United States Department of Agriculture

Natural Resources Conservation Service

Part 630 Hydrology

National Engineering Handbook

Chapter 9: Hydrologic Soil-Cover Complexes

Acknowledgements

Chapter 9 was originally prepared by **Victor Mockus**, (deceased) hydraulic engineer, USDA Soil Conservation Service, and was published in 1964. It was reprinted with minor revisions in 1969. This version was prepared by the Natural Resources Conservation Service (NRCS)/Agricultural Research Service (ARS) Curve Number Work Group and **Helen Fox Moody**, retired hydraulic engineer, NRCS, Beltsville, Maryland.

A previous revision was prepared by the Natural Resources Conservation Service (NRCS)/Agricultural Research Service (ARS) Curve Number Work Group.

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The authors and contributors to this September 2017 revision are indebted to their original work.

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630.0900 General

A combination of a hydrologic soil group (soil) and a land use and treatment class (cover) is a hydrologic soil-cover complex that defines a Curve Number (**CN)**. This chapter provides tables and graphs of runoff curve numbers (**CNs**) assigned to such complexes. The CN indicates the runoff potential of a complex during periods when the soil is not frozen or there is no snow on the ground. CNs are used to estimate runoff from rainfall, only. A higher CN indicates a higher runoff potential and specifies which runoff curve or Figure 10–2 in National Engineering Handbook, Part 630 (NEH 630 (USDA NRCS (1999)), Chapter 10, is to be used in estimating runoff for the complex. Applications and further description of CNs are given in NEH 630, Chapters 10 and 12.

630.0901 Determinations of complexes and Curve Numbers

(a) Agricultural land

Complexes and assigned CNs for combinations of soil groups of NEH 630, Chapter 7 and land use and treatment classes of NEH 630, Chapter 8, are shown in Table 9–1. Impervious surfaces and water surfaces, which are not listed, are always assigned a CN of 97.

(1) Historic assignment of CNs to complexes

Table 9–1 was initially developed as follows:

The data literature was searched for watersheds in single complexes (one soil group and one cover); watersheds were identified for most of the listed complexes.

A median CN for each watershed was obtained using rainfall-runoff data for all storms producing the annual peak runoff. The watersheds were generally less than 1 square mile in area, the number of watersheds for a complex varied, and the storms were of one day (24 hours) or less duration.

A plot of rainfall versus runoff was developed for all the watersheds in the same complex and the median value was selected. A curve for each cover was drawn with greater weight given to CNs based on data from more than one watershed, and each curve was extended as far as necessary to provide CNs for ungauged complexes.

All but the last three lines of CN entries in Table 9–1 are taken from these curves**.** For the complexes in the last three lines of Table 9–1, the proportions of different covers were estimated and the weighted CNs computed from previously derived CNs.

Table 9–1 has been significantly changed since developed in 1954 and CNs for crop residue cover treatment have been added. CNs for selected urban condition were developed subsequently and are shown in other tables. These urban CNs are based on limited data and are currently being used by several government agencies across the county. CNs for the National Land Cover Data (NLCD) set have been added.

(2) Use of Table 9–1

Chapters 7 and 8 of NEH 630 describe how soils and covers of watersheds or other land areas are classified in the field. After the classification is completed, CNs are selected from Table 9–1 and applied as described in Chapter 10. The principle use of CNs is for estimating runoff from rainfall. Some examples of applications are given in Chapter 10.

Table 9- 1. Runoff Curve Numbers for agricultural lands[1]

Cover description			**CN for Hydrologic Soil Group**			
Land Use or Cover type	Land Treatment[2]	Hydrologic condition[3]	A	B	C	D
Fallow	Bare Soil	-----	70	81	88	91
	Crop residue cover (CR)	Poor	69	80	87	86
		Good	67	77	84	85
Row crops	Straight row (SR)	Poor	64	75	84	88
		Good	59	69	80	85
	SR + CR	Poor	63	74	82	86
		Good	56	68	76	80

	Contoured (C)	Poor	62	73	77	84
		Good	56	68	76	81
	C + CR	Poor	61	71	77	82
		Good	57	76	75	80
	Contoured & Terraced (C &T)	Poor	55	64	72	74
		Good	58	63	71	73
	C & T + CR	Poor	54	63	71	75
		Good	52	62	70	74
Small grain	SR	Poor	57	69	79	84
		Good	55	68	77	82
	SR + CR	Poor	56	68	77	81
		Good	42	64	74	79
	C	Poor	55	67	76	80
		Good	52	66	75	79
	C + CR	Poor	53	66	75	79
		Good	51	64	74	79
	C & T	Poor	52	64	73	76
		Good	50	62	71	75
	C & T + CR	Poor	51	63	71	75
		Good	49	61	69	74
lose-seeded or broadcast legumes or rotation meadow	SR	Poor	58	70	80	85
		Good	51	63	70	75
	C	Poor	53	66	76	78
		Good	43	59	75	80
	C & T	Poor	56	66	74	77
		Good	52	59	69	76
Pasture, grassland, or range – continuous forage for grazing[4]		Poor	60	73	81	85
		Fair	40	61	73	79
		Good	31	52	67	74
Meadow – continuous grass, protected from grazing and generally mowed for hay		Good	23	49	63	71
Brush – brush – forbs – grass mixture with brush the major element[5,6]		Poor	39	59	70	77
		Fair	27	47	62	70
		Good	23	39	57	66
		Poor	48	66	76	81

Wood – grass combination (orchard or tree farm)[7]		Fair	35	57	69	76
		Good	25	49	64	73
Woods[8]		Poor	37	58	70	77
		Fair	28	51	66	73
		Good	23	46	62	70
Forests		See Table 9-3				
Farmstead – buildings, lanes, driveways, and surrounding lots		-----	50	67	76	81
Roads (and right of way)	Dirt	-----	64	76	82	85
	Gravel	-----	69	80	85	88

[1] Average runoff condition, and Ia = 0.05S.

[2] Crop residue cover applies only if residue is on at least 5 percent of the surface throughout the year.

[3] Hydrologic condition is based on combinations of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good $\geq$ 20%), and (e) degree of surface toughness.

[4] Poor: < 50% ground cover or heavily grazed with no mulch.

Fair: 50 to 75% ground cover and not heavily grazed.

Good: >75% ground cover and lightly or only occasionally grazed.

[5] Poor: <50% ground cover.

Fair: 50 to 75% ground cover.

Good: > 75% ground cover.

[6] If the CN is less than 30, use CN = 30 for runoff computations.

[7] CNs shown were computed for areas with 50 percent woods and 50 percent grass (pasture) cover. Other combinations of conditions may be computed from the CNs for woods and pasture.

[8] Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.

Fair: Woods are grazed, but not burned, and some forest litter covers the soil.

Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table 9-1 was derived from the original table values using Ia/S = 0.05. The original table values with Ia/S = 0.20 were developed from available data and other information.

(b) National and commercial forest: forest-range

(1) Forest-range in Western United States

In the arid and semiarid forest-range regions of the United States, soil group, cover type, and cover density are the principle factors used in estimating CNs. Table 9-2 shows the relationships between these factors and CNs for soil-cover complexes. The figures are based on information in

Table 9- 2. Runoff Curve Numbers for arid and semiarid rangelands[1]

Cover description		**CN for Hydrologic Soil Group**			
Land Use or Cover type	Hydrologic condition [2]	A[3]	B	C	D
Herbaceous – mixture of grass, weeds and low-growing brush, with brush the minor element	Poor		74	82	90
	Fair		63	75	85
	Good		53	67	71
Oak-Aspen – mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush	Poor		58	67	73
	Fair		41	50	58
	Good		25	36	41
Pinyon-juniper – pinyon, juniper, or both; grass understory	Poor		70	81	86
	Fair		52	66	74
	Good		33	52	63
Sage-grass – sage with an understory of grass	Poor		59	74	80
	Fair		42	55	62
	Good		28	38	46
Desert shrub – major plants include saltbush, greasewood, creosote bush, black brush, bursage, paloverde, mesquite, and cactus	Poor	55	70	80	84
	Fair	46	67	75	81
	Good	40	60	73	79

[1] Average runoff condition, and I_a = 0.05S. For range in humid regions, use Table 9-1.

[2] Poor: < 30% ground cover (litter, grass, and brush over story).
Fair: 30 to 70% ground cover.
Good: > 70% ground cover.

[3] Curve Numbers for HSG A have been developed only for desert shrub.

Table 2–1, part 2, of the USDA Forest Service's Handbook on Methods of Hydrologic Analysis (USDA 1959) and limited field data. The amount of litter is taken into account when estimating the density of cover. Table 9–2 also lists CNs for arid and semiarid rangelands.

<u>(Classical) Forest Watersheds:</u> At one extreme are the well-watered and well-forested watersheds, often with multiple canopies and abundant litter and low-intensity management. Organic material is copious and evident. These are characterized by humid climates – at least seasonally - and display high infiltration abilities, often live (flowing) headwater streams, and may be found in steep topography. Intermittent channels and rills are rare, and there may be extensive areas with no evidence of overland flow. There is negligible bare soil except on roads and disturbances. True forests approximate the "climax" vegetation type for the humid region. The current NEH CN table listings for "Woods" are not appropriate because of Complacent-Violent runoff behavior during extreme rainfall events. [Runoff behaviors are described in detail in Appendix 2 of this chapter.]

While frequently found on National Forests and/or classified as Commercial forests, these characteristics alone are insufficient to specify the above condition. Many examples are found in traditional small forested watershed research sites of the USDA-Forest Service. In high-elevation snow-dominated watersheds, summer rainfall event runoff is infrequent. For example, at Wagon Wheel Gap in Colorado, elevation circa 9500 feet, there was only a single summer runoff event in ten (10) years of data collection.

There is no currently accepted alternative to the Curve Number method at this level of technology to treat these situations. Similarly, there are no techniques for the systematic estimation of silvicultural actions on runoff relations from such watersheds. The effects of fire however, may be profound - though frequently short-lived - and are described elsewhere in Chapter 12 of the NEH.

Forests (in name only): At the other extreme are such tree-associated lands as parks, cemeteries, savannahs, oak woodlands, grass-forest transitions, pinyon-juniper landscapes, orchards, and vineyards, characterized by finer soils and lower organic matter. Other typical land uses include grazed farm woodlots, horticultural efforts, or grazing. Evidence of overland flow may be seen in ephemeral channels, gullies, and rilling. Usually, on gentler slopes, these source areas watersheds are assumed to be CN compliant. Within the known limits of the CN method, the NEH listings for “Woods” are more appropriate here.

Mixtures and Others: For cases between the well-forested watersheds and those in name only, professional judgment and site familiarity is required. The difference between these two extremes are the differences in the cover, climate, soils, geology, land slopes, land use and flow source processes.

There is also an effect of drainage area. Larger drainage areas of well-forested lands often contain a mixture of watershed types and soils, often with urban, agricultural or pastoral lands intermingled. These mixes may exhibit Standard response, albeit with low CNs in the 45-65 range.   In these cases, it is suggested that a distributed source model (a model that considers the runoff from each contributing area in a watershed) be applied to include the high CN portions (roads, urban, agriculture) and the low CN heavily forested portions, and direct channel portions of CN=100.

Hydrologic Soils Group (HSG) A soils: These soils have high infiltration but may overlay an impervious layer at varying depths resulting in delayed surface and subsurface responses observed in event hydrographs. HSG A soils have very little runoff even with frequently occurring storms (mainly from rainfall falling on roadways and waterways). As rainfall return period increases, a point will be reached in which the storage of the porous soil above the impervious layer is reached, and nearly all rainfall will appear as runoff. HSG A soils are generally not suited for the CN method and the method should not be assumed valid (see Table 9-3).

Current knowledge is insufficient for providing precise guidance when modelling HSG A soils, and additional research is needed. Other hydrologic response models such as Wildcat5 (Hawkins and Barreto-Munoz, 2016) and TopModel (Bevin, 2012) should be considered for use in HSG A watersheds. In the absence of alternative modeling approaches, a conservative approach would be to assign a high CN (e.g., 90+) when designing for extreme events having life and property implications downstream such as flood control dams.

<u>HSG B and C Soils:</u> The Complacent-Violent response is possible on these soils, particularly on steeper slopes with the classical forest as described above. As the soil becomes less permeable, the CN method becomes an appropriate tool. As the tree cover becomes more like the Forest-in-name-only or a frequently harvested commercial forest, the CN for woods become a more suitable choice. The recommendation of distributed modeling approaches for regions with mixed tree cover, and other vegetation types is highly recommended with HSG B and C soils, especially on steeper topographies. As with HSG A, one may use a high CN on steeper forest soils when life and property considerations are judged to be significant such as design of flood control dams. Professional judgment is required, and consultation with a soil scientist regarding the nature of the soil profile is strongly recommended.

<u>HSG D Soils:</u> Because the HSG D soil has a relatively low permeability, the Complacent-Violent behavior is unlikely. Thus, the CN method is expected to be relevant in classical forests, commercial forests, forests-in-name-only, and in mixed and other cover types.

Table 9- 3. Limitations on the use of Curve Numbers in forests

Soil Group	Slope	Subsurface Flow	Available Storage	Precipitation Event	Use of CN Method
Group A	High	Yes	Moderate	Extreme	Not Recommended
Group A	Low	No	High	2--100 yr	Possible
Group B or C				2--100 yr	Questionable

Group D	High	Yes	Moderate	2--100 yr	Acceptable
Group D	Low	No	Low	2--100 yr	Acceptable

The factor of significance decreases from left to right in the table.

Table 9-3 provides additional insight to the problems associated with the use of the CN method in forested watersheds. Tollner (2017) has presented on this topic.

(c) Urban and residential land

Several factors, such as the percentage of impervious area and the means of conveying runoff from impervious areas to the drainage system, should be considered in computing CNs for urban areas (Rawls et al., 1981). One must determine if the impervious areas connect directly to the drainage system or do they outlet onto lawns or other pervious areas where infiltration can occur.

The urban and residential CNs shown in Table 9–4 were developed for typical land use relationships based on specific assumed percentages of impervious area. These CN values were developed on the assumptions that

- pervious urban areas are equivalent to pasture in good hydrologic condition,
- impervious areas have a CN of 98 and are directly connected to the drainage system, and
- the cover types listed have assumed percentages of impervious area as shown in Table 9–6.

(1) Connected impervious areas

An impervious area is considered connected if runoff from it flows directly into the drainage system. It is also considered connected if runoff from it occurs as shallow concentrated flow that runs over another pervious area and then into a drainage system.

Table 9- 4. Curve Numbers for urban conditions[1]

Cover type and hydrologic condition	Average percent impervious area [2]	CN for Hydrologic Soil Group			
		A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]					
Poor condition (grass cover < 50%)	--	60	73	81	85
Fair condition (grass cover 50% to 75%)	--	40	61	73	79
Good condition (grass cover > 75%)	--	31	52	67	74
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)	--	97	97	97	97
Streets and roads:	--				
Paved; curbs and storm sewers (excluding right of way)	--	97	97	97	97
Paved; open ditches (including right of way)	--	77	85	89	97
Gravel (including right of way)	--	69	80	85	88
Dirt (including right of way)	--	64	76	82	85
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[4]		55	62	80	84
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)	--	94	94	94	94
Urban districts:					
Commercial and business	85	85	89	92	93
Industrial	72	75	84	88	90
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	70	80	86	89
1/4 acre	38	52	68	77	82
1/3 acre	30	48	64	76	81
1/2 acre	25	45	62	74	80
1 acre	20	42	60	73	79
2 acres	12	37	57	70	76
Developing urban areas:					

Newly graded areas (pervious areas only, no Vegetation)	--	70	81	88	92

[1] Average runoff conditions and Ia = 0.05S.

[2] The average percent impervious area shown was used to develop the composite CNs. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 97, and pervious areas are considered equivalent to open space in good hydrologic condition.

[3] CNs shown are equivalent to those of pasture. Composite CNs may be computed for other combinations of open space type.

[4] Composite CNs for natural desert landscaping should be computed using Figures 9-3 or 9-4 based on the impervious area percentage (CN=98) and the pervious area CN. The pervious area CNs are assumed equivalent to desert shrub in poor hydrologic condition.

If all of the impervious area is directly connected to the drainage system, but the impervious area percentages in Table 9–4 or the pervious land use assumptions are not applicable, use Equation 9–1.

$$CN_c = CN_p + (P_{imp}/100)(97 - CN_p) \qquad [9\text{-}1]$$

where:

CN_c = composite runoff Curve Number,

CN_p = pervious runoff Curve Number, and

P_{imp} = percent imperviousness.

(2) Unconnected impervious areas

If runoff from impervious areas flows on to a <u>pervious</u> area as sheet flow prior to entering the drainage system, the impervious area is <u>unconnected</u>. To determine CN when all or part of the impervious area is not directly connected to the drainage system, use:

- Equation [9–2] if the total impervious area is less than 30 percent of the total area or

- Equation [9–1] if the total impervious area is equal to or greater than 30 percent of the total area, because the absorptive capacity of the remaining pervious areas will not significantly affect runoff.

$$CN_c = CN_p + (P_{imp}/100)(97 - CN_p)(1 - 0.05R) \qquad [9\text{-}2]$$

where:

CN_c = composite runoff Curve Number,

CN_p = pervious runoff Curve Number,

P_{imp} = percent imperviousness, and

R = ratio of unconnected impervious area to total impervious area.

Low Impact Development (LID). LID measures are being used in urban and urbanizing areas to help mitigate the impact of increased impervious cover conditions. LID measures can include pervious pavement, green roofs, infiltration beds, and planting pot. Local agencies should be consulted about the proper method and requirements of the local ordinances.

The following tables for certain features of urban areas with selected LID measures have been developed from the literature and are examples of what can be used (Tables 9-5 and 9-6).

Green roofs are roofs have live vegetation with a limited soil profile and drainage from the roof if the profile is saturated. Permeable pavement is generally used in parking lots or other areas of lower traffic and the purpose is to reduce runoff by increasing the permeability.

Table 9- 5. Curve Numbers for green roofs

Roof Thickness (in)	2	3	4	6	8
CN	92	89	84	80	70

Curve Numbers in Table 9-5 are based on a paper by Fassman-Beck et al. (2016). The information was developed from available data.

Table 9- 6. Curve Numbers for permeable pavement over HSG subbases

Subase (inches)	**HSG B**	**HSG C**	**HSG D**
6	69	79	90
9	53	57	70
12	32	46	62

Average runoff condition, and $I_a = 0.05S$

The values in Table 9-6 are based on the assumption there is adequate positive drainage within the pavement conditions. It there is no positive drainage, the CN is equal to fallow or bare soil. They were taken from information provided by Schwartz (2010) and Ballestor (personal communication, 2016). Both tables were developed from data.

(d) Karst Hydrology and the CN Method

The CN method is not applicable to watersheds which have karst conditions influencing the hydrology. The primary reason is that the karst terrain creates subsurface flow conditions that can dominate over surface soil conditions in controlling rainfall losses. The Virginia Department of Conservation and Recreation in Technical Bulletin No.2 Hydrologic Modeling and Design in Karst (2017) recognizes that a karst loss factor (i.e., a factor describing surface runoff loss into underlying limestone bedrock) is not the same as other calculation factors, such as Curve

Numbers, that describe losses on the land surface. Although Malago et al. (2016) for Island of Crete watersheds and Amin et al. (2017) for the Spring Creek, Pennsylvania, USA, watershed used the SWAT model (Arnold et al., 1998) and its underlying use of the CN method, they did so by treating the CN value as an optimization parameter. Malago et al. (2016) varied the CN by ±15% but did not state the final set of calibrated CNs for the 22 watersheds in the study which ranged in area between 21 km^2 and 523 km^2. The flow data were monthly outflow totals and not rainfall-runoff events. In the work by Amin et al. (2017), the authors used the SWAT model (Arnold et al., 1998) and a variation called Topo-SWAT that incorporates the topographic wetness index proposed by Beven and Kirkby (1979). The watershed in Amin et al. (2017) was 370 km^2 in area, the streamflow data were daily discharge values, and the calibrated CN_{II} was 47 (calibrated downward from an initial value of about 63). Use of large models such as SWAT with many calibration parameters may obscure the most representative CN value because of competing adjustments in other parameters. A caution about and reasoning for not using the CN method in karst watersheds was presented by Iacobellis et al. (2015) using a case study on a 22.3km^2 karst endorheic (closed basin) watershed in south-eastern Italy. Their major objection is that the loss rate in the CN method goes to zero as S is satisfied whereas karst terrain will always exhibit a loss rate because of the underlying bedrock conditions. However, karst dominated drainage systems can contribute significant amounts of subsurface flow.

Because the bedrock conditions and other factors are not conducive to the underlying principles of the CN method, the CN methods is not recommended for karst dominated watersheds. If local information on rainfall and runoff from karst watersheds is available, then that information should be used to create a predictive approach better suited for the area.

630.0902 Curve Number Variation with Slope

Despite its conceptual effects, there is no mention in the current handbooks of the influence of watershed or plot slope on CN. There is no direct accounting for the influence of slope on CN.

In general, the slopes of the agricultural watersheds Mockus was familiar with were perhaps 5% or less. Slope may not play a major role in the volume of runoff in the data set he analyzed or the watersheds he visited. He may have been talking about the estimation of peak flow rather than the estimation of runoff volumes. Other researchers have found a variety of effects as shown in Table 9-7.

Table 9- 7. Summary of slope effects on CN

Source	Effect ΔCN/%slope	Remarks
Hawkins and Ward (1998)	**-2.87**	5 plots, Jornada Range, NM, r^2 =0.37
Garg et al. (2003)	**-1.30**	AGNPS model, 5 watersheds, central OK
VerWeire et al. (2005)	**-1.72**	27 watersheds, GIS studies
Neitsch et al. (2002)	**+0.25 to +0.90**	SWAT model inputs 5% land slope
Getter et al. (2007)	**+-0.25**	Green Roofs, r^2= 0.88
Fassman et al. (2015)	**+0.33**	Lining roofs, r^2 = 0.02
Hastings, NE, ARS data	**+2.45**	Rain-fed agricultural

The Neitsch et al. (2002) reference refers to work done by the ARS to develop a slope adjustment equation for the various continuous computer models, which adjusted equations in the model to achieve agreement between the output and watershed data. Whether the ARS used watershed data to develop the adjustments is not known. The equation developed and used by others for a slope adjustment is:

$$CN_{2\alpha} = 1/(3(CN_3 - CN_2)(1-2e^{-13.86\alpha})) + CN_2 \qquad [9\text{-}3]$$

where:

CN_2 and CN_3 are the SCS CN for soil runoff conditions 2 (average) and 3 (wet), and

α (m/m) is the slope.

The $CN_{2\alpha}$ is then used, instead of CN_2, in the subsequent calculations of the runoff volume. A value of Ia/S = 0.20 was used.

Research from China indicates the CN varies with slope as (Huang et al., 2005):

$$CN_{2\alpha} = CN_2(322.79 + 15.63\alpha)/(\alpha + 323.52) \qquad [9\text{-}4]$$

where:

α is the watershed slope (m/m), and

CN_2 is the Curve Number for ARC II from the SCS handbook with Ia/S = 0.20.

The slopes varied from 0.14 to 1.4%. Measured runoff volumes with natural (not simulated) rainfall were analyzed. The cover on the plots was alfalfa and pasture on a loess soil.

There have been several papers from India that indicate that CNs varied with the slope of the experimental plot. One paper using plot data and rainfall data from sugar cane on a HSG C soil indicated that the NEH-4 values and the plot data were quite close. The results for a range of slopes of 1%, 3% and 5% are 87.82, 89.72, and 91.83, respectively, as compared to 85 to 88 for sugar cane from NEH-4 (Anubhav et al., 2013). These results suggest CN values increase with slope.

Another paper from India indicates that for maize plot data with natural rainfall the derived CN values for 1% plot slope were nearly equal to that derived from NEH-4 table for 1% slope whereas NEH-4 values were lower than those derived for the 3% and 5% slopes (Raj Kaji et al., 2013). These results suggest slope increases CN values.

A paper by Ebrahimian et al. (2012) using information from watersheds in Iran indicated that there is some variation in CN with slope, although his study failed to show a strong effect of slope on runoff generation in the watershed. Assessment of slope on runoff generation should be studied in additional detail. The Iran watershed studied was in watersheds with mainly range cover crop, a wide range of HSGs, and natural rainfall events.

There are a variety of results, including some counter-intuitive negative relations, but there is a lack of consistency or general affirmation. There is no final committee consensus decision on the impact of slope. It should be noted that if there is concern with the impact of slope on Curve Number, then additional local studies and local decisions should be employed.

630.0903 Curve Number Variation with Season

Studies suggest that CN values for selected land uses or cover types vary by season or month. The physical reason is that the stage of the vegetation has an impact on rainfall losses. However, a lack of data has not permitted researchers to establish the magnitude of the variation.

Price (1998) in a MS thesis entitled “Seasonal Variation in Runoff Curve Numbers” found that there was some seasonal variation. Price (1998) indicated that for forest in humid areas the CN varies, with the average of the monthly asymptotic CNs (with Ia/S = 0.20) ranging between 57 and 91 for cropped watersheds and between 64 and 92 for grassland watersheds. The monthly average CN for the forest land use, ranging between 41 and 85, is generally lower than those for the other two land use types. Price (1998) also reported some variation in seasonal CNs in arid and semiarid land uses. The CN value generally decreased as the vegetation or cover increased.

Tedela et al. (2012) reported some seasonal variation in CNs in humid forest in the eastern US. They selected the dormant and growing seasons as the groupings with the difference ranging between 3 and 14 CN units (with Ia/S = 0.20) lower in the growing season.

Even if seasonal variation is exhibited in watersheds, it has minor impact because of the concept of single-event-runoff-determination hydrology. One of the underlying principles of single-event hydrology using CNs is that it represents the average conditions of the watershed when flooding occurs. It is recognized, however, that seasonal variation of CNs is important in simulation models.

630.0904 Regional Variation

Similar crops and cover on similar HSGs do not necessarily have the same CN values. For example, corn on an HSG B soil in Iowa and in Maryland may have different CNs. Analysis of the available documentation and available data are limited so general conclusions supporting that concept have not been developed.

630.0905 Drainage Area Limitations

There is no directly stated NRCS guidance in NEH4/630 limiting watershed size in application of the CN method. The one oblique piece of advice in NEH4/630 is “These [drainage units] should be no greater than 20 square miles and should have a homogeneous drainage pattern.” Twenty square miles is 12800 acres, 51.83 square kilometers, or 5183 hectares.

The drainage areas of the 199 watersheds in 24 locations from which the first CN tables were constructed (omitting Culbertson, Montana) vary from 0.24 to 46,080 acres with the middle 60% between 3 and 300 acres with a median of 19.7 acres. Though specific watersheds used are not known, soils homogeneity was a major criterion in the original selections. Because of an awareness of spatial variability of soils and land use properties, spatial variability was and is a concern when computational simplicity encourages the lumped parameter (area-weighted CN) form.

Various local and modeling applications references suggest drainage area limits from about 5 mi^2 to about 100 mi^2. Ponce (1989) suggests application for mid-sized catchments, or roughly 100-5000 km^2. Pilgrim and Cordery (1992) mention its application to “Small to medium … drainage basins.” Singh (1989) comments that “the method can be applied to large watersheds with multiple land uses.” Boughton (1989) mentions application to “catchment sizes from 0.25 ha to 1000 km^2”, the latter is supported by Williams and LaSeur (1976). These upper ranges approximate the statutory upper limit for PL566 watersheds of 250,000 acres.

In regions of more uniform rainfall, the CN has been applied at the river basin scale with favorable results. For example, analysis of basin-wide rainfall-runoff data (Singh, 1971) from

Salt Creek, Illinois (334 mi), gives a CN value of 71 consistent with handbook expectations. The CN method has been usefully and rationally applied on a 414 km^2 basin in Panama (Calvo et al., 2006), and the 69.1 km^2 Little Vermillion River in Illinois (Walker et al., 2005). A conspicuous example of river basin application appears in NEH4: Amicalola Creek, Georgia, shows CN definition on drainage areas of 84.7square miles (219.4 km^2).

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

630.0906 Local Information Tables

Local tables refers to CN tables generated by technical, social, or administrative agreements with or without resort to local data. They may be heavily judgment- or experience-based, and may have data to bolster the values, and use extrapolation, extension, and interpolation. Similarly, they may be consensus-based, i.e., groups do not know the CNs for the area, but agree on what will be used. They are agreed usage conventions, and are common in applied hydrology. It is thought that some of the original tables in the NEH 630 may have been consensus-based.

This local-tables approach suggests that for practical local application such tables can be expected. However, they should not be anonymous and should list the authors by name, the dates, locations, authority, conditions, and the basis for use. Otherwise with time, such sources become encased in unknown authority, and without a clear source, become unchallengeable and treated as fact.

630.0907 Examples

The following examples demonstrate how to evaluate the effect varying percent impervious pavement and/or connected or non-connected have the CN for land cover conditions other than what is listed in Table 9-4.

Example 9–1 Calculation of composite urban residential CN with different percentage of impervious area than that assumed in Table 9–4.

Given: Table 9-4 gives a CN of 62 for 1/2-acre lot in HSG B with an assumed impervious area of 25 percent. The pervious area CN is 52.

Problem: Find the CN to be used if the lot has 20 percent impervious area.

Solution: Solve Equation [9-1] with CN_p, the pervious runoff CN, equal to 52 and the P_{imp}, the percent imperviousness, equal to 20:

$$CN_c = 52 + (20/100)(97-52)$$

$$CN_c = 61.$$

The CN difference between 62 in Table 9-4 and the computed value of 61 reflects the slight difference in the percent of impervious area.

Example 9–2 Calculation of a composite urban residential CN with different CN for the pervious area than that assumed in Table 9–4.

Given: Table 9-4 gives a CN of 62 for 1/2-acre lot in HSG B with an assumed impervious area of 25 percent. The pervious area CN is 52.

Problem: Find the CN to be used if the lot's pervious area has a CN of 69, indicating fair condition instead of good condition.

Solution: Solve Equation [9-1] with CN_p = 69 and the P_{imp} = 25:

$CN_c = 69 + (25/100)(97\text{-}69)$

$CN_c = 76.$

The CN difference between 62 in Table 9-5 and the computed value of 76 reflects the difference in pervious area CN.

If runoff from impervious areas enters a pervious area as sheet flow prior to entering the drainage system, the impervious area is unconnected. To determine CN when all or part of the impervious area is <u>not directly connected to the drainage system</u>, use:

• Equation [9–2] if the total impervious area is less than 30 percent of the total area

• Equation [9–1] if the total impervious area is equal to or greater than 30 percent of the total area, because the absorptive capacity of the remaining pervious areas will not significantly affect runoff.

$$CN_c = CN_p + (P_{imp}/100)(98 - CN_p)(1 - 0.05R) \qquad [9\text{-}2]$$

where:

CN_c = composite runoff curve number,

CN_p = pervious runoff curve number,

P_{imp} = percent imperviousness, and

R = ratio of unconnected impervious area to total impervious area.

Example 9–3 Determine the composite CN with unconnected impervious areas and total impervious area less than 30%

Given: A 1/ 2-acre lot in HSG B has an assumed impervious area of 20 percent, 75 percent of which is unconnected. The pervious area CN is 52 from Table 9.4.

Problem: Find the CN to be used for the lot.

Solution: Solve Equation [9-2] with CN_p = 52; P_{imp}= 20, and R, the ratio of unconnected impervious area to total impervious area, equal to 0.75:

CN_c = 52 + (20/100)(97-52)(1 – 0.05(0.75))

CN_c = 52 + (0.20)(45)(0.825)

CN_c = 59.4 (round to 59 as the closet whole value).

The CN difference between 52 and the computed value of 59 reflects the difference of unconnected pervious area on CN.

630.0908 Appendices

Appendix 1 – Suggested Curve Number Assignments for the National Land Cover Database (NLCD): Ia/S = 0.05 Basis

The following text and descriptions are excerpted directly from Moglen (2016). The original table was modified for this update and the Curve Number values were converted to the Ia/S = 0.05 basis.

Recognizing that assignment of Curve Numbers is now generally done through automated algorithms that interpret GIS characterizations of both land use/land cover and hydrologic soil group information, the demand for tables that assign Curve Number values as a function of widely-available datasets is assured. This Appendix 1 provides a suggested tabulation of Curve Numbers for one of these most available datasets: The National Land Cover Database (NLCD) (US Geological Survey, 2017). NLCD datasets are available for 1992, 2001, 2006, and 2011.

NLCD products are prepared by the multi-resolution land characteristics (MRLC) consortium which includes the following federal agencies: the US Environmental Protection Agency (USEPA), the National Oceanic and Atmospheric Administration (NOAA), the US Forest Service (USFS), the US Geological Survey (USGS), the Bureau of Land Management (BLM), the US Department of Agriculture (USDA), the National Park Service (NPS), the National Aeronautics and Space Administration (NASA), the US Fish and Wildlife Service (USFWS), and the US Army Corps of Engineers (USACE).

Table 9A-1 shows suggested Curve Number assignments based on NLCD land cover classifications and Hydrologic Soil Group (HSG). Although these assignments have been well-vetted, care and critical evaluation from the analyst must be exercised. Curve Number values in Table 9A-1 are based on Ia/S = 0.05.

The analyst engineer must be particularly sensitive to the distinction between land use and land cover. On this issue, Moglen and Kim (2007, p162-163) state, "*Land use* records the human activities land like agriculture, or recreation, and requires information not detectable from imagery alone, such as parcel boundaries. In contrast, *land cover* records what covers the land surface, like wetlands, grass, or roads, and can generally be determined from remote observation. These approaches are different. For example, the medium density residential land use might include residential, roads/transportation, and deciduous forest land covers. A land cover classification algorithm might choose forest as the dominant land cover for a number of pixels in an older residential neighborhood with rooftops, sidewalks, driveways, and storm drainage infrastructure, although a forest would generate runoff much differently than such a residential neighborhood. A system based on land use would recognize such an urban neighborhood in spite of the mature trees. Thus, land use and land cover are not interchangeable, and using one or the other to calculate imperviousness may lead to predictable biases."

Table 9A- 1. NLCD land cover classes, descriptions, and associated CNs. A, B, C, and D Hydrologic Soil Groups

Major Land Cover Class and Code Value	**Classification and Description**	**HSG A-Soils**	**HSG B-Soils**	**HSG C-Soils**	**HSG D-Soils**
Water					
11	**Open Water** - areas of open water, generally with less than 25% cover of vegetation or soil.	100	100	100	100

12	**Perennial Ice/Snow** - areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.	Not Applicable N/A	N/A	N/A	N/A
Developed					
21	**Developed, Open Space** - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.	52	68	78	84
22	**Developed, Low Intensity** - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.	81	88	90	93
23	**Developed, Medium Intensity** - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.	84	89	93	94
24	**Developed High Intensity** -highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.	88	92	93	94
Barren					
31	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris,	70	81	88	92

	sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.				
Forest					
41	**Deciduous Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.				
42	**Evergreen Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.				
43	**Mixed Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.				
Shrubland					
51	Dwarf Scrub- Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.		42	55	62
52	Shrub/Scrub- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.		42	55	62

Herbaceous					
71	**Grassland/Herbaceous** - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.		63	75	85
72	**Sedge/Herbaceous** - Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.		63	75	85
73	**Lichens** - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.	74	74	74	74
74	**Moss** - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.	79	79	79	79
Planted/Cultivated					
81	**Pasture/Hay** - areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.	40	61	73	79
82	**Cultivated Crops** - areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.	62	74	82	86
Wetlands					

90	**Woody Wetlands** - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water with high water table or standing water. See classification 50 for dry conditions.	86	86	86	86
95	**Emergent Herbaceous Wetlands** - areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	80	80	80	80

CNs in the table are based on Ia/S = 0.05.

The CNs in Table 9A-1 were developed primarily from information in Tables 9-1 and 9-2. Classes 51, 52, 71 and 72 have no CNs for HSG A soils because of the lack of data plus there are minimal HSG A soils in semi-arid and arid climates assignment. The Curve Number method is not recommended for forests, so no Curve Numbers are listed for code values 41, 42, and 43.

Appendix 2 - Determination of Curve Numbers from Data

Introduction

Curve Number estimates based on soils plus land use and condition are listed in previous tables. Alternatively, if local rainfall-runoff data are available, then CNs may be determined by data analysis, and used to check or adjust table entries, or determine local or seasonal variations for land or soil types not included.

Prior versions of the NEH contained only minimal instructions for determination of CNs from rainfall-runoff data, or how the original CN table entries were determined. The current availability of data sets in electronic form has enhanced the local determination of CNs and comparisons with the NEH entries. The task is to find the CN that best describes the data, consistent with the intended application or interpretation, and within the limits of the data.

Two main approaches are suggested here, aligning with two alternative interpretations and applications:

The ***Process*** interpretation that recognizes and roughly mimics the single event physical processes inferred with Mockus' original concepts and the variability encountered. It uses "natural" data meaning Precipitation (rainfall P) and Runoff (Q) from the same event (P:Q pairs).

The ***Frequency Matching*** (or rank-ordered) interpretation, which uses the CN equation based on return-period rainfalls to the same return-period runoffs. For example, the 50-year rainfall leads to the 50-year runoff. This is in keeping with the original major use of the method, and is **<u>the primary definition of CN in this NEH update</u>**. This interpretation uses rank-ordered (or simply, ordered) data, and the procedure usually shows the asymptotic behavior (CN approaches a steady value with increasing precipitation depth, P) for a watershed. CN determination is based on this approach.

Variations in this approach include the following. The graphical fitting of CN to transfer annual series or partial duration rainfall frequency to runoff frequency has been done by Hjelmfelt (1980, 1983), and McCutcheon et al. (2006).

The interpretation of CN technology as a soil moisture management algorithm in daily time step (continuous) models is not considered in this update.

In addition, the CNs appropriate to the three different interpretations above are not necessarily congruent. For example, a CN found using the frequency matching approach is not necessarily appropriate to use in a daily time step model, and vice-versa.

The procedures outlined here are applicable to *Standard* response watersheds only, and infrequently to *Violent* response. The *Complacent* response is not consistent with the CN method but is discussed in context with the other two types. These three types of response are shown in the following sections. The subscripts 05 and 20 are used to denote application to the cases of Ia/S=0.05 and Ia/S= 0.20, respectively.

General

Runoff equations: The basic runoff equation, for the case of Ia/S=0.05 is:

$$Q = (P-0.05S_{05})^2/(P+0.95S_{05}) \qquad \text{for } P>0.05S_{05} \qquad [9A-1]$$

This solves for S for any P:Q pair with $0 \le Q \le P$

$$S_{05}=20[P+9.5Q-\sqrt{(90.25Q^2+20QP)}] \qquad [9A-2]$$

giving

$$CN_{05}=1000/(10+S_{05}) \text{ where S05 is in inches.} \qquad [9A-3]$$

Thus any P:Q pair with $0 \le Q \le P$ can define a Curve Number

Data bias: Experience has shown that “small” storms usually do not produce significant recorded runoff. But they are numerous and will occasionally produce runoff under unusual surface conditions or short-duration high intensities. These become a part of the data record and produce high CNs with Equations [9A-2] and [9A-3]. Thus, there is a bias to high CNs for small storms. This finding is characteristic of CN rainfall-runoff data sets and is seen clearly in the following appendix figures. It should also be noted that events with no runoff (i.e., Q=0) are usually not included in data sets, further adding to the upward bias.

However, with increasing storm size P, achieving a Q>0 runoff response increases. At and above a sufficiently large storm threshold, most storms will produce runoff, and the bias effect is diminished. For example, as seen in Figure 9A-1a, at about P = 0.50 inches, the loose *cloud* of plotted points clearly separates from the line of Q=0. Above this rainfall depth all points are assumed bias-free. In prior work with Ia/S=0.2, this was taken to occur at $P/S_{20} \approx 0.5$. This strategy is applied in the process definition of CN.

The trend of these CNs, as seen in their means and medians, is a decline with increasing rainfall P. With sufficient sample size and sufficiently large storms, CNs often approach a near-constant (*asymptotic*) value, illustrated in several figures in this appendix. This stable-value strategy is exploited in the return-period matching definition of CN, i.e., the ordered, asymptotic approach. Conveniently, both approaches – process and ordered - can be described in a single figure of CN vs P for both the natural and rank-ordered data sets.

Preliminary determinations. An analysis should first determine that the data displays Complacent response, Standard response, or – with large enough samples – a fixed Violent response. This is accomplished by plotting Q against P, and CN against P and affirming the behavior by inspection. If a **Complacent** response (no trend towards an asymptotic value) is shown, or if the trends are indeterminate, the data are inadequate to define CN by the methods presented here.

Methods for Complacent Response

The Complacent case or response is a distinctive low, linear runoff response to a rainfall that has a constant Q to P ratio of Q/P = C or Q = CP for non-trivial values of storm rainfall P. Values of the runoff fraction C are found in the range of about 0.003 to 0.07.

The runoff faction C has been found to be related to the watershed's fractional surface area of water surface (Hawkins and Pankey, 1981). However, this behavior can also occur on cropped land given sufficient cover. Sartori et al. (2011) give examples for sugarcane in Brazil under full cover on lateritic soils for up to 3 inches of event rainfall with C values ranging from 0.008 to 0.016.

Although the runoff fraction C is sometimes regarded as a disused rule-of-thumb, this response type does occur, but with very small C values. The Complacent case can occur for watersheds with runoff sources from small impervious near-channel contributing areas, with the remainder of the drainage in non-runoff surfaces. A general example of this situation is well-developed humid upland forests with deep soils, base flow streams and the direct channel interception.

When CN values are calculated from P:Q pairs and then plotted with P, the result is a monotonically decreasing relationship between CN and P. An example of this relationship is presented in Figure 9A-1 for the West Donaldson Creek watershed in Oregon.

The mathematical nature of this CN-P behavior stems from the Q = CP behavior of the Complacent mode. If the ratio Q/P can be expressed as equal to αP^{β}, the Complacent case occurs when $\beta = 0$ and $\alpha = C$. CN values can be calculated from P:Q data pairs by using Equations [9A-2] and [9A-3] and by substituting CP for Q into Equation [9A-2] resulting in

$$S_{05} = aP \qquad [9A\text{-}4]$$

where $a = 20\,[1+9.5C-\sqrt{(90.25C^2+20C)}]$. At C = 1, $S_{05} = 0$ and Q = P. For all $0<C<1$, S is a constant fraction of P and will monotonically increase as P increases. Because CN is inversely related to S, the CN computed from P will monotonically decrease with P which is seen in the CN-P plots for Complacent watersheds such as West Donaldson Creek. For this update, the Complacent response is represented by C less than ~ 0.070. This limit is based on judgment and experience. Higher “C” responses do exist, but are rare in the observed data.

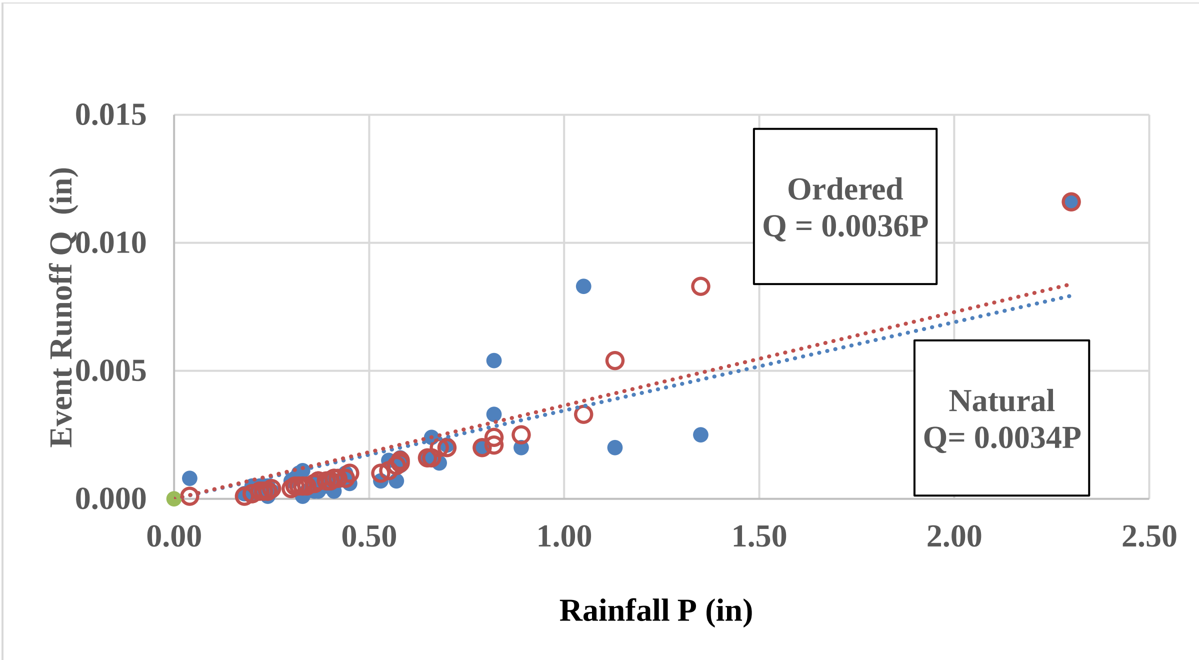

Figure 9A-1 a.

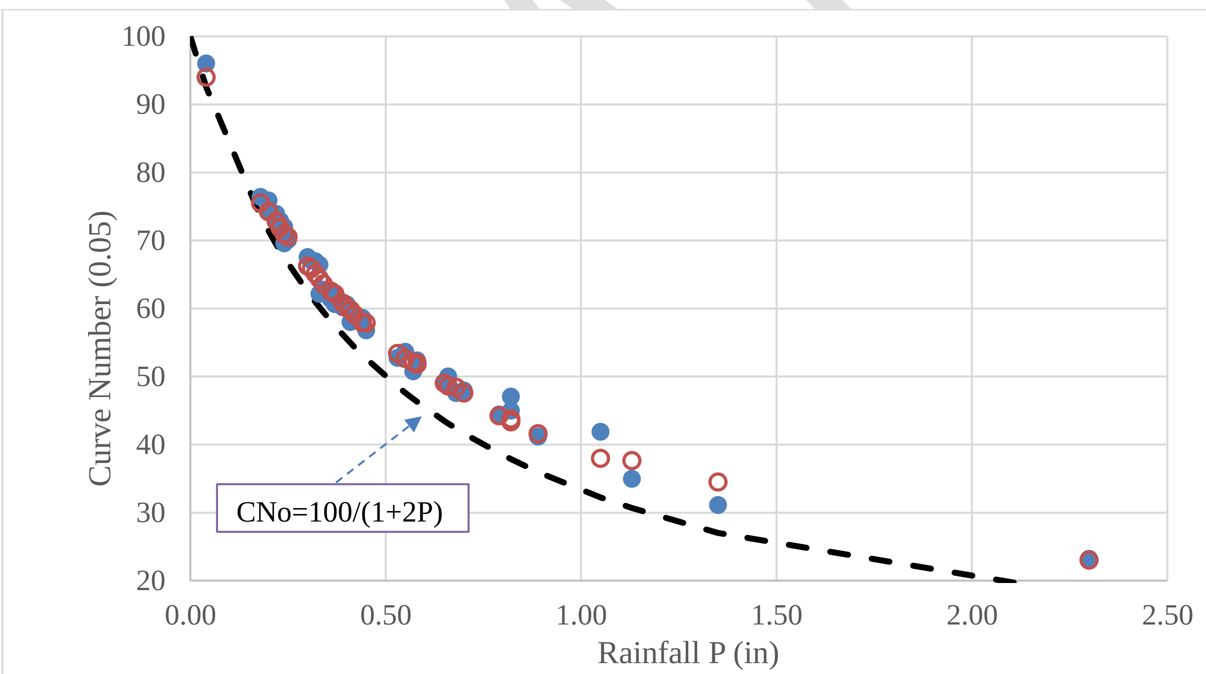

Figure 9A-1 b.

Figures. 9A-1a and 9A-1b. Rainfall (P) -Runoff (Q) and Complacent Curve Numbers for West Donaldson Creek, Oregon. Drainage Area=960 acres. 1979-1984. N=48 events, for the case of

Ia/S=0.05. Figure 9-1a is runoff Q and rainfall P and Figure 9-1b is calculated CN_{05} and P. Data from US Forest Service (Higgins et al., 1989). In both figures, the open circles are for rank-ordered P:Q pairs, the closed circles are for natural data. The dashed line is the limit of Q>0 or where $P=0.05S_{05}$.

In contrast is the Standard mode where the ratio of Q/P increases with P until at large P the ratio Q/P approaches 1.0. When this is the case, CN values become asymptotic to a constant value. Therefore, one method to determine if a watershed exhibits a Complacent or a Standard mode is to calculate Q/P from ordered data and determine if that ratio increases with increasing P (i.e., $\beta>0$ in the previous discussion). For a Complacent response, the Q/P ratio will not vary significantly with P, but for a standard response the ratio will increase with P.

Methods for Standard response

Event or "Process" (natural) definition of CN. Use measured P:Q data pairs and all events of $0<Q\leq P$. The goal is to find the CN that best describes the data, consistent with the application or interpretation.

Limits: All P:Q data points cannot be used to determine a valid CN. Computational limits are imposed because of a high CN bias for small storms. As a result, calculated CNs decline with increasing rainfall P.

Using Equations 9A-2 and 9A-3 the CNs are plotted against P. This is illustrated in Figures 9A-2. The line of P=Ia is given as well, because it shows the lower possible limit (no runoff). The data are not shown here. For Ia/S=0.05, P=Ia limit is CNo=100/(1+2P).

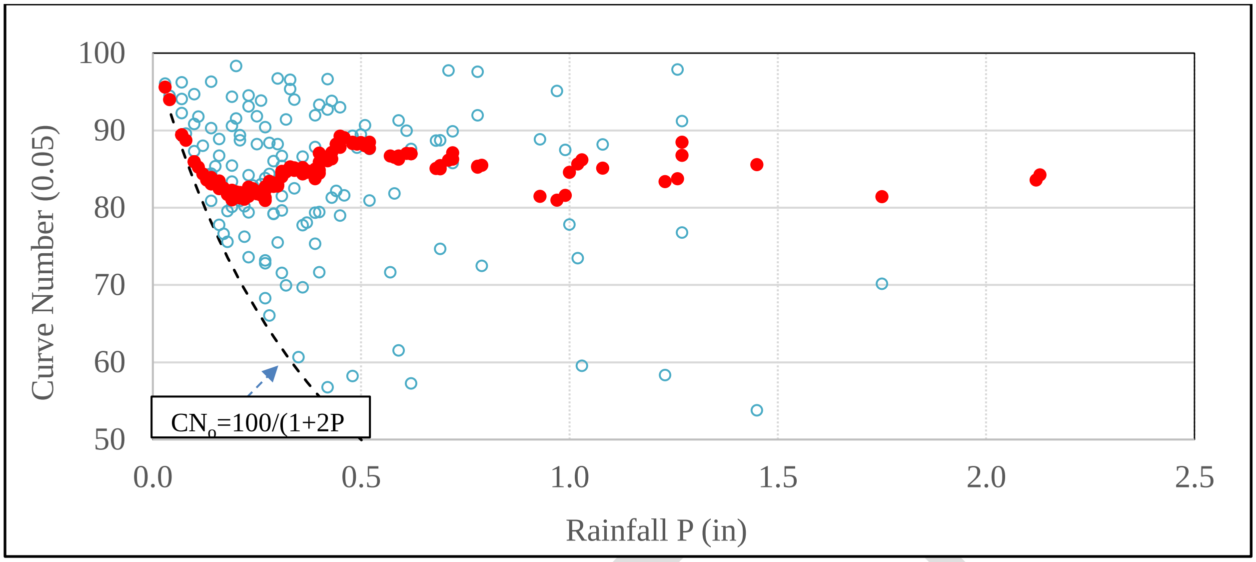

Figure 9A-2 a. CN determination for plot CL4, Jornada Range, New Mexico. Drainage Area (DA) = 43.1 ft^2. (Hawkins and Ward, 1998). N=133 events from July 1989 to October 1994. CNs for both natural and rank-ordered data are shown, and the CN_∞ for the ranked data is selected from the plot as about 85. The calculated mean CN_{05} for $P \geq 0.30$ inches is 85.5 with a standard deviation of 1.8 units. Analysis done for the case of Ia/S=0.05. CN_o is the locus of all points of P=Ia.

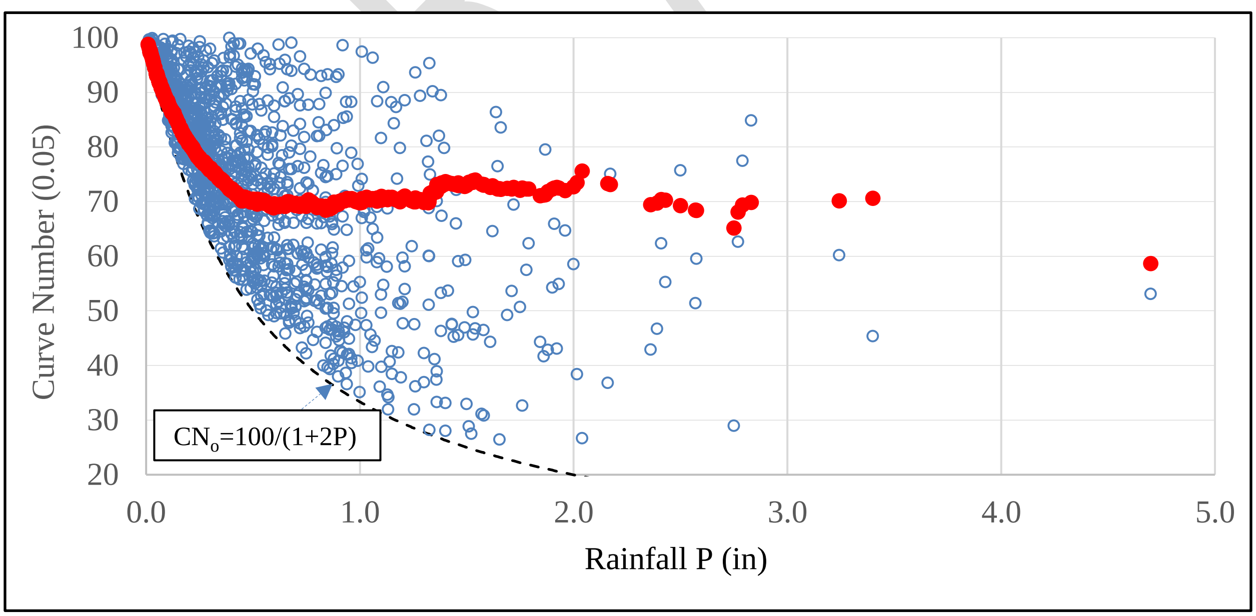

Figure 9A-2 b. CN determination for watershed 26020, Coshocton, Ohio. DA= 723 ac., N=1289 events from 1940 to 1986. CNs for both natural and rank-ordered data are shown, and the CN_∞ for the ranked data is selected from the plot as 70. The calculated mean CN_{05} for P from 0.5 to 3.5 inches is 70.1, with a standard deviation of 1.2 units. The non-conforming point at P=4.7 inches is not considered. Analysis done for the case of Ia/S=0.05. CN_o is the locus of all points of P=Ia.

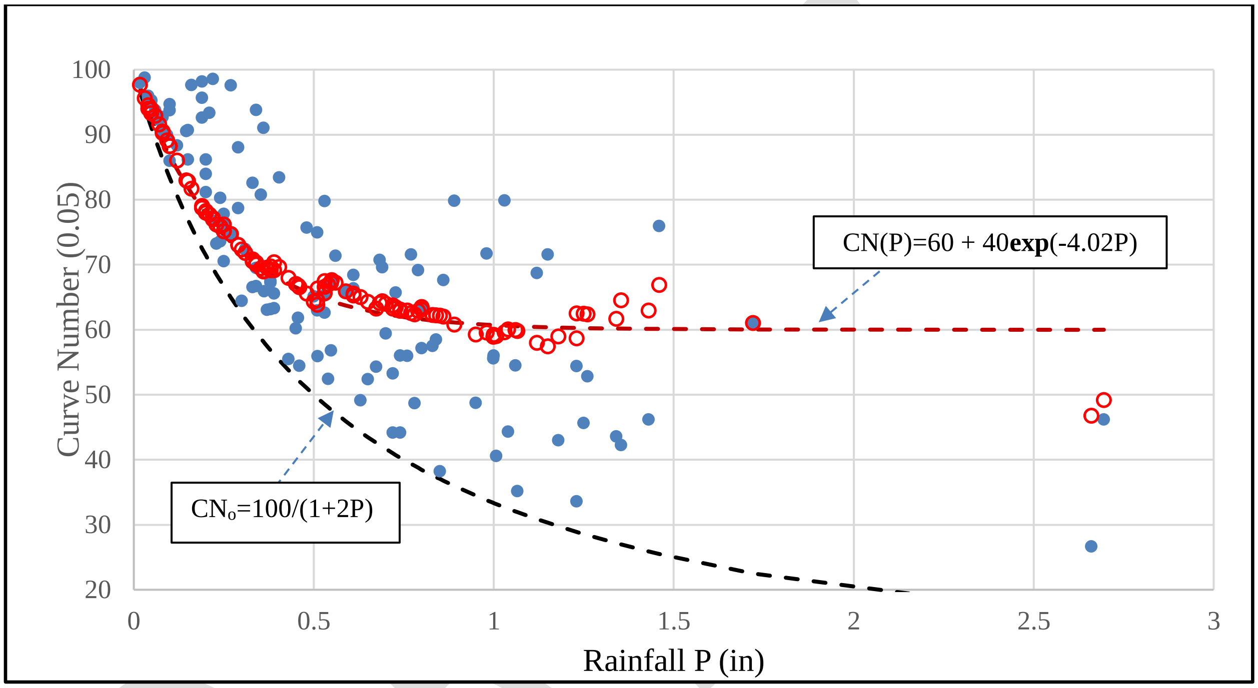

Figure 9A-2 c. CN determination for Safford watershed 4, Arizona. DA= 1.56ac, for 121 events from 1940 to 1986. For the ranked data and P>1 inch, CN_∞ is selected from the plot as 60, and calculated as 59.5, with a standard deviation of 2.4 units. For the natural data and P>1 inch, the calculated mean is 51.8 with a standard deviation of 13.8 CNs, the median is CN is 46.1. The fitted asymptotic line is CN(P)=60 + 40exp(-4.02P)

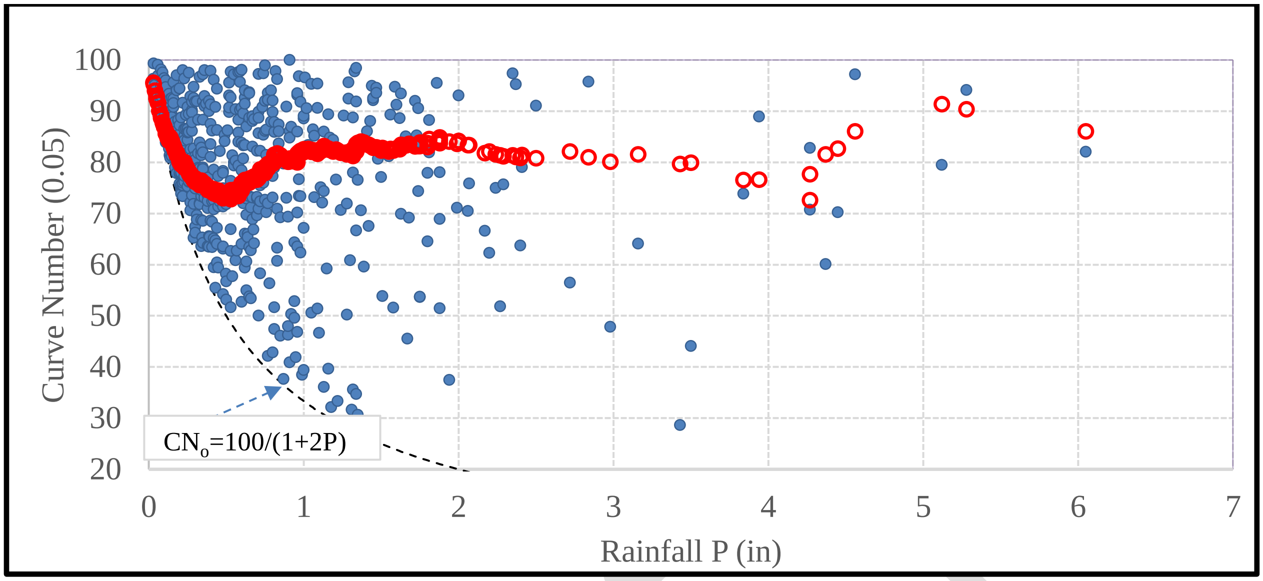

Figure 9A-2 d. CN determination for Edwardsville watershed 2, Illinois. DA=50.0 ac, for 174 events from 1939 to 1954. For the ranked data and P>0.80 in, the CN is estimated from the plot as 81, and calculated as 82.0 with a standard deviation of 1.8 units. For the natural data and P>1.3 in, (n=85) the mean CN is 74.5 with a standard deviation of 18.2 units. The median is 78.0.

In the figures, the threshold minimum rainfall is judged by inspection as the point where the group of plotted data (Q) separates from the line of Q=0. It is assumed that all rainfalls in excess of this P value produce runoff and there is no exclusion bias in the remaining sample.

The defining CN is the one observed at a stable value evidenced at higher rainfalls. This is also consistent with original use of the CN method for extreme events. For the natural data cases shown in Figures 9A-2, the means and medians of the unbiased sample points were calculated and listed in Table 9A-2.

It should be noted that if there is no evident group departure of the natural runoffs from the Q=0 line in the plotted figures, this procedure is assumed to give a biased estimate. Also the validity of the estimates is a function of the unbiased sample size, or ‘n” in the above table; the larger the unbiased sample “n” the more reliable (less sampling error) is associated with the determination. Sampling statistics apply as in as in any determination of the mean or median.

Table 9A- 2. Data for fitted CNs for selected illustrative cases, natural data case

Watershed	**DA**	**P_t**	**N**	**n**	**mean (SD)**	**median**
Name and Location	(ac)	(in)	#	#	CN_{05}	CN_{05}
CL4-Jornada NM Plot	.001	0.5	133	34	80.6(13.5)	**86.6**
Coshocton Oh 26020	1.26	1.8	1289	28	54.8(15.5)	**54.6**
Safford 4 AZ	723	1.0	121	20	51.1(13.8)	**46.1**
Edwardsville IL	49.95	1.3	546	85	75.5(18.2)	**78.0**

Notes: Pt is the lower limit of data used to calculate CN, and n is the number of points>Pt. N = total P:Q pairs.

Frequency matching definition; Asymptotic determination: Use rank-ordered P:Q data (all events of $0<Q\leq P$) and apply the asymptotic behavior concept.

As previously described, first separately rank-order the P and Q points and match the P and Q by rank order. The CNs for these P:Q points are calculated, and the points are plotted as shown in the figures. The line of Q=0, or $CN_o = 100/(1+2P)$, should be included on the plot.

The near-constant values achieved as rainfall increases are selected from the plot. Examples are given – along with the natural data CN plot - in Figures 9A-2. Both scaled and calculated values are given in Table 9A-3. The bold-faced entries are the CN_{05} estimates from these data along with their standard deviations. These are equivalent to CN_{∞}. It should be noted that the procedure creates a spurious correlation because the CN-P plot has P included in the CN calculation, and is thus on both axes. Therefore, the r-squared metric is affected.

Table 9A- 3. Data for fitted CNs for selected illustrative cases, rank-ordered (asymptotic) case

Watershed	**DA**	**P_t**	**N**	**n**	**Scaled**	**Calculated**
Name and Location	(ac)	(in)	#	#	CN_{05}	CN_{05}(SD)

CL4-Jornada NM Plot	.001	0.5	133	77	85	**85.5**(1.8)
Coshocton Oh 26020	1.26	0.5	1289	783	70	**70.1**(1.2)
Safford 4 AZ	723	1.0	121	20	60	**59.5**(2.4)
Edwardsville IL	49.95	1.3	546	174	81	**82.0**(1.8)

Notes: Pt is the lower limit of data used to calculate CN, and n is the number of points>Pt. N = total P:Q pairs

If the constant value is ***<u>not</u>*** clearly apparent, or if there are insufficient points to define it, but it *is* judged to approach a constant value, then one should extrapolate the curve graphically by eye, using careful judgement, to a steady-state (asymptotic) value. This value is then selected as CN_{∞}.

If the data are insufficient for reliable visual extrapolation, then one can fit the asymptotic equation to the data set as:

$$CN(P) = CN_{\infty} + (100 - CN_{\infty})\mathbf{exp}(-kP) \qquad [9A\text{-}5]$$

This can be accomplished by non-linear fitting programs or by trial and error. The result yields CN_{∞} as a fitting parameter. The exponent "k" is necessary to do the fitting, but has no other use. Fitting Equation [9A-5] is also an option in any other of the above cases.

Exponential coefficient "k"

In the calibration the asymptotic P:CN behavior, values of CN_{∞} are taken from plots and calculation based on the judgment of the analyst. The complete description also requires the exponential coefficient "k." No general tables relating k to CN_{∞} or other factors have been developed.

However, k estimates for specific data sets can be made once CN_{∞} has been determined. It is done by the following procedure;

- Determine CN_{∞} as described

- Select/assume a representative CN point on the mass of the P-sensitive (i.e., draw-down" portion) portion of the data to match. Call it CN(P). Note the P value.

- Complete the asymptotic equation for the assumptions

$$CN(P) = (100 - CN_{\infty})\mathbf{exp}(-kP)$$

- Solve for k

For example, in the Safford 4 case previously presented, $CN_{\infty} = 60$ is used, and the representative drawdown point of CN(P)=70.6 and P=0.33 in is taken from the data set (not shown here). Thus substituting in the previous equation for CN(P) gives 70.6 = (100-60)**exp(**-0.33k)'

This equation can be used find $k = 4.0243 in^{-1}$. With this k value, an estimate of a prediction error for these approximate conditions can be made. This is not a least squares fitting, although a variance reduction calculation ("r^2") can be made for these conditions.

Methods for Violent response

As described elsewhere in this report, the Violent behavior type is inconsistent with the CN method and is better described as a high fraction, high rainfall threshold response. However, it does asymptotically approach a constant CN (CN_{∞}) as P grows larger after the violent response P threshold has been surpassed as shown in Figure 9A-3 for the Berea Watershed 6, Kentucky.

Because of this runoff type's overall rarity in rainfall-runoff records, and the larger rainfalls depths required to express it, example data sets are scarce. The simple analysis shown here is in accord with those previously given for the Standard asymptotic estimates. That is, the limits of the CN determination are selected by judgment and the representative CN value calculated from the data. For the Berea Watershed 6, Kentucky, the lower limit (threshold) of P was taken as 2.00 inches. A comparison of CN values for the Berea 6 watershed is shown in Table 9A-4.

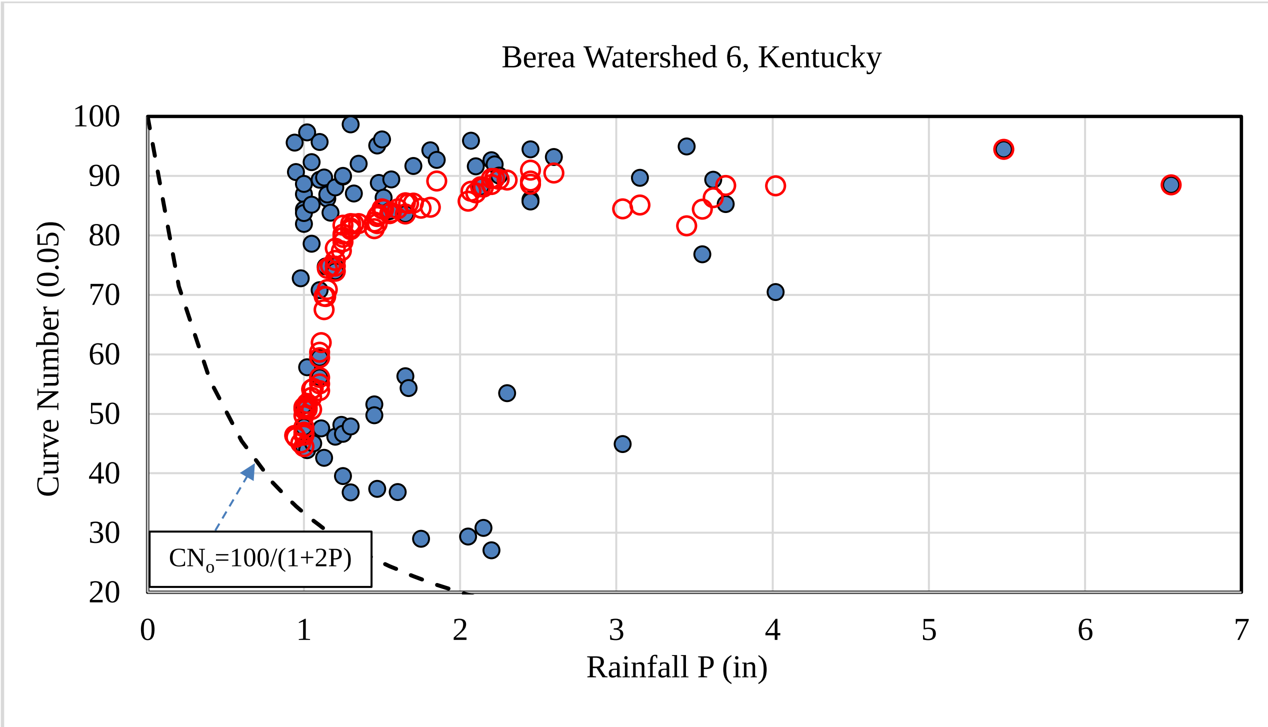

Figure 9A- 3. Berea Watershed 6, Kentucky. CN_{05} and rainfall P for natural (closed dark circles, ●) and ordered (open circles, ○). The dashed line is the locus of all points of Q=0, or CN_o=100/(1+2P). DA=299 ac. Data is of US Forest Service origin, provided by J. D. Hewlett from University of Georgia. The data, for all P>23mm, was also used in a prior paper, Hewlett et al. (1984).

Table 9A- 4. Violent response summary for CN_∞

	N	**n**	**CN_{05}**	**Standard Deviation**
<u>Approach</u>	#	#		
Ordered data	84	23	88	2.6
Natural data	84	23	77	22.1

N is the total number of points; n is the number used to calculate CN.

The ordered data calculated value of CN_{05} = 88 agrees with visual estimates. Note, however, the bimodal uncertainty displayed by the natural data, splitting into distinct clusters. About half of the storms in the 1- to 3-inch rainfall range show a CN in a cluster of 30 to 55, while the remainder show higher CNs in the 75-95 range. The natural and ordered values converge with increasing rainfall P. In either case, the high CNs are inconsistent expectations for this well-forested watershed.

Other issues

Annual Peak series: Historic NEH methods used the median CN from the P and Q for annual flood peak series as the defining value. A clear disadvantage of this approach is that it requires a long period of record. Annual flood series give but a single point from a year of data collection. In addition, the median event for an annual series defines a de-facto 2-yr return period. As such, it minimizes the widely observed downward trend of CN with increasing P.

An alternative approach is to complete dual-plotted frequency curves of P and Q, in either annual or partial duration series. This differs from the annual peak series median described above, and has been successfully demonstrated by Hjelmfelt (1980), and McCutcheon et al. (2006).

Ordered Data: The ordered data methods above short-cut the long data requirement by using individual events over a shorter period of record. In such, the ordered P and Q still matches return periods, but for the more frequent events, and by plotting the resulting CNs against P the asymptotic relationship results. Steady-state CNs found at higher rainfalls will likely include P:Q pairs in the annual series as well. Prior work by Hjelmfelt (1980), Hawkins et al. (2009), McCutcheon et al. (2006), and Tedela et al. (2007, 2012) illustrate the convenience and efficacy of this approach. The precedent for this approach in hydrologic engineering is given by Schaake et al. (1967).

Calibration on peak flows and hydrograph models: Where the CN equation is used as a time-incremental generator of rainfall excess in hydrograph models, several other factors of timing and routing are involved as well. Thus fitting on complete hydrographs or event peak flows obscures the single role of CN in the calculation. An example of this given in Titmarsh et al. (1989). This approach is not recommended for estimating CNs for a watershed.

<u>Asymptotic phenomenon:</u> Several hypotheses may be offered for observed <u>a</u>symptotic response:

1) Mixtures of source runoff properties across the contributing area which generate runoff as P grows larger and the watershed becomes more extensively wetter. Illustration of this possibility is given in Appendix 2 of Chapter 10.
2) Data censoring that excludes Q=0 events from analysis. This has been explored and the effects demonstrated in Hawkins et al. (2015).
3) Differences between natural runoff generating processes and the basis for the CN equation.

The asymptotic response is seen with both ordered and natural data, but is clearly more evident in the ordered set. Regardless of the source cause, a steady-state CN is usually approached as P grows larger, and these values have been found (Van Mullem, 2016) to approximate those observed in the traditional Ia/S = 0.20 tables based on soils and land use/condition (Rietz and Hawkins, 2000)

<u>Confirmation Bias in Rainfall-Runoff data:</u> Only data points of Q>0 are found in most rainfall-runoff data sets and analysis, and thus in determining CN. As larger storms are included, fewer events of no runoff occur, and thus lower data-defined CNs may be included in the sample. See Hawkins et al. (2015). This source of bias alone gives a CN compared to what actual on-the-ground conditions would encounter.

<u>Use of 0.20 and Conversions:</u> If Ia/S = 0.20 is used, then the equivalent of Equation [9A-2] is

$$S = 5[P+2Q-\sqrt{(4Q^2+5PQ)}] \qquad [9A\text{-}6]$$

If data determined CNs exist using Ia/S = 0.20, then the *approximate* conversion is

$$S_{05} = 1.42S_{20} \quad \text{and} \qquad [9A\text{-}7a]$$

$$CN_{05} = CN_{20}/(1.42-0.0042CN_{20}) \qquad [9A\text{-}7b]$$

and conversely

$$S_{20} = 0.7043S_{05} \quad [9A\text{-}8a]$$

$$CN_{20} = 1.42CN_{05}/(1+0.0042CN_{05}) \quad [9A\text{-}8b]$$

These equations are appropriate for asymptotic values and ordered data conditions.

General considerations: From experience, CNs determined from measured P:Q data are more accurate and well-defined under the following conditions:

1. Larger data sets: i.e., more P:Q observations at higher P values (higher N)
2. Bigger storms, thus higher P values included in the sample
3. Higher intrinsic (natural) CNs.

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Amin, M.G.M., Veith, T. L., Collick, A. S., Karsten, H. D., and Buda A. R. (2017). "Simulating hydrological and nonpoint source pollution processes in a karst watershed: A variable source area hydrology model evaluation." *Agricultural Water Management*, 180, 212-223.

Chaudhary, A., Mishra, S.K., and shish Pandey, A. (2013). "Experimental Verification of the effect of slope on runoff Curve Numbers", J. Indian Water Resour. Soc., Vol. 33 No. 1, January.

Arnold, J. G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. (1998). "Large area hydrologic modeling and assessment. Part I: model development." *J. Am. Water Resour. Assoc.*, 34, 73-89.

Ballestor, T. (2016) Porous pavements Personnel Communications

Bevin, K. (2012). "Hydrologic similarity, distribution functions and semi-distributed rainfall-runoff models." In *Rainfall-runoff modelling: The primer* (2nd Edition) by K. Bevin. John Wiley & Sons, Ltd., Oxford, UK., 457 pp.

Beven, K.J., and Kirkby, M. J. (1979). "A physically-based, variable contributing area model of basin hydrology." *Hydrol. Sci. Bull.*, 24, 43–69.

Boughton, W.C. (1989). “A review of the USDA SCS curve number method.” *Australian Journal of Soil Research*, 27, 511-523.

Calvo, L. L., Ogden, F.L., and Hendrickx, J.M.H. (2006). “Infiltration in the upper Rio Chagres basin, Panama: the Soil Conservation Service ‘curve number’.” Water Sciences and Technology Library 52 Ch 11, 11pp. Springer, Netherlands.

Ebrahimian, E., Nuruddin, A., Soom, M. Sood, A., Jlew, N. (2012). “Runoff Estimation in Steep Slope Watersheds with Standard and Slope-Adjusted Curve Number Methods”; Pol J Environ. Stud. Vol 21 No 5 1191-1202 .V. Waszuk. B.

Fassman-Beck, E., Hunt, W., Berghage, R., Carpenter, D., Kuertz, T., Stovin, V., and Wadzuk, B. (2016). “Curve Number and Runoff Coefficients for Extensive Living Roofs.” *Journal of Hydrologic Engineering*, ASCE 21(3). (March).

Garg .V., Chaubey, L., and Haggard, B. E. (2003). “Impact of calibration watershed on runoff model accuracy.” *Transactions American Society of Agricultural Engineers* 46(5) 1347-1353.

Getter, K.L., Rowe, D.B., and Andresen, J.A. (2007). Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering 31(4), 225-231.

Hawkins R. H., and Ward T.J. (1998). “Site and cover effects on event runoff Jornada Experimental Range, New Mexico.” *Symposium Proceedings, Conference on Range and Management and Water Resources*, American Water Resources Association, 361-370, Reno, NV.

Hawkins, R.H., Ward, T.J., Grillone, G., D’Asaro, F., and Shaked, M. (2015). “Standard Asymptotic Response and Runoff from Curve Number theory”. *Proceedings ASCE Watershed Management Conference*, Reston Virginia, August, 12pp, CD.

Hawkins, R.H. and Barreto-Munoz. A. (2016). *Wildcat5 for Windows, a rainfall-runoff hydrograph model: User manual and documentation*. USDA-USFS General Technical Report RMRS-GTR-334, Rocky Mountain Research Station, Ft. Collins, CO, 70 pp.

Hawkins, R.H., and Pankey, J.M. (1981). “Stormflow as a Function of Watershed Impervious Area.” *Proceedings Arizona Section Am. Water Resources Association, and Hydrology Section Arizona-Nevada Academy of Sciences*. Tucson, Arizona, May 1-2.

Hawkins, R.H., Ward, T.J., and Woodward, D.E. (2015). “The Complacent-Violent Runoff Behavior: a Departure from Tradition”. Proceedings ASCE Watershed Management Conference, Reston Virginia, August 2015. 12pp, CD.

Hawkins, R.H., Ward, T.J., Woodward, D.E., and VanMullem, J.A. (2009). *Curve Number Hydrology: State of the Practice.*, American Society of Civil Engineering, 106 pp.

Higgins, D.A, Maloney, S.B., Tiedemann, A.R., and Quigley, T. M. (1989). “Storm Runoff Characteristics of Grazed Watersheds in Eastern Oregon”. *Journal American Water Resources Association* 25(1), 87-100.

Hjelmfelt, Jr., A.T. (1980). “Empirical Investigation of Curve Number Technique. *Proc. Am. Soc. Civ. Eng*. 106 (HY9), 1471-1475. (September).

Hjelmfelt, Jr, A.T. (1983). “Curve numbers: A personal interpretation”. *In Proceedings of the Specialty Conference on Advances in Irrigation and Drainage,* Jackson, Wyoming. American Society of Civil Engineers, New York. pp208-215.

Hewlett, J. D., Forsten, J. C., and Cunningham, J. B. (1984.) “Additional tests on the effect of rainfall intensity on stormflow and peak flow from wild-land basins” *Water Resources Research* 20(7), 985-989. (July).

Hong, Y., Adler, R.F, Hossain F., Curtis, S., and Huffman, G.J. (2007). “A first approach to global runoff simulation using satellite rainfall estimation” *Water Resources Research* 43(W08502) 8pp.

Iacobellis, V., Castorani, A., Di Santo, A. R., and Gioia, A. (2015). “Rationale for flood prediction in karst endorheic areas.” *Journal of Arid Environments*, 112, 98-108.

Malagò, A., Efstathiou, D., Bouraoui, F., Nikolaidis, N. P., Franchini, M., Bidoglio, G., and Kritsotakis, M. (2016). “Regional scale hydrologic modeling of a karst-dominant geomorphology: The case study of the Island of Crete.” *Journal of Hydrology*, 540, 64-81.

McCutcheon, S. C., Negussie, T., Adams, M. B., Kochenderfer, J., Swank, W., Campbell, J., Hawkins, R. H., and Dye, C.R. (2006). “Rainfall-runoff relationships for selected eastern U.S. forested mountain watersheds: Testing of the curve number method for flood analysis.” Report prepared by Environmental and Hydrologic Engineering, Athens, Georgia for the West Virginia Division of Forestry Charleston, West Virginia. ca 270pp.

Huang, M., Gallichand, J., Wang, Z., and Goulet. M. (2005). “A modification to the Soil Conservation Service curve number method for steep slopes in the Loess Plateau of China” *Hydrol. Process.* 20, 579–589 published online 18 October 2005 in Wiley InterScience.

Moglen, G.E. and Kim, S. (2007). "Limiting imperviousness: Are threshold-based policies a good idea?" *Journal of the American Planning Association*, 73(2): 161-171.

Moglen, G. (2016). “Suggested Curve Number Assignments for the National Land Cover Database (NLCD): Draft 1.” Unpublished draft, October 7, 2016.

Neitsch, S.L. Arnold J.G., Kiniry, J. R., Williams, J. R., and King K. W. (2002). “Soil and water assessment tool (SWAT) theoretical documentation, version 200. “Texas Water Resources Institute, College Texas, TWRI Report TR-191.

Pilgrim, D.H. and Cordery, I. (1992). “Flood runoff,” Chapter 9 in *Handbook of Hydrology,* D.L. Maidment, Editor. McGraw-Hill, Inc., New York, NY.

Ponce, V. M. (1989). *Engineering Hydrology, Principles and Practices,* Prentice-Hall, Englewood Cliffs, NJ. 640pp.

Price, M.A. (1998). *Seasonal Variation in Runoff Curve Numbers*. Master Thesis, School of Renewable Natural Resources, University of Arizona, Tucson, Arizona.

Shrestha, R. K., Mishra, S.K. and Ashish Pandey, A. (2013). “Curve Number Affected by Slope of Experimental Plot have Maize Crop.” J. Indian Water Resour. Soc., Vol. 33, No. 2, April.

Rawls, W.J., Shalaby, A., and McCuen, R.H. (1981). “Evaluation of methods for determining urban runoff curve numbers.” Trans. Amer. Soc. Agricul. Eng. 24(6):1562-1566.

Rietz, P. D. (1999). “Effects of land use on runoff curve numbers.” MS thesis, University of Arizona (Watershed Management), Tucson, AZ. 115pp.

Rietz, P. D., and Hawkins, R. H. (2000). “Effects of land use on runoff curve number.” *Proceedings of Symposium on Watershed Management 2000*, (Edited by M. Flug and D. Frevert). American Society of Civil Engineers. 11pp.

Sartori, A, Hawkins, R.H., and Genovez, A.M. (2011). “Reference Curve Numbers and Behavior for Sugar Cane on Highly Weathered Tropical Soils.” *Journal of Irrigation and Drainage Division,* Amer Soc of Civ Eng., 137(11), 705-11. (November).

Schaake, J. C., Geyer, J. C., and Knapp, J. W. (1967). “Experimental examination of the rational method.” *Journal of the Hydraulics Division*, American Society of Civil Engineers, 93(HY6), 353-370. (November).

Schwartz, S. S. (2010). “Effective Curve Numbers and Hydrologic Design of Pervious Concrete Storm -Waters Systems.” *Journal of Hydrologic Engineering*, ASCE, 15(6). (June).

Singh, K.P. (1971).”Role of baseflow in rainfall-runoff relations.” ASCE *meeting preprint 1291, Nation Water Resources Engineering Meeting*, Phoenix AZ, Jan 1-15.

Singh, V.P. (1989) *Hydrology Systems, Volume II, Watershed Modeling.* Prentice-Hall, Englewood Cliffs, NJ. 320pp.

Tedela, N.H., McCutcheon, S.C., Campbell, J.L., Swank, W.T., Adams, M.B. and Rasmussen, T. C. (2012) “Curve Numbers for Nine Mountainous Easter United States: seasonal variation and forest cutting.” *Journal of Hydrologic Engineering* ASCE November. pp1199-1203.

Tedela, N., McCutcheon, S.C., Adams, M.B., Swank, W., and Campbell, J. (2007). Rainfall volume and return interval *versus* curve number (CN) for Appalachian watersheds. Poster at Kindsvater Lecture, ASCE Georgia Section Environmental and Water Resources Technical Group, Atlanta, GA, February 5 (invited).

Tollner, E. W. (2017). “Forested Watersheds” Invited presentation at a NRCE/ASCE Curve Number Task Committee meeting, June.

Titmarsh, G.W., Pilgrim, D.H., Cordery, I., and Hoissein, A.A. (1989). “An examination of design flood estimations using the US Soil Conservation Services Method.” *Proceedings Hydrology and Water Resources Symposium, Christchurch NZ,* 23-30 October. pp247-251.

United States Department of Agriculture, Forest Service. (1959). Section 1 of Handbook on methods of hydrologic analysis. Washington, DC

United States Department of Agriculture, Natural Resources Conservation Service. (1999). National, Hydrology Engineering Handbook Part 630 Hydrology.

US Geological Survey. (2017). Multi-Resolution Land Characteristics Consortium. <http://www.mrlc.gov/index.php>, (September 20, 2017).

Van Mullem, J.A. (2016). “CN Table Conversions.” Internal memo, ASCE EWRI CN Task Committee, dated February 2016.

VerWeire, K. E., Hawkins, R. H. Quan, Q. D., Scheer, C. C. (2005). “Relationship of hydrologic soils groups to curve numbers; results of a study.” Presentation at American Society of Civil Engineers Watershed Management Conference, Williamsburg Virginia July 20, 2005.

Virginia Department of Conservation and Recreation (2017). “Hydrologic Modeling and Design in Karst Technical Bulletin No. 2.” <http://www.deq.virginia.gov/Programs/Water/StormwaterManagement/Publications.aspx>, (August 2, 2017).

Walker, S.E., Banasik, K., Northcott, W.J., Jiang, N., Yuan, Y., and Mitchell, J. K. (2005). “Application of the SCS Curve Number Method to Mildly-Sloped Watersheds.” Southern Cooperative Series Bulletin <http://s1004.okstate.edu/S1004/Regional-Bulletins/Modeling-Bulletin/paper98-draft1.html> (September 19, 2017).

Williams, J. D., and LaSeur, W. V. (1976). “Water yield model using SCS curve numbers,” *Journal of the Hydraulics Division,* ASCE 102(HY9), pp1241-1253. (September).