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Chapter 10: Estimation of Direct Runoff from Storm Rainfall

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630.0000 Prologue to 2017 Edition

This work is based on progress in applied event hydrology since the original USDA-SCS Hydrology Guide, NEH4 (USDA, 1954) was generated in 1954.

At that time, hydrologic knowledge was less well developed, data analysis and data sharing were limited, as were awareness, capabilities, and precedent experiences. NEH4 was generated as product of those times, and to service the needs of the USDA program Watershed and Flood Prevention Act of 1954 (PL 566). It was the only rainfall-runoff estimation procedure of its kind to that date, and effectively, to the present.

In the intervening years, interest in rainfall-runoff has expanded in response to evolving water legislation, and environmental concerns and programs. Hydrology education has expanded, as have information exchange, journal outlets, research findings, and the numbers of practicing hydrologists. The scope of recognized land uses has grown, as has the awareness of land use change impacts on hydrologic response.

The user community is now better informed and more capable. There is an active cross-professional culture of hydrology. Technology has progressed including the routine use of computers and computer-based models, more and better watershed data, enhanced access to and better analyses of data, GIS technology, satellite imagery and other remote sensing technologies and a better developed and organized body of knowledge and professional experience.

The current practice benefits from what has been learned since 1954. The intervening years allowed prolonged examination of the Curve Number (CN) methodology. With the familiarity of frequent use, it has been applied, tested, compared, dissected, and critiqued, and its relationship to general rainfall-runoff hydrology identified. The following section summarizes the departures from and enhancements to the original CN hydrology method.

630.0001 Summary of updates of Curve Number method

Relying on 2016 knowledge and findings about general rainfall-runoff, and using the CN Method as the template, the following summarizes how the previous NEH4 (now NEH630 (USDA NRCS,

1999) is changed with this 2017 update. This summary assumes some familiarity with the current (1954) method. Thus, the following is given as reference in this update. The 1954 runoff equation is

$$Q = (P-0.2S)^2/(P+0.8S) \text{ for } P>0.2S,\ Q=0 \text{ otherwise.} \qquad [10\text{-}1]$$

In the above, P is event rainfall depth, Q is the event direct runoff depth, and S is a measure of the watershed potential storage, defined as the maximum possible difference between P-0.2S and Q, and is approached as $P\rightarrow\infty$. An important feature of this is that as $P\rightarrow\infty$, $P-Q \rightarrow 1.2S$. The relationship between watershed descriptor CN and S is CN=1000/(10+S) where S is in inches. CN varies from 0 to 100, S from 0 to ∞. Equation [10-1] assumed an initial abstraction (Ia) of 0.20S, and gives *median* runoff for the given P. Since 1954, all tables of CN, or 1000/(10+S), were provided based on the Ia/S = 0.20 assumption.

Some significant developments and findings of the intervening decades are summarized in the following sections and are discussed more fully in the updated chapters.

1. The CN method is used in three different roles, modes, or applications:

    a. To determine/estimate the return period runoff depth Q from the same return period rainfall P. This is a popular application in applied hydrology and is the main assumption in this update.
    b. As a process model to describe how the infiltration and rainfall excess rates vary with time in a specific storm; or to aid in estimating soil water content, especially in continuous runoff models.
    c. As an individual probabilistic event model with error descriptions of the variation from the central trend of Equation [10-1].

2. The CN method is not applicable to all watersheds. That is, the original Equation [10-1] does not universally calculate results that follow the general observed rainfall-runoff response for all watersheds or river basins. Descriptions of non CN-compliant watersheds, such as forested watersheds and karst-dominated watersheds, are presented in Chapter 9 and in the Chapter 10 appendices.

3. Three dominating types of runoff responses to rainstorm have been observed, rather than the single type suggested by the CN method and Equation [10-1] (see the appendix). These are the Complacent, Standard, and the Violent cases, or rainfall-runoff response modes. None of these modes wholly supports Equation [10-1] in its presented form. They all show that CN itself – as defined on rainfall-runoff data – varies with event rainfall depth.

   The “Standard” type conforms to the CN concept as a limit. In the Standard case, the data-defined CN approaches a steady-state or asymptotic value at higher rainfall depths. This mode is the most consistent with the existing CN method and is the mode most commonly found in rainfall-runoff data sets. About 80% of all data sets examined are consistent with the Standard mode.

4. The asymptotic equation

$$CN(P)=CN_{\infty} + (100-CN_{\infty})\mathbf{exp(}-kP) \qquad [10\text{-}2]$$

   has been shown to fit the Standard case fairly well as P increases and CN stabilizes. Here, CN(P) is the estimated CN at the rainfall depth P, CN_{∞} is the steady-state CN approached as P grows larger, and k is a fitting parameter. Note that at P=0, CN(P)=100, and that applying Equation [10-1] to that case gives Q=0. Also, as P grows larger, CN(P) approaches CN_{∞}. However, using Equation [10-2] gives *mean* values of CN for the given P, not the median CN as found with Equation [10-1]. Every storm depth P>0 has an *average* (mean) Q>0, however small. To apply the asymptotic Equation [10-2] to calculate a CN or runoff Q for a P requires the parameter k.

5. CN_{∞} is defined to be CN_{II}, or the NEH concept of CN at Antecedent Runoff Condition II (ARC II). That is, CN_{∞} is approximately equivalent to current handbook entries. The asymptotic Equation [10-2] reflects the observation that smaller storms have higher data-defined CNs, i.e., small P values give high CN values.
6. Complacent and Violent runoff types are not consistent with the CN method. There are a number of alternative process-based, like the Water Erosion Prediction Project (WEPP; Srivastava et al., 2013) and the Distributed Hydrology and Soil Vegetation Model (DHSVM, Wigmosta et al., 1994) that are able to model these runoff types, or statistically-based methods (Ries 2007) that can be applied to such watersheds.

7. The initial abstraction coefficient, Ia/S, (referred to as λ, or lambda) shown in Equation [10-1] as the coefficient of 0.2 is variable, and more appropriately 0.05. The use of 0.05 value is recommended. With this change in λ, Equation [10-1] becomes

$$Q = (P-0.05S_{05})^2/(P+0.95S_{05}) \text{ for } P>0.05S_{05}, \qquad Q = 0 \text{ otherwise.} \qquad [10\text{-}3]$$

   Note that Equation [10-3] defines S as S_{05} which is not the same S as in [1]. Here, as $P\rightarrow\infty$, $P-Q \rightarrow 1.05S_{05}$, whereas previously $P-Q \rightarrow 1.20S_{20}$.

8. There are empirical equations to convert from S_{20} to S_{05}, and thus CN_{20} to CN_{05}. The original CN transformation CN=1000/(10+S) is preserved for Ia/S=0.05 but is identified with a subscript, i.e., $CN_{05}=1000/(10+S_{05})$. S and S_{05} are inches of depth (SI units are not used here).
9. CNs in NEH handbook soils and land use tables do not always match well with those found through analyses of rainfall-runoff data.
10. The calculation of Q from Equation [10-1] is more sensitive to errors in CN than to errors in P.
11. The original handbook contained no detailed or exampled instructions for determining CNs from data. The most defensible method, given adequate data and what is identified as a Standard mode, is fitting CN to the asymptotic equation (i.e., Equation [10-2]) to large complete, ordered data sets (see appendix in Chapter 9).
12. The Antecedent Moisture Condition (AMC) – later re-labelled as Antecedent Runoff Condition (ARC) – is described with probabilities and pertain to all causes of deviations for the central trend, and is not solely viewed as a measure for initial soil water conditions.

630.0002 Major Changes

The major changes to the CN method in this update are:

1. Use Ia/S = 0.05 instead of Ia/S = 0.20. This changes all the tables and charts that were based on the initial Ia/S = 0.20 assumption. It also redefines S to a different value because the limit difference between the natural P and Q is no longer 1.20S, but 1.05S. Empirical relationships between the two "S" values, S_{05} and S_{20}, are provided.

2. Recommendation for use of distributed, area-weighted weighted runoff from source area CNs. This technique emulates the observed asymptotic, or rainfall-dependent, CN values widely found in data.
3. Revision of the basic CN definition from a physical event process basis to a group property based on paired return period rainfall and runoff depths.
4. Endorsement of using CN tables based on local conditions. CN values should be developed under local professional and jurisdictional auspices, and as open documents. Local judgement, experience, data analysis, documentation, and negotiated conventions are suggested. However, the tables may need to be adjusted to apply to the recommended Ia/S = 0.05
5. Discussion of the likely computational errors in Q.
6. Recommendations for characteristic non-CN rainfall-runoff responses such as observed in humid forested watersheds

This update is a guide, but use of the content is not mandatory. It is supported by technical rhetoric, literature references, and the heritage wisdom of the prior handbooks. The contents are tempered by the professional opinions and experiences of the authors.

This update is based on knowledge to date. It assumes user access to computer services, modern rainfall-runoff hydrograph models, and information sources. It encourages - if needed, justified, and available – use of local data and analysis and fitting, thereby suggesting defensible assignment of CNs.

Historically, this document and Chapter 10 played a significant and pioneering role in applied hydrology by introducing, describing, and promoting the CN method. That approach is followed here, but in updated form. A **major** post-1954 finding is that the CN method <u>is not applicable in all instances</u> of rainfall-runoff, and that enhancements and corrections are in order.

Organization and approach: Considering the familiarity with the current method using Ia/S=0.20, that will be the starting point to introduce the revisions. The changes with the most profound effects are 1) the use of Ia/S = 0.05 and the necessary changes in CN values; and 2) the strong recommendation for the use of distributed CN source areas in runoff modeling. The newer methodology is developed and demonstrated in parallel to the existing method.

The existing method using Ia/S=0.20 is referred to as "original." The proposed updates centering on using Ia/S=0.05 and the asymptotic options is referred to as "proposed."

Limitations: This update does not consider 1) the use of CNs in continuous or daily time step models, 2) generation of unit hydrographs, or 3) runoff timing measures such as time of concentration or lag.

Intended Audience: The original 1954 (and following) release was SCS-limited and targeted on the hydrologic design needs for PL 566 and similar USDA programs. Because of its generality, content, and availability, the CN method quickly filled a waiting technological niche in applied hydrology beyond the original audience. It is used internationally, and in several applications not included in the original handbooks. This release is intended to service the larger more general audience, as well as the traditional agency users.

Subscripts and Symbols: This version parallels and builds on the original method, and - as a result of data-based findings in the interim - unavoidably complicates it. The variables and symbols used in this and the related chapters (8, 9, and 12) are defined in the following table.

Symbols and Subscripts

Symbols	**Description and Dimensions**
P	Storm event rainfall depth, (L)
Q	Storm event direct runoff depth, (L)
Ia	Start-of-storm rainfall depth required to initiate runoff. (L)
P_e	Effective storm rainfall, or depth following I_a (L), P-I_a
F	Effective in-storm loss to runoff, Pe - Q (L)
S	Maximum possible loss following satisfaction of Ia. The limiting or lim(P_e-Q) as $P \to \infty$, Maximum post-Ia on-site retention possible (L)
CN	Dimensionless transformation of S by CN=1000/(10+S) with S in inches or CN=25,400/(254+S) if S is in mm.
λ	Ia/S, or "lambda" used as either 0.05 or 0.20. Ex: CN_{20}, S_{05}, etc, dimensionless.
k	Fitting parameter in the exponent of asymptotic fitting equation $CN(P)=CN_\infty + (100 - CN_\infty)\mathbf{exp}(-kP)$ in units of in^{-1} or mm^{-1}.

Subscripts	**Discussion and example**
05, 20	Indicates the Ia/S, or λ "lambda" used as either 0.05 or 0.20. Example CN_{20}, S_{05},
I, II, III	Presumed ARC status. Example: Q_{II}, $CN_{II.}$ Condition II is the default value in CN descriptions. Traditionally, non-subscripted values are assumed as either Condition II, or a general undefined status.
nat, ord	Natural or ordered (rank ordered) condition. Example P_{ord}, Q_{ord}, CN_{ord}, P_{nat}, etc. The ordered condition is used only in CN determination from P:Q data sets.
∞	Status with asymptotic method as $P \rightarrow \infty$. Ex: CN_{∞}, S_{∞}
o	Used with CN_o and P_o, or the condition at threshold Q=0. For example, CN_{o20}=100/(1+P/2) with P in inches, and Ia/S=0.20. The threshold CN for Q=0. Similarly, CN_{o05} would be the CN at which Q=0 for the given P with Ia/S = 0.05.

630.1000 Introduction

The Natural Resources Conservation Service (NRCS) method of estimating direct runoff from storm rainfall is described in this chapter. The rainfall-runoff relationship is developed, parameters are described, and applications are illustrated by examples.

The NRCS method of estimating direct runoff from storm rainfall was the end product of a major field investigation and the work of numerous early investigators (Sherman 1942, Mockus 1949, and Mockus, 1964). A major catalyst for releasing this procedure was the passage of the Watershed Protection and Flood Prevention Act (Public Law 83-566) in August 1954. As a result, studies associated with small watershed planning requiring solutions of hydrologic problems were expected to produce a quantum jump in hydrologic computations within NRCS (Rallison, 1980; Rallison and Miller, 1982). Most NRCS work is with small, ungauged, agricultural watersheds, so the method was developed for rainfall and watershed data that were available or easily obtainable.

The method is a direct descendent of the hydrologic heritage developed in the United States in the first half of the 20th century. In the early 1900's investigators commonly plotted total runoff versus total rainfall to describe river hydrology. Mead (1919) showed several of these plots, which were reasonably useful on an annual basis. However, for shorter periods, such as seasons or months, the scatter became excessive. More than just rainfall depth alone was involved in determining the amount of runoff. Sherman (1942) attempted to include additional information by plotting runoff versus rainfall with separate curves for each month and a tabular adjustment for antecedent rainfall. This was an attempt to deal with event situations; however, the scatter of the data was still significant. Kohler and Linsley (1951) expanded upon the approach of Sherman with the multiple correlation diagram. This incorporated such items as antecedent precipitation, week of the year, and storm duration along with the basic rainfall and runoff values. Coaxial correlation diagrams were required to be generated for each basin, so this approach could not be used in ungauged situations.

Victor Mockus's goal was to develop a procedure for use on small, ungauged agricultural watersheds. No evidence indicates that the coaxial graphical correlation diagrams were in mind when he started the work that led to CNs. It does seem appropriate, however, to consider the procedures to be related when CN tables take the place of some graphs used for coaxial correlation work. Rallison (1980) and Rallison and Miller (1982), in describing the origin and evolution of the runoff equation, point to this heritage.

The intended principal application of the method is for estimating quantities of runoff in flood hydrographs or in relation to flood peak rates (National Engineering Handbook 630 (NEH-630), Chapter 16). An understanding of runoff source types is necessary to apply the method properly in different climatic regions.

630.1001 General rainfall-runoff

This work covers the generation of event runoff volumes from rainstorms as portrayed as Q in Figure 10-1. That is, the quantity of runoff Q as shown in the hydrograph resulting from a rainstorm. While the actual physical processes are complex, spatially and temporally varied, and not consistent from event to event, the general process as portrayed in Figure 10-1 is assumed to apply.

Such information is useful in 1) generating design flood hydrographs; 2) post-event forensics; 3) water quality applications; 4) rainfall-runoff and soil moisture accounting in full-service (daily time step) models, and 5) expressing land use impacts. The CN method is a sub-set of general rainfall-runoff concepts.

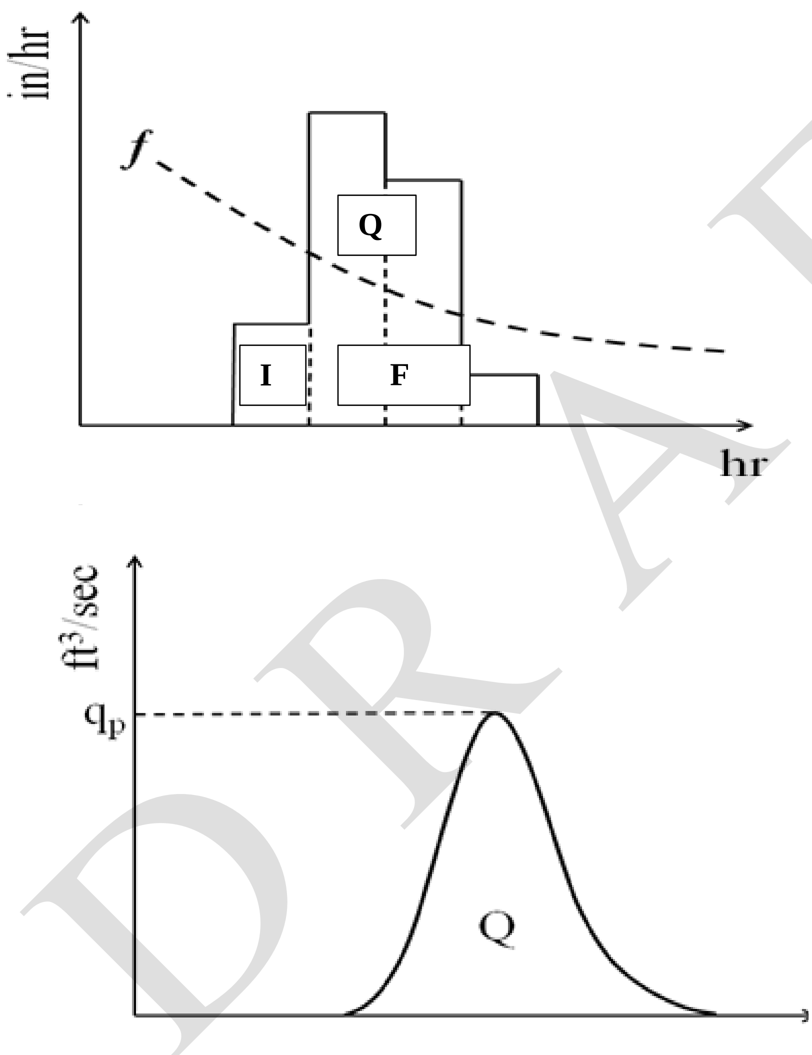

Figure 10- 1. Schematic of rainfall event partitioning components in the generation of a hydrograph. Note that stream runoff starts when Ia is satisfied, and that losses F may continue past the generation of runoff. In the rainfall (upper panel) the Q volume, called rainfall excess, is the same volume included in the runoff hydrograph in the lower panel.

630.1002 Definitions

Surface runoff, or overland flow, occurs when the momentary rainfall rate (intensity) is greater than the site's infiltration capacity (rate). The CN method strongly infers this process, but actually includes all types of runoff described as direct runoff. The resulting runoff flows downslope over the watershed surfaces and through rills and channels to the point of reference. This type of runoff appears in the hydrograph after the initial abstractions (Ia) of interception, preliminary infiltration, and surface storage have been satisfied. It varies during the storm and ends soon after the storm ends. This overland flow process dominates in many agricultural and urban settings and is the assumed central process in many rainfall-runoff models.

The runoff flowing down dry and infiltrating channels in arid, semi-arid, or sub-humid climates may be reduced by transmission losses. Such channels may be large enough to absorb the entire surface runoff (See NEH630, Chapter 19).

Subsurface flow occurs when infiltrated waters meet a subsurface horizon of lower hydraulic conductivity, travels laterally along the interface, and reappears as a seep or a spring, often contributing to surface flow during the hydrograph. It is often called "quick flow" or "interflow". This flow is common in steep watersheds in humid forested lands (Dun et al., 2009; Srivastava et al., 2013).

Baseflow occurs as prolonged flow during rainless periods, coming from an upland-local or regional aquifer replenished by infiltrated rainfall, snowmelt, or surface runoff (Srivastava et al., 2013 and 2015). Changes to this type of runoff seldom appear soon enough after the storm to have an influence on the rainstorm generated hydrograph. An increase in baseflow from a previous storm source increases the start-of-storm streamflow rate and influences channel interception.

Baseflow must be considered in the design of principal spillways of floodwater retarding structures (NEH 630, Chapter 21). However, baseflow is not a part of direct runoff, and the direct runoff equations do not include baseflow.

<u>*Channel runoff*</u>**,** or channel interception, occurs when rain falls directly on a flowing stream surface. If there is baseflow, channel runoff appears in the hydrograph immediately at the start of the storm, and continues throughout, varying only with the rainfall intensity and changing channel surface area. This runoff source process is generally a negligible quantity in the generation of flow from upland surfaces. However, it can be a major fraction of the runoff when the other processes are minor or absent. Runoff from impervious near-channel and other source areas also mimics the direct interception process.

<u>*Direct runoff*</u> is the rainstorm-driven runoff found in event hydrographs from the three sources of overland flow, subsurface flow, and channel runoff, in mixed proportions. Often in upland small watersheds without baseflow, direct runoff is the entire runoff and water yield source. The CN method and related equations concern direct runoff.

All types of runoff sources do not regularly contribute for all storms or on all watersheds. Climate is one indicator of the types of runoff that may occur in a given watershed. In arid regions, the flow of smaller watersheds is nearly always surface runoff, or overland flow. Subsurface flow and baseflow are more likely in humid regions. A long succession of storms, however, may produce subsurface flow or changes in baseflow, even in arid climates, although the probability of this is lower in arid regions than in humid regions. It should be noted that baseflow source areas enable channel runoff. Channel runoff in turn allows direct channel interception onto its impervious surface.

While overland flow was the basis for the development of the CN method, mixtures of the three processes previously discussed may also occur and give overall rainfall-runoff results consistent with the general CN method.

630.1003 Rainfall-runoff Relationship: The Curve Number Method

(a) Development

Figure 10-1 and the following equations show the major variables of: 1) event rainfall P, or the depth or rainfall over the watershed; 2) the event runoff Q, or the volume of runoff passing the downstream station, expressed as a depth spread over the drainage area, and 3) Ia, the initial abstraction, or the amount of rainfall required for runoff Q to be initiated. During a rainstorm, the evaporation is ignored as either insignificant or assumed to be suppressed during the cool moist moments of the storm event.

The general conservation of mass statement for a rainstorm is

$$P = Q + F + Ia \qquad [10\text{-}4]$$

The difference between (P-Ia) and Q is F, or the water retained on the site in the soil and vegetation. The quantity (P-Ia) has been called "effective rainfall", or P_e, so that Equation [10-4] is sometimes stated as

$$P_e = Q + F \qquad [10\text{-}5]$$

Concept of S: In 1954, Victor Mockus envisioned a maximum possible loss S, or the maximum possible difference between rainfall and runoff following the satisfaction of Ia. (Mockus' original development did not acknowledge inclusion of Ia). The site profile and soil column can only hold so much water, envisioned as a function of soil properties including depth, porosity, and the limiting infiltration capacity. Accordingly, it is defined on a watershed basis as

$$S = \lim(F) = \lim(P\text{-}Ia\text{-}Q) \quad \text{as } P\rightarrow\infty \qquad [10\text{-}6]$$

Runoff proportion: From this, Mockus proposed the following ratio as descriptive of the net rainfall runoff process:

$$Q/P=F/S \qquad [10\text{-}7]$$

The left-hand side, Q/P, is the runoff ratio. The right-hand side, F/S, is the fraction of the potential – from start of storm - water storage space (S) occupied. This may also be interpreted as the transient soil moisture fraction.

There is no underlying background or previous conceptualization for the proportional equivalency. With it, every P>0 generates a Q>0. However, it ignores the initial abstraction Ia. Thus (P-Ia) (or P_e) was substituted for P in Equation [10-7], resulting in

$$Q = (P\text{-}Ia)^2/(P\text{-}Ia+S) \qquad \text{for } P \geq Ia \qquad [10\text{-}8a]$$

$$Q = 0 \qquad \text{for } P \leq Ia \qquad [10\text{-}8b]$$

Equation [10-8] is the fundamental runoff equation, depending on the rainfall P, the initial abstraction Ia, and the soils-site property S, in units of depth, originally in units of inches. It should be noted that the maximum possible difference between P and Q is (Ia+S).

<u>Time</u>: Time (t) plays an unappreciated role in the concept: While there is no time dimension included, S is defined at the onset of the storm (t=0), and Ia is defined at the time streamflow begins to appear. Furthermore, in application to hydrograph generation, both Q and P are taken as P(t) and Q(t), or transient values during the time progress of a rainstorm. In addition, the original 1954 development was done with daily rainfall and runoff volumes (depths), even though the event durations for both rainfall and runoff were usually much less.

<u>Relationship of Ia to S</u>: To simplify the equations, prior work asserted that

$$Ia = 0.20S \qquad [10\text{-}9]$$

leading to the original expression

$$Q = (P-0.2S_{20})^2/(P+0.8S_{20}) \qquad \text{for } P \geq 0.2S_{20} \qquad [10\text{-}10a]$$

$$Q = 0 \qquad \text{for } P \leq 0.2S_{20} \qquad [10\text{-}10b]$$

This applied the long-used original value of Ia/S. Later works (e.g., Jiang, 2001) found the relation to more appropriately be

$$Ia = 0.05S_{05}. \qquad [10\text{-}1]$$

The value of 0.05 for Ia/S will be introduced and stressed in this NEH update. An end-of-chapter Appendix enlarges on this choice of Ia/S. Using Equation [10-11] with Equation [10-8] results in

$$\mathbf{Q = (P-0.05S_{05})^2/(P+0.95S_{05})} \qquad \textbf{for } \mathbf{P \geq 0.05S_{05}} \qquad [10\text{-}12a]$$

$$\mathbf{= 0} \qquad \textbf{for } \mathbf{P \leq 0.05S_{05}} \qquad [10\text{-}12b]$$

Equation [10-12] is the proposed, <u>updated</u> rainfall-runoff equation in the CN method. Note the subscript 05 to indicate the use of Ia/S=0.05 in contrast to the original value of 0.20. The maximum possible difference between P and Q is $1.05S_{05}$.

As noted earlier, some references use the symbol λ (lambda) as a general Ia/S, or Ia= λS. The runoff Equations [10-8] through [10-12] are dimensionally homogeneous. That is, if P and S are in millimeters, then the runoff Q is also in millimeters.

(b) Storage Index S and Curve Number (CN)

The storage measure S is transformed to the CN by the expression

$CN_{05}=1000/(10+S_{05})$ where S_{05} is in inches [10-13]

or

$CN_{05}=25{,}400/(254+S_{05})$ where S_{05} is in mm. [10-14]

This continues the structure of the CN-S relationship as in prior usage. Similarly,

$S_{05} =1000/CN_{05} -10$ where S_{05} is in inches. [10-15]

The use of CN in place of S is an enhancement: with it, runoff is a positive function of CN. The larger the CN the larger the runoff. CN varies from 0 (no runoff for any P) to 100 (Q=P for any P.) CNs are dimensionless. Runoff is inverse to S: at S=0, Q=P for any P; at S=∞, Q=0 for any P. Figure 10-2 presents the array of runoffs Q with rainfall depth P for families of CN_{05}. Tables of CNs for application are shown in Chapter 9.

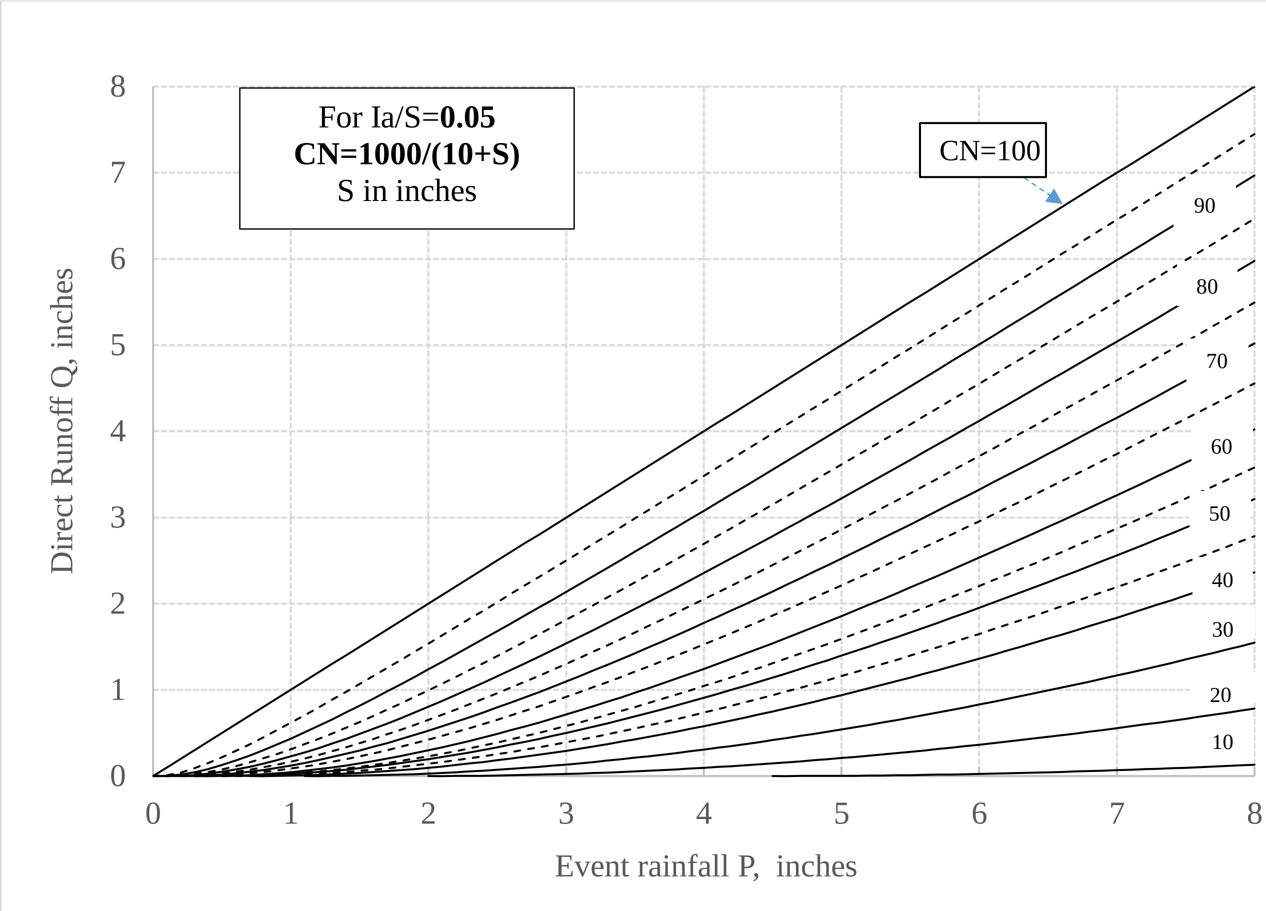

Figure 10- 2. Rainfall and direct runoff for the case of Ia/S=0.05, Equation [10-12a]

<u>Conversion between 020 and 0.05:</u> Conversion from the original system using Ia/S=0.20 to a basis of Ia/S=0.05 can be made by the following recommended equation as:

$$S_{\infty,05} = 1.42S_{\infty,20} \qquad [10\text{-}16]$$

Substituting Equation [10-16] into Equation [10-15] yields

$$CN_{05} = CN_{20}/(1.42-0.0042CN_{20}) \qquad [10\text{-}17]$$

Equations [10-16] and [10-17] pertain to values of CN_{∞} in both systems as defined by *ordered* asymptotic fitting as described in the Appendix of Chapter 9. An alternative expression (Jiang, 2001; Hawkins et al, 2009) taken from direct least squares fits of CN and S to P:Q *natural* (not rank-ordered) data sets is

$$S_{05} = 1.33(S_{\infty,20})^{1.15} \qquad [10\text{-}18]$$

with S_{05} and S_{20} in inches. These two equations ([10-16] and [10-18]) give similar results in the range of CN_{20} from about 65 to 85. They are also used for CN_{∞}, the limiting steady-state value of CN as P grows larger; as widely-observed and defined by an asymptotic equation. CN_{∞} for the case of Ia/S=0.20 has been found to be a close approximation to the original NEH table entries, i.e., the CN at ARCII. Thus, use of these 0.05 and CN_{∞} values are consistent with original practices and uses, except that the Ia/S = 0.05 is used in place of Ia/S = 0.20. The respective CNs will give slightly different runoff depths, however. Table 10-1 lists the equivalent CNs based on Equation [10-17].

(c) Curve Number Variability; Antecedent Runoff Conditions (ARC)

Rainfall-runoff data do not precisely fit the CN method concept. Variation in the observed runoff and CN may result from effects of rainfall intensity, distribution, duration, and total rainfall; soil moisture conditions; cover density; stage of vegetation growth; temperature, season; and model representation and data error. The observed variability is collectively described with three (3) *Antecedent Runoff Conditions* (ARC) classes. Condition II is for the median experienced conditions when runoff occurs for the given rainfall, and is the identifying reference or signature CN for the watershed. Condition I describes the lower extremes of conditions, and Condition III is for the higher extremes of conditions.

Table 10-2 shows CN values for the three ARC conditions, as stated in the original NEH4, converted to the condition of Ia/S=0.05. The ARC II is the reference condition; i.e., the identifying CN used for a watershed description. A plot of the relationship standardized on S_{05II} is shown in Figure 10-3.

Table 10- 1. CN_{20} and CN_{05} Conversions*

$CN_{20} \rightarrow CN_{05}$		$CN_{05} \rightarrow CN_{20}$	
100	100	100	100
99	99	99	99
98	97	98	99
97	96	97	98
96	94	96	97
95	93	95	96
94	92	94	96
93	90	93	95
92	89	92	94
91	88	91	94
90	86	90	93
89	85	89	92
88	84	88	91
87	83	87	91
86	81	86	90
85	80	85	89
84	79	84	88
83	78	83	87
82	76	82	87
81	75	81	86
80	74	80	85
79	73	79	84
78	71	78	83
77	70	77	83
76	69	76	82
75	68	75	81
74	67	74	80
73	66	73	79
72	64	72	79
71	63	71	78
70	62	70	77
69	61	69	76
68	60	68	75
67	59	67	74
66	58	66	73
65	57	65	73
64	56	64	72
63	55	63	71
62	54	62	70
61	52	61	69
60	51	60	68
59	50	59	67
58	49	58	66
57	48	57	65
56	47	56	64
55	46	55	63
54	45	54	62
53	44	53	62
52	43	52	61
51	42	51	60
50	41	50	59
49	40	49	58
48	39	48	57
47	38	47	56
46	38	46	55
45	37	45	54
44	36	44	53
43	35	43	52
42	34	42	51
41	33	41	50
40	32	40	49
39	31	39	48
38	30	38	47
37	29	37	45
36	28	36	44
35	28	35	43
34	27	34	42
33	26	33	41
32	25	32	40
31	24	31	39
30	23	30	38
29	22	29	37
28	22	28	36
27	21	27	34
26	20	26	33
25	19	25	32
24	18	24	31
23	17	23	30
22	17	22	29
21	16	21	27
20	15	20	26
19	14	19	25
18	13	18	24
17	13	17	22
16	12	16	21
15	11	15	20
14	10	14	19
13	10	13	18
12	9	12	16
11	8	11	15
10	7	10	14
9	6	9	12
8	6	8	11
7	5	7	10
6	4	6	8
5	4	5	7
4	3	4	6
3	2	3	4
2	1	2	3
1	1	1	1
0	0	0	0

* $S_{05} = 1.42 S_{20}$

Table 10- 2. Curve Numbers (CN) - ARC conversions and constants for the case $Ia = 0.05S_{05}$

ARC			
II	I	III	Ia_0(in)
100	100	100	0.00
95	87	99	0.03
90	78	97	0.06
85	69	94	0.09
80	62	92	0.13
75	56	89	0.17
70	50	85	0.21
65	44	82	0.27
60	40	79	0.33
55	36	75	0.41

ARC			
II	I	III	Ia_0(in)
50	31	70	0.50
45	27	66	0.61
40	23	60	0.75
35	19	56	0.93
30	16	50	1.17
25	12	44	1.50
20	10	37	2.00
15	6	29	2.83
10	4	22	4.50
5	2	12	9.50
0	0	0	∞

Note: Ia_0 is the initial abstraction (in) for the case of ARCII

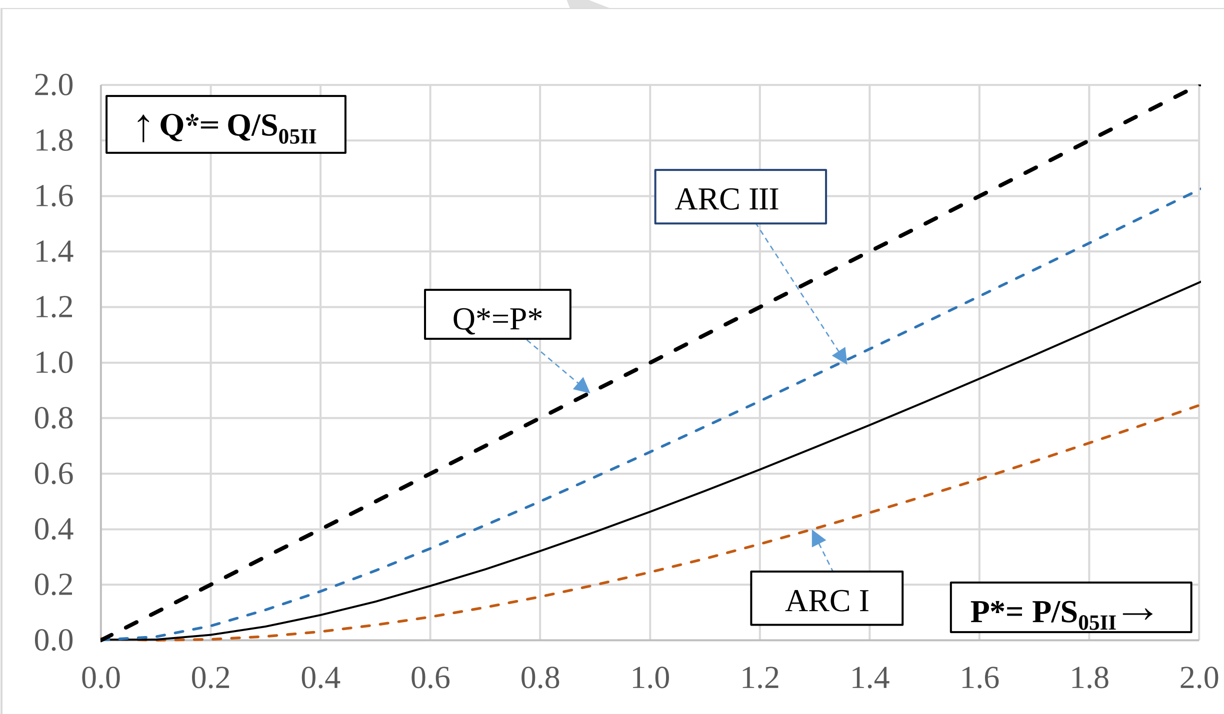

Figure 10- 3. Dimensionless rainfall and runoff for the case Ia/S=0.05. The following equations are used: For ARCI; $Q^*=(P^*-0.1155)^2/(P+2.1945)$; For ARCII; $Q^*=(P^*-0.05)^2/(P+0.95)$; For ARCIII; $Q^*=(P^*-0.0216)^2/(P+0.4113)$.

The ARC describe a reasonable range of runoff Q for a given P, but may or may not be attributable to prior rainfall. While given as a watershed (CN) property, ARC is really a measure of all the watershed <u>and</u> storm event conditions. Thus, the CN and runoff variation as described by the ARC is a result of *all* the influencing factors, e.g., storm duration and cover conditions.

Past attempts to quantitatively explain the scatter in the runoff data have focused on the antecedent (soil) moisture condition (AMC), usually as defined by the prior 5-day precipitation depth. Included in earlier editions of National Engineering Handbook Section 4 (now Part 630, Hydrology), the AMC approach is no longer supported by the NRCS and ***<u>should not be used</u>***.

Since the NEH4 release in 1954, a number of studies have shown only weak or inconsistent association of prior rainfall with departures from the general trend of runoff from rainfall. These results are typical for upland agricultural watersheds where surface runoff prevails. For examples, studies by Cronshey (1983), Hjelmfelt et al. (1982), Hjelmfelt (1987, 1991), Van Mullem (1992), and Hawkins and VerWeire (2005) all lead to the same general conclusions: While there is some evidence for prior rainfall effects on runoff and CN at the higher extremes, there is no consistent relationship between antecedent rainfall and CN throughout the entire range of conditions.

Several researchers have presented the values in Table 10-2 ARC I and ARC III classes as cumulative percentages of occurrence. The results are surprisingly similar and presented in Table 10-3. It should be noted the ARCII, or the standard condition, is the 50% event, or median, for a given P. These values have not been confirmed for Ia/S = 0.05.

Table 10- 3. Exceedance percentages for ARC

Source	ARCI	ARCII	ARCIII	N
Hjelmfelt et al. (1982)	10	50	90	12
Grabau et al. (2009)	12	50	88	134

The table entry is the percent of events with lesser runoff, including events with no runoff. N is the number of watersheds studied. Pertains to Ia/S=0.20.

630.1004 Standard asymptotic rainfall-runoff

From many rainfall-runoff studies (e.g., Hawkins, 1990a, 1990b, 1992), it has been widely recognized that CNs calculated from event rainfall-runoff data invariably show a strong secondary trend with rainfall depth. Three (3) dominating types of such runoff responses to rainstorm depth are seen in plots of CN versus P. These types are: 1) Complacent; 2) Standard; and 3) the Violent cases, or rainfall-runoff response modes. None of these types completely conforms to the relationship as presented in Equation [10-1]. However, the Standard mode is asymptotically compatible with the CN method as P grows larger, and the Standard mode has been found to be a good predictor of runoff response in a large majority of monitored watersheds. The Complacent and Violent cases are treated later in this chapter.

The Standard mode is illustrated in Figure 10-4. It is characterized by a path of CNs - determined with recorded data for storms resulting in Q>0.00 - that begins at P=0, CN=100, and declines with increasing rainfall and approaches a steady state value as P grows larger. The steady state value is called CN_∞. In Figure 10-3, CN_0 is the locus of all points of P=Ia, or the threshold of runoff.

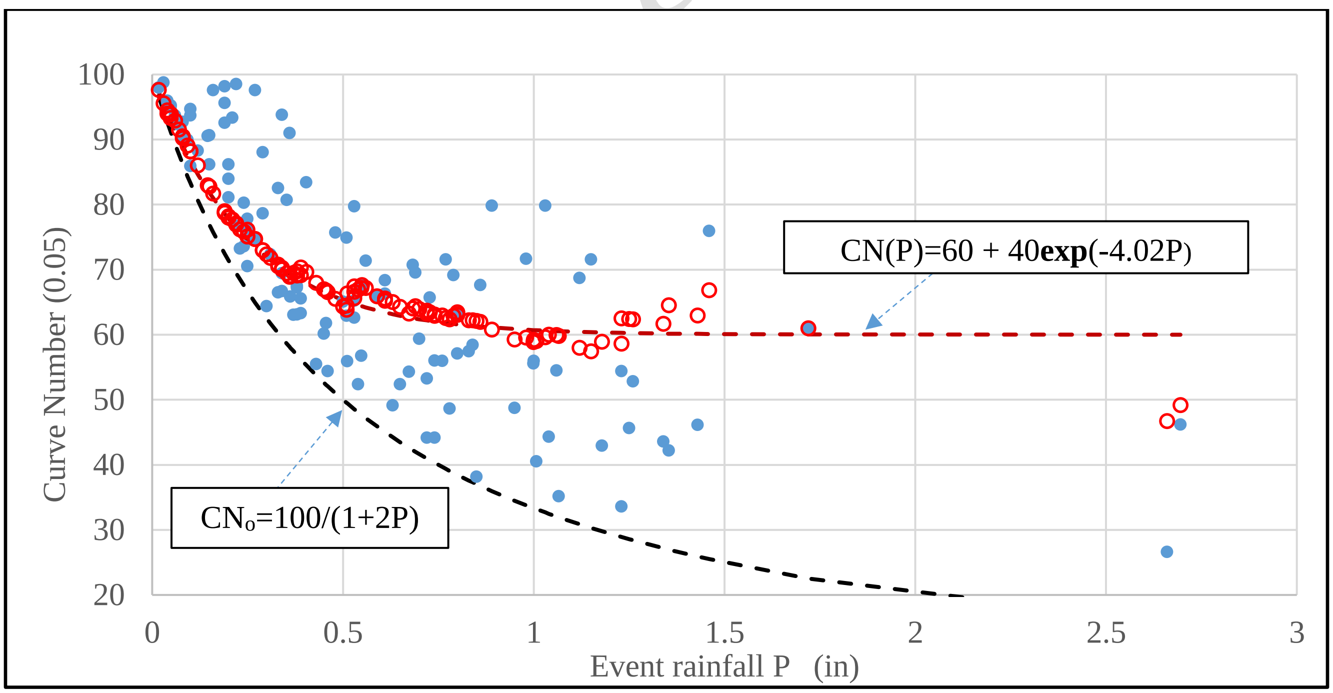

Figure 10- 4. Example of Standard asymptotic ordered CN response. Safford watershed 4, Arizona, Drainage Area (DA) = 723ac, for 121 events from 1940 to 1986, for natural P:Q data pairs (closed darkened circles) and rank-ordered data pairs (open circles). The asymptotic line fitted to the ordered is CN(P)=60+40exp(-4.02P). CN_0 is the locus of all points of P=Ia, or the Q=0 threshold.

The CN-P relationship as exemplified in the Figure 10-4 was not a part of the original 1954 method, but was detected by analysis of smaller (by area) watershed data sets. While found in many different watershed conditions, variations do abound. This mode becomes more predominant with increasing drainage area, and is nearly universal in upland cropped rain-fed watersheds, the data conditions for the derivation of the original CN method.

The relationship that matches the Standard mode is the asymptotic equation of

$$CN(P) = CN_\infty + (100 - CN_\infty)\mathbf{exp(}-kP) \qquad [10\text{-}19]$$

where:

CN(P) is the CN for the rainfall depth P,

P = rainfall depth in inches,

CN_∞ = the ARCII CN for the watershed,

k = asymptotic fitting coefficient in units of (1/inch),

exp(x) **=** the exponential function of natural logarithms, i.e., e^x, where $e \approx 2.7183$,

and the rank-ordered data sets are used. With these data sets, the largest rainfall event and the largest runoff event from each year of record are paired, even if they did not happen on the same day. These pairs of rank-ordered data are then used to determine the CN value for that watershed using a method similar to that presented in the example in the appendices.

It may be noted that this is the algebraic form comparable to the well-known Horton infiltration equation (Horton, 1940). The observed asymptotic phenomenon is the basis in this update for determination of CNs from event rainfall-runoff data sets, or groups of storms, but it is not recommended to use not CN(P) to estimate direct runoff Q from individual storms. Instead, use CN_∞ to estimate direct runoff Q.

As shown later in this chapter, the asymptotic effect can be created with distributed CN source area calculations. That practice is recommended as a standard procedure and is discussed later.

630.1005 Precision and reliability of CN and runoff estimates

Experience has shown that the CNs selected by users from handbook tables based on Hydrologic Soil Groups (HSGs) and land use are not precise, and will vary among different users. Those CN tables are *estimates* of the potential hydrologically-defined values, but based on perceived soils and land use descriptors. Numerous studies have demonstrated a lack of overall correlation between data-defined and handbook-estimated CNs (Hawkins, 1984; Hossein et al., 1989; D'Asaro et al., 2014a; Hawkins and Ward, 1998; Tedela et al., 2012a, and Woodward et al., 2010). While extremes are much greater, about half (i.e., 50%) of the CN differences are in the general range of about ±10 CNs. A summary of these differences is given in Table 10-4.

Table 10- 4. Selected expression of uncertainty in estimation of CN from soils and land use

Source	CN_{20}	Error range	Comments
Hawkins (1984)	50-90	-10 to +10	110 watersheds, USA
Hossein et al. (1989)	60-90	-3 to +10	96 basins, Queensland
Hawkins and Ward (1998)	62-78	+2 to +12	17 plots, New Mexico, rangelands
Woodward et al. (2010)	60-90	-4 to +4	USDA-ARS watersheds
Tedela et al. (2012a)	45-45	0 to +1-	10 forested watersheds, SE US
D'Asara et al. (2014a)	65-85	-10 to +2	36 Sicilian watersheds

Note: Error range contains roughly 50% of the observed instances

This CN disparity happens for several reasons. **First**, there is uncertainty in the definition of HSG (Nielson and Hjelmfelt, 1998). In the central range of HSG B and HSG C soils, a consistent assignment between the two is made only about half the time. Stewart et al. (2012) found divergence between handbook HSGs and data-derived local values for a number of semi-arid watersheds in southern Arizona, even with local measured conductivity corrections. When mismatching occurs, errors in the estimation of the CN may be in excess of ± 4-8 CNs.

Second, even for in local well-defined, well-instrumented and apparently uniform rain-fed agricultural sites with common crops, the calculated CNs vary between adjacent watersheds over a scale of about ±5 units. (Rietz, 1999; Rietz and Hawkins, 2000). This is natural variability occurring within a site and soils classification, and shown in Figure 10-5 and Table 10-6.

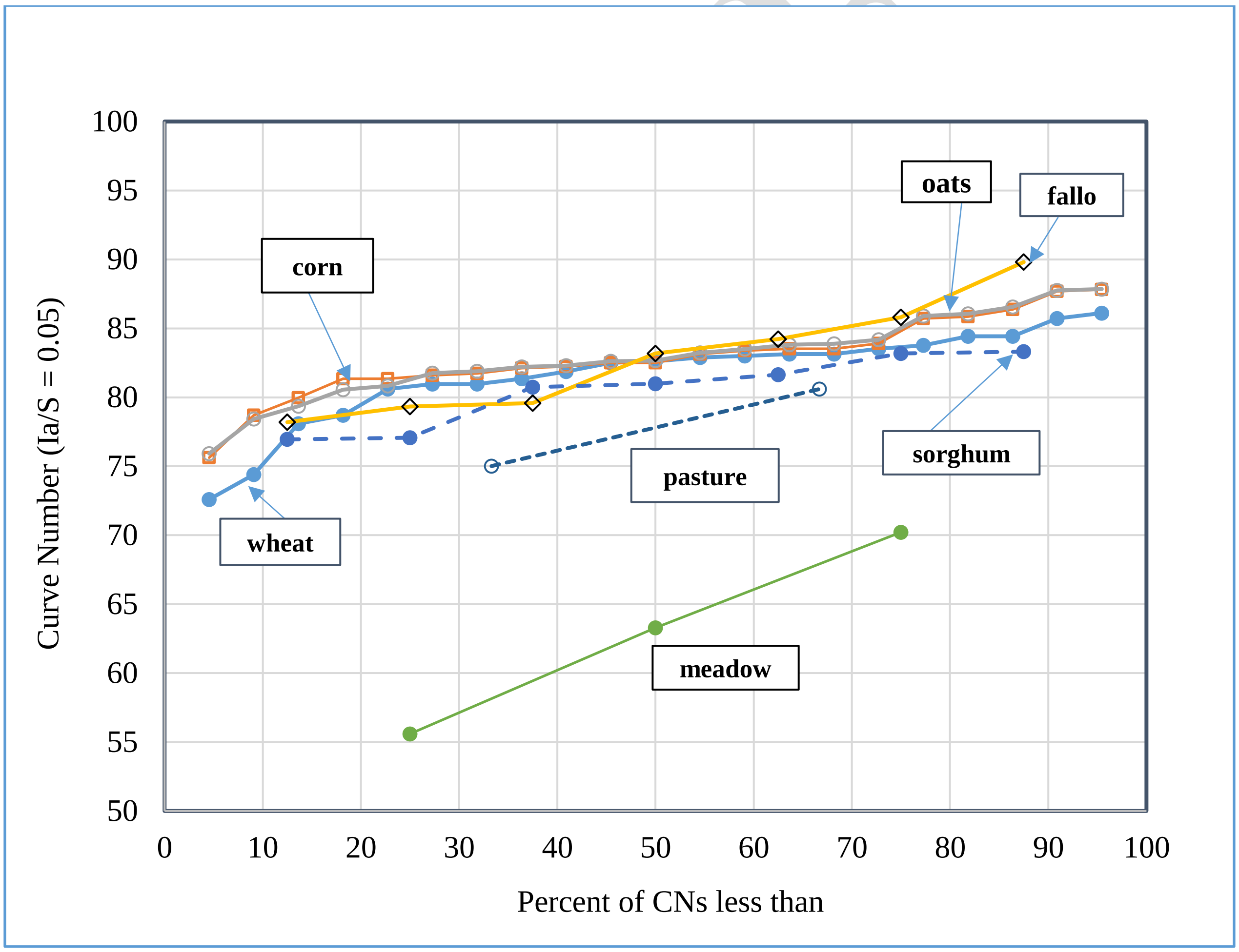

Figure 10- 5. Curve Numbers (for Ia/S=0.05; converted from Ia/S = 0.20 by Equation 10-17) found for various land uses and crops in Hastings, Nebraska, watersheds. Within each crop/type, each point is a separate watershed in that crop. CNs determined by asymptotic fitting.

Third, the land use/conditions descriptions are by nature imprecise and/or subjective. Furthermore, there are seasonal variations that are not usually acknowledged in routine application. (D'Asaro et al., 2014b; Price, 1998). The variations in Table 10-6 encompass about 50% of observed variations in the stated central range of handbook table CNs encountered. Positive deviations mean that the data-defined CNs were greater than the handbook value. These variations are important because the runoff calculation is <u>more sensitive to the choice of CN</u> than it is to the precision of the input rainfall P (Hawkins et al., 2009). Accordingly, runoff calculations using the CN method should show the uncertainty possible in estimating runoff Q. Uncertainty varies with the basic CN level; higher CNs have less variation. Minimum acknowledgment of runoff calculation uncertainty is suggested in Table 10-5 based on Table 10-4.

Table 10- 5. Suggested acknowledged variation in estimated CN selection

CN_{20}	Range of CN_{20}			CN_{05}	Range of CN_{05}	
	Lower	Upper			Lower	Upper
100		100			100	100
90	89	91		90	89	91
80	78	82		80	78	82
70	66	74		70	67	73
60	56	64		60	57	64
50	45	55		50	46	54
40	34	46		40	35	45
30	23	37		30	25	37
20	12	28		20	14	26
10	1	19		10	4	17

In Table 10-5 and for CN_{20}, the lower range column is estimated by $1.1CN_{20}-10$, the upper range column by $0.9CN_{20}+10$. The ranges for CN_{05} are direct transfers from CN_{20} using $S_{05} = 1.42S_{20}$, or $CN_{05} = CN_{20}/(1.42\text{-}0.0042CN_{20})$ (Equation [10-17]). These error ranges are suggested for $CN_{20}>10$ and $CN_{05}>7$.

630.1006 Distributed source areas accounting

The original CN method applied to a small drainage area, assumed to have constant (i.e., "lumped") properties throughout. Natural watersheds are mixtures of different land uses and soils, and thus of different contributing CNs. This mixture is particularly true for larger watersheds. Previous practice has been to average – on an area-weighted basis - the assigned CNs and use that average CN in the calculation of runoff of the entire watershed.

However, this practice of averaging the CNs does not account for the sometimes-important effects of extremes, especially at rainfall and CN conditions close to the threshold of runoff, such as found for smaller storms and higher CN portions of the watershed.

Many alternative and derivative models use CN in a distributed runoff approach; that is, averaging the areas with weighted runoff from individual units. This is the approach suggested in this update. The expression of this approach is

$$Q = \Sigma\alpha_i[(P-0.05S_{05i})^2/(P-0.95S_{05i})] \qquad \text{for } P>0.05S_{05i} \qquad [10\text{-}20]$$

where α_i is the fraction of the watershed area for that S_{05} (CN_{05}) with $\Sigma\alpha_i = 1.00$, and all P>Ia constraints observed. This approach will create runoff from the higher CN elements at smaller rainfall P, and create a declining CN with P, in keeping with the observed asymptotic behavior. The use of Equation [10-20] and other approaches discussed previously are demonstrated in the following examples.

EXAMPLES

Example 1: Calculating direct runoff Q with Ia/S=0.05 and 0.20. Determine the direct runoff volume (depth) from a 100-acre pasture watershed with HSG B soils from a 6-hour storm of 3.00 inches. To illustrate the use of the historical system with Ia/S=0.20, the above conditions will give $CN_{20} = 69$ and, from Equation [10-15], S_{20}=4.493 inches. Using the original equation

$Q_{20} = (P-0.2S_{20})^2/(P+0.8S_{20})$

with 0.2S = 0.8985 in; 0.8S = 3.5942 in gives

$Q_{20} = (3.00-0.8985)^2/(3.00+3.5942) =$ **0.67** in

Using Equation [10-16]

$S_{05} = 1.42S_{20} = 1.42(4.4928) = 6.3798$ in $CN_{05}=1000/(10+6.3798)=61.1$

$Q_{05} = (P-0.05S_{05})^2/(P+0.95S_{05})$ for all $P>0.05\ S_{05}$

with $0.05S_{05} = 0.05(6.3798) = 0.3180$ in; $0.95S_{05} = 0.95(6.37987) = 6.0608$ in.

$Q_{05} =$ **0.79** inches.

Results for P up to 5 inches are shown in Table 10-EX1. The results for P=3 inches are highlighted.

Table 10-EX1. Rainfall and runoff for CN_{20}=69, CN_{05}=61

P(in)	Q_{20}(in)	Q_{05}(in)	Comments
0			
0.200		0	
0.318		0	Ia for 0.05
0.400		0.001	
0.600		0.012	
0.800		0.034	
0.899	0	0.048	Ia for 0.20
1.000	0.002	0.066	
2.000	0.217	0.351	
3.000	**0.670**	**0.793**	**Example case**
4.000	1.267	1.347	
5.000	1.957	1.982	

Comparisons clearly show that Q_{05} is not the same as Q_{20}; and it is not expected to be equal. Also note that runoff is generated at lower P values for CN_{05} and that the $Q_{05} > Q_{20}$ for all P in this range, i.e., more conservative for design.

Example 2. Effects of CN uncertainty in calculation of direct runoff Q. The effects of tabulated CN value uncertainty are illustrated by using values given in Table 10-6 for the example storm and watershed used in the previous example. For CN_{05}=61.1, the suggested uncertainty limits are 57.6 and 64.5 the results are shown in Figure 10-EX2. The relative effects are more profound at lower rainfalls and smaller CNs.

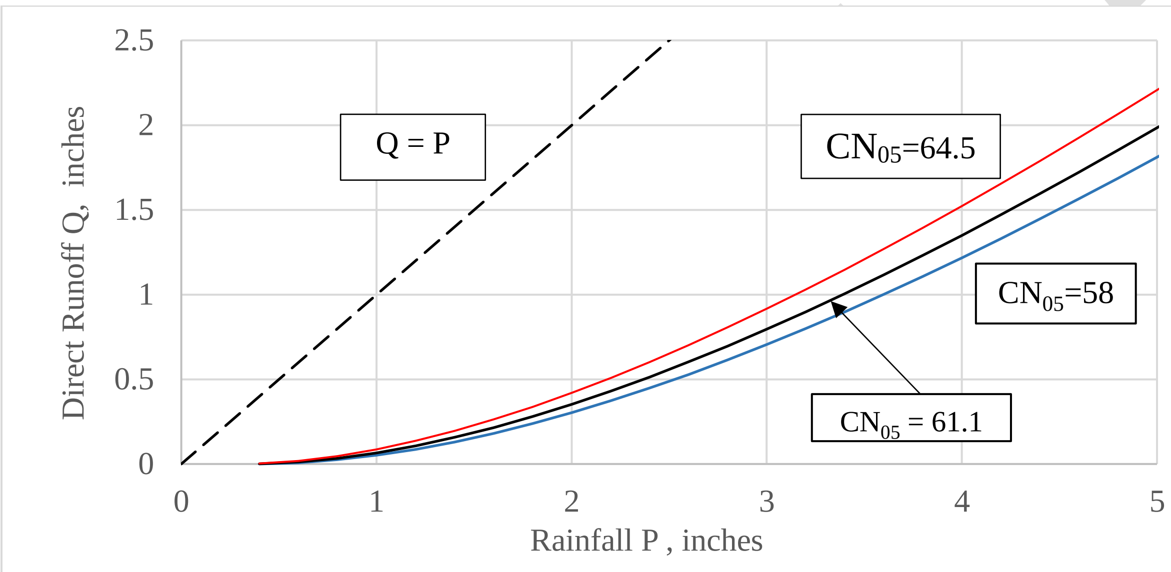

Figure 10-EX2. Effect of CN uncertainty on calculated Q for the example of CN_{05}=61.1. Rainfall P from 0 to 5 inches for Ia/S=0.05. At the stated design value of P=3.0 inches, the variation in Q is about ±10%.

Example 3: Using distributed CN source areas and distributed runoffs. In this example, the watershed data are refined and found from more detailed soils and land use analysis and found to be composed of 25 acres of CN_{20} = 55, 50 acres of CN_{20} = 69, and 25 acres of CN_{20} = 83. The fractions are 25/100, 50/100, and 25/100, respectively. The area-averaged CN20 here is still equal to the example 1 value of 69. The watershed runoff is the sum of the weighted runoffs from the contributing components, or

$$Q = \Sigma\alpha_i[(P-0.05S_{05i})^2/(P+0.95S_{05i})] \qquad \text{for } P\geq 0.05S_{05} \qquad [10\text{-}20]$$

This better expresses the influence of runoff from the varied contributing areas. This is especially noticeable for the higher CN portions which begin contributing at lower rainfalls. The results for this example are shown in Table EX2**.** The rounded CNs for Ia/S=0.05 are calculated as 46, 61, and 77, respectively, for an area-weighted average of 61 compared to 61.1 in example 1.

Table 10-EX2. Example of runoff calculation with mixed sources, for Ia/S=0.20 and Ia/S=0.05

	Ia/S=0.20						**Ia/S=0.05**				
Fraction	0.25	0.50	0.25		1.00		0.25	0.5	0.25		1.00
CN	55	69	83		69		46	61	77		61
Ia (in)	1.6364	0.8986	0.4096		0.8986		0.5799	0.3183	0.1452		0.3130
P (in)	**Runoff, Q (in)**										
	Partial			**Sum**	**Lumped**		**Partial**			**Sum**	**Lumped**
0.00					0.0000				0.0000	0.0000	0.0000
0.20					0.0000			0.0000	0.0002	0.0002	0.0000
0.40			0.0000	0.0000	0.0000			0.0005	0.0048	0.0054	0.0010
0.60			0.0040	0.0040	0.0000		0.0000	0.0059	0.0148	0.0207	0.0118
0.80		0.0000	0.0156	0.0156	0.0000		0.0003	0.0168	0.0291	0.0462	0.0337
1.00		0.0011	0.0330	0.0341	0.0022		0.0010	0.0328	0.0471	0.0809	0.0656
1.20		0.0095	0.0550	0.0645	0.0189		0.0021	0.0534	0.0683	0.1239	0.1068
1.40	0.0000	0.0252	0.0807	0.1059	0.0503		0.0027	0.0783	0.0922	0.1742	0.1566
1.60	0.0001	0.0474	0.1094	0.1568	0.0947		0.0058	0.1071	0.1158	0.2313	0.2141
1.80	0.0010	0.0753	0.1406	0.2169	0.1506		0.0082	0.1395	0.1468	0.2945	0.2789
2.00	0.0050	0.1084	0.1738	0.2873	0.2168		0.0112	0.1752	0.1769	0.3633	0.3504
2.20	0.0121	0.1461	0.2088	0.3671	0.2923		0.0146	0.2141	0.2086	0.4373	0.4282
2.40	0.0223	0.1880	0.2453	0.4555	0.3761		0.0184	0.2558	0.2417	0.5160	0.5117
2.60	0.0355	0.2337	0.2830	0.5521	0.4673		0.0227	0.3003	0.2761	0.5990	0.6006
2.80	0.0517	0.2827	0.3219	0.6563	0.5654		0.0274	0.3472	0.3115	0.6862	0.6945
3.00	0.0710	0.3348	0.3617	**0.7675**	**0.6696**		0.0326	0.3965	0.3479	**0.7771**	**0.7930**
4.00	0.2134	0.6333	0.5716	1.4182	1.2665		0.0653	0.6732	0.5420	1.2805	1.3464
5.00	0.4321	0.9786	0.7936	2.2043	1.9573		0.1091	0.9903	0.7504	1.8498	1.9806

* “Sum” is the sum of the three partial component contributions; “Lumped” is the runoff calculated with the area-weighted average CN for the conditions shown.

The estimated Q values for P = 3 inches are highlighted and emphasized for comparisons to example 1. Note the lumped area-weighted CN_{05} of 61.5 is a bit higher than the 61.1 in example 1 leading to slightly higher Q_e in example 3. In contrast, the CN_e lumped value of 69 is the same as that in example 1 so there is no difference in the lumped Q_e estimates between the examples. For the traditional average CN method with Ia/S=0.20, runoff does not begin until P ≈ 0.50 in., but for the distributed source method with Ia/S=0.05, calculated runoff begins at P ≈ 0.15 inches.

630.1006 Summary

Chapter 10 reconciles and updates the widely-used Curve Number method with observation-based rainfall-runoff hydrology findings developed during the several decades since the CN method's first introduction. The following steps, recommendation, and developments are offered:

- The basic form of the CN runoff equation is preserved as $Q=(P-Ia)^2/(P+S-Ia)$ for all P>Ia
- The transform between S and CN is preserved, that is CN=1000/(10+S(in)).
- The role of S as the limiting possible difference between rainfall and (Rainfall excess + Initial Abstraction) is preserved.
- Based on several studies, the initial abstraction coefficient, Ia/S or lambda (λ) is changed from 0.20 to 0.05. This proposed value changes the underling definition of S from the basis of 0.20 to 0.05. The recommended transfer function is $S_{05}=1.42S_{20}$.
- From analysis of rainfall-runoff events across a wide range of watershed conditions, an unexpected variety in basic rainfall-runoff response patterns has been recognized. In addition to the responses demonstrated and characterized by the Curve Number method, several alternatives exist which are inconsistent with the method.
- The CN equation (and method) is not consistent with a Complacent response. The method is not easily adapted to the Violent response case.
- The Standard response is asymptotically consistent with the CN equation with increasing P. This is expressed through the standard asymptotic pattern of CN with P. Most watershed data sets show this case; thus the CN method can be applied.
- Use of distributed CNs and weighted/fractional runoff sources is recommended in lieu of using average CNs. For watersheds with distinctly varied runoff properties, the observed standard asymptotic patterns are much better modeled.
- Equivalent CNs for the traditional ARC bands are given.

- Errors in the estimation of CN are outlined and suggested procedures introducing that uncertainty into runoff calculations are offered
- Although the Curve Number method is roughly patterned after physical processes, professional application is more appropriate to the rainfall-runoff return-period matching interpretation.

630.1007 Appendices

Appendix 1 - Exceptions to the CN method

The CN method is not appropriate for all rainfall-runoff responses or cases. It is appropriate to upland rain-fed agricultural plots, fields, and small watersheds. Subsequent experience shows the observed rainfall-runoff patterns suitable for the CN method are seen in urban lands, many range lands, parks, and woodlands. In these cases, overland flow is a major component of the runoff process. In addition, the equation's form is of such general applicability that many river basins, when analyzed on a rainfall-runoff basis, also display the same rainfall runoff patterns (Tedela et al., 2012b).

There are, however, several watershed runoff response patterns that are not in accord with the form of the CN method and equation. The CN method should not be used to represent them. These non-CN conditions are documented in Hawkins et al. (2009)

As shown in following figures, three general modes or cases of rainfall-runoff responses have been identified by data analysis. These are 1) Standard (CN method applies asymptotically); and 2) Complacent and 3) Violent (CN method does not apply to either). The latter two, Complacent and Violent may be represented individually, and may be observed as a sequential pair as illustrated in the following figures.

The CN method and equation are inappropriate for the Complacent case, and applicable to the Violent case only at the extremes. Following are some suggested general criteria for identifying the cases from field observation and soils/land use data. They are illustrated in Figures 10A-1 and 10A-2.

<u>Standard Case:</u> Curve Number method is applicable

Overland flow occurs, as shown by direct observation, or by geomorphic evidence: active rills and swales, bare channels, surface erosion, and/or bare finer-grained soils. Most upland rain-fed cropped lands display the standard mode. The Complacent case is also common in urbanized watersheds and some arid wildlands. Equations [10-12a] and [10-12b] are assumed to be applicable.

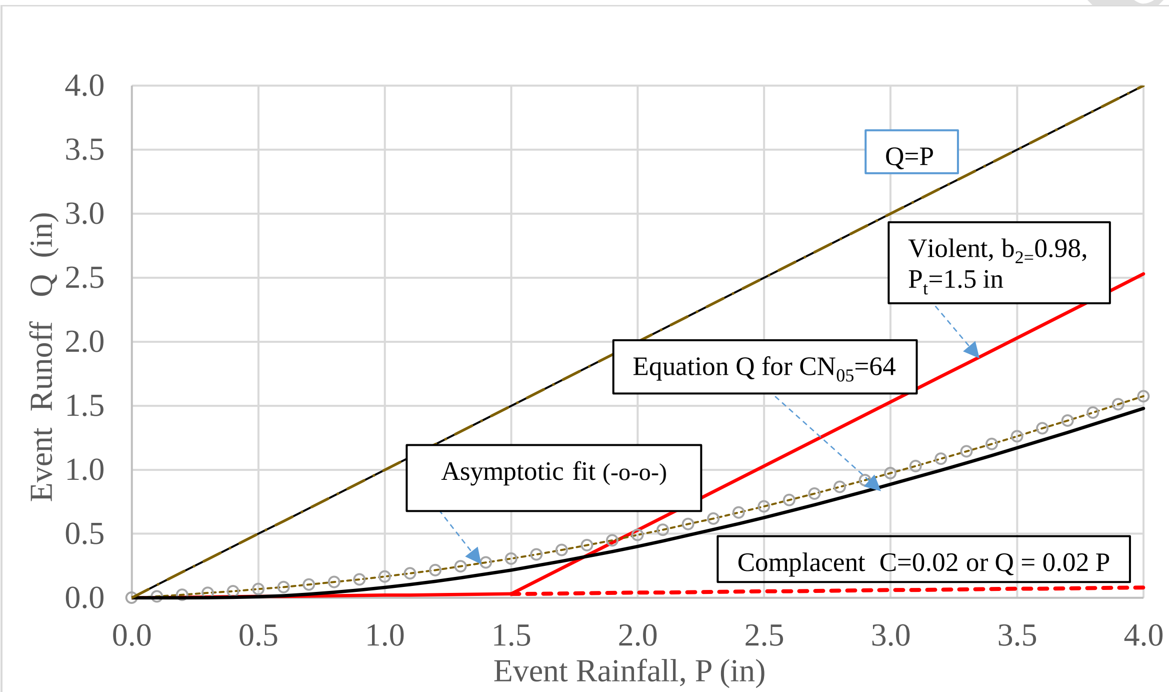

Figure 10A- 1. Idealized portrayals of Complacent-Violent [Equations 10-21 and 10-22] and Standard rainfall-runoff behaviors. The Standard is represented here by the CN Equation [10-11] and CN_{05}=64, and the Complacent-Violent for C = 0.02, P_t = 2 in, and b_2 = 0.98. The asymptotic line shown (- - -) corresponds to that shown in Figure 10A-2 as displayed with the asymptotic form fit to the data.

<u>Complacent-Violent Case</u>: Curve Number method is not applicable

In these cases, or combined cases, there is little evidence of overland flow. Observed watershed characteristics are high upland infiltration, little upland dissection or active rills/land erosion, good organic cover, and a humid setting. There may be continuous or prolonged intermittent channel flow. Channel or impervious interception and subsurface return flow are the main sources of runoff for these watersheds. This condition is frequently observed in mature forests and other pervious wildlands (Dun et al., 2009; Srivastava et al., 2013 and 2015; Elliot et al., 2016).

In this case, the rainfall-runoff is expressed by the following equations

$$Q = CP \quad \text{for } P \leq P_t \quad 0 \leq C \leq 1 \quad [10\text{-}21]$$

$$Q = CP + b_2(P - P_t) \quad \text{for } P \geq P_t \quad 0 \leq b_2 \leq (1-C) \quad [10\text{-}22]$$

where Equation [10-21] represents the Complacent mode and Equation [10-22] represents the

Violent mode. The coefficient C is the fraction of P that appears as direct runoff and the coefficient b2 is the fraction of the P in excess of the threshold P_t that complements the runoff once the threshold is surpassed. Note that the Violent mode is characterized by a Complacent period before the rainfall threshold P_t is reached.

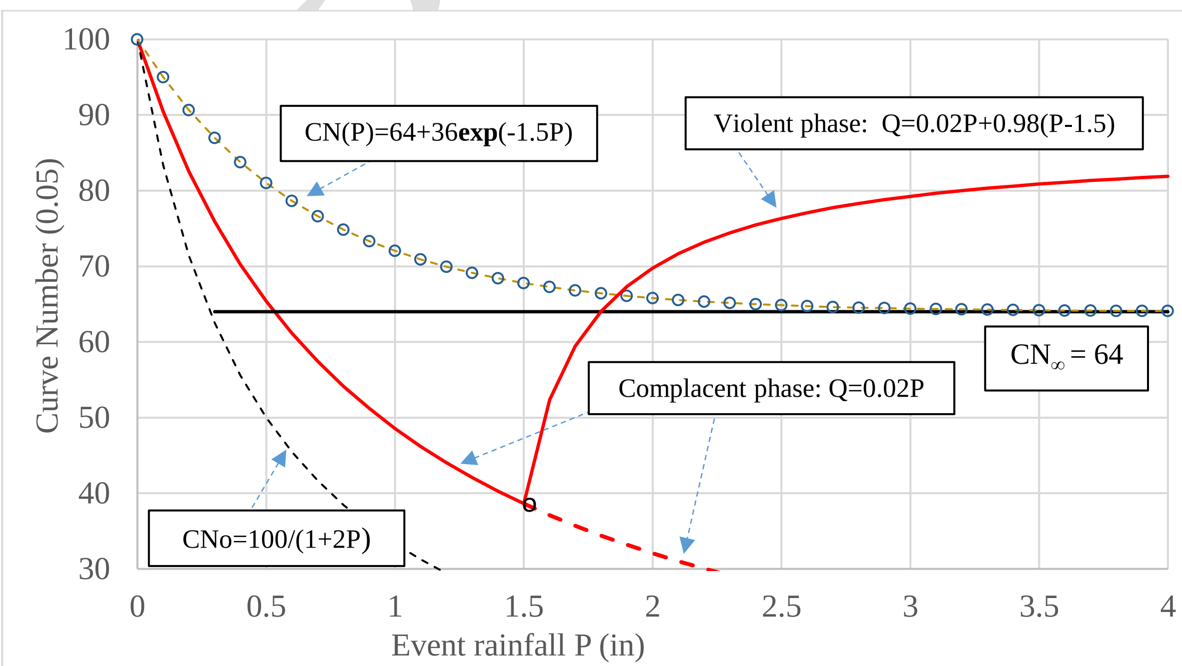

Figure 10A- 2. Idealized Curve Number interpretations of rainfall-runoff patterns for Ia/S=0.05. The Complacent line past P_t=1.5 in is shown for example continuation only, and exists as the background contribution once the Violent phase is initiated. Example asymptotic effects for data-derived CNs are shown as approaching CN_∞=64, and is given by the expression CN(P)=64+36exp(-1.5P).

Inactive watersheds. There exist instrumented small watersheds with no record of rainfall-runoff during the period of observation, which may be over several decades. These may be seen as the Complacent-Violent case with C=0 and P_t higher than the highest recorded rainfall for the no runoff watersheds.

While these watersheds are defined at a point on a topographic channel or swale, they show no fluvial evidence of channel flow having occurred. For example, the swales/channel and banks may be rounded, and contain needles, leaves, twigs, cones, and live vegetation. This watershed condition, of course, does not conform to the CN method.

In such cases, infiltrated subsurface flow may intercept a topographic break further down slope. Redefining the watershed mouth to a larger drainage area to include this may define a de-facto active Complacent watershed. Also, the hydrologically inactive upland slopes of A and B soils may respond with overland flow to rainstorms following a wildfire (Elliot et al., 2016).

Ambiguous cases: The above modes assume distinctive links between land types, hydrologic processes, and rainfall-runoff patterns. However, the overall observed rainfall-runoff patterns for shallow subsurface rapid return flow may also show as standard cases without appreciable overland flow present.

Appendix 2 - Demonstration of (Standard) asymptotic response with distributed source CNs

This example illustrates the process of generating the Standard asymptotic response by distributing source-area runoffs. For this example, a 1000-acre watershed is assumed and CN selection is based on Hydrologic Soil Group (HSG) and cover/land use is guided by Table. 9.2.

Table 10A- 1. Watershed characters for example of asymptotic response created by multiple source areas (Ia/S=0.05)

Cover/use	**HSG**	**Acres**	**CN_{05}**	**S_{05}(in)**	**Ia_{05}(in)**
Water surface	NA	10	99	0.101	0.01
Herbaceous range	D	30	90	1.111	0.06
Gravel roads	C	50	80	2.500	0.13
Brush	D	200	70	4.286	0.21
Pasture	B	250	60	6.667	0.33
Desert shrub	A	460	45	12.222	0.61
Area-Weighted means			**57.4**	**3.342**	**0.16**

In this example, the following distributed runoff Equation [10-20] is used for an array of rainfalls from 0 to 4 inches,

$$Q = \Sigma\alpha_i[(P-0.05S_{05i})^2/(P-0.95S_{05i})] \qquad \text{for } P \geq 0.05S_{05i} \qquad [10\text{-}20]$$

and the resultant estimated net runoff Q is used to re-calculate the lumped watershed CN_{05} values the each of the P values. The equation to back-calculate a single S_{05} from a single P:Q data pair is the quadratic equation solution for S from Equation [10-12a], i.e.,

$$S_{05}=20\mathbf{[}P+9.5Q-\sqrt{90.25Q^2+20QP)}\mathbf{]} \qquad [10\text{-}23]$$

$$CN_{05}=1000/(10+S_{05}) \qquad [10\text{-}24]$$

with S in inches. The results are plotted in Figure A3 and demonstrate that the use of area-weighted Q values to compute (with corresponding P values) a CN results in a CN-P plot that mimics a Standard asymptotic response mode.

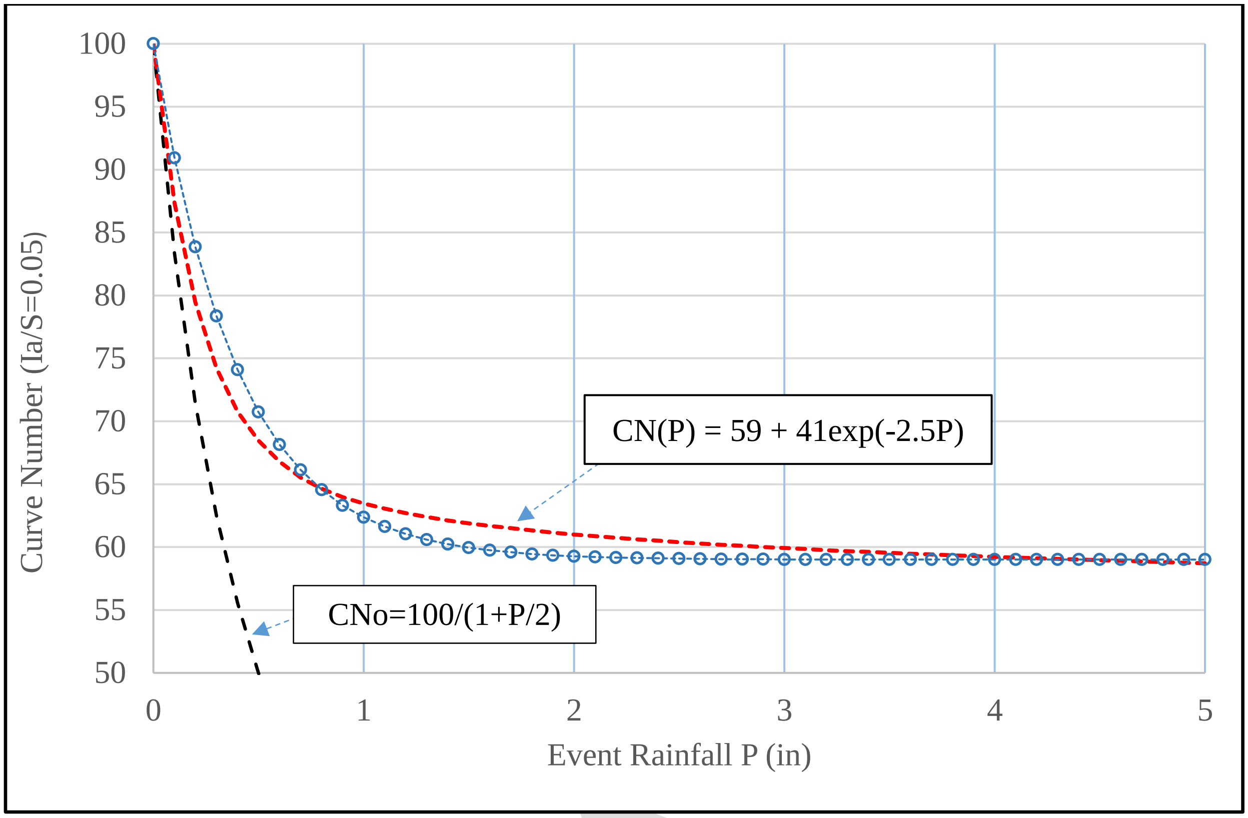

Figure 10A- 3. Illustration of back-calculated CN_{05} for a hypothetical mixed CN watershed Information given in Table 10A-1. The back-calculated CNs (open circles) with the properties shown in the following table, and runoff calculated as distributed source elements for Ia/S=0.05. Note that this outcome takes the asymptotic form and approaches a steady state CN_{05} of about 59. The dashed line to the left is the locus of all points of P=Ia, and is represented by CN_o=100/(1+2P). The plot of CN(P) = 59 + 41exp(-2.5P) was fitted by trial and error and displays a correspondence to the CN:P pairs. The area-weighted average CN_{05} for this watershed is 57.4.

Appendix 3. Initial abstraction adjustments

The original efforts in development of the CN rainfall-runoff equation by Victor Mockus and others used an Initial abstraction (Ia) of 20% of S, the maximum potential storage (i.e., Ia = 0.20S, or Ia/S = 0.20).

This convention was shown in Figure 10-2 in National Engineering Handbook (NEH-4). However, there is no NRCS documentation to support Figure 10-2, and, in fact, an equation fitted to the data shows the relationship as Ia= 0.111S. There is documentation indicating that the original concept was to use a value of Ia/S = 0. It was subsequently reasoned that some value of Ia > 0 should be used for all but completely impervious surfaces, thus a value of Ia = 0.2S was selected for use in NEH-4. In a later interview with Dr. V. M. Ponce, Mockus indicated that he could support a value other than 0.2 if the documentation supported it (Ponce, 1996).

In 1989, an ARS/SCS Hydraulic Engineers Meeting led to the establishment of an ARS/SCS CN work group. One of the goals of the work group was to develop documentation to support the initial CN development, including the Ia/S ratio. The work group contracted with the University of Arizona to perform several studies resulting in documentation.

These studies found that Ia/S is not a consistent value of 0.20, but is usually substantially less. This finding was subsequently supported by other research (Hawkins et al., 2009). In the primary Arizona studies, Jiang (2001) found that the *mean* Ia/S value for 307 watersheds was 0.077. For a different subset of 134 ARS watersheds using different analysis methods, a mean value of 0.055 was found and many values were 0.0.

The ARS/SCS CN work group completion report(s) (Woodward et al., 2002, 2003, 2004) endorsed using Ia/S = 0.05. As a result, the ASCE/ASABE/ NRCS CN Update Task Group members agreed in early meetings to use a value of Ia/S = 0.05 in the revisions of Chapters 8, 9 10 (this chapter) and 12. Thus, all CN values in those chapters are applicable to the runoff equation of:

$$Q = (P-0.05S)^2/(P+0.95S) \text{ for } P > 0.05S, \qquad \text{otherwise } Q = 0. \qquad [10\text{-}12a]$$

with S = (1000/CN) – 10 and CN based on Ia/S = 0.05 (Q, P, and S in inches). In usage, the “S” value should be properly identified with its Ia/S ratio: here as S_{05}, and assumed (but unstated) in Equation [10-2a]. Prior usage of Ia/S=0.20 should be shown and referred to as S_{20}.

The CN values in previously published tables have been converted to the S_{05} basis in this update.

630.1008 References

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