CONTINUING EVOLUTION OF RAINFALL-RUNOFF AND THE CURVE NUMBER PRECEDENT

Richard H. Hawkins, University of Arizona, Tucson, AZ 85721, rhawkins@ag.arizona.edu; Timothy J. Ward, Manhattan College, Riverdale, NY 10471, tim.ward@manhattan.edu; Donald E. Woodward, USDA, NRCS (ret), Gaithersburg, MD 20877, dew7718@comcast.net; and Joseph A. Van Mullem, USDA, NRCS (ret), Bozeman, MT 59715, jvanmullem@bresnan.net

Abstract. Ongoing development, user improvements, and new applications of the Curve Number method are described. The basics of the method are summarized and put into perspective, and recent findings and enhancements are summarized. Major issues of recent concern and attention are the initial abstraction ratio, I_a/S (or λ); land slope effects on CN; parameterization from field data; the use of small plot and infiltration data; aligning the CN method with process-based models; concern for the use of CNs with some forested watersheds; and departures from the original method. Based on this information, suggested topics for research, development, and investigation in rainfall-runoff processes- centered around CN procedures – are offered.

INTRODUCTION

As essentially the only member of its genre, and as an openly available rainfall-runoff method with auspicious agency origins and a long history of prior use, the Curve Number method is applied in an off-the-shelf fashion to perform to a variety of roles in surface water hydrology. Since its origin as an agency method in the mid 1950s, it has evolved via testing with field data, application adjustments, insights, and institutional alterations to the method, leading to a more credible representation of rainfall-runoff hydrology. Although often being found lacking in form, function, and parameters, it continues to be widely used, and with apparently satisfied users. This continued use of the method occurs is driven by the inertia of prior use, convenience, authoritative agency origins, and lack of suitable alternatives.

A state of the knowledge as of early 2008 was summarized in an EWRI Task Committee report from the American Society of Civil Engineers (Hawkins et al., 2009). The report chronicled the method from several perspectives, identified problems and fruitful grounds for further study, and suggested professional challenges. De-facto progress and user development continues, through formal and informal studies, continued investigation, and imaginative user improvisation.

This paper briefly summarizes the basic background of the Curve Number method, selectively covers interim progress, and accents avenues for future development efforts by the patron agency (NRCS), the hydrologic user community, and researchers. Space limitations here restrict a fuller coverage.

CURVE NUMBER METHOD

Background. The Curve Number method is widely used in rainfall-runoff hydrology and fills an active professional niche. It enjoys a long history of application. However, it is generally regarded as “blue collar” hydrology, albeit quite successful. It was created by the USDA Soil Conservation Service (or “SCS,” now Natural Resources Conservation Service, or “NRCS”) in the mid-1950s as an agency method to deal uniformly with rainfall-runoff hydrology issues faced by the newly authorized Public Law 566.

The method centers on an event runoff equation (Equation [1] below), characterized by a coefficient called a "Curve Number" (CN), with an accommodation for runoff variation often attributed to prior site moisture. The basic CN is defined by the hydrologic properties of the soil, by series and texture, and by considerations of cover, condition and land use. The equation is

$$Q = (P-0.2S)^2/(P+0.8S) \qquad P \geq 0.2S \qquad [1a]$$
$$Q = 0 \qquad P \leq 0.2S \qquad [1b]$$

where Q is the direct runoff depth, P is the event rainfall depth, and S is defined as the maximum possible difference between P and Q for the watershed as $P \rightarrow \infty$. With the above variables in inches, S is transformed to the dimensionless expression

$$CN=1000/(10+S) \qquad [2]$$

CN is merely a transformation of S taken to be a measure of watershed response to a rainstorm. CN may vary from 0 (no runoff from any rainstorm) to 100 (all rain becomes runoff for every rainstorm). Both Equations [1a] and [1b] are components of the full equation. The 0.2 and 0.8 in Equation [1] result from an early assertion that an "initial abstraction", or I_a, is required at the onset of the storm before runoff is initiated. Originally stated to be 0.2S, later work has challenged the 0.2 multiplier, as will be elaborated later. Values of CN by soil groups (Hydrologic Soil Groups, or "HSG"), cover conditions, and land use are suggested by various agency handbooks and guides. By experience, these have been found – in general - to be more accurate on rain-fed agriculture and urban lands than on wild lands. It should be noted that the method as originally developed contained no time dimension: the calculations are for rainfall and runoff depths only. Also, the "P" stands for *rain*, not general "precipitation," such as snow, hail, or fog drip.

Application. The method is used in several different interpretations, or modes of application. These are not necessarily congruent, and critique of the method often springs from a lack of awareness of these different modes or intended applications.

First, it is used to calculate the matched return period runoff from rainfall; for example, the 100-year runoff depth from the 100-year rainfall depth in design hydrology. With this application, the subscripts "rp", for return period, should be affixed to the P and Q in Equation [1], or P_{rp} and Q_{rp}, respectively. This is perhaps the most frequent and robust application of the method and assumes that the rp rainfall will produce the rp runoff.

Second, it is used to generate time-distributed runoff pulses to from time-distributed rainfall in hydrograph models. With the introduction of time variant rainfall depths, this application generates rainfall intensities, infiltration rates, and runoff rates not present in the original development of the method or its underlying data. In this application, the functional notation of (t) should made on Equation [1], leading to P(t) and Q(t) .

Third, it has been creatively applied in continuous soil moisture models – often on a daily time step - as inter-dependent runoff and soil moisture accounting components. Such applications, which may also draw heavily on available soil physics thresholds, such as wilting point and field capacity, have found wide use in water quality modeling as an active separate subfield of the method.

The method acknowledges observed CN (or runoff) variation between events based on basin factors, originally explained as "AMC" or Antecedent Moisture Condition, with three classes (I, II, III) defined on 5-day prior or antecedent rainfall. This 5-day rainfall approach is no longer endorsed by NRCS, and the approach has been generalized to "ARC," or Antecedent *Runoff* Condition. A probabilistic interpretation to cover all sources of variation –including prior site moisture - has been offered. The ARC II status is accepted as the reference condition and is the basis for CN handbook tables. This is not an application as much as an accessory interpretation of storm-to-storm variation, and amounts to Equation [1] with or without "runoff from other factors".

While Equation [1] is usually applied directly with a design P and a CN based on soils and land use, it is also to evaluate land condition impacts for environmental studies or for post-event forensic analysis. There is also an emerging concept and application of the CN parameter as a general geographic descriptor. That is the CN value becomes a measure of overall land condition, thus utilizing table entries as integrating expressions of soil and cover**,** without focused application to rainfall-runoff. An interesting example of this application is given by Hong et al. (2007) who determine a world-wide CN of 72.8 using GIS methods.

Analysis. Given a watershed with rainfall P and runoff Q>0, any event will provide a computed CN. Solution of Equation [1] for S via the quadratic equation leads to:

$$S = 5[P+2Q-\sqrt{(4Q^2+5PQ)}] \qquad \text{if } Q>0 \qquad [3]$$

or

$$CN=1000/(10+S) = 100/\{1 + ½[P+2Q-\sqrt{(4Q^2+5PQ)}]\} \qquad [4]$$

For Q=0, the CN cannot be defined insofar as the initial abstraction has not been exceeded. In this case for the given P, the CN at which runoff occurs, CN_o, can be calculated as:

$$CN_o=100/(1+P/2) \qquad [5]$$

Frequency Matching. Insofar as the return period for the runoff is assumed to be the return period of the rainfall in design event hydrology, it is instructive to analyze field data under the same assumption. This is done by rank ordering the rainfalls and runoff separately, and reassembling them as rank-ordered pairs. This is called "ordered" data, as contrasted with "natural" data (the P and Q pairs as observed naturally). This ordering has become a useful technique in rainfall-runoff analysis.

Behavior Classes. One unexpected finding from CN analyses has been the array of different response types and trajectories demonstrated by small watershed rainfall-runoff data. When the CNs found from Equation [4] are plotted against the causative rainfall P, CN variation with P is almost always seen (Hawkins, 1993).

In the *Standard* response, observed CNs decrease with increasing P but do approach stable or constant values. This stable value, denoted as $CN_{\infty,}$ is characterized as the watersheds identifying CN, applicable to larger design storms. A large majority of watersheds analyzed show this tendency.

In the *Complacent* response, observed CNs fall with increasing P, but do not approach a near-stable value, at least in the range of the observed data. A consistent CN cannot be identified in this case.

In the *Violent* response CN initially declines with rainfall depth in the manner of the Complacent response, but rises abruptly at some threshold rainfall, then approaches a near-stable higher value of CN_{∞} with increasing rain depth. This response is often seen in data from humid forested watersheds, with the abrupt rise thresholds in the range of 1 to 3 inches of rain.

ISSUES

The CN method is a compromise between the ease, convenience, simplicity and handbook authority on one hand, and the of real-life truths of observed rainfall-runoff processes on the other. While obviously and admittedly imperfect, there is a substantial body of literature on rainfall-runoff with the CN hypotheses, oriented mainly towards 1) explaining or contrasting observed rainfall-runoff with the CN method in all application modes; 2) cataloging and referencing CNs with field data; and 3) relating the CN method to other or competing models. Because of user popularity, these efforts continue and may be roughly interpreted as *making Curve Numbers work*. Much of this literature was covered in the Task report, but some is re-interpreted, updated, or enhanced in the following sections.

Initial Abstraction Ratio. The original value of the I_a/S ratio (λ) was established as 0.20. Several subsequent studies have re-examined that value and found λ values in the range of 0.02 to 0.07. Thus, λ is considered an identifying watershed variable and has been subjected to increased scrutiny. Table 1 shows studies directed at detecting λ or using it as a model variable. Other studies examined aspects of the method or its application, but tested them under different assumption of λ. Some results are summarized briefly in Table 2.

Users should be the alert to the fact that the existing handbook CN tables are based on the assumption of λ=0.20. A transfer to equivalent CNs having λ=0.05 may be attained via the empirically derived equation:

$$S_{0.05} = 1.33(S_{0.20})^{1.15} \quad [7]$$

with the S values in inches. This is result was obtained by direct least squares fitting of 307 natural data sets (Jiang, 2001). A conversion to asymptotic values of $CN_{\infty\ (0.05)}$ from $CN_{\infty\ (0.20)}$ should be similar, but has not been developed. Unpublished analytical work by two of the authors shows that the ratio of $S_{0.05}/\ S_{0.20}$ is inversely related to the ratio of Q/P.

Table 1. Summary of studies involving $\lambda = I_a/S$ for events.

Investigators	λ	Comments	Measure	Location
Baltas et al. (2007)	0.014	Lower WS	Average	Greece
	0.037	Upper WS		
El-Hakeem and Papanicolaou (2009)	0.142	Summer storms	Median	Iowa
	0.069	Fall storms		
Shi et al. (2009)	0.040		Median	China
Grillone (2008)	0-0.11	4 basins, 31-469km^2	Range	Sicily
D'Asaro and G. Grillone (2009)				Sicily
Jiang *et al* (2002)	0.050	243 watersheds, consensus values		USA

Table 2. I_a/S ratio testing and model variable studies.

Investigators	Best λ	Comments
Lim et al. (2006)	0.05	L-THIA model for annual water yield
Chandramohan and Mathew (2005)	0.30	3 watersheds in India (events)
White et al. (2009)	0.05	SWAT model. Little River, GA
Wang et al. (2008)	None	Comparable results, 0.05, 0.20. Forest River ND
Lamont et al. (2007)	NA	Used 0.05, 0.20 fitting CN to HSPF events, WV.

In light of the mounting evidence of λ departing from the original value of 0.20 and the growing interest from the user community, a recent report to NRCS (Woodward et al., 2010) recommended adopting/recognizing a value of 0.05 for agency use.

Curve Number Parameterization. Handbook table values of CN give guidance in the absence of better information, but incorporate only limited land uses and conditions and are often untested. With increasing user sophistication, coupled with the awareness that the runoff calculation is more sensitive to CN than to rainfall, interest in determining local CNs from local rainfall-runoff data has grown. Three methods of analyzing local event rainfall and runoff for CN are outlined here.

From watershed data: *First,* the median CN as calculated from rainfall and runoff depths associated with the annual peak flow events appears to have been the source of the original handbook table values. This procedure has the benefits of simplicity, precedent, and consistency with existing tables. However, it requires long records (one observation per year) and is incapable of capturing short term or transient effects, such as a fire or changes in agronomic practices. In addition, to the extent that CNs vary with return period, the median CN is the 2-year event, and may not be suitable for the 100-year design. This discrepancy is particularly evident in light of decreasing CN values with increasing P values seen in event data.

It should be noted that the above approach used annual (i.e., an annual series) peak data only. The following have been applied using essentially all available P:Q data, or a partial-duration sampling. A minimum, or threshold, rainfall or runoff level may be chosen based on user preference.

Second, a least squares objective function can be used to find the best fit for S to Equation [1], i.e., by minimizing the sum of squared differences between the observed runoffs and the calculated runoffs. When using natural data, this method addresses the variability that characterizes rainfall-runoff observations.

Third is the so-called “asymptotic” approach, in which a determination is made of the CN as P increases, using ordered P:Q data. The most common relationship is with the Standard response, which has been found to be described by the following:

$$CN(P) = CN_{\infty} + (100 - CN_{\infty})\mathbf{e}^{(-kP)} \qquad [8]$$

Equation [8] has the algebraic structure of the Horton infiltration equation, and the “k” is a fitting parameter in the units of 1/P. The recent report to NRCS (Woodward et al., 2010) recommends this procedure as the preferred technique for CN parameterization. Both graphical and computer-based computational options are possible here.

For data showing the Violent response, a similar approach may be used. As with the Standard case, the near-constant CN as P grows larger is identified. The following equation has been used to determine the reference CN value:

$$CN(P) = CN_{\infty}[1 - \mathbf{e}^{-k(P-Pth)}] \qquad [9]$$

for $P>P_{th}$, where P_{th} is the threshold rainfall or the P at the abrupt departures from the commonly-found early storm Complacent response.

In the case of Complacent behavior, a reference CN cannot be adequately defined. The rainfall-runoff relationship is better described as Q=CP, with the coefficient C usually in the range of 0.005 to 0.05. With this definition, the calculated CN will decrease predictably without attaining a steady-state value. It should also be noted that Violent response is usually preceded by a Complacent behavior at $P<P_{th}$. This abrupt change of runoff scale makes identification of the threshold rainfall depth (P_{th}) very important.

For use in continuous models, calibration of the reference CN appears to be in its infancy. CNs determined by any of the above 3 methods may not be fully appropriate for use in continuous model accounting schemes.

From small plots and rainfall simulation: Rainfall simulation is an effective technique to gather hydrologic data for different types of soil-vegetation-land use combinations. Rainfall simulation experiments are usually conducted to determine infiltration rates or erosion properties, but insofar as infiltration rates and Curve Numbers both deal with losses to rainfall, the comparisons are temptingly obvious. However, there are several important differences between rainfall simulation on plots of limited size and watershed runoff response to natural rainfall. These differences include spatial variability of land conditions and rainfall, the inherent artificiality of simulated rainfall, and the limited runoff processes which can occur on plots. In addition, the infiltration rate information taken from plot faces a different problem, i.e., the CN method has no time dimension, so attempt to define CN from derived infiltration measures are tenuous at best.

Nevertheless, simulation on plots does result in a rainfall depth P and a runoff depth Q so that CNs can be calculated directly from Equation [4]. CNs so calculated are dependent on simulated rainfall intensities and durations of the rainfall. As shown elsewhere in this paper, when rainfall increases, the corresponding CN decreases for many watershed situations. The same can be seen in data from simulator experiments, as the following figure illustrates.

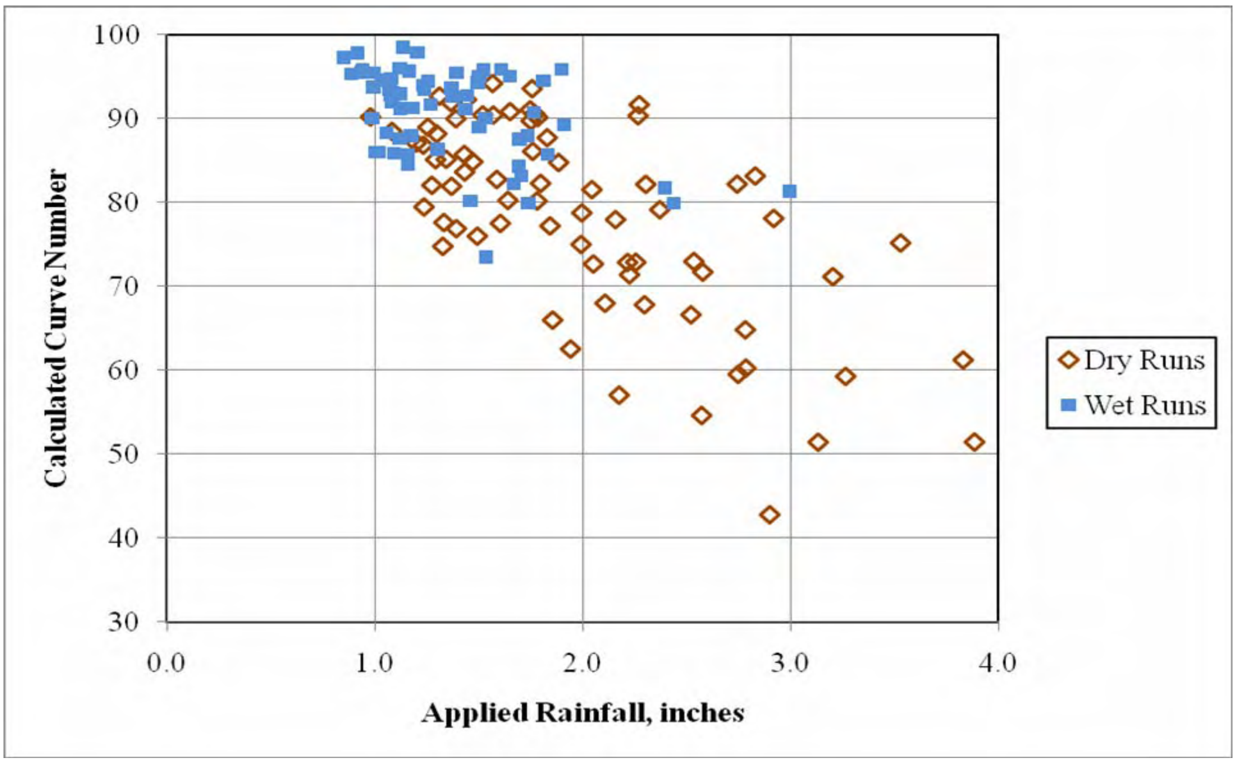

Figure 1. Curve Numbers calculated from small plot rainfall simulator data. Dry runs are on plots without previous rainfall application and wet runs are on the same plots 12 to 24 hours after the dry runs. There are 74 dry run observations and 63 wet run observations on the figure. Data are from Ward and Bolin (1989) and Ward and Bolton (1991).

The simulation data in the figure were from experiments conducted in Arizona and New Mexico with the same small, 1 meter square plots on similar soils with an average applied rainfall rate of 3.4 inches per hour until steady-state runoff (steady loss rate) was achieved. Steady state took more time for "dry" runs than "wet" (previously rained upon) runs. Thus, the average depth of applied rainfall for the wet runs is about 30% less than the dry runs. As the figure indicates, almost any CN could be attained by adjusting run duration, intensity, and depth.

Despite these problems, some success in plot studies was attained by El-Hakeem and Papanicolaou (2009) who derived CNs - based on rainfall and runoff depths - for several soils and agricultural practices in Iowa. Most of the above-mentioned difficulties were minimized, or failed to materialize, because of the uniformity of the soils studied, the small plots, the high CNs, and the realistic nature of the applied rainfall depth and distribution. Insofar as there is no "gold standard" or ultimate ground truth for Curve Numbers, success was judged by comparison with existing handbook values, the origin of which is unknown. Nevertheless, their work gives direction for future studies under similar conditions. It also contributed additional perspective to the I_a/S issues described elsewhere in this paper.

Effects of watershed slope on CN. The available, limited evidence shows that CNs are not clearly positive with land slope. In fact, the relationship may be negative, i.e., the steeper the slope, the *smaller* the CN. Recent work by Pandit and Heck (2009) on asphalt and concrete with rainfall simulation give minimum affirmation for this observation. The accumulated findings in CN change per % land slope are shown in Table 3.

Table 3. CN variation with land slope.

Investigators	CN/%	Conditions/Comments	
Garg et al. (2003)	-1.30	AGNPS model, 5 watersheds central Oklahoma	
VerWeire et al. (2005)	-1.72	27 watersheds, GIS studies	
Pandit and Heck (2009)	+0.01	Concrete	CNs of 99.5 - 100
	-0.54	Asphalt	CNs of 96.9 - 99.9
Neitsch et al. (2002)	+0.25 to +0.90	SWAT model inputs 5% land slope	

The SWAT model (Neitsch et al., 2002) uses a mildly positive CN-slope function developed locally, but it is yet to appear in the open literature. Insofar as these negative CN change with slope results are counter-intuitive, and the evidence is limited, additional investigations are warranted.

Equivalence of Curve Numbers with other models. A traditional complaint about the CN method has been that it had no basis in fact; it did not interface with the realities of hydrologic processes. With that, and given its popularity, considerable effort has been given to adjust, explain, and enhance the CN method to acceptable levels of credibility. Thus, a number of efforts reconcile and interpret the Curve Number hydrology in terms of alternative more physically-based models. Nachabe (2006) interpreted TOPMODEL and the CN model in terms of variable source areas and drew equivalences for the distribution of F, or the soil moisture deficit ("D" in Nachabe, 2006). More recently Lamont et al. (2008) duplicated previously observed CN-P behavior (Standard and Violent patterns) using a simplified standardized version of HSPF with historical rainfall data in West Virginia.

Beyond Curve Numbers. While the CN method is robust, enduring, and popular, it is not universally appropriate, and other approaches might be more valid and fitting in some cases. An obvious case is the Complacent response, which is much better represented by a simple runoff fraction of the form:

$$Q = CP \qquad [10a]$$

which is at some variance from Equation [1]. This relation can, of course, be forced into a CN framework, resulting in contorted expressions, e.g., $S=5P[1+2C-\sqrt{(4C^2+5C)}]$, and a monotonically declining CN with P. Watersheds displaying this pattern show "C" in the range of 0.005 to 0.05, which may be realistically attributed to a small fraction of the watershed in stream surface area or near-channel impervious areas, without significant contributions from the watershed surface. This is a partial area effect which can be represented in distributed models by assigning a small portion (i.e., C) of the basin to CN=100. It might be noted that Equation [10a] is a form of the popular, but much-maligned, Rational equation.

Where observed, the Complacent response occurs at the onset of rainfall (i.e., no I_a), and may continue until a rainfall threshold (called P_{th} here) is attained, beyond which rainfall excess is generated from the remainder of the watershed by more traditional processes. Thus:

$$Q = CP \qquad P<P_{th} \qquad [10b]$$

is more appropriate. Beyond this point, the Violent case often follows. That is, a high rainfall response past the threshold. An appropriate expression for this might then be:

$$Q = CP + b_2 (P-P_{th}) \qquad P>P_{th} \qquad [11]$$

where b_2 is the Violent limb runoff coefficient, knowing that $0 < (C+b_2) \leq 1$, and P_{th} is the rainfall depth threshold as described previously. These 3 parameters, C, P_{th}, and b_2, all have physical interpretations or limitations that may be estimated from watershed soils, site data, or inspection. Values of b_2 for data analysis are commonly in the range 0.80 to 0.95, so that incremental runoff with rainfall approaches a 1:1 ratio. Values of P_{th} found in studies range from 1to 3 inches, and can be related to soil depth and water holding properties. Except at the extreme as $P\rightarrow\infty$, the CN method cannot mimic the step function shown in Equations [10b] and [11].

From both anecdotal and documented evidence, cases of this type of rainfall-runoff response occur in humid zone headwater basins with shallow, high infiltration soils overlying impervious strata, steep topography, and base-flow. Such watershed characteristics are at conceptual variance with the origins of the CN method. These situations are widely found in small upland forested watersheds, where the conditions are too steep, too rocky, too droughty, or too shallow to successfully support rain-fed agriculture, but are quite capable of supporting the more robust and well-adapted forest vegetation. In this case, little overland flow is generated. Instead, flow occurs from subsurface flow across confining layers or local, temporal water tables. Thus, the CN method is notorious for poor performance on such upland forested watersheds (McCutcheon et al., 2006). These conditions may also prevail on some range lands.

This example for upland watersheds is a call to initiate awareness and possibilities in rainfall-runoff beyond the Curve Number method, but at the same level and scale. For the case above, an expected difficulty in routine practice would be to flag such non-standard cases with site descriptions, e.g., soils, cover, slope, and geology, and to provide parameterization. Current practice directs users to tables of soils, cover, and land use, invariably directed by default to the CN equation, which is blind to the Complacent-Violent response.

SUMMARY AND DISCUSSION

The Curve Number method is alive and well, and is increasingly being used in roles beyond its original intent. However, we caution against over-devotion or over–attention to it. The issue is not Curve Numbers, but the larger phenomenon of rainfall-runoff processes, for which the Curve Number method is merely a touchstone. The vocabulary the method provides and the issues it raises are valuable beyond its mere convenience and use. Thus, attention to several gaps in our knowledge of the method, and rainfall-runoff processes in general, is strongly encouraged.

Additional lines of study. Curious investigators seeking fertile study topics may wish to consider the following as fruitful research topics. These are only briefly elaborated and not in any order of perceived importance.

- CN parameterization in continuous models.
- Identification of required threshold rainfalls.
- Examples of non-CN watersheds and alternatives approaches.
- Application and testing of alternative I_a/S for effective S relationships under different assumptions.
- Examples, testing, and alternatives for forested watersheds.
- Evaluation of prior moisture/rainfall effects.
- Determination of CNs for un-calibrated small watersheds: cataloging and handbook comparisons.
- Isolation of HSG roles in rainfall-runoff.
- Estimation and interpretation of ‘k’ in the standard asymptotic equation. Transient CNs.
- Use of CNs under low rainfall and low return period (rp) conditions.
- Critical examination of application to extreme events [See recent views by Alila et al. (2009)]. The validity of small storm CNs for large storms with high return periods.
- Rainfall simulation and CNs, and vice-versa.
- Land use effects – how CNs change with land use patterns [Silvicultural effects are generally unknown in quantitative detail, as are fire effects].
- Land slope-CN relationships.

Investigations of these topics and the questions they raise will go well beyond the Curve Number method. They can offer insights that may be extended to better understandings of general rainfall-runoff hydrology.

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