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2 Natural Resources Conservation Service

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## 5 **Chapter 10: Estimation of Direct Runoff from Storm Rainfall**

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32

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89

90

91 **630.0000 Prologue to 2017 Edition**

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

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

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

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

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

114

115 **630.0001 Summary of updates of Curve Number method**

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

118 1999) is changed with this 2017 update. This summary assumes some familiarity with the current  
 119 (1954) method. Thus, the following is given as reference in this update. The 1954 runoff equation  
 120 is

$$121 \quad Q = (P-0.2S)^2/(P+0.8S) \text{ for } P>0.2S, Q=0 \text{ otherwise.} \quad [10-1]$$

122 In the above, P is event rainfall depth, Q is the event direct runoff depth, and S is a measure of the  
 123 watershed potential storage, defined as the maximum possible difference between P-0.2S and Q,  
 124 and is approached as  $P \rightarrow \infty$ . An important feature of this is that as  $P \rightarrow \infty$ ,  $P-Q \rightarrow 1.2S$ . The  
 125 relationship between watershed descriptor CN and S is  $CN=1000/(10+S)$  where S is in inches.  
 126 CN varies from 0 to 100, S from 0 to  $\infty$ . Equation [10-1] assumed an initial abstraction (Ia) of  
 127 0.20S, and gives *median* runoff for the given P. Since 1954, all tables of CN, or  $1000/(10+S)$ ,  
 128 were provided based on the  $Ia/S = 0.20$  assumption.

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

- 131 1. The CN method is used in three different roles, modes, or applications:
  - 132 a. To determine/estimate the return period runoff depth Q from the same return period  
 133 rainfall P. This is a popular application in applied hydrology and is the main assumption in  
 134 this update.
  - 135 b. As a process model to describe how the infiltration and rainfall excess rates vary with time  
 136 in a specific storm; or to aid in estimating soil water content, especially in continuous  
 137 runoff models.
  - 138 c. As an individual probabilistic event model with error descriptions of the variation from the  
 139 central trend of Equation [10-1].
- 140 2. The CN method is not applicable to all watersheds. That is, the original Equation [10-1] does  
 141 not universally calculate results that follow the general observed rainfall-runoff response for  
 142 all watersheds or river basins. Descriptions of non CN-compliant watersheds, such as forested  
 143 watersheds and karst-dominated watersheds, are presented in Chapter 9 and in the Chapter 10  
 144 appendices.

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

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

155 4. The asymptotic equation

$$156 \quad \text{CN}(P) = \text{CN}_\infty + (100 - \text{CN}_\infty) \exp(-kP) \quad [10-2]$$

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

165 5. CN<sub>∞</sub> is defined to be CN<sub>II</sub>, or the NEH concept of CN at Antecedent Runoff Condition II  
 166 (ARC II). That is, CN<sub>∞</sub> is approximately equivalent to current handbook entries. The  
 167 asymptotic Equation [10-2] reflects the observation that smaller storms have higher data-  
 168 defined CNs, i.e., small P values give high CN values.

169 6. Complacent and Violent runoff types are not consistent with the CN method. There are a  
 170 number of alternative process-based, like the Water Erosion Prediction Project (WEPP;  
 171 Srivastava et al., 2013) and the Distributed Hydrology and Soil Vegetation Model (DHSVM,  
 172 Wigmosta et al., 1994) that are able to model these runoff types, or statistically-based methods  
 173 (Ries 2007) that can be applied to such watersheds.

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

$$177 \quad Q = (P - 0.05S_{05})^2 / (P + 0.95S_{05}) \text{ for } P > 0.05S_{05}, \quad Q = 0 \text{ otherwise.} \quad [10-3]$$

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

180 8. There are empirical equations to convert from  $S_{20}$  to  $S_{05}$ , and thus  $CN_{20}$  to  $CN_{05}$ . The original  
 181 CN transformation  $CN = 1000 / (10 + S)$  is preserved for  $I_a/S = 0.05$  but is identified with a  
 182 subscript, i.e.,  $CN_{05} = 1000 / (10 + S_{05})$ .  $S$  and  $S_{05}$  are inches of depth (SI units are not used here).

183 9. CNs in NEH handbook soils and land use tables do not always match well with those found  
 184 through analyses of rainfall-runoff data.

185 10. The calculation of  $Q$  from Equation [10-1] is more sensitive to errors in CN than to errors in  
 186  $P$ .

187 11. The original handbook contained no detailed or exemplified instructions for determining CNs  
 188 from data. The most defensible method, given adequate data and what is identified as a  
 189 Standard mode, is fitting CN to the asymptotic equation (i.e., Equation [10-2]) to large  
 190 complete, ordered data sets (see appendix in Chapter 9).

191 12. The Antecedent Moisture Condition (AMC) – later re-labelled as Antecedent Runoff  
 192 Condition (ARC) – is described with probabilities and pertain to all causes of deviations for  
 193 the central trend, and is not solely viewed as a measure for initial soil water conditions.

194

## 195 **630.0002 Major Changes**

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

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



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

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

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

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

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

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

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

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

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

243 **Symbols and Subscripts**

<b>Symbols</b>	<b>Description and Dimensions</b>
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, $P_e - Q$ (L)
S	Maximum possible loss following satisfaction of $I_a$ . The limiting or $\lim(P_e-Q)$ as $P \rightarrow \infty$ , Maximum post- $I_a$ 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.
$\lambda$	$I_a/S$ , 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  $CN(P)=CN_\infty + (100 - CN_\infty)\exp(-kP)$ in units of $\text{in}^{-1}$ or $\text{mm}^{-1}$ .

244

<u>Subscripts</u>	<u>Discussion and example</u>
05, 20	Indicates the Ia/S, or $\lambda$ “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.
$\infty$	Status with asymptotic method as $P \rightarrow \infty$ . Ex: $CN_{\infty}$ , $S_{\infty}$
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 $Ia/S = 0.05$ .

245

246 **630.1000 Introduction**

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

250

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

260 The method is a direct descendent of the hydrologic heritage developed in the United States in the  
 261 first half of the 20th century. In the early 1900's investigators commonly plotted total runoff

262 versus total rainfall to describe river hydrology. Mead (1919) showed several of these plots,  
263 which were reasonably useful on an annual basis. However, for shorter periods, such as seasons  
264 or months, the scatter became excessive. More than just rainfall depth alone was involved in  
265 determining the amount of runoff. Sherman (1942) attempted to include additional information  
266 by plotting runoff versus rainfall with separate curves for each month and a tabular adjustment for  
267 antecedent rainfall. This was an attempt to deal with event situations; however, the scatter of the  
268 data was still significant. Kohler and Linsley (1951) expanded upon the approach of Sherman  
269 with the multiple correlation diagram. This incorporated such items as antecedent precipitation,  
270 week of the year, and storm duration along with the basic rainfall and runoff values. Coaxial  
271 correlation diagrams were required to be generated for each basin, so this approach could not be  
272 used in ungauged situations.

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

279

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

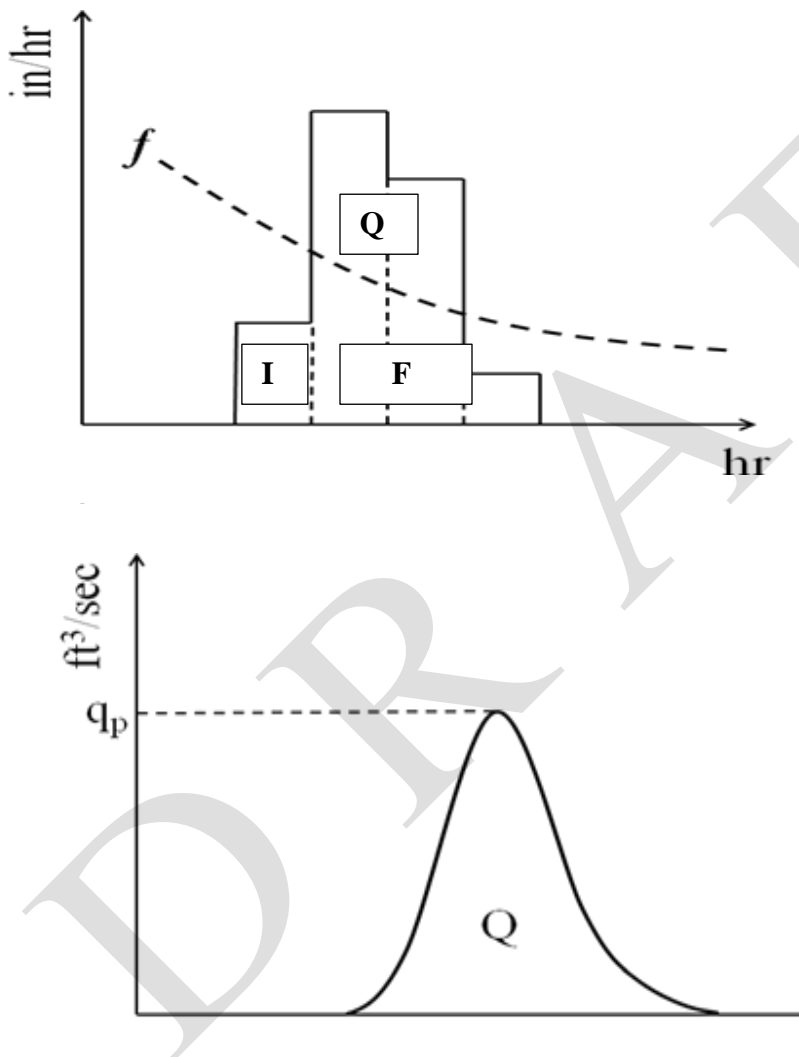
284

### 285 **630.1001 General rainfall-runoff**

286 This work covers the generation of event runoff volumes from rainstorms as portrayed as  $Q$  in  
287 Figure 10-1. That is, the quantity of runoff  $Q$  as shown in the hydrograph resulting from a  
288 rainstorm. While the actual physical processes are complex, spatially and temporally varied, and

289 not consistent from event to event, the general process as portrayed in Figure 10-1 is assumed to  
 290 apply.

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



295

296

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

301

302 **630.1002 Definitions**

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

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

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

319 Baseflow occurs as prolonged flow during rainless periods, coming from an upland-local or  
320 regional aquifer replenished by infiltrated rainfall, snowmelt, or surface runoff (Srivastava et al.,  
321 2013 and 2015). Changes to this type of runoff seldom appear soon enough after the storm to  
322 have an influence on the rainstorm generated hydrograph. An increase in baseflow from a  
323 previous storm source increases the start-of-storm streamflow rate and influences channel  
324 interception.

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

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

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

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

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

350

### 351 **630.1003 Rainfall-runoff Relationship: The Curve Number Method**

#### 352 **(a) Development**

353 Figure 10-1 and the following equations show the major variables of: 1) event rainfall  $P$ , or the  
354 depth or rainfall over the watershed; 2) the event runoff  $Q$ , or the volume of runoff passing the

355 downstream station, expressed as a depth spread over the drainage area, and 3)  $I_a$ , the initial  
 356 abstraction, or the amount of rainfall required for runoff  $Q$  to be initiated. During a rainstorm, the  
 357 evaporation is ignored as either insignificant or assumed to be suppressed during the cool moist  
 358 moments of the storm event.

359 The general conservation of mass statement for a rainstorm is

$$360 \quad P = Q + F + I_a \quad [10-4]$$

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

$$364 \quad P_e = Q + F \quad [10-5]$$

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

$$370 \quad S = \lim(F) = \lim(P-I_a-Q) \quad \text{as } P \rightarrow \infty \quad [10-6]$$

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

$$373 \quad Q/P = F/S \quad [10-7]$$

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

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



$$380 \quad Q = (P-Ia)^2/(P-Ia+S) \quad \text{for } P \geq Ia \quad [10-8a]$$

$$381 \quad Q = 0 \quad \text{for } P \leq Ia \quad [10-8b]$$

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

385 Time: Time ( $t$ ) plays an unappreciated role in the concept: While there is no time dimension  
 386 included,  $S$  is defined at the onset of the storm ( $t=0$ ), and  $Ia$  is defined at the time streamflow  
 387 begins to appear. Furthermore, in application to hydrograph generation, both  $Q$  and  $P$  are taken as  
 388  $P(t)$  and  $Q(t)$ , or transient values during the time progress of a rainstorm. In addition, the original  
 389 1954 development was done with daily rainfall and runoff volumes (depths), even though the  
 390 event durations for both rainfall and runoff were usually much less.

391 Relationship of  $Ia$  to  $S$ : To simplify the equations, prior work asserted that

$$392 \quad Ia = 0.20S \quad [10-9]$$

393 leading to the original expression

$$394 \quad Q = (P-0.2S_{20})^2/(P+0.8S_{20}) \quad \text{for } P \geq 0.2S_{20} \quad [10-10a]$$

$$395 \quad Q = 0 \quad \text{for } P \leq 0.2S_{20} \quad [10-10b]$$

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

$$398 \quad Ia = 0.05S_{05}. \quad [10-11]$$

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

$$401 \quad Q = (P-0.05S_{05})^2/(P+0.95S_{05}) \quad \text{for } P \geq 0.05S_{05} \quad [10-12a]$$

$$402 \quad = 0 \quad \text{for } P \leq 0.05S_{05} \quad [10-12b]$$

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

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

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

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

$$411 \quad CN_{05} = 1000 / (10 + S_{05}) \quad \text{where } S_{05} \text{ is in inches} \quad [10-13]$$

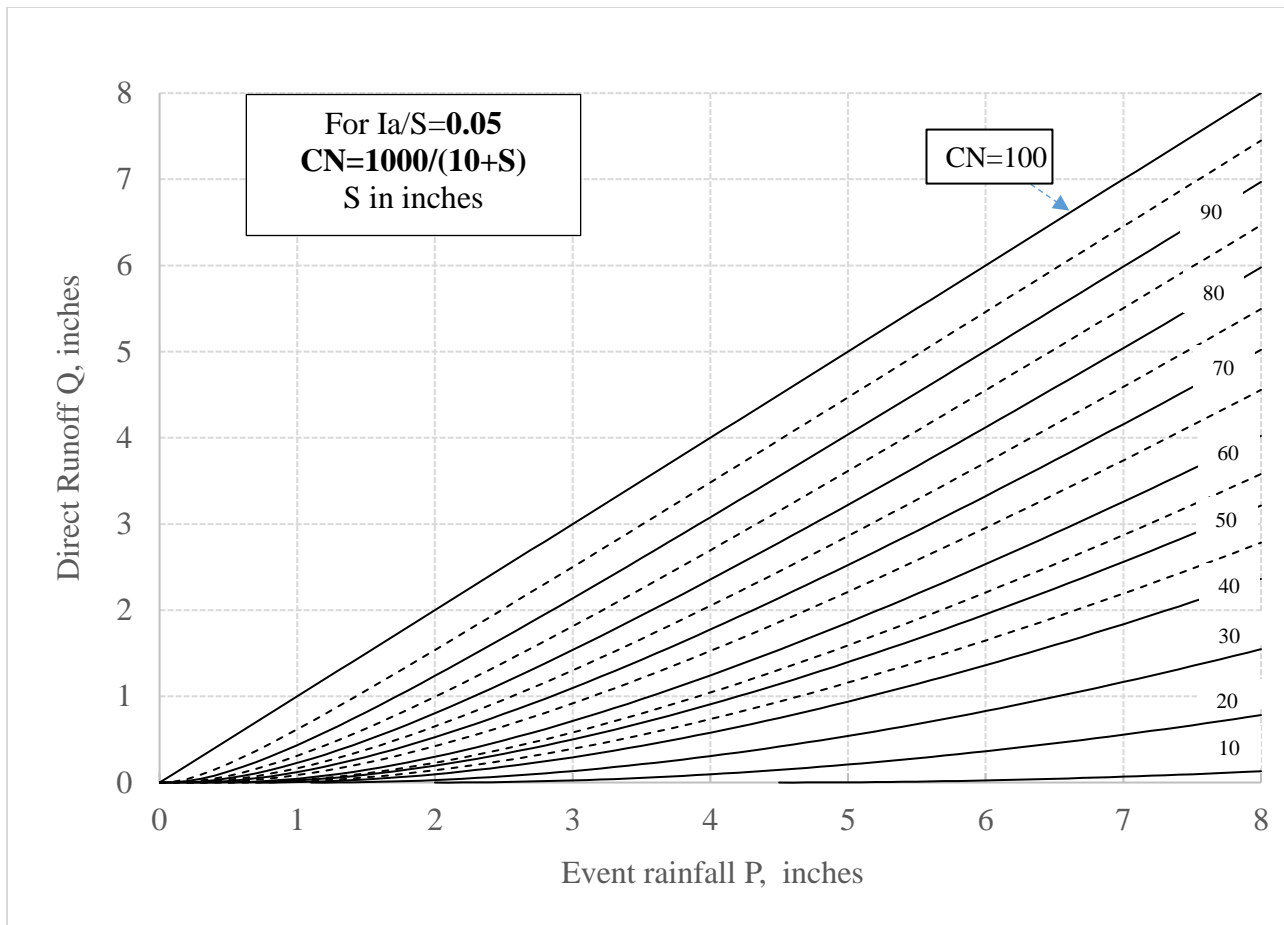
412 or

$$413 \quad CN_{05} = 25,400 / (254 + S_{05}) \quad \text{where } S_{05} \text{ is in mm.} \quad [10-14]$$

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

$$415 \quad S_{05} = 1000 / CN_{05} - 10 \quad \text{where } S_{05} \text{ is in inches.} \quad [10-15]$$

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



421

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

423

424 Conversion between 0.20 and 0.05: Conversion from the original system using  $Ia/S=0.20$  to a  
 425 basis of  $Ia/S=0.05$  can be made by the following recommended equation as:

426 
$$S_{\infty,05} = 1.42S_{\infty,20} \quad [10-16]$$

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

428 
$$CN_{05} = CN_{20}/(1.42-0.0042CN_{20}) \quad [10-17]$$

429 Equations [10-16] and [10-17] pertain to values of  $CN_{\infty}$  in both systems as defined by *ordered*  
 430 asymptotic fitting as described in the Appendix of Chapter 9. An alternative expression (Jiang,

431 2001; Hawkins et al, 2009) taken from direct least squares fits of CN and S to P:Q *natural* (not  
432 rank-ordered) data sets is

$$433 \quad S_{05} = 1.33(S_{\infty,20})^{1.15} \quad [10-18]$$

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

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

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

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

455

456

457

458 **Table 10- 1.** CN<sub>20</sub> and CN<sub>05</sub> Conversions\*

CN <sub>20</sub> → CN <sub>05</sub>		CN <sub>05</sub> → CN <sub>20</sub>	
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

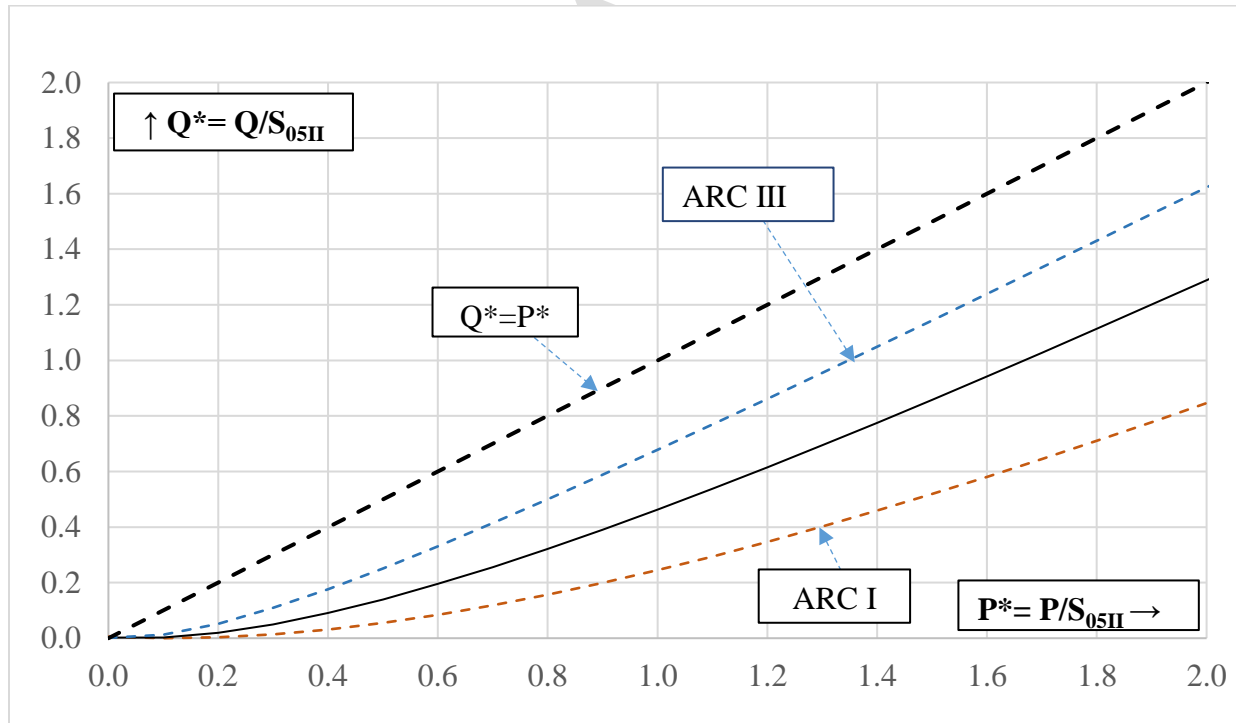
459 \* S<sub>05</sub> = 1.42S<sub>20</sub>

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

ARC				ARC			
II	I	III	$I_{a0}(in)$	II	I	III	$I_{a0}(in)$
100	100	100	0.00	50	31	70	0.50
95	87	99	0.03	45	27	66	0.61
90	78	97	0.06	40	23	60	0.75
85	69	94	0.09	35	19	56	0.93
80	62	92	0.13	30	16	50	1.17
75	56	89	0.17	25	12	44	1.50
70	50	85	0.21	20	10	37	2.00
65	44	82	0.27	15	6	29	2.83
60	40	79	0.33	10	4	22	4.50
55	36	75	0.41	5	2	12	9.50
				0	0	0	$\infty$

461 Note:  $I_{a0}$  is the initial abstraction (in) for the case of ARCI

462



463

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

467

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

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

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

484 Several researchers have presented the values in Table 10-2 ARC I and ARC III classes as  
 485 cumulative percentages of occurrence. The results are surprisingly similar and presented in Table  
 486 10-3. It should be noted the ARCI, or the standard condition, is the 50% event, or median, for a  
 487 given P. These values have not been confirmed for  $I_a/S = 0.05$ .

488 **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

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

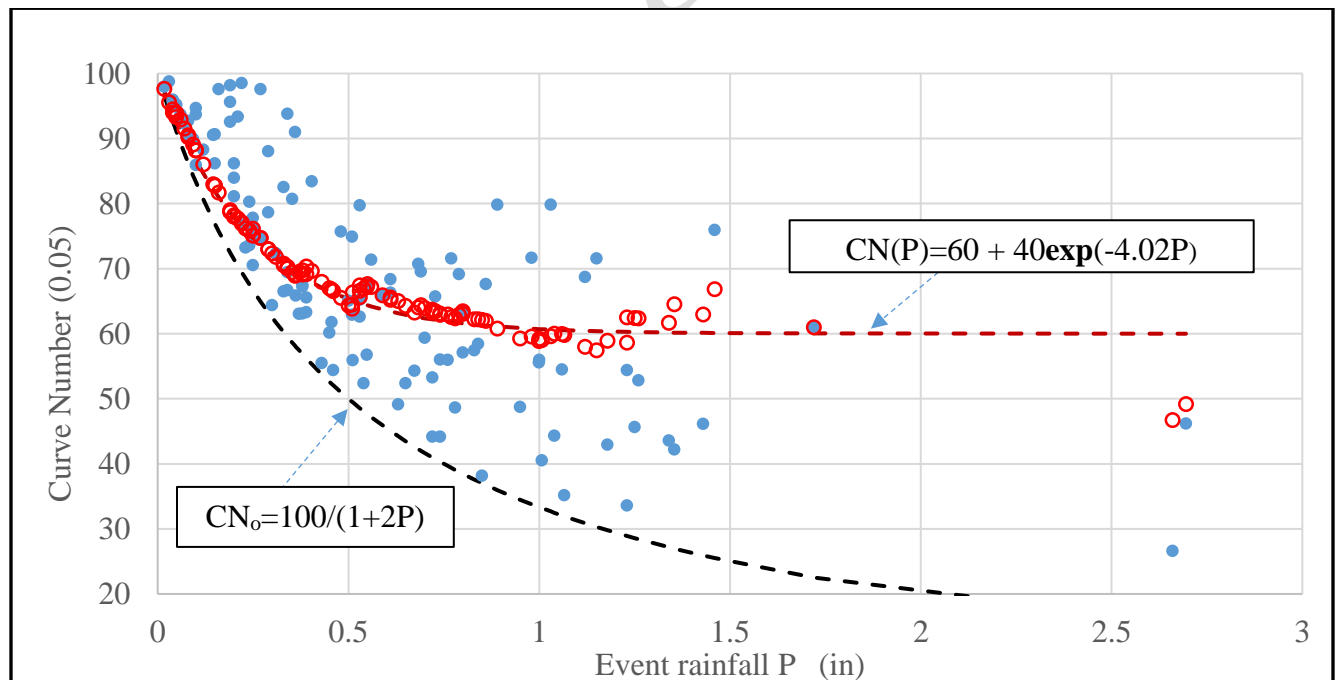
491

492 **630.1004 Standard asymptotic rainfall-runoff**

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

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

506



507



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

513

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

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

$$520 \quad CN(P) = CN_{\infty} + (100 - CN_{\infty})\mathbf{exp}(-kP) \quad [10-19]$$

521 where:

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

523  $P$  = rainfall depth in inches,

524  $CN_{\infty}$  = the ARCI CN for the watershed,

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

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

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

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

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

538

539 **630.1005 Precision and reliability of CN and runoff estimates**

540 Experience has shown that the CNs selected by users from handbook tables based on Hydrologic  
 541 Soil Groups (HSGs) and land use are not precise, and will vary among different users. Those CN  
 542 tables are *estimates* of the potential hydrologically-defined values, but based on perceived soils  
 543 and land use descriptors. Numerous studies have demonstrated a lack of overall correlation  
 544 between data-defined and handbook-estimated CNs (Hawkins, 1984; Hossein et al., 1989;  
 545 D’Asaro et al., 2014a; Hawkins and Ward, 1998; Tedela et al., 2012a, and Woodward et al.,  
 546 2010). While extremes are much greater, about half (i.e., 50%) of the CN differences are in the  
 547 general range of about ±10 CNs. A summary of these differences is given in Table 10-4.

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

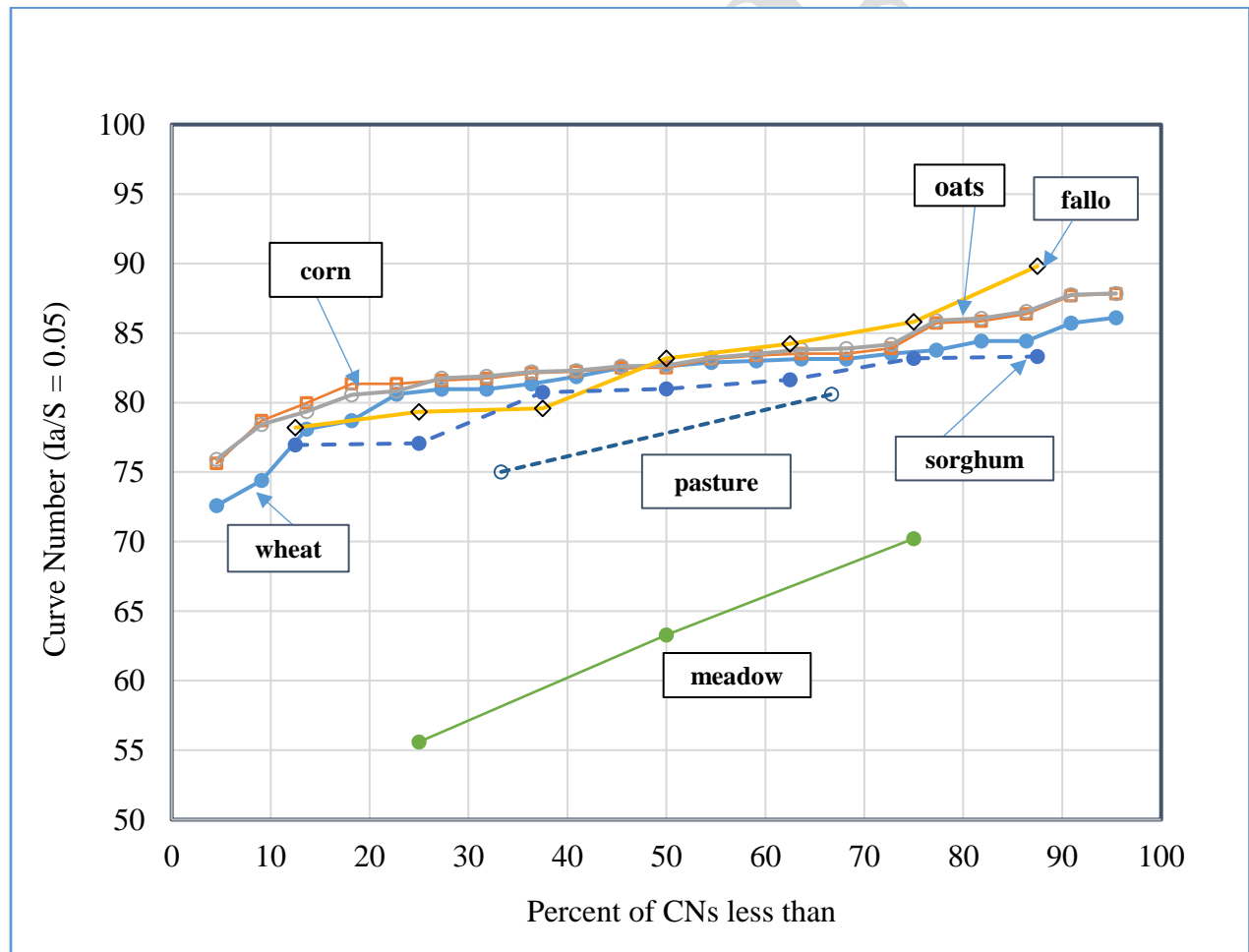
Source	CN <sub>20</sub>	Error range	Comments
Hawkins (1984)	50-90	-10 to +10	110 watersheds, USA
Hossein et al. (1989)	60-90	-3 to +10	96 basins, Queensland
Hawkins and Ward (1998)	62-78	+2 to +12	17 plots, New Mexico, rangelands
Woodward et al. (2010)	60-90	-4 to +4	USDA-ARS watersheds
Tedela et al.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

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

550

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

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



561

562

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

566

567 **Third,** the land use/conditions descriptions are by nature imprecise and/or subjective.  
 568 Furthermore, there are seasonal variations that are not usually acknowledged in routine  
 569 application. (D’Asaro et al., 2014b; Price, 1998). The variations in Table 10-6 encompass about  
 570 50% of observed variations in the stated central range of handbook table CNs encountered.  
 571 Positive deviations mean that the data-defined CNs were greater than the handbook value. These  
 572 variations are important because the runoff calculation is more sensitive to the choice of CN than  
 573 it is to the precision of the input rainfall P (Hawkins et al., 2009). Accordingly, runoff  
 574 calculations using the CN method should show the uncertainty possible in estimating runoff Q.  
 575 Uncertainty varies with the basic CN level; higher CNs have less variation. Minimum  
 576 acknowledgment of runoff calculation uncertainty is suggested in Table 10-5 based on Table 10-  
 577 4.

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

CN <sub>20</sub>	Range of CN <sub>20</sub>		CN <sub>05</sub>	Range of CN <sub>05</sub>	
	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

579

580 In Table 10-5 and for CN<sub>20</sub>, the lower range column is estimated by  $1.1CN_{20}-10$ , the upper range  
 581 column by  $0.9CN_{20}+10$ . The ranges for CN<sub>05</sub> are direct transfers from CN<sub>20</sub> using  $S_{05} = 1.42S_{20}$ ,

582 or  $CN_{05} = CN_{20}/(1.42-0.0042CN_{20})$  (Equation [10-17]). These error ranges are suggested for  
 583  $CN_{20}>10$  and  $CN_{05}>7$ .

584

### 585 **630.1006 Distributed source areas accounting**

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

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

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

$$597 \quad Q = \sum \alpha_i [(P - 0.05S_{05i})^2 / (P - 0.95S_{05i})] \quad \text{for } P > 0.05S_{05i} \quad [10-20]$$

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

### 603 **EXAMPLES**

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

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

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

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

611 Using Equation [10-16]

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

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

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

615  $Q_{05} = \mathbf{0.79}$  inches.

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

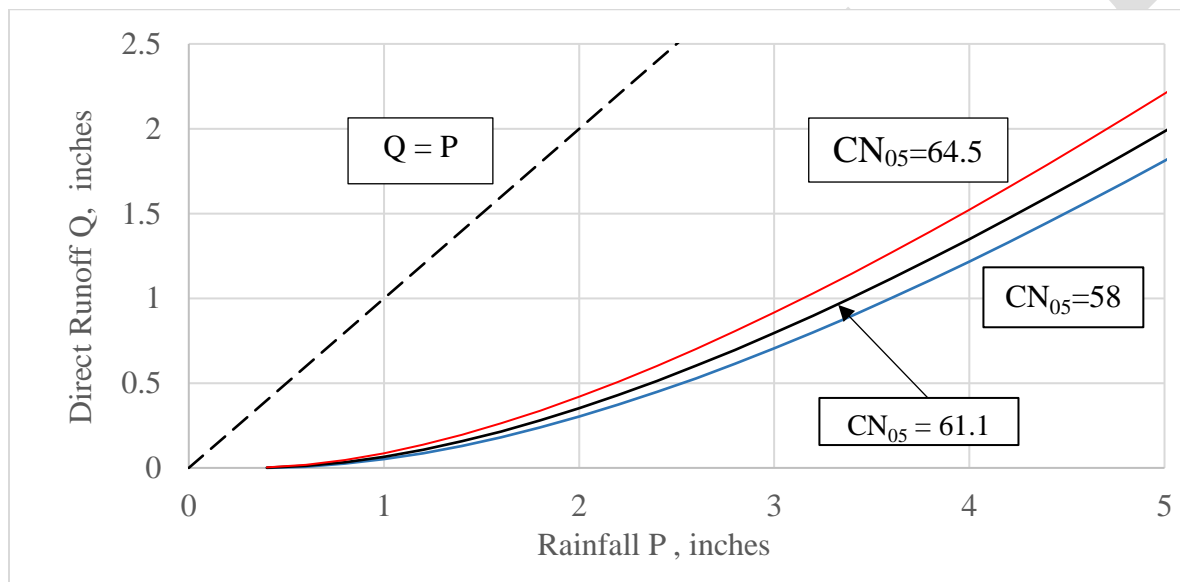
618 **Table 10-EX1.** Rainfall and runoff for  $CN_{20}=69$ ,  $CN_{05}=61$

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	
<b>3.000</b>	<b>0.670</b>	<b>0.793</b>	<b>Example case</b>
4.000	1.267	1.347	
5.000	1.957	1.982	

619

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

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



628  
 629 **Figure 10-EX2.** Effect of CN uncertainty on calculated Q for the example of  $CN_{05}=61.1$ . Rainfall  
 630 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  
 631 is about  $\pm 10\%$ .

632  
 633 **Example 3: Using distributed CN source areas and distributed runoffs.** In this example, the  
 634 watershed data are refined and found from more detailed soils and land use analysis and found to  
 635 be composed of 25 acres of  $CN_{20} = 55$ , 50 acres of  $CN_{20} = 69$ , and 25 acres of  $CN_{20} = 83$ . The  
 636 fractions are 25/100, 50/100, and 25/100, respectively. The area-averaged  $CN_{20}$  here is still equal  
 637 to the example 1 value of 69. The watershed runoff is the sum of the weighted runoffs from the  
 638 contributing components, or

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

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

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

	<b>Ia/S=0.20</b>						<b>Ia/S=0.05</b>				
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
<b>P (in)</b>	<b>Runoff, Q (in)</b>										
	<b>Partial</b>		<b>Sum</b>	<b>Lumped</b>			<b>Partial</b>		<b>Sum</b>	<b>Lumped</b>	
0.00					0.0000			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
<b>3.00</b>	0.0710	0.3348	0.3617	<b>0.7675</b>	<b>0.6696</b>		0.0326	0.3965	0.3479	<b>0.7771</b>	<b>0.7930</b>
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

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

647

648 The estimated Q values for P = 3 inches are highlighted and emphasized for comparisons to  
 649 example 1. Note the lumped area-weighted  $CN_{0.05}$  of 61.5 is a bit higher than the 61.1 in example  
 650 1 leading to slightly higher  $Q_e$  in example 3. In contrast, the  $CN_e$  lumped value of 69 is the same



651 as that in example 1 so there is no difference in the lumped  $Q_e$  estimates between the examples.  
652 For the traditional average CN method with  $I_a/S=0.20$ , runoff does not begin until  $P \approx 0.50$  in.,  
653 but for the distributed source method with  $I_a/S=0.05$ , calculated runoff begins at  $P \approx 0.15$  inches.

654

### 655 **630.1006 Summary**

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

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

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

684

## 685 **630.1007 Appendices**

### 686 **Appendix 1 - Exceptions to the CN method**

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

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

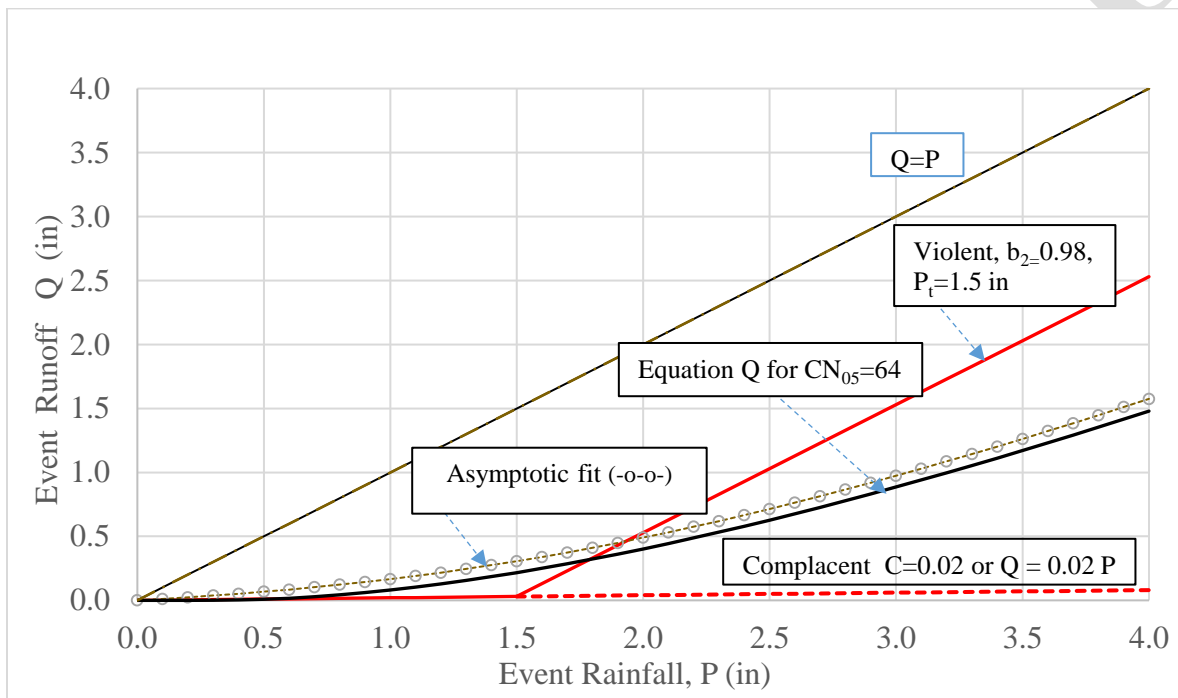
697 As shown in following figures, three general modes or cases of rainfall-runoff responses have  
698 been identified by data analysis. These are 1) Standard (CN method applies asymptotically); and  
699 2) Complacent and 3) Violent (CN method does not apply to either). The latter two, Complacent 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

702 The CN method and equation are inappropriate for the Complacent case, and applicable to the  
703 Violent case only at the extremes. Following are some suggested general criteria for identifying  
704 the cases from field observation and soils/land use data. They are illustrated in Figures 10A-1 and  
705 10A-2.

706 Standard Case: Curve Number method is applicable

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

712



713

714

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

720

721 Complacent-Violent Case: Curve Number method is not applicable

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

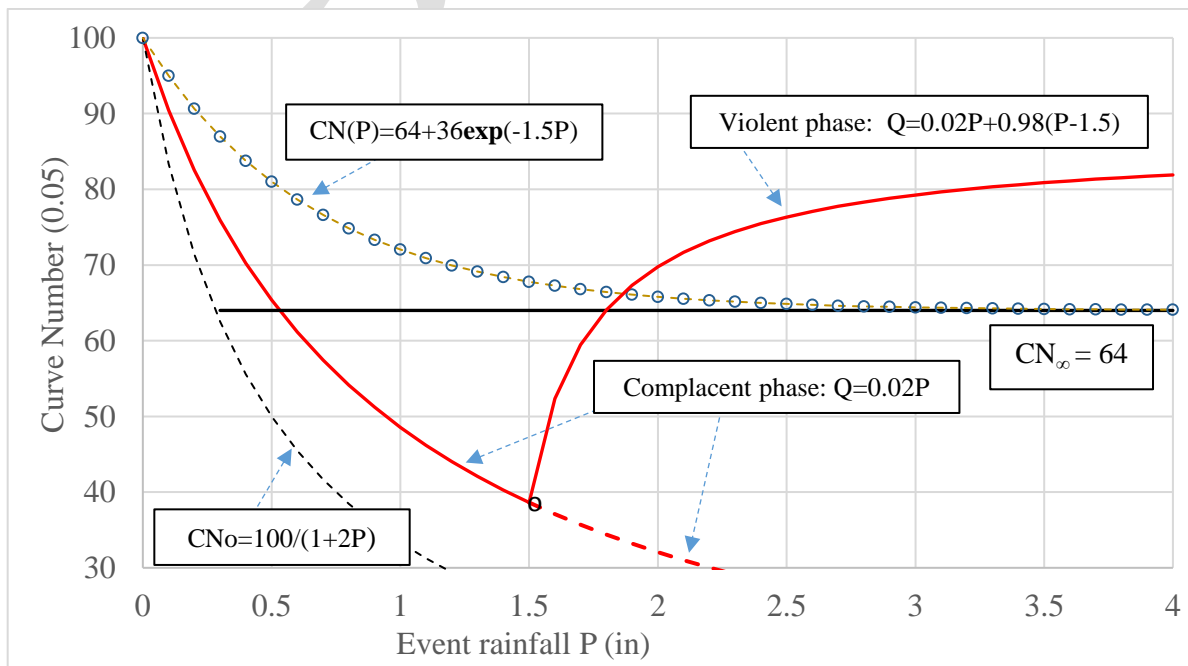
728 In this case, the rainfall-runoff is expressed by the following equations

729  $Q = CP$  for  $P \leq P_t$   $0 \leq C \leq 1$  [10-21]

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

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

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



736

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

742

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

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

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

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

759

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

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

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

Cover/use	HSG	Acres	CN <sub>05</sub>	S <sub>05</sub> (in)	Ia <sub>05</sub> (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
<b>Area-Weighted means</b>			<b>57.4</b>	<b>3.342</b>	<b>0.16</b>

766

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

769 
$$Q = \sum \alpha_i [(P - 0.05S_{05i})^2 / (P - 0.95S_{05i})] \quad \text{for } P \geq 0.05S_{05i} \quad [10-20]$$

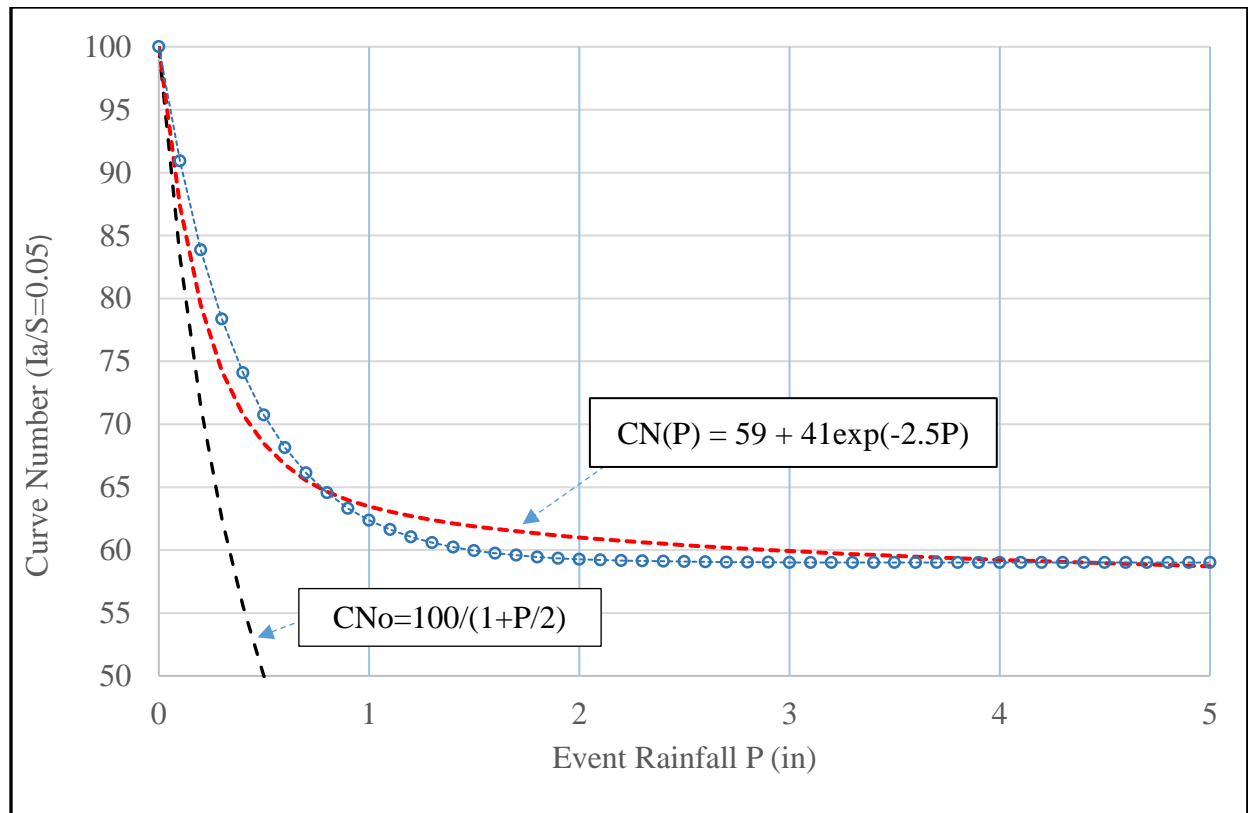
770 and the resultant estimated net runoff Q is used to re-calculate the lumped watershed CN<sub>05</sub> values  
 771 the each of the P values. The equation to back-calculate a single S<sub>05</sub> from a single P:Q data pair is  
 772 the quadratic equation solution for S from Equation [10-12a], i.e.,

773 
$$S_{05} = 20[P + 9.5Q - \sqrt{90.25Q^2 + 20QP}] \quad [10-23]$$

774 
$$CN_{05} = 1000 / (10 + S_{05}) \quad [10-24]$$

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

778



779

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

788

789 **Appendix 3. Initial abstraction adjustments**

790 The original efforts in development of the CN rainfall-runoff equation by Victor Mockus and  
 791 others used an Initial abstraction ( $Ia$ ) of 20% of  $S$ , the maximum potential storage (i.e.,  $Ia =$   
 792  $0.20S$ , or  $Ia/S = 0.20$ ).

793 This convention was shown in Figure 10-2 in National Engineering Handbook (NEH-4).  
 794 However, there is no NRCS documentation to support Figure 10-2, and, in fact, an equation fitted  
 795 to the data shows the relationship as  $I_a = 0.111S$ . There is documentation indicating that the  
 796 original concept was to use a value of  $I_a/S = 0$ . It was subsequently reasoned that some value of  $I_a$   
 797  $> 0$  should be used for all but completely impervious surfaces, thus a value of  $I_a = 0.2S$  was  
 798 selected for use in NEH-4. In a later interview with Dr. V. M. Ponce, Mockus indicated that he  
 799 could support a value other than 0.2 if the documentation supported it (Ponce, 1996).

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

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

809 The ARS/SCS CN work group completion report(s) (Woodward et al., 2002, 2003, 2004)  
 810 endorsed using  $I_a/S = 0.05$ . As a result, the ASCE/ASABE/ NRCS CN Update Task Group  
 811 members agreed in early meetings to use a value of  $I_a/S = 0.05$  in the revisions of Chapters 8, 9  
 812 10 (this chapter) and 12. Thus, all CN values in those chapters are applicable to the runoff  
 813 equation of:

$$814 \quad Q = (P - 0.05S)^2 / (P + 0.95S) \text{ for } P > 0.05S, \quad \text{otherwise } Q = 0. \quad [10-12a]$$

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

818 The CN values in previously published tables have been converted to the  $S_{0.05}$  basis in this update.

819



820 **630.1008 References**

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