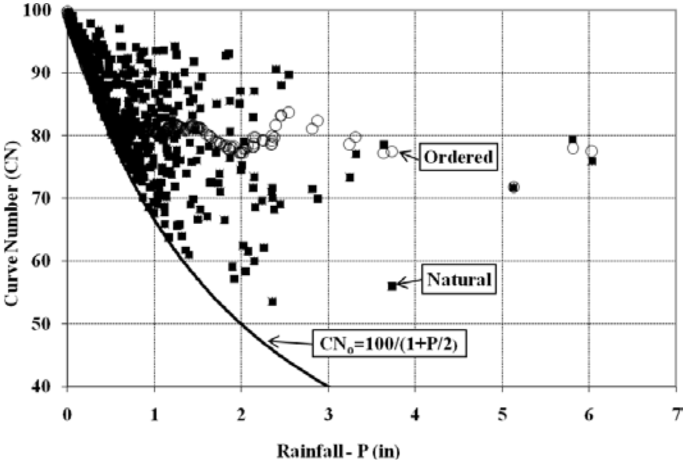


Figure 9. Complacent CN response to rainfall. The natural P:Q data from which these area drawn data are a composite for 13 small wild land (mainly forested) watersheds in Colorado, Utah, Arizona, and Idaho, totaling 313 events.

The data in Figure 9 are drawn from several different primary sources (see Springer and Hawkins, 2005). Note the similarity of response for natural (not ordered) data points, the lines of low runoff ratio C, and that no stable constant CN is apparent. In Figure 10, the drainage area for Hastings is 411 acres (166 ha), and the cover was a variety of rainfed row crops [data from USDA, Agricultural Research Service]. The drainage area for Zulu 15 was 1364 ha. Those data were supplied by Dr. Roland Schulze, University of Natal (now University of KwaZulu-Natal), Pietermaritzburg. The watershed is described by Hope (1980), and it has cover from a variety of rainfed agricultural crops, grasslands, and woodlands. The drainage area for Berea 6 in Figure 11 is 287 acres (116 ha), and the cover is a hardwood forest on "very shallow sandy loam soils." (details in see Hewlett et al., 1984). In Figures 10 and 11, CNs for natural (squares) and ordered (empty circles) data are shown.



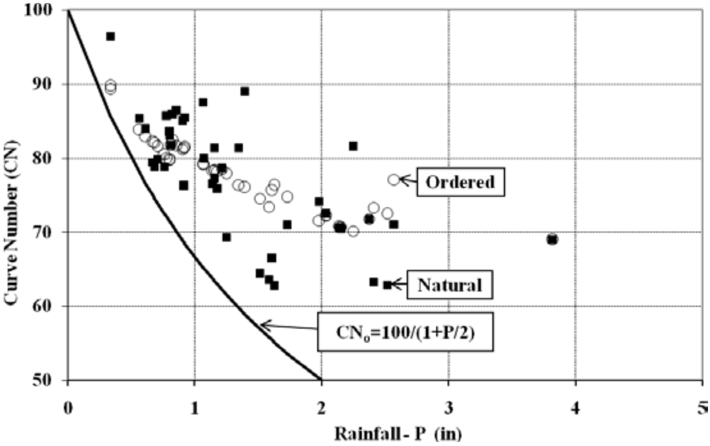


Figure 10. Standard CN response to rainfall. The upper figure is for Hastings, Nebraska, 44002 for 482 events from 1939 to 1967. The lower figure is for 44 events from Zulu 15 in South Africa.

The three main patterns above are observed with both natural and ordered data sets, though as shown it is more apparent with ordered data. However, only the Standard and Violent data cases are suitable for CN definition. The several phenomena and opportunities described above should be observed in extracting CNs from field data. For example, the rainfall–CN effect precludes determining mean CNs from small data sets, which will usually over-sample the smaller, high CN events, and thus lead to a high CN bias. The equilibrium values found at higher rainfalls will be more fitting to the higher rainfall design situation, and are a more stable measure of the watershed response. And finally, all watersheds do not follow the CN rainfall-runoff response pattern. Complacent behavior is not appropriate to the CN rainfall-runoff response.

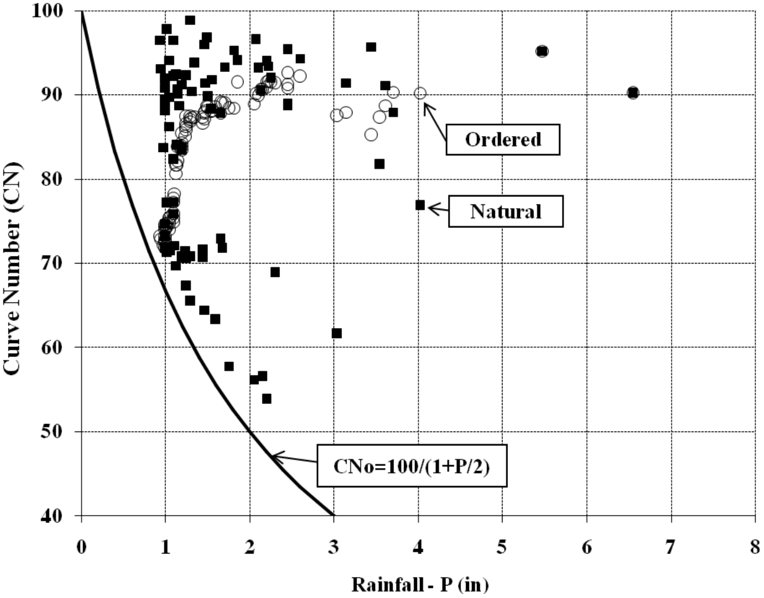


Figure 11. Violent CN response to rainfall. Illustrated by rainfall and runoff for Berea 6, Kentucky, covering 84 events from 1969-76 [data from USDA Forest Service].

Several other P-CN pattern clusters have also been observed, and are described here for perspective. The *Abrupt* pattern (or a low threshold form of Violent behavior), is characteristic of very highly urbanized and impervious watersheds, and is CN consistent. The *Inactive* grouping describes watersheds which show no event runoff over a long period of instrumentation. No CNs can be determined for this case. *Indeterminate* watersheds respond to rainfall, but in such a subdued manner that no clear or realistic association of rainfall data to runoff hydrographs can be made. These three categories are not relevant here. It should also be noted that the P-CN relationships described above also have corresponding expression in the P-Q plane (Hawkins, 1990a, b).

Alternatives to annual series: Most rainfall runoff data sets contain more than a single event per year sampling the rainfall-runoff process. Using an annual peak series provides only a single sample for an entire year, but respects the original NEH4 example and the accompanying notion that the method is intended only for annual peak calculation. In the interest of data economy (i.e., large samples) many investigators have used multiple events per year, on the assumption that the smaller storms express the same identifying hydrologic characteristics as do the annual flood events.

The above three considerations; data ordering, effects of rainfall depth, and sample selection/data censoring (i.e., annual series or complete series, and minimum storm size) dominate the choice of specific procedures applied.

Least Squares method: Here the task is to find the value of S such that it achieves the minimum value of the objective function, F, or

$$\text{Minimize } F = \Sigma[Q_{calc}-Q_{obs}]^2 \qquad [58]$$

where Q_{calc} is given from the CN runoff equation [1], including Q=0 for the $P \leq 0.2S$ condition, and the observed rainfall P, (or P_{obs} to be consistent above). Recalling the high-CN low-P effects, a consideration here is the lower limit of rainfalls. It is common to use all $P_{obs}>1$ inch, for example, or to censor the data so that $P_{min}/S>0.46$ (Hawkins et al., 1985). It does treat the quantity of interest, i.e., the direct runoff, and is perhaps the most intuitive method, especially when using natural data. It provides easily understood and traditional goodness-of-fit measures; r^2 and S_e. Negative values of r^2 (as a measure of variance reduction) are possible, and there should be no trend of residual error with P. Both ordered and natural data may be so treated.

Perhaps the earliest effort with least squares was by Walker (1970), who used a trial-and-error least squares fitting to storm runoff data from several small watersheds in Utah's Wasatch Front. Simanton et al. (1973), Springer et al. (1980), Cooley and Lane (1981), Montgomery (1980) and Montgomery and Clopper (1983), Curtis et al. (1983), Bales and Betson (1980) also used least squares fitting to arrive at values of S, apparently without a lower limit to storm size.

Asymptotic method: This method builds on the observation of CN as a function of P, and inserts user judgment into a major role. It deals with CN directly, rather than Q, and with both natural and ordered data cases. Event CNs are determined for both the natural and ordered P:Q sets, and CN (Y-Axis) plotted against P (X-axis). To outline the lower limits, the $CN_o = 100/(1+P/2)$ should also be shown.

A. From inspection, if a well-defined constant CN is apparent for the higher P values, then that portion of the data is isolated and the mean CN determined. This may occur with Standard, Violent, or Abrupt cases. This is the preferred method.

B. If the constant CN is not apparent, but there is a recognizable partial trend towards such a steady-state condition, then asymptotic least squares fitting may be done to extend the trend to the stable value. For Standard cases, the fitting equation is

$$CN(P) = CN_{\infty} + (100-CN_{\infty})\mathbf{exp(}-kP) \qquad [59]$$

The decay equation is structurally the same as Horton's (1939) infiltration equation.

For Violent cases, the following has been used

$$CN(P) = CN_{\infty}\,[1-\mathbf{exp}(-kP)] \qquad [60]$$

A variation on this is to use $P-P_{min}$ in the place of P, where P_{min} is determined by inspection or judgment for individual data sets. In both of the above the k's are fitting coefficients, and the fitted CN_{∞} is taken as the target CN. The aim in both equations [59] and [60] is to extend the trend to an expected asymptotically constant CN value at higher rainfalls.

C. For Complacent data sets, several options are possible, depending upon user goals. First, the CN search might end, acknowledging that the data is inapplicable to the CN method. The simple linear function Q=CP usually fits such data sets nicely, and is more appropriate to the suspected source processes. Second, the Standard fitting might be done, (i.e., equation [59]) acknowledging the insecurity and inapplicability of such extrapolation. Third, the simple equation

$$CN(P) = CN_o + k(100-CN_o) \qquad [61]$$

has been suggested and used (Hawkins, 1973), where CN_o is as previously defined, is 100/(1+P/2). With this form, as $P\rightarrow\infty$, $CN(P)\rightarrow 100k=CN_u$, which might be used as an identifying CN. These latter two (Standard fitting and Equation [61] above) should be seen as purely curve-fitting endeavors.

The k coefficients in equations [59]-[61] are not equivalent. The Complacent case is unsettling. It indicates low response, but with a large undeveloped, unmeasured runoff potential. While seemingly benign, it may perform as a lead-in to the high-response Violent pattern at some unknown higher threshold, above which runoffs and flood peaks may be orders of magnitudes greater. This rainfall threshold may be either just above the largest storm in the data set, or well beyond human experience. Thus, extending experienced Complacent behavior beyond the data to higher rainfalls contains some risk. This uncertainty, and the definition of the threshold based on storm and watershed factors, is worthy of further investigation.

For the Standard asymptotic fitting via equation 59, it is tacitly assumed that the CN_{∞} - taken as the watershed CN - is appropriate for remote return period rainfalls (P). That is, that the equation with large values of P calculates CN(P) that closely approaches CN_{∞}.

This assumption has not been widely tested. In fact, McCutcheon et al. (2006) suggest that with the heavily forested watersheds of their experience, the transient values, i.e., CN(P), are important, and should be applied. This is tantamount to a non-constant, P-defined CN, a notion at some variance from the original concept of S as a limit of F, and from current practice and handbook values.

In addition, the runoff-response group assignments are made via judgmental inspection of plotted data. A declining CN with P without a hint of approaching a stable value might interpret as a Complacent pattern, a potentially Violent condition, or merely an incompletely developed Standard response. These should be treated differently.

From experience, ordered data gives the most consistent and reliable results, and makes better use of the available data resources. CNs determined for ordered data are usually1to 3 CNs higher than those from natural data. Also, from experience, a minimum sample size (N=number of P:Q events) is about 30, though some settings produce more consistent storm-to-storm behavior, and a smaller sample (ca 15) may suffice. As with most data requirements, more is better.

Distribution matching method: This method treats both P and Q as distributed (i.e., random) variables, and seeks the CN that best transforms the P distribution to the Q distribution via the CN runoff equation. This was first developed in several works by Hjelmfelt (1980b, 1983), Hjelmfelt et al. (1982), and Hjelmfelt et al. (1983). The P and Q distributions are displayed on lognormal plots, and the calculated transformation, or the CN that best recreates the Q distribution from the P distribution is determined visually. The Hjelmfelt (1980b) paper gives four examples with good fits, but an aberrant data set – displaying complacent behavior - was also shown, giving an early suggestion that not all data sets conform to either the distribution transform notion, or to the CN equation. However, this approach is in line with the frequency matching interpretation application mode of the CN method.

Enlargement and formalization of this approach was done by Bonta (1997) who used "derived distributions" and statistical testing to replace Hjelmfelt's visual fits. Using a trial-and error procedure varying CN, he used the Kolmogorov-Smirnov test to determine the best fit between the cumulative distributions of calculated P (back-calculated using observed Q and the CN equation) and observed P. The P:Q data was censored to P/S>0.465. He determined CNs for a number of Standard and Violent data sets, but was unable to achieve satisfactory fittings with Complacent data, which was in keeping with Hjelmfelt's findings. It should be noted that while the lognormal distribution was used, it is not intrinsically required by the CN method.

This general method of matching the observed and P-CN generated Q distributions has also been recently applied by McCutcheon et al. (2006) in determining CNs from forested watersheds in the southeastern US.

Fitting to continuous and event hydrograph models: As described elsewhere in this report, CNs are used frequently in continuous models in a soil moisture management mode, so the underlying CN(II) can be treated as a fitting variable. When so treated, a descriptive CN can be determined via the usual techniques of model calibration. Also, when the flood peak is of primary interest in event hydrograph models, a CN can be chosen that produces the observed peak, regardless of the volume considerations. This approach was used by Titmarsh et al. (1989), and Titmarsh et al. (1995, 1996). This general model fitting method was also pursued - though not centered on flood peaks - by Garg et al. (2003).

However, insofar as these methods use CN with other interacting/competing components in the model, they mask/confuse the independent role of CN. Continuous models with assumption of soils moisture thresholds, drainage, and evapotranspiration are examples. Furthermore hydrograph models intertwine the direct runoff pulses and their sequences dictated by the CN equation with routing procedures. Thus, the elemental CN feature - a function of only P and Q - is not isolated in these cases.

CNs from rainfall simulation plots: While usually done to measure site infiltration properties, rainfall simulation plots offer a tempting avenue to utilize the accompanying P and Q data to provide CNs. In addition, the hope remains that CNs – like infiltration measures – are unique measures of site hydrology – and should be tightly related. Because of the small plot size, routing considerations are assumed to be minimal, and runoff is taken to be identical to rainfall excess. By their very nature they assure that overland flow is the dominating process. Additional positive attributes are the high quality of the rainfall measurement, usually at several points over the plot area and along the plot boundaries, and the ability to visually observe the flow generation in some detail.

Several problems exist in these attempts. First, the rainfalls applied are almost never a valid sample of the site's resident rainfall across all seasons, depths, durations, and intensity patterns. Applied rainfalls are usually at a fixed duration (0.5 to 1.0 hour are typical) and uniform intensity, typically 25, 50, 75, or 100 mm/hr. Additionally, infiltration capacities as measured in such environments are usually found to be intensity-dependent (Hawkins, 1982). While this is consistent with the CN equation, the CN equation leads to an infiltration rate form which achieves a stable equilibrium rate of zero, in contrast to observed positive steady-state values greater than zero for almost all reigning infiltration formulations. The P and Q generated may hang on what may be arbitrarily selected measurement protocols. In fact, CNs so generated tend to be inconsistent and variable with the above factors.

Nevertheless, such direct CN interpretations have been made and discussed by several investigators, including Sabol et al. (1982), Steichen (1983), Partsch and Jarrett (1991), and Kuntner (2002). A slightly different approach was used by Hawkins (1979a) who fitted the CN infiltration rate equation to plot infiltration rate data. Numerical infiltration-based simulations to simulate rainfall-runoff with real break-point rainfall data were performed by Pierson et al. (1995), and produced credible – though variable – CN:P relations.

Indirect fitting of CN to sprinkler infiltrometer data was done by Wood and Blackburn (1984) who compared predicted runoff Q (based soil and cover based handbook CNs) with observed runoffs from 1200 rainfall simulation plots runs at 12 range sites in

Nevada, Texas, and New Mexico. They found generally poor comparisons, and attributed these results to the inappropriate assignment of Hydrologic Soil Groups for arid rangelands.

Summary: In brief, the major methods for CN determination from watershed rainfall-runoff data are:

"*NEH4 Method*": *Means or medians* of groups of event CNs, with the *median* of annual q_p events being the default historical NEH4 handbook example. However this approach avoids the known tendency of found CNs to decline with storm depth P, and may bias towards high CNs. An inconvenient interpretation is that when using the annual q_p series, the median CN defines the 2-yr return period CN. Also, the use of only one event per year requires a corresponding long period of record to gain a statistically-comfortable large sample size. Because of this long-record requirement (one data point per year), shorter term or transient land use effects – such as fires, seasonal cropping practices, silviculture activities, and grazing, may be quite difficult to detect.

From an operational standpoint, one clear appeal of the method is its intrinsic simplicity. The historical precedent and authority issues make it the default standard. This method is most appropriate using natural data, though ordered data can be used.

Least Squares fits to a large number of P:Q events. This is a familiar curve-fitting technique that gives well-known goodness-of-fit statistics. However, the CN-P problem described directly above occurs here too, and the biasing effects of high CNs for small storms can be dealt with by using only the larger storms, such as P>1", or for P/S>0.46. Using natural data makes the best use of the least squares capabilities and is consistent with the original rhetoric that developed the CN equation: i.e., individual events and variability around a central trend.

Asymptotic fitting, which recognizes the different runoff response patterns and the observed CN-P relationships. It provides a CN_∞, or the CN as P (and its return period) approaches infinity, and the parameters for intermediate events. Also it recognizes that not all P:Q data sets fit comfortably to the CN equation, i.e., the Complacent case. This is the method recommended for NEH630 adaptation by the ARS/NRCS Curve Number Working Group. (Woodward et al. 2003). Ordered data has been found to work well with this method. Additionally, as practiced, it makes economical use of the data by selecting events form the entire data record, not jus the annual events.

Frequency curve transformation of P to Q via the CN equation meets the return period matching application of the CN method, but is not appropriate in all cases: in particular, if the annual flood peak CNs displays a trend with rainfall. This method is, however, fully appropriate to the P-Q return period matching mode of application.

Other methods are also found. Though not uncommon, fitting with continuous models or complete hydrograph models complexes the CN rainfall-runoff effects with other model processes, though this approach is not uncommon. There is little justification or fixed protocols for using rainfall simulation-infiltrometer results to find CNs with present techniques.

Methods comparisons: Given the several approaches to extracting CN from data described above, the CNs generated by each may be different, and make different fundamental definitions of CN. Thus, method used should be appropriate to the intended application. The best fit CN from an annual series analysis (the NEH4 method) may not make the best CN for use in continuous models. General response descriptions reflecting and runoff event variety might be best achieved with least squares fits to natural P:Q data sets.

In addition, the data choices (ordered vs. natural, annual peaks vs. all significant event, etc.) lead to different CNs, as will differences in the fitting criteria. For example, asymptotic fittings to ordered P:Q data usually give CNs 1-3 units above those for natural data. Outside of the "NEH4 method" - with known limitations as described previously - there does not seem to be a general consensus choice. As future data sets are developed, this should be a fruitful ground for further research and inquiry.

PERFORMANCE COMPARISONS

CN table comparisons: A measure of the method's utility is the ability to accurately estimate CNs from soils and land information, and thus the ensuing runoff response. Several studies have tested this feature. Hawkins (1984) compared handbook estimates against P:Q defined (mainly as means and medians) 110 watersheds, and found essentially no relationship overall. When land types were considered, the best estimates were for rain-fed agricultural watersheds, and the least accurate were for forested watersheds. Later, similar studies by Titmarsh et al. (1989, 1995, and 1996) used the entire hydrograph modeling process to make similar comparisons, and came to similar results, as shown in Figure 12. From these two studies, the CN tables and their use (soils) do not compare well with the reality suggested from gage data. It would be worthwhile to repeat these studies using current data-based CN identification techniques.

Studies giving similar results are also provided by Fennessey (2000), Fennessey et al., (2001), Hawkins and Ward (1998), and Bales and Betson (1980). A study by Woodward (2003) with 97 urban watersheds with at least three years of data gave a reasonable comparison between the *average* data-defined (average CNs for each site) and handbook (i.e., from TR55). The average data-defined CN for the 97 watersheds was 85, and from the handbook tables 86. CN correspondence for individual watersheds varied considerably. A plot of the results from Hawkins and Ward (1998) is given in Figure 13. This figure highlights a problem in such analyses: several different tables and charts in local or regional usage were available for the "handbook estimates," and gave different results.

On the other hand, as described previously, Hansen et al. (1981) used least squares to find CNs on 25 small watersheds in Montana, Wyoming, and South Dakota, and found general agreement with handbook values. They used the peak events plus any summer runoff events with greater than 6 mm of runoff.

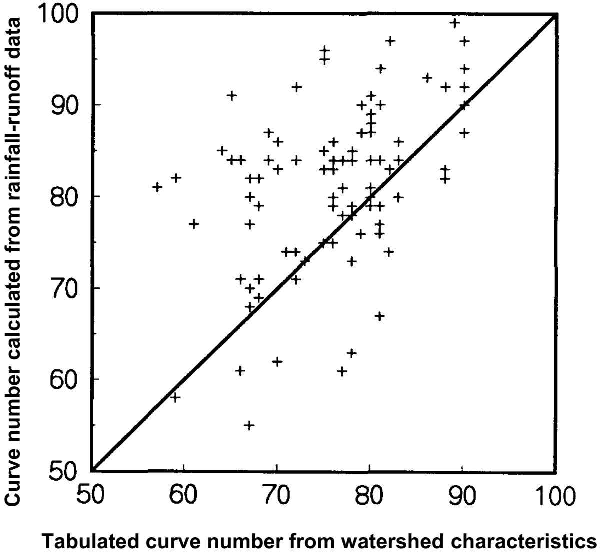


Figure 12. Comparison of CNs from watershed soils and land use with data-defined CNs. From Titmarsh et al. (1989, 1995, 1996).

Green-Ampt comparisons: In recent years, CN critique and more advanced demands have sought alternative means of modeling event rainfall excess. Essentially all of these are infiltration rate driven, with most prominent candidate being the Green-Ampt (Green and Ampt, 1911) equation, one form of which is

$$f(t) = Ke(1+n\Psi/F(t)) \qquad [62]$$

where f(t) is the loss rate (L/T), K_e is the effective hydraulic conductivity (L/T), n is the porosity, Ψ is the soil matric suction (L), and F(t) is the accumulated infiltration (L).

This has the justification of a process-based model: It springs from Darcy's equation and soil physics, and automatically incorporates storm intensity and distribution effects. Although it is a point expression, it is used as a loss rate function in numerous event and continuous models, and several performance comparisons – without calibration - against gauged data have been made. Wilcox et al. (1990) tested it on rangelands on daily, monthly and annual time scales, and found utility in the Green-Ampt approach, but that the simpler CN method simulated runoff "about as well."

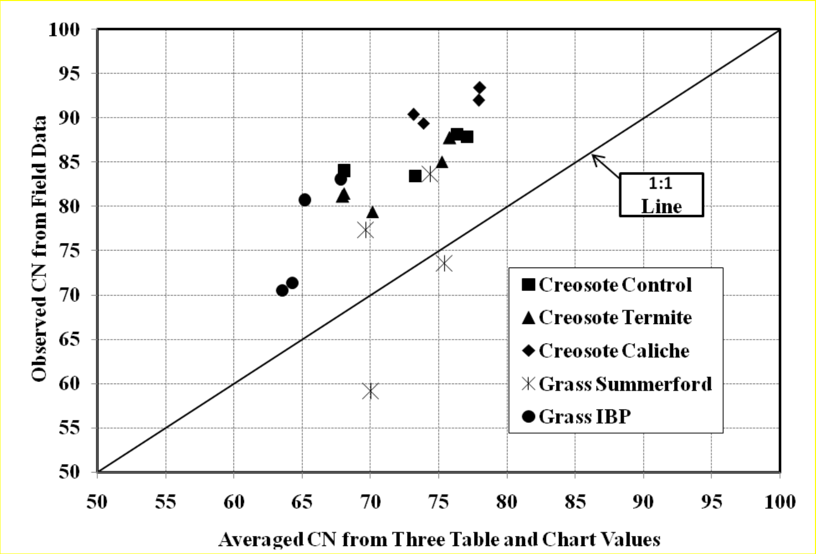


Figure 13. Observed Curve Numbers (CN) and various handbook table and chart estimates. Data from 21 runoff plots at five sites at Jornada Range, NM. Observed CNs are determined by asymptotic analysis. (Data from Hawkins and Ward, 1998)

Van Mullem (1991a, b) compared runoff depth and peak flows against measured results on 12 western rangeland watersheds using recorded storms, both the Curve Number and Green-Ampt loss functions, and the unit hydrograph techniques given in SCS TR 20 (USDA, SCS, 1982). No calibrations were done: CNs and Green-Ampt parameters were taken from standard sources. For this study, the Green-Ampt based model performed better in both average and event basis for both the runoff depths (Q) and the peak flows (qp). The CN method did especially poorly for the smaller rainfall events.

Comparison with Rational Method: Investigations by Montgomery (1980) and Montgomery and Clopper (1983) examined event runoff on a number (7 and 6 respectively) of small ARS watersheds, and concluded that "The CN method is not substantially better than the rational method for predicting storm runoff." Here the "rational method" was in an abstracted form, i.e., $Q=C(P-I_a)$, and fitting the curvilinear CN equation yielded r^2 values that were not significantly different at the 95% level.

Multiple comparisons: Using split samples and data from fourteen (14) western watersheds, McGurk (1982), and McGurk and Hawkins (1983) compared the ability of four different methods to predict rainstorm runoff volumes. The four methods were the ϕ-index, the runoff ratio Q/P (i.e., the rational method), a modified infiltration kernel from the Stanford model (i.e., a distributed loss rate), and the Curve Number method. The results showed the simple runoff ratio to be the best method, and the Curve Number the least successful.

For two different watersheds in North Carolina, Generaux (2003) compared return period flood peaks calculated by 4 different methods, one of which was the TR-55 procedures (USDA-SCS, 1986), which incorporates the CN method for generating rainfall excess. While TR55 gave the highest peaks, no two of the methods were in close agreement: There was no clear preferred method. Zarriello (1998) compared the observed and the modeled peak flow results for six storms from nine uncalibrated models applied to two urban watersheds, one in the Denver area, and one in the Seattle area. Three of the models (HEC-1, PSRM, and TR20) used the CN method to generate runoff. "..the models based on the SCS curve number had the poorest fits."

APPLICATIONS to/with REMOTE SENSING and GIS

The advent of remote sensing encourages detection of land characteristics and cover from observed spectral properties. Insofar as Curve Numbers are related to soils and cover, the joint use of Geographic Information Systems (GIS) and soils data bases (like SSURGO (USDA, 1995)) permits the estimation of table-based CN over widespread areas. Usually this is pursued as follows:

1. Remotely sensed scans of the earth surface provide several bands of spectral information.
2. This is related on a case-by-case basis to ground cover.
3. In a GIS environment, soils data – incorporating HSGs - is superimposed on the cover.
4. Soil and cover combinations are converted to CNs with look-up tables combining soils (HSGs) and cover types, using published or accepted CN tables (e.g., Table 2 here). In much of the literature, this step is assumed without explicit statement, implying a routine task, and equating the status handbooks tables to that of (say) tables of Manning's "n".

After selection, these distributed combinations of CN can be used in continuous or discrete storm models, such as SWAT (Nietsch et al., 2002), HEC-1 and PSRM (DeBarry and Carrington, 1990), or AGNPS (Young et al., 1989). This strategy allows for the variety of hydrologic responses to be considered.

The procedure – including finding an area-weighted CN and the runoff calculation - has been institutionalized in GIS systems. For example, with ArcView, an extension called ArcCN-Runoff (Huang and Zhan, 2004) is available as a download from the ESRI Support Center site (http://arcscripts.esri.com), and "…generates[s] maps of curve number if soil (hydro group) and land use data provided."

Note that this strategy merely uses the remote sensing and GIS to identify land uses to overlay with soils data. The remotely sensed information is used much as basic photogrammetry might be: the spectral information and reflectance are not fully exploited to identify intrinsic hydrologic properties of the sites directly, but rather to identify cover clusters. CNs are constructed from existing handbook CN tables, which are taken to be reliable and/or authoritative.

A few notable remote sensing studies have attempted to isolate soils properties and/or data-based Curve Numbers directly from various spectrally-related measures. Early studies tied CN to hydrologically-defined CNs, with some success (Sneller 1985; Zevenbergen 1985; Zevenbergen et al., 1988; Blanchard and Bausch, 1978).

A creative application is given by Jacobs et al. (2003), who used remotely sensed soil moisture data to improve CN runoff estimate on the Southern Great Plains. This not only initiates the application with soil moisture, but suggests that previous studies on moisture-runoff relationships may have suffered for lack of adequate areal representation. It should be noted that the remotely sensed associations are with handbook/table CNs, which are only soils-and-cover-based estimates of the ideal ground-truth hydrologically-defined CNs.

Comparisons between the two - which suggest inconsistent predictive abilities - are made elsewhere in this report. This issue is made more cogent by the imprecision in estimating the Hydrologic Soil Groups, as also described elsewhere here (Nielsen and Hjelmfelt, 1998). However, when used en masse in hydrologic models there seems to be an averaging of errors that may lead to reasonable outputs.

CURRENT USAGE AND PROFESSIONAL PRACTICE

Professional practice rests on acceptance of results and methods by approving jurisdictions. Practical application requires something that “works” routinely for specific areas and situations, implying technical credibility and authoritative origins. Professional responsibility, augmented by judgment becomes a major factor.

Accordingly, many day-to-day practices rely on the authority of accepted manuals, handbooks, or textbooks, and not necessarily current scientific investigations or recent data. A good example of this is the persistence of the climate-based AMC categories, which have been disavowed by SCS/NRCS formally and informally about the last 25 years, but which continue to survive in practice and in several widely-used models and continue to be reproduced.

Authority: Thus, insofar as NEH630 and NEH4 bear the authority of a well-know federal agency, the CN tables, charts, and procedures tend to be accepted, and the methods incorporated into larger packages. CNs from handbook tables and charts based on available soil surveys and recent cover (often by remote sensing and GIS) are used by default. Event-based local CN calibrations, while admirable, are rare, as little might be gained by departures from handbook precedents and traditions. Smith (1997, p146) described the underlying motivation “…that should be admitted by all engineers, i.e., that it is a method in a publication of, and supported by a U.S. government agency that gives the users basic protection in a case of litigation. Anyone dubious of the significance of this rationale has not worked in consulting engineering.”

Nevertheless, a wide variety of local manuals, agency techniques and adaptations, both formal and informal can be found. Given the protean nature of the CN method, it finds application and adjustment locally, and within various agencies. Also, in efforts to match local judgments or special situations with the CN method, local adjustments may be made. Thus, the CN method is a tool that has been used creatively and freely to meet needs not otherwise serviced.

Myths, misunderstandings, misapplications, and misconceptions: Perhaps because of its popularity, ease of application and transparency, the method is often easily misrepresented, misunderstood, and misused in professional practice. A number of such misstatements or myths encountered by the authors are covered here, and might be seen as paraphrased Frequently Asked Questions (FAQs). These cover outright misunderstandings and unsupported technical assertions.

- *"There are files or documents on record supporting the statements in NEH4 and the CN method."* Unfortunately, most of the files and supporting data used in the development have been lost, destroyed, or misplaced over the years. In addition, it never underwent a critical open review, and the supporting data were never published. Only the tradition, written summaries, the customs of entrenched usage survive. The institutional memory is starting to pass also.

- *"Table CNs were determined from uniform small watersheds around the country."* Hopefully this is so, but lamentably the record on the matter is sparse. It is known that most of the basic information was taken from small agricultural watersheds in humid settings, but without much basis in fact for deserts, forest, or urban watersheds. In addition, there is some indirect evidence that data from small river basins were also used.

- *"The handbook CNs are factual, credible, and documented."* While there is some basis for this in fact, they seem to be predominantly estimates and/or conventions, or judgments based on soils and vegetation to be used in the absence of local data. They are of a similar ilk to the Manning's "n" used in open channel hydraulics. By their nature, CNs are most validly defined by what actually falls on a watershed (P) and comes off of it (Q), and not from handbooks or tables. An additional problem is that local jurisdictions have adopted CN tables for administrative purposes (planning and design) based on local judgment, experience, choice, or precedent, but without data-based documentation or pedigree.

- "*It's a flood peak method."* In fact, it's simply a rainfall-runoff depth (i.e., volume) method, providing rainfall excess, but not rates. A triangular hydrograph methodology developed at the same historical moment was (and is) included in the same agency handbook, but is really not the CN method. The CN method is often used to generate the input to a flood peak method, but is not by itself a flood peak method.

- "*CN maps out 1:1 on infiltration capacity parameters*: *or, if the infiltration parameters are known, then so is the CN, and vice versa."* This is simply not so: the two notions are different. While HSGs are loosely defined in infiltration terms, other runoff source processes and the variety of storm depths and intensities makes the assertion true only under quite specific conditions.

The basic conflict between popular infiltration rate equations and the CN method is that there is no time dimension in the CN system. Beyond that, when a time dimension is assumed and superimposed then 1) most infiltration equations have a positive steady state rate (such as K_s, f_c), and for CN it's zero; and 2) an intensity-sensitive effect in the CN equation. In addition, some watersheds respond to rainfall without infiltration-dominated processes.

- "*It's overland flow only…. It's infiltration excess driven.*" While figures in the original handbook showed infiltration excess diagrams, other handbook qualifying statements and subsequent wider analyses have shown it to fit a spectrum of generating source processes, including quick flow and mixtures with direct channel interception. Everything is covered as direct rainfall response.

- "*It's an infiltration equation.*" This is similar to the above point. As shown elsewhere here (see equations 34-36 and related text), the CN equation can be contrived to be an expression of losses to rainfall with time. Furthermore, application of it in hydrograph models exploits the relationship. However, not all real-world watershed "losses" to flow are comparable to infiltration theory and fact. At the watershed level, other processes such as channel interception and quick return flow may also be in play. While the quick return flow process does invoke infiltration (usually equal to rainfall intensity), it also contains a rapid drainage feature. Only if infiltration – with sustainable retention – is the sole process producing rainfall excess, can the CN equation be validly compared with traditional infiltration equations, albeit representing the effective infiltration losses from an area with spatially varied properties. Also, its profound differences from the traditional point infiltration equations, such as its response to intensity, and a zero final rate should be acknowledged.

- "*'AMC' is the 5-day prior rainfall depths from Chapter 4 in NEH4.*" The term AMC (Antecedent Moisture Condition) has been modified to "ARC" (Antecedent Runoff Condition) to encompasses all sources of variation from the central trend of rainfall-runoff. While prior rainfall may induce such effects independently, the concept suggests ARCs as general "error bands." Current NRCS manuals and technical releases no longer include the 5-day prior rainfall tables. The M in AMC does not necessitate "moisture."

- "*It's a site model, responsive to soil moisture.*" This is similar to the above. Unfortunately, data analysis only mildly supports this assertion.

- "*S exists as limit of F as $P\rightarrow\infty$.*" This is a technical assumption that becomes an article of faith, but not widely affirmed by data. Most P:Q data sets fail to demonstrate it, and in the cases where it is shown it's on the more impervious surfaces, higher CN watersheds, and in climates with plentiful large storms. In addition, the limit between P and Q is 1.2S, not S, including I_a.

Similar to the above, it is claimed – in continuous models, for example - that CN defines S, which defines soil moisture storage limits. This is a tempting idea: S=soil depth*water-holding porosity, but evidence of this idea is evasive in hydrologic data analysis.

• "*All watersheds act this way… that is, concave upward and approaching a constant loss depth.*" Surprisingly, most do, at least with higher rainfalls. But other variants also exist that cannot be ignored, and are inappropriate for CN application. All watersheds do not respond to rainfall in a manner consistent with the CN equation.

• "*CNs are regionally consistent. That is, same soils and cover lead to the same CN no matter where.*" There is much evidence that this is not so. Climatic variation in number and amounts of storms and storm types with resulting soil moisture changes lead to different rainfall-runoff regimes. This is best illustrated - and documented - by the Texas experience, described in this report.

• "*Soils-hydrology classifications are reliably determined by a known open, scientific, objective process*." In the US, these classifications are done by agency soils scientists using professional judgment and precedent. There is no general pan-scientific key for arriving at soils grouping objectively on the basis of texture, depth, structure, cover, or climate. Fuzzy logic studies suggest that the current classifications are good only ± 1 HSG.

• "$I_a = 0.2S$." While this is integral to the development of the method, the available evidence gives little encouragement. Later work has shown that $I_a/S \approx 0.05$ is closer.
While it's of minimum importance through much of the applied range, it is quite important at the high and low extremes of P/S. However, users should not change the I_a/S ratio and then continue with the established CN tables, which are based on $I_a=0.2S$. Some suggestions for making appropriate adjustments are given elsewhere in the body of this report.

• "*It only works for BIG storms*." This is intuitively important, but few studies have treated it. Much rests of the definition of a "big" storm. A storm of P=0.50 inches may be "big" on a paved parking lot, but a storm of P=2 inches is small for a well-forested watershed with deep soil. One way to treat this problem is to apply it only for P/S greater than some threshold level, such as 0.5, or its Q/P equivalent of about 0.14.

• "*Since rainfall isn't determined very closely anyway, why worry about having a precise CN?*" Several sensitivity studies have shown CN to be the single most influential variable where used in rainfall runoff models and clearly so. Simply stated, it's more important to have good information on CNs than good information on P.

• *"Are CNs from small data sets valid?"* In CN analysis, small data sets may lead to misleading CN estimates. Almost all data sets display a distinct secondary P effect: Small storms have high CNs, larger storms have smaller CNs. This counter-intuitive trend should be taken it into account, despite the acknowledged spurious correlation created by using P is used to get the CN from the P:Q data.

Creativity in professional practice: A number of practical choices, judgments, and user techniques arise in using the CN method in practice often to meet conditions or assumptions not included in the original release. Some example of these are covered and discussed here.

- *Mean CN for a mixed CN watershed.* This technique calculates the runoff using an area-weighted mean CN, and the corresponding "S" with the runoff equation. This shortcut has the appeal of simplicity, and is defensible with a narrow spread of CNs. However, the question is becoming moot, as most modern models can treat mixed CN sources as independent source areas, and make a volume weighted mix of the rainfall excesses. This option seems to be preferable.

- *Adjusting handbook CNs for local climate.* This claim spins from an argument of the following genre: It's always dry here, so we should use the CN(I). Often this leads to client-favorable lower design flood peaks and reduced detention storages requirements. However, CN(II) is the local reference CN for the site soil and cover status, regardless of the climate, and is the CN for annual flood series to be used in design. There is little justification to use ARC I or ARC III in design. Runoff and CN variation results from more than mere variations in site moisture.

Such assertions can be resolved by sidestepping handbook estimates and calibrating local watersheds for CN based on experienced P and Q. In such a spirit, a recent study (Thompson, 2004) documented a significant drop of CN (as compared to handbook expectations) moving from east to west across Texas.

Several other creative examples can be cited. San Diego County adjusts CNs via fractional AMC categories for watershed location and storm size (San Diego County, 2003). Standardized design methodology in southeastern Arizona adjusts CN upward for maximum 1-hour storm intensity in order to align computed peak frequencies with local observations (Zeller 1981; Simons, Li, & Associates, 1995).

- *Alternative values of I_a/S.* Some users have found different values of $\lambda = I_a/S$ to be more appropriate or pleasing to local applications. This is encouraged by a realistic inspection of the original I_a/S plots in NEH4, and by recent research that finds $\lambda = 0.05$ to be more typical. However, adjusting I_a/S also affects the handbook CN tables entries. Current tables are based on $I_a/S = 0.2$. So far, only a single data-based study (Hawkins et al., 2002) makes conversions between CNs with the two assumptions.

A related issue is whether I_a/S can exceed 1.00. Such cases do occur – albeit rarely - with analysis of data. Algebraically the constraint of $P > \lambda S$ ($Q = 0$ otherwise) still dominates and keeps the numerator from becoming zero or negative. That is, λS is greater than $(1-\lambda)S$ in the general equation $Q = (P-\lambda S)^2/(P+(1-\lambda)S)$ for $P > \lambda S$.

CRITIQUE

Given its coarse-grained origins, widespread use well beyond original capabilities, crucial technological niche, approximations to processes, and three different non-congruent modes of application, it is not surprising that the CN method has numerous critics. For example, Smith (1978) elaborates on its failure as an infiltration process as follows:

> "1. The CN methodology cannot respond to differences in storm intensity… It cannot distinguish between the effect of 4 inches of precipitation in 1 hour, and 4 inches in 12 hours, although both the infiltration amounts and runoff rates would be considerably different.
>
> 2. Closely related to the above, the SCS methodology does not properly predict initial abstraction (I_a) for shorter more intense storms, since it assumes (I_a) to be constant.
>
> 3. The method cannot be extended to properly predict infiltration patterns within a storm. Attempts to use the CN Method within a storm have highlighted its physical invalidity - the resulting infiltration decay curve ($P>I_a$) is forced to rise and fall with rainfall rate, rather than controlled by soil conditions as in nature.
>
> 4. The CN Method postulates a maximum depth of infiltration (S), after which all rainfall becomes runoff. Selection of an S to approximate response to short storms can produce poor results for extended storms. Existence of such an S is not physically supported."

Critical examinations in more detail are given in thesis work by Clopper (1980), and by Montgomery (1980). A fundamental critical analysis of the method and many of its assumptions was given by Hjelmfelt (1991). Discussions by Smith (1997), Golding (1997), and Willeke (1997) further elaborate problems in application, the questionable justification for its continuation, and the lack of adequate review in its original offering. All are legitimate observations. A thorough and discussion-provoking treatise on the method's misuse, misinterpretation, and acceptance is given by Garen and Moore (2005a, b) and Walter and Shaw (2005). A lengthy and entertaining critique of urban hydrology methods, including the CN components, is given as "Voodoo Hydrology" by Reese (2006).

Numerous additional concerns as well as many of the above have been brought out in the course of this review. Many of these are developed as recommendations in Chapter IV following.

IV. SUMMARY, CONCLUSION, DISCUSSION, AND RECOMMENDATIONS

SUMMARY AND CONCLUSIONS

Origins: The CN method arose in the mid-1950s to meet specific program needs of the Soil Conservation Service, and was developed in accordance with the current technology, data, and the urgency of the situation. From an administrative standpoint it met the agency's needs admirably. From a general hydrology standpoint, it filled the waiting technological niche.

The method simply intended to calculate a rainstorm's direct runoff depth Q (inches) from a storm of depth P (inches) given a land condition index, Curve Number (CN). CN in turn depends on soils, cover and land use, and (perhaps) soil moisture. The agency provided table values of CN for an array of different soils and land use combinations, and the method has been in use since.

Evolution: Because of its role in agency programs and the imprimatur offered by this association, and because it filled the prevailing conceptual notions of rainfall-hydrology, it soon became adapted outside of the original agency intent, and expanded to opportune newer applications, in both engineering and land management circles. As issues arose in the user community, an inevitable closer examination of its functions and background also occurred.

As a result, a number of inevitable adjustments, enhancements, redefinitions, and clarifications were made, and the method grew in response to awareness and critique and newer needs. The SCS pioneered and supported much of this evolution. For example: The role and nature of the AMC relations was transformed to "ARC;" the inclusion of I_a as an addition to S was restated and clarified; new CN tables were developed, application to urban settings was espoused and demonstrated; and the several modes of application of the method were elucidated and recognized. The prospect of changing λ from 0.20 to 0.05 on an institutional basis is currently (2008) under consideration.

Non-agency sources have also explored, tested, developed, applied, extended, challenged, clarified, and re-expressed the method to a level well beyond the original offering. Frequency interpretations were given; limits of appropriate application were demonstrated; techniques for the hydrologic definition of site CNs were developed; new lands and land use types were tested; mathematical expression of the method and its derivatives were created; shortcomings and needs were demonstrated. This development and evolution continues.

Adaptation and survival: Changing societal needs and new technologies have utilized the CN concepts widely. Via science and professional development and a free-market environment for the technology, the CN method has provided component tools or building blocks for much of what is currently used in environmental and water resource management. Perhaps the best example of this is its wholesale incorporation of the CN method's inferred soil moisture dynamics into the driving hydrology in continuous water quality models. Simultaneously, computer driven models, satellite data collection, and Geographic Information Systems were not available at the methods outset in the 1950s, but all have opportunistically combined with Curve Number concepts.

In addition, creative in-house adjustments have solved some application difficulties. The regional CN adjustments in Texas are an example of local modification (Thompson 2002, 2004)

General hydrology: A subtle but important default role is that the CN method has given "form and example to questions that would exist with valid content in the absence of the CN method: The CN method merely becomes the discussion point, and serves as a lightning rod for general rainfall-runoff hydrology. Perhaps this is its greatest asset." (Ponce and Hawkins, 1997). For example, it gives substance to larger unresolved issues of rainfall-runoff hydrology. Some of these – in CN terms – are: (1) does "S" exist in all cases: i.e., is there a limiting loss; (2) are the characteristic nonlinear asymptotic forms of the P-Q phenomenon applicable in every setting; (3) can land-use effects on runoff be effectively quantified; (4) What is the importance of rainfall intensity factors as compared to ambient moisture; and (5) how should censored (threshold) data be treated?

In addition to these conceptual templates it provides, it also gives a vocabulary of reference names or "handles," such as Initial Abstraction, AMC (site conditions at the storm's onset), and certainly the CN itself (a measure of a land's characteristic response to rainfall). The watershed storage index "S" leads to scaling rainfall and runoff on the capabilities of the watershed, and offers relative perspective to the notion of "big" or "small" storms.

Current status: The above history has led to the current status, in which the Curve Number method is alive and thriving in engineering and land and environmental management circles. Though no metrics are available, popular current uses are 1) event hydrology modeling, generating rainfall excess for the subsequent hydrograph generation; 2) continuous models where it plays a soil-moisture management function as well as generating event flows, and quite often with water quality tie-ins; and 3) as a hydrologic concept tool box, or "poster boy" surrogate for hydrologic reality. The current situation must also include 4) the ongoing barrage of examination, testing, critique, and development to new applications that the method invites.

As outlined in the body of this report, almost every aspect of the original CN method has undergone examination, extension, critique, improvement, or amendment. That is: the equation itself and its development, CN tables, Hydrologic Soil Groups, roles of prior rainfall and site moisture, modes of application, calibration, site moisture and soil physics, initial abstraction, application limits, climatic and seasonal effects on CN, and the spatial distribution of upland processes. In short, very little of the original technology survives unchallenged.

DISCUSSION

Is it science? Scientific hydrology circles and journals have generally ignored the CN method, regarding it as a engineering method devised for administrative purposes. Nevertheless, the soft boundaries between science and engineering invite scientific inspection.

In this regard, it is useful to view the CN method in the same light as Manning's equation: a semi-empirical engineering method, and which uses selected table coefficients (roughness "n") with a tradition of use and acceptance, but strictly only applicable to a certain set of conditions (normal, uniform, steady flow). Interestingly, as needed, the CN method is extended, extrapolated, approximated, and used beyond the proper limits, as is Manning's equation.

In the culture of science, the heart of the CN method – particularly those parts describing processes - might be described as a series of falsifiable hypotheses, and thus subject to examinations, testing, and rejection. Thus, the various component hypotheses, which spring from the original assumptions and the development, can be evaluated in this setting:

S exists as the limit of (P_e-Q): Despite the image of a finite water storage capacity in a soil profile, field data at the small watershed level as evidence of a fixed difference between P and Q has been limited.

$Q/P_e = F/S$: This is the original proportion loosely justified on the basis of equality at extremes. It leads to the CN equation $Q=P_e^2/(P_e+S)$ and its characteristic shape on the P:Q plane, so that the equation speaks for the original proportion. In general, the shape is correct (it matches field observations and theory), monotonically concave upwards, and not exceeding a 1:1 slope. But as described above, it manifests the definition of S, which is only rarely demonstrated. That is to say, the equation is only partially affirmed.

However, the equation itself has also been derived from more basic assumptions (Schaake et al., 1996; Yu, 1998) in a distributed system. As described elsewhere in this review, an alternative starting point of dQ/dP =F/S also leads to an acceptable runoff function, $Q=P_e-S[1-\mathbf{exp}(-P_e/S)]$, which fits data well, thus questioning the uniqueness of the existing formulation.

$I_a = 0.2S$: This assumes that an initial abstract exists (an observed and common concept in infiltration hydrology), and that it is fixed at 0.2S. As both an operational simplicity and a specific process this has been studied extensively. Great variety has been found in I_a (and its relation to S) between watersheds and between storms, and the value of 0.2 has been widely challenged. This is clearly an unconvincing point in the method.

Climate and AMC/ARC relations: The effects of prior rainfall and/or soil moisture on event runoff - while intuitive and often cited – are only rarely demonstrated. The climatic descriptors (5-day prior rainfall by season) originally proposed with the CN method were found to be inappropriate and have been dropped as a part of the method (i.e., as a candidate hypotheses). In its stead, a probabilistic description of event runoff has survived and can be viewed as the current hypothesis.

Universality: While not stated explicitly, it was assumed (a default hypothesis) that the CN system would fit a wide variety of (unknown and undefined) watershed types. Subsequent investigation has shown a number of different characteristic event runoff response patterns, not all of which are appropriate to the CN method. It is however, applicable to the majority of cases where it is used, primarily rain-fed agricultural, urban, and range lands. It has notable shortcoming in many well-forested watersheds however. It is not universal.

CN tables, charts, soils: While necessary for engineering use, the veracity of the CN tables and charts, the soils classifications, and CN aligner are not appropriate for scientific examination. They are operational requirements for use, as are tables of Manning's "n" and standardization of channel shapes.

Others: Several other aspects of scientific inclusion might also be mentioned. A frequent criterion to the question of scientific inclusion might ask if the method/equation can be derived from and obeys more basic principles of physics. It should be noted that – as described earlier - the CN runoff equation has been "derived" from assumed distributions of rainfall and loss properties by several different investigators (Schaake el al., 1996, Hawkins 1982; Yu, 1998). Moreover, it should be noted that it does observe conservation of mass insofar as all the components of a rainstorm are included: $P=I_a+F+Q$. Also – though not by design - it does uniquely show the observed positive variation of infiltration rates with rainfall intensity. (This is caused by partial area considerations, and not by the rainfall itself.) And finally, it should be noted that the equation itself is dimensionally homogeneous, an attribute generally regarded as a necessary but not sufficient condition for good physical science: for example in hydraulics and fluid mechanics. This feature encourages scaling, compact dimensionless ratios, and units-free manipulation.

A recurring complaint of the CN method from the scientific hydrology community is its privileged and non-traditional development. It was introduced and widely used with no pan-scientific peer review, no open literature, no critique, and – to this day - no surviving supporting documents of many of its key elements. Somehow CN hydrology and its series of component concepts were and are exempted from the generally-accepted protocols of science. That is; the gauntlet of publication, data review, open discussion and critique, survival, and then (perhaps) acceptance and application. Also missing was the basic framing of hypotheses, testing, and rejection. At the current stage of its evolved use, most practitioners look to an agency (NRCS) for authority and leadership, rather than to science-based published independent studies in the open scientific literature, and accompanying ventilating discussion.

Does it work?

Administrative success: By its widespread use and its apparent user satisfaction, it works well by definition. By carrying the authority of the agency (see Smith, 1997), it is applied with the confidence that it will be accepted by agencies and public works jurisdictions. That is to say, it the CN method has "worked" in the political-administrative sense that structures are built, land use decisions are made, and budgets are continued, and without litigation. In this view, user credibility and satisfaction, and not scientific or technical acceptance, is the criterion.

Technical success: Technical examinations on the method components, such as the credibility of the CN tables, the AMC criteria, initial abstraction ratio, and the ability to reproduce specific event flows, general rainfall-runoff experiences, or flood frequency curves may give a different picture, and have been described in the body of the report. But there are few reports of structural or land management failure arising from technical inadequacies that have risen to the levels of administrative or legal concern.

This may be, however, a reflection on the nature of hydrologic engineering. Methodological or professional shortcomings are difficult to identify given the remote frequency of the design events, the poor data situations endemic to them, and the vagaries of post-event forensics. These issues are even more subtle when the CN method is used for some continuous modeling applications and its effects are masked by other processes.

Can it be replaced? This question must consider that the endurance of the CN method is due its brevity, authority, transparency, compactness, and overall intuitive correctness. While more process-detailed models are available, their more complete descriptions require more data to operate, and more coefficients/parameters as model inputs. In addition, the question is often moot: many more complex models incorporate the CN method as a canned rainfall-runoff or soil moisture component. So in answer to the topic question; yes, it can be replaced, but at an operational price.

To consider an alternative model of the same complexity, most of the same components would be required, as would the general geometry of the P:Q relationship. The current model already monopolizes almost all the factors, inputs, and characteristics considered to be important. That is soils, cover, ambient conditions, rainfall depth, and the rainfall-runoff geometry. While improvements might explore inclusion of rainfall duration or intensity factor, studies have shown that rainfall depth alone explains most of the event runoff variation (e.g., Hawkins and Cate, 1998; Hawkins and VerWeire, 2005).

Can it be improved? This is dealt with in some detail in the discussions on findings and professional practices. Important avenues of potential improvement involve local calibrations for more reliable CNs, including non-handbook land types, inclusion of a more realistic I_a/S, better HSG data, acknowledgment and recognition of non-CN watersheds. In the authors' opinions much of the leadership for such actions should rest with NRCS.

RECOMMENDATIONS

This report exposes a number of opportunities and needs for further investigation, or for development, and steps that might be taken to create consistency, understanding, utility with the CN method. This includes a number of unresolved technical questions of interest.

Keeper: An obvious need is for a caring and ecumenical "keeper" of the CN method. By analogy, such a role exists with other current models such as SWAT, EPIC, HSPF, STAR, WEPP, and the HEC series. While the NRSC is the obvious candidate, agency priorities are largely elsewhere, and historically its role has been episodic and directly only towards agency program needs. Given the utility of the method, its widespread application, and its identification with the agency, this leadership role remains to be filled. Insofar as keeper activities would update and correct, they are in consort with good science, which – via hypothesis testing and rejection – is self-correcting.

Information exchange: An alternative or augmenting strategy to the above might be a web site or discussion board for CN information exchange, discussions, new findings, handbook updates, FAQs, professional opinions and user experiences, perhaps sponsored by on an inter-society (such as ASCE, ASABE, AWRA) basis with agency cooperation. Numerous issues described in this report might be suitable topics for coverage.

Reconfiguring I_a/S: Recent work (e.g., Jiang 2002) with a large body of data examining the initial abstraction coefficient ($I_a/S=\lambda$) shows a more fitting value in the vicinity of 0.05. These more enlightened values of $I_a/S=\lambda$ should be pursued as appropriate, and as an alternative to the current value. However, wide scale incorporation of this notion in the many CN applications and agency handbooks has not yet occurred. Such application should carry the caveat that the current CN definitions are based on the traditional value of $I_a = 0.2S$. Changing λ will change the basic definition of "S" in the rainfall-runoff equation, thus requiring new – and λ-specific - CN tables.

Curve Numbers in continuous modeling systems: A major application of the CN concepts has been in continuous modeling, often for secondary purposes of water quality management. Coupled in such a manner, the otherwise arbitrary assignment of CNs to soil moisture levels and their dynamics can have strong effects on the outcomes. This is often hidden in details of the model operation and source code. Several recent papers (Garen and Moore, 2005, Young et al*.,* 2005), have stressed this and promoted an awareness of such problems, and suggest the importance of enlightened use (or non-use) of the CN method in this context. These issues should be examined closely and illuminated.

Remote sensing: Curve numbers have found fruitful application in Geographic Information Systems, defining cover from remotely sensed data and using existing GIS-based soils information, CNs are determined on a table look-up basis. However, such procedures are largely only computer versions of a pencil-and-paper approach to the current tables, and thus really offer little new in hydrology insights. This suggests a latent prospect to develop more basic hydrologic properties from remotely sensed data and ground-based hydrology, or perhaps to determine CNs directly from remote sensing.

Local calibrations: In actual usage, most CNs used are drawn from agency tables of unknown original sources, or from consensus tables agreed to for local usage. Given this and the method's sensitivity to the selected CN, local calibrations on local rainfall and runoff data from local watersheds seem both appropriate and professional, and should be encouraged.

As a part of this recommendation, leadership and development is needed on CN calibration under different methods, hopefully relating and reconciling the results of the several approaches suggested here to the original NEH4 annual series median procedures. This is needed on the basis of data economy, application to short term impacts, and consistency.

Climatic adjustments: The above leads to the allied practice of regional CN studies such as those undertaken spanning the humid-to-arid spectrum of Texas (Thompson 2002, 2004). Its success should encourage similar investigations and adjustments elsewhere. However, insofar as the root causes of the CN variation has not been determined, direct extrapolation of the Texas values should be avoided.

Infiltration associations: Rainfall simulation infiltrometry has been popular for the past several decades, and a wealth of such data exists. Notwithstanding the basic conflicts between the concepts, methods to extend this information to CNs via the exhibited infiltration parameters should be encouraged.

Non-CN situations: As outlined in the body of this report, watersheds with certain combinations of cover and soils and climate do not respond to rainfall in a manner consistent with the CN equation, and are thus not "CN appropriate." Additional studies are needed to identify such conditions, and their exception should be clearly stated in CN literature and agency technical policy.

Forested watersheds: Many – but not all - of the "non-CN" situations described above are found in classically forested watersheds with deep soils, heavy cover, and humid climates, and base-flow. The CN method is largely out of place in these settings, and performs poorly when compared to other land types (Hawkins, 1984). Contemporary work by McCutcheon et al. (2006) highlights difficulties in applying the CN method to well-forested situations, including the perceived inability to reflect the effects of silviculture operations. However forests – and forested watersheds – are widespread, and despite the questionable CN application, valid applied hydrology and environmental management needs do exist. Thus a rainfall-runoff method appropriate to these watersheds is badly needed. Such development should be encouraged.

Land management applications: Despite its widespread use in engineering planning and design - with strong reference to urban hydrology - there exists considerable unutilized opportunity for application to general land management decision-making. Its potential to routinely appraise alternative choices of land use – and their costs and benefits on downstream and on-site interests - is largely unappreciated and unused by the professional land management community. This is particularly true on publicly-owned wild lands, and decisions on forest and rangelands management. In the interests of hydrologic responsibility, the opportunity for applying the CN technology – originally developed to include land uses influences on hydrology – should be encouraged.

Hydrologic Soil Groups: This review has shown the importance of soils in defining CN, and the subsequent importance of CN in determining direct runoff. However, there is evidence that the classifications are inconsistent, and that there are no objective procedures easily or widely available in the open literature. This shows up clearly in international applications. This awkward state of affairs needs to be remedied for a more professional understanding and a better CN method. Given the current organizational arrangement and precedent, this leadership option must remain within NRCS.

EPILOGUE

"*…it is a characteristic of wisdom not to do desperate things*" - H. D. Thoreau

In the end, attempts to understand the rainfall-runoff process have been unavoidably dominated by the need to simplify it. The concept and formulation of the CN method, embodying the subtractive and non-linear nature of hydrology, has been insightful in that regard. As a conceptual and computational model, the CN method, and even the CN values themselves, has remained and will remain an icon to our understanding of hydrology.

APPENDIX I. Solutions to the Curve Number Equation

Full form (dimensioned)		**Standardized Form (dimensionless)**: $P_* = P/S \quad Q_* = Q/S \quad \lambda = I_a/S$	
Effective Rainfall Form: $I_a = 0$			
$Q = P^2/(P+S)$	$0 \le P$	$Q_* = P_*^2/(P_*+1)$	$0 \le P_*$
$S = P^2/Q - P$	$0 \le Q \le P$		
$P = (Q/2) + \sqrt{[(Q/2)^2+QS]}$	$0 \le Q \le P$	$P_* = (Q_*/2) + \sqrt{[(Q_*/2)^2+Q_*]}$	$0 \le Q_* \le P_*$
Initial Abstraction Form: $I_a \ge 0$			
$Q = (P-I_a)^2/(P-I_a+S)$	$0 \le I_a \le P$	$Q_* = (P_*-\lambda)^2/(P_*-\lambda+1)$	$0 \le \lambda \le P_*$
$Q = 0$	$0 \le P \le I_a$	$Q_* = 0$	$0 \le P_* \le \lambda$
$S = [(P-I_a)^2/Q] - (P-I_a)$	$0 \le Q \le P$		
$I_a = P-(Q/2)-\sqrt{[(Q/2)^2+QS]}$ $0 \le Q \le P$		$\lambda = P_*-(Q_*/2)-\sqrt{[(Q_*/2)^2+Q_*]}$	$0 \le Q_* \le P_*$
$P = I_a+(Q/2)+\sqrt{[(Q/2)^2+QS]}$ $0 \le Q \le P$		$P_* = \lambda+(Q_*/2)+\sqrt{[(Q_*/2)^2+Q_*]}$	$0 \le Q_* \le P_*$
NEH4 Form: $I_a = 0.2S$			
$Q = (P-0.2S)^2/(P+0.8S)$	$0 \le 0.2S \le P$	$Q_* = (P_*-0.2)^2/(P_*+0.8)$	$0 \le 0.2 \le P_*$
$Q = 0$	$0 \le P \le 0.2S$	$Q_* = 0$	$0 \le P_* \le 0.2$
$S = 5[P+2Q-\sqrt{(4Q^2+5PQ)}]$	$0 \le Q \le P$		
$I_a = [P+2Q-\sqrt{(4Q^2+5PQ)}]$	$0 \le Q \le P$	$\lambda = [P_*+2Q_*-\sqrt{(4Q_*^2+5P_*Q_*)}] = 0.2$	$0 \le Q_* \le P_*$
$P = 0.2S+Q/2+\sqrt{[(Q/2)^2+QS]}$	$0 \le Q \le P$	$P_* = 0.2+Q_*/2+\sqrt{[(Q_*/2)^2+Q_*]}$	$0 \le Q_* \le P_*$
General Lambda Form: $I_a = \lambda S$			
$Q = (P-\lambda S)^2/(P+(1-\lambda)S)$	$0 \le \lambda S \le P$	$Q_* = (P_*-\lambda)^2/(P_*+1-\lambda)$	$0 \le \lambda \le P_*$
$Q = 0$	$0 \le P \le \lambda S$	$Q_* = 0$	$0 \le P_* \le \lambda$
$S = [2\lambda P+Q(1-\lambda)-\sqrt{\{[Q(1-\lambda)]^2+4\lambda QP\}}]/(2\lambda^2)$	$0 \le Q \le P$		
$\lambda = [P-Q/2-\sqrt{(Q/2)^2+Q)}]/S$	$0 \le Q \le P$	$\lambda = P_*-Q_*/2-\sqrt{[(Q_*/2)^2+Q_*]}$	$0 \le Q_* \le P_*$
$P = \lambda S+(Q/2)+\sqrt{[(Q/2)^2+QS]}$	$0 \le Q \le P$	$P_* = \lambda+Q_*/2+\sqrt{[(Q_*/2)^2+Q_*]}$	$0 \le Q_* \le P_*$

APPENDIX II. List of Symbols and Acronyms

List of Symbols

Symbol	Meaning	Dimensions	Common Units*
a	Coefficient in Modified CN equation	dimensionless	
C	Runoff ratio = Q/P	dimensionless	
C_e	Effective runoff ration = Q/P_e	dimensionless	
CN	Curve Number = 1000/(10 + S)	dimensionless	S in inches
CN_o	Curve Number at $P = I_a$, Q = 0	dimensionless	
CN_∞	Curve Number as $P \rightarrow \infty$	dimensionless	
d	Derivative operator	NA	
exp( )	Indicates exponentiation, e.g. **exp**(y) = e^y		
f	Loss or infiltration rate = dF/dt	L/T	in/hr
F	Loss depth = P_e-Q	L	in
F_*	Standardized loss depth = F/S	dimensionless	
g( )	Probability density function , or pdf	NA	
G( )	Cumulative density function, or cdf	NA	
i	Rainfall intensity = dP/dt	L/T	in/hr
I_a	Initial abstraction, or rainfall prior to runoff	L	in
k	Fitting parameters in asymptotic equations	P^{-1}	in^{-1}
k	Fitting parameter in Complacent fitting	dimensionless	
K_e	Effective hydraulic conductivity	L/T	in/hr
n	Effective pore fraction	dimensionless	
n	Manning's roughness coefficient	$TL^{-1/3}$	sec/ft$^{-1/3}$
P	Event rainfall depth	L	in
P_e	Effective rainfall depth = P - I_a	L	in
P_*	Standardized rainfall depth = P/S	dimensionless	
Q	Event runoff or rainfall excess depth	L	in
Q_*	Standardized runoff depth = Q/S	dimensionless	
q	Runoff intensity or rate = dQ/dt	L/T	in/hr
S	Loss parameter, the limit of (P-Q) as $P \rightarrow \infty$	L	in
t	time	T	hr
α (alpha)	Land slope	dimensionless(fraction)	
Δ (delta)	Difference operator	as used	
ε (epsilon)	"error" in general	as used	
λ (lambda)	Initial abstraction ratio = I_a/S	dimensionless	
Φ (phi)	Time-constant loss rate	L/T	in/hr
ψ (psi)	Matric suction in soils	L	in

Subscripts:

a	Indicates slope-corrected value
*	Indicates standardization on the loss parameter S
0.2, 0.05	Indicates $\lambda = I_a/S$ for the case under discussion
I, II, III	Indicates AMC or ARC for the case under discussion
rp	Return period

*Note: corresponding SI units will be in millimeters (mm), centimeters (cm), or meters (m), and mm/hr or cm/hr.

List of Acronyms

AMC	Antecedent Moisture Condition
ARC	Antecedent Runoff Condition, formerly AMC
ASCE	American Society of Civil Engineers
CN	Curve Number or Runoff Curve Number
GIS	Geographic Information Systems
EWRI	Environmental and Water Resources Institute, ASCE
FAO	Food and Agricultural Organization (United Nations)
HRU	Hydrologic Response Unit
HSG	Hydrologic Soil Group
NEH4	National Engineering Handbook, Section 4 Hydrology
NEH630	National Engineering Handbook, Section 630 Hydrology
NRCS	Natural Resources Conservation Service, USDA, formerly SCS
POE	Probability of Exceedance
RMS	Root-mean-square
SCS	Soil Conservation Service, USDA
TR	Technical Release
USDA	United States Department of Agriculture
USFS	United States Forest Service, Department of Agriculture
USGS	United States Geological Survey, Department of Interior

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