Module 205—SCS Runoff Equation

Introduction

The NRCS method of estimating direct runoff from rainfall was developed by SCS hydrologists during the early 1950's. The primary uses for such estimates are to establish safe limits for hydrologic design and to compare the effects of alternative conservation measures in a watershed. Runoff needs for NRCS work include volume estimates for "short" duration detention and peak discharge estimates.

Watersheds that NRCS are generally concerned with are small and ungaged (no streamgage records available), thus any runoff procedures should be appropriate for these conditions. Data that are generally available or that can be easily obtained for a watershed include:

- Watershed location
- Published rainfall-frequency data
- Land use and cover information
- Soils information

Considering the needs of NRCS and the data that were available at the time the model was developed, an event model with generalized runoff parameters was used. Streamflow data for small watersheds were available from the Agricultural Research Service and the U.S. Geological Survey. This information formed the data base for the runoff curve numbers that would be used in the SCS runoff equation.

Water Balance

A water balance accounts for all water that enters and leaves a system. For our needs, the system is a watershed and the balance is:

Rainfall = Runoff + Losses

Solving the water balance for runoff yields:

Runoff = Rainfall - Losses

Runoff

Runoff is classified by type as it flows through the watershed. The runoff types and their characteristics are:

- Channel runoff—Rainfall that falls on the watercourse. Generally this is a negligible quantity.
- Surface runoff—Generated when the rainfall rate exceeds the infiltration rate.
- Subsurface flow—The horizontal movement of infiltrated water in the soil. Subsurface flow may reappear as surface runoff shortly after rainfall (through seeps or springs). It can also be referred to as "quick return flow" or "interflow."
- Direct runoff—A collective term that includes all the above runoff types.
- Baseflow—A fairly steady release of water from natural or manmade storage areas, such as lakes, swamps, or maybe underground aquifers. It is the flow that lingers on after the immediate effects of a runoff event have occurred.

Rainfall

Rainfall as used in the SCS runoff equation is considered an event amount. Data that were available for development of the procedure were not for events, but for calendar days or 24-hour periods. During times of thunderstorms, either of these amounts could include more than one actual event.

Losses

Losses include rainfall interception, soil infiltration, surface storage, and evaporation.

- *Interception*—Rainfall that does not reach the ground because it has contacted something (generally vegetation or buildings).
- *Infiltration*—Water that reaches the ground and enters the soil. Infiltrated water may become part of subsurface flow or the ground water table.
- *Surface storage*—Water that reaches the ground and is collected in depressions (low spots) along the flow path or in a closed basin. Water in surface storage must either infiltrate or evaporate.
- *Evaporation*—Water that goes back to the atmosphere. It is usually a negligible amount.

Water Balance Equation

Expressing the water balance as an equation:

$$Q = P - (Ia + F)$$

where:

Q = direct runoff (ins)

P = rainfall (ins)

Ia = sum of all losses before the beginning of runoff (ins)

and

F = retention after runoff begins (ins)

The water balance equation has four parameters. During development of the SCS runoff equation, Q and P were measured in the field. Ia could have been computed but a generalized relationship was developed from data. F was solved for and generalized as the variable S (which will be explained later).

For the application phase of the equation, Q is the quantity that is unknown. P can be obtained from either actual measurements or generalized rainfall-frequency analysis. Ia and F are functions of S and are fitted based on the development work. S was created to express Ia and F in terms of one equation fitting parameter and represents the hypothetical limit of storage. It is defined as the potential maximum retention after runoff begins. S lumps all variation in the runoff response because of land use, soils, soil moisture, or rainfall pattern, duration, or intensity, plus any other variation into one variable.

Because all of the losses are grouped together and not defined by amount and source, the model to be developed is called a "lumped system" model.

SCS Runoff Equation

To transform the water balance equation to what is called the SCS runoff equation, two assumptions were made:

Assumption # 1

The ratio of the percent water that has been retained to the maximum potential retention is the same as the ratio of the percent water that ran off to the maximum rainfall available for runoff. This assumption is expressed as:

$$F/S = Q/(P-Ia)$$

where F is the amount of rainfall retained (after runoff begins);
S is the maximum potential retention (after runoff begins);
Q is the amount of runoff, and
P-Ia is the maximum rainfall available for runoff.

At the limit where P is exceptionally large:

$$Q/(P-Ia) << 1, \text{ and}$$

$$F/S << 1.$$

When no runoff occurs, P = Ia, both F and Q are zero. Therefore:

$$F/S << 0, \text{ and}$$

$$Q/(P-Ia) << 0$$

Because these ratios are equal in their extremes, they are assumed to exhibit similar characteristics throughout their range. To get the generalized rainfall-runoff relation, solve both the water balance and the assumption #1 ratios for F and equate, thus eliminating F.

Water balance	$F = (P - Ia) - Q$
Assumption #1	$F = QS/(P - Ia)$
Equate	$(P - Ia) - Q = QS/(P - Ia)$
Multiply by (P - Ia)	$(P - Ia)[(P - Ia) - Q] = QS$
Group Q on one side	$(P - Ia)^2 = Q(P - Ia + S)$
Solve for Q	$(P - Ia)^2 /(P - Ia + S) = Q$

Assumption #2

Ia can be expressed as a function of S. If Ia is expressed as a function of one of the other equation parameters, then the runoff equation is greatly simplified because only rainfall and one fitting parameter (S) are needed to solve for runoff. The relationship that is used by NRCS is:

$$Ia = 0.2\ S.$$

Substituting for Ia in the generalized runoff equation produces

$$Q = (P - 0.2\ S)^2 /(P - 0.2\ S + S)$$

and collecting terms produces the SCS runoff equation:

$$Q = (P - 0.2\ S)^2 /(P + 0.8\ S)$$

During development, Ia was measured at sites that had both continuous rainfall and runoff records. With both of these known, a solution for S could be found from the water balance and assumption # 1. A log plot of S versus Ia for many such events produced the scatter diagram in figure 1. The mean value of the relation (Ia = 0.2 S) was selected. The data used to develop figure 1 were primarily from small agricultural watersheds and represent a wide range of storm conditions.

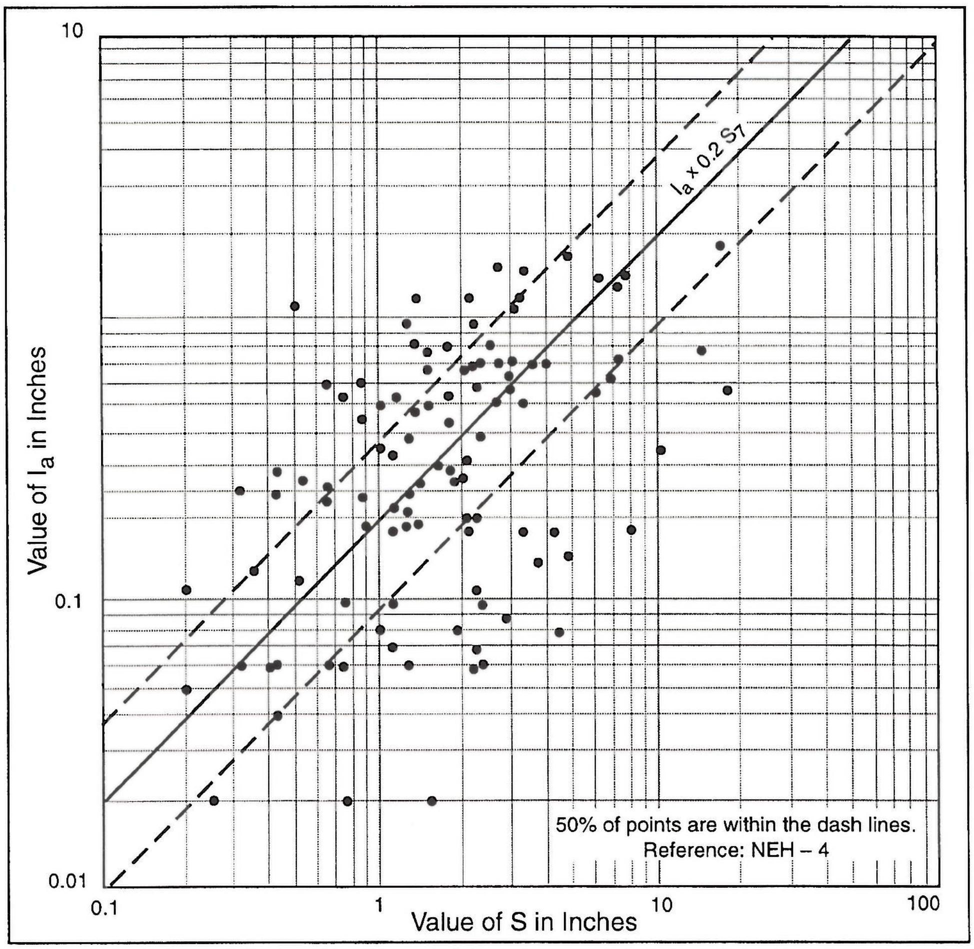

Figure 1. Relationship of Ia and S based on experimental watershed data. Reference: NEH-4.

Runoff Curve Numbers (CN)

The potential maximum retention after runoff begins (S) has a range of values from 0 to infinity. S also requires the use of several decimal places to achieve any type of accuracy in its practical range (0 to 15). To use a more convenient value, a new parameter called curve number (CN), was established. The relationship between CN and S is an inverse relationship and the range of CN is limited by 0 and 100. Its practical range is 40 to 98. CN is also used only as an integer value.

The relationship between CN and S is:

$$CN = \frac{1000}{(S + 10)} \quad \text{or} \quad S = \frac{1000}{CN} - 10$$

Table 1 is a solution of the above equations for the range of curve numbers 40 to 98.

Tables that give the CN to use in the runoff equation for various cover types and hydrologic soil groups are available. The cover types describe not only what is on the land, but in some cases its condition from a hydrologic standpoint (good, fair, or poor). The soils for the site are classified into one of four hydrologic soil groups, depending on the soils' ability to infiltrate water. The soil groups are called A, B, C, and D, which indicate the greatest infiltration capacity to the least, respectively. Cover/hydrologic soil group/CN data are given in table 9.1 in the National Engineering Handbook, Section 4 (Hydrology); Tables 2-3a through 2-3d in the Engineering Field Manual and Table 2-2a through 2-2d in Urban Hydrology for Small Watersheds (TR-55). The tables have been expanded over time and the most complete table is in TR-55. Table 2 is a sample.

Curve Number (CN)	Potential Maximum Retention (S)		Curve Number (CN)	Potential Maximum Retention (S)
40	15.000		70	4.286
41	14.390		71	4.085
42	13.810		72	3.889
43	13.256		73	3.699
44	12.727		74	3.514
45	12.222		75	3.333
46	11.739		76	3.158
47	11.277		77	2.987
48	10.833		78	2.821
49	10.408		79	2.658
50	10.000		80	2.500
51	9.608		81	2.346
52	9.231		82	2.195
53	8.868		83	2.048
54	8.519		84	1.905
55	8.182		85	1.765
56	7.857		86	1.628
57	7.544		87	1.494
58	7.241		88	1.364
59	6.949		89	1.236
60	6.667		90	1.111
61	6.393		91	0.989
62	6.129		92	0.870
63	5.873		93	0.753
64	5.625		94	0.628
65	5.385		95	0.526
66	5.152		96	0.417
67	4.925		97	0.309
68	4.706		98	0.204
69	4.493			
70	4.286			

Table 1. Curve numbers and equivalent potential maximum retention values.

Cover description			Curve numbers for hydrologic soil group—			
Cover type	Treatment*	Hydrologic condition**	A	B	C	D
Fallow	Bare Soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

Table 2. Sample curve numbers. Reference: TR-55

Average runoff condition, and Ia=0.2S.

**Crop residue cover* applies only if residue is on at least 5% of the surface throughout the year.

**Hydrologic condition is based on a combination 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 in rotations, (d) percent of residue cover on the land surface (good ≤ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

The CN's published in these tables are for an average runoff condition. While the exact conditions that are considered average are not defined, some items that can cause runoff conditions to vary are:

- Rainfall amount,
- Rainfall pattern,
- Maximum rainfall intensity,
- Rainfall duration,
- Antecedent soil moisture, and
- Air temperature.

When the curve number tables were originally developed, sample watershed P and Q data pairs were plotted to produce a scatter of points. The CN for each event was determined by "reverse engineering" the runoff equation to solve for S and then converting S to CN. A median curve number was determined and plotted along with the sample data. This median CN represents the average runoff condition. The range of the remaining CN's were noted and later smoothed mathematically. This range is considered to define the limiting values for a specified average runoff condition CN. Table 3 lists the limiting CN values.

Theoretically, any value within the range could be expected to occur in a watershed for some event, some time. Thus if rainfall and runoff data are available for an event, an event CN could be computed. This event CN should fall within the range listed for the appropriate average condition CN. Also, any CN within the range could be used for watershed analysis and design. Any variation from the average condition CN should be documented. In most situations the average condition value is adequate.

Average Condition CN	Lower Limit CN	Upper Limit CN		Average Condition CN	Lower Limit CN	Upper Limit CN
40	22	60		70	51	85
41	23	61		71	52	86
42	24	62		72	53	86
43	25	63		73	54	87
44	25	64		74	55	88
45	26	65		75	57	88
46	27	66		76	58	89
47	28	67		77	59	89
48	29	68		78	60	90
49	30	69		79	62	91
50	31	70		80	63	91
51	31	70		81	64	92
52	32	71		82	66	92
53	33	72		83	67	93
54	34	73		84	68	93
55	35	74		85	70	94
56	36	75		86	72	94
57	37	75		87	73	95
58	38	76		88	75	95
59	39	77		89	76	96
60	40	78		90	78	96
61	41	78		91	80	97
62	42	79		92	81	97
63	43	80		93	83	98
64	44	81		94	85	98
65	45	82		95	87	98
66	46	82		96	89	99
67	47	83		97	91	99
68	48	84		98	94	99
69	50	84				
70	51	85				

Table 3. Curve number ranges for average condition curve numbers.