6631 U-004-307 .7

ESTIMATION OF DIRECT RUNOFF FROM STORM RAINFALL, IN NATIONAL ENGINEERING HANDBOOK, SECTION 4, U. S. DEPARTMENT OF AGRICULTURE, SOIL CONSERVATION SERVICE, WASHINGTON, DC - (USED AS A REFERENCE IN OU 2 RI REPORT)

08/00/72

NEH NOTICE 4-102

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REPORT

10-i

NATIONAL ENGINEERING HANDBOOK

SECTION 4

HYDROLOGY

CHAPTER 10. ESTIMATION OF DIRECT RUNOFF FROM STORM RAINFALL

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1964

Reprinted with minor revisions, 1972

NEH Notice 4-102, August 1972

6631

10-71

SCS NATIONAL ENGINEERING HANDBOOK

SECTION 4

HYDROLOGY

CHAPTER 10--ESTIMATION OF DIRECT RUNOFF FROM STORM RAINFALL

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CHAPTER 10. ESTIMATION OF DIRECT RUNOFF FROM STORM RAINFALL

The SCS method of estimating direct runoff from storm rainfall is described in this chapter. The rainfall-runoff relation of the method is developed, parameters in the relation are discussed, and applications of the method are illustrated by examples.

Introduction

The SCS method of estimating direct runoff from storm rainfall is based on methods developed by SCS hydrologists in the last three decades, and it is in effect a consolidation of these earlier methods. The hydrologic principles of the method are not new, but they are put to new uses. Because most SCS work is with ungaged watersheds (not gaged for runoff) the method was made to be usable with rainfall and watershed data that are ordinarily available or easily obtainable for such watersheds. If runoff data are also available the method is adaptable to their use as illustrated in chapter 5.

The principal application of the method is in estimating quantities of runoff in flood hydrographs or in relation to flood peak rates (chap. 16). These quantities consist of one or more types of runoff. An understanding of the types is necessary to apply the method properly in different climatic regions. The classification of types used in this handbook is based on the time from the beginning of a storm to the time of the appearance of a type in the hydrograph. Four types are distinguished:

Channel runoff occurs when rain falls on a flowing stream or on the impervious surfaces of a streamflow-measuring installation. It appears in the hydrograph at the start of the storm and continues throughout it, varying with the rainfall intensity. It is generally a negligible quantity in flood hydrographs, and no attention is given to it except in special studies (see the discussion concerning the relationship of I_a to S in figure 10.2).

Surface runoff occurs only when the rainfall rate is greater than the infiltration rate. The runoff flows on the watershed surface to the point of reference. This type appears in the hydrograph after the initial demands of interception, infiltration, and surface storage have been satisfied. It varies during the storm and ends during or soon after it. Surface runoff flowing down dry channels of watersheds in arid, semiarid, or subhumid climates is reduced by transmission losses (chap. 19), which may be large enough to eliminate the runoff entirely.

Subsurface flow occurs when infiltrated rainfall meets an underground zone of low transmission, travels above the zone to the soil surface downhill, and appears as a seep or spring. This type is often called "quick return flow" because it appears in the hydrograph during or soon after the storm.

Base flow occurs when there is a fairly steady flow from natural storage. The flow comes from lakes or swamps, or from an aquifer replenished by infiltrated rainfall or surface runoff, or from "bank storage", which is supplied by infiltration into channel banks as the stream water level rises and which drains back into the stream as the water level falls. This type seldom appears soon enough after a storm to have any influence on the rates of the hydrograph for that storm, but base flow from a previous storm will increase the rates. Base flow must be taken into account in the design of the principal spillway of a floodwater-retarding structure (chap. 21).

All types do not regularly appear on all watersheds. Climate is one indicator of the probability of the types. In arid regions the flow on smaller watersheds is nearly always surface runoff, but in humid regions it is generally more of the subsurface type. But a long succession of storms produces subsurface or base flow even in dry climates although the probability of this occurring is less in dry climates than in wet climates.

In flood hydrology it is customary to deal separately with base flow and to combine all other types into *direct runoff*, which consists of channel runoff, surface runoff, and subsurface flow in unknown proportions. The SCS method estimates direct runoff, but the proportions of surface runoff and subsurface flow (channel runoff is ignored) can be appraised by means of the runoff curve number (CN), which is another indicator of the probability of flow types: the larger the CN the more likely that the estimate is of surface runoff. This principle is also employed for estimating watershed lag as shown in figure 15.3. The rainfall-runoff relation of the SCS method can be made to operate with a particular type of flow; it was linked with direct runoff, as described in chapter 9, for the convenience of applications.

The Rainfall-Runoff Relation

The most generally available rainfall data in the United States are the amounts measured at nonrecording rain gages, and it was for the use of such data or their equivalent that the rainfall-runoff relation was developed. The data are totals for one or more storms occurring in a calendar day, and nothing is known about the time distributions. The relation therefore excludes time as a variable; this means that rainfall intensity is ignored. If everything but storm duration or intensity is the same for two storms, the estimate of runoff is the same for both storms. Runoff amounts for specified time increments of a storm can be estimated as shown in example 10.6, but even in this process the effect of rainfall intensity is ignored.

DEVELOPMENT

If records of natural rainfall and runoff for a large storm over a small area are used, plotting of accumulated runoff versus accumulated rainfall will show that runoff starts after some rain accumulates (there is an "initial abstraction" of rainfall) and that the double-mass line curves, becoming asymptotic to a straight line. On arithmetic graph paper and with equal scales, the straight line has a 45-degree slope. The relation between rainfall and runoff can be developed from this plotting, but a better explanation of the relation is given by first studying a storm in which rainfall and runoff begin simultaneously (initial abstraction is zero). For the simpler storm the relation between rainfall, runoff, and retention (the rain not converted to runoff) at any point on the mass curve can be expressed as:

$$\frac{F}{S} = \frac{Q}{P} \qquad (10.1)$$

where:

F = actual retention after runoff begins
S = potential maximum retention after runoff begins ($S \geq F$)
Q = actual runoff
P = rainfall ($P \geq Q$)

Equation 10.1 applies to on-site runoff; for large watersheds there is a lag in the appearance of the runoff at the stream gage, and the double-mass curve produces a different relation. But if storm totals for P and Q are used equation 10.1 does apply even for large watersheds because the effects of the lag are removed.

The retention, S, is a constant for a particular storm because it is the maximum that can occur under the existing conditions if the storm continues without limit. The retention F varies because it is the difference between P and Q at any point on the mass curve, or:

$$F = P - Q \qquad (10.2)$$

Equation 10.1 can therefore be rewritten:

$$\frac{P - Q}{S} = \frac{Q}{P} \qquad (10.3)$$

Solving for Q produces the equation:

$$Q = \frac{P^2}{P + S} \qquad (10.4)$$

which is a rainfall-runoff relation in which the initial abstraction is zero.

If an initial abstraction (I_a) greater than zero is considered, the amount of rainfall available for runoff is $P - I_a$ instead of P. By substituting $P - I_a$ for P in equations 10.1 through 10.4 the following equations result. The equivalent of equation 10.1 becomes:

$$\frac{F}{S} = \frac{Q}{P - I_a} \qquad (10.5)$$

where $F \leq S$, and $Q \leq (P - I_a)$. The total retention for a storm consists of I_a and F. The total potential maximum retention (as P gets very large) consists of I_a and S.

Equation 10.2 becomes:

$$F = (P - I_a) - Q \qquad (10.6)$$

equation 10.3 becomes:

$$\frac{(P - I_a) - Q}{S} = \frac{Q}{(P - I_a)} \qquad (10.7)$$

and equation 10.4 becomes:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (10.8)$$

which is the rainfall-runoff relation with the initial abstraction taken into account.

The initial abstraction consists mainly of interception, infiltration, and surface storage, all of which occur before runoff begins. The insert on figure 10.1 shows the position of I_a in a typical storm. To remove the necessity for estimating these variables in equation 10.8, the relation between I_a and S (which includes I_a) was developed by means of rainfall and runoff data from experimental small watersheds. The relation is discussed later in connection with figure 10.2. The empirical relationship is:

$$I_a = 0.2\ S \qquad (10.9)$$

Substituting 10.9 in 10.8 gives:

$$Q = \frac{(P - 0.2\ S)^2}{P + 0.8\ S} \qquad (10.10)$$

which is the rainfall-runoff relation used in the SCS method of estimating direct runoff from storm rainfall.

Retention Parameters

Using the equation 10.9 relationship, the total maximum retention can be expressed as 1.2 S. I_a, as previously stated, consists mainly of interception, infiltration, and surface storage occurring before runoff begins. S is mainly the infiltration occurring after runoff begins. This later infiltration is controlled by the rate of infiltration at the soil surface or by the rate of transmission in the soil profile or by the water-storage capacity of the profile, whichever is the limiting factor. A succession of storms, such as one a day for a week, reduces the magnitude of S each day because the limiting factor does not have the opportunity to completely recover its rate or capacity through weathering, evapotranspiration, or drainage. But there is enough recovery, depending on the soil-cover complex, to limit the reduction. During such a storm period the magnitude of S remains virtually the same after the second or third day even if the rains are large so that there is, from a practical viewpoint, a lower limit to S for a given soil-cover complex. Similarly, there is a practical upper limit to S, again depending on the soil-cover complex, beyond which the recovery cannot take S unless the complex is altered.

In the SCS method, the change in S (actually in CN) is based on an antecedent moisture condition (AMC) determined by the total rainfall in the 5-day period preceding a storm. Three levels of AMC are used: AMC-I is the lower limit of moisture or the upper limit of S, AMC-II is the average for which the CN of table 9.1 apply, and AMC-III is the upper limit of moisture or the lower limit of S. The CN in table 9.1 were determined by means of rainfall-runoff plottings as described in chapter 9. The same plottings served for getting CN for AMC-I and AMC-III. That is, the curves of figure 10.1, when superimposed on a plotting, also showed which curves best fit the highest (AMC-III) and lowest (AMC-I) thirds of the plotting. The CN for high and low moisture levels were empirically related to the CN of table 9.1; the results are shown in columns 1, 2, and 3 of table 10.1, which also gives values of S and I_a for the CN in column 1. The rainfall amounts on which the selection of AMC is based are given in table 4.2; the discussion in chapter 2 concerns the value of rainfall alone as a criterion for AMC. Use of tables 4.2 and 10.1 is demonstrated later in this chapter. In the section on comparisons of computed and actual runoffs, an example shows that for certain problems the extreme AMC can be ignored and the average CN of table 9.1 alone applied.

RELATION OF I_a TO S. Equation 10.9 is based on the results shown in figure 10.2 which is a plotting of I_a versus S for individual storms. The data were derived from records of natural rainfall and runoff from watersheds less than 10 acres in size. The large amount of scatter in the plotting is due mainly to errors in the estimates of I_a. The magnitudes of S were estimated by plotting total storm rainfall and runoff on figure 10.1, determining the CN, and determining the S from table 10.1. The magnitudes of I_a were estimated by taking the accumulated rainfall from the beginning of a storm to the time when runoff started. Errors in S were due to determinations of average watershed rainfall totals; these errors were very small. Errors in I_a were due to one or more of the following: (i) difficulty of determining the time when rainfall began, because of storm travel and lack of instrumentation, (ii) difficulty of determining the time when runoff began, owing to the effects of rain on the measuring installations (channel runoff) and to the lag of runoff from the watersheds, and (iii) impossibility of determining how much interception prior to runoff later made its way to the soil surface and contributed to runoff; the signs and magnitudes of these errors are not known. Only enough points are plotted in figure 10.2 to show the variability of the data. The line of relationship cuts the plotting into two equal numbers of points, and the slope of the line is 1:1 because the data do not indicate otherwise. A significant statistical correlation (chap. 18) between I_a and S can be made by adding more points and increasing the "degrees of freedom," but the standard error of estimate will remain large owing to the deficiencies in the data.

Graphs and Tables for the Solution of Equation 10.10

Sheets 1 and 2 of figure 10.1 contain graphs for the rapid solution of equation 10.10. The parameter CN (runoff curve number or hydrologic soil-cover complex number) is a transformation of S, and it is used to make interpolating, averaging, and weighting operations more nearly linear. The transformation is:

$$CN = \frac{1000}{S + 10} \qquad (10.11)$$

or

$$S = \frac{1000}{CN} - 10 \qquad (10.12)$$

Tables for the solution of equation 10.10 are given in SCS Technical Release 16 for P from zero to 40.9 inches by steps of 0.1-inch and for all whole-numbered CN in the range from 55 through 98.

USE OF S AND CN. It is more convenient to use CN on figure 10.1, but it will generally be necessary to use S for other applications such as the analysis of runoff data or the development of supplementary runoff relationships. Example 5.5 and figure 5.6(b) illustrate a typical use of S. The relationship is developed using S, but a scale for CN is added later to the graph for ease of application.

July, 1969

Table 10.1. Curve numbers (CN) and constants for the case $I_a = 0.2\ S$

1	2	3	4	5	1	2	3	4	5
CN for condition II	CN for conditions		S values*	Curve* starts where P =	CN for condition II	CN for conditions		S values*	Curve* starts where P =
	I	III	(inches)	(inches)		I	III	(inches)	(inches)
100	100	100	0	0	60	40	78	6.67	1.33
99	97	100	.101	.02	59	39	77	6.95	1.39
98	94	99	.204	.04	58	38	76	7.24	1.45
97	91	99	.309	.06	57	37	75	7.54	1.51
96	89	99	.417	.08	56	36	75	7.86	1.57
95	87	98	.526	.11	55	35	74	8.18	1.64
94	85	98	.638	.13	54	34	73	8.52	1.70
93	83	98	.753	.15	53	33	72	8.87	1.77
92	81	97	.870	.17	52	32	71	9.23	1.85
91	80	97	.989	.20	51	31	70	9.61	1.92
90	78	96	1.11	.22	50	31	70	10.0	2.00
89	76	96	1.24	.25	49	30	69	10.4	2.08
88	75	95	1.36	.27	48	29	68	10.8	2.16
87	73	95	1.49	.30	47	28	67	11.3	2.26
86	72	94	1.63	.33	46	27	66	11.7	2.34
85	70	94	1.76	.35	45	26	65	12.2	2.44
84	68	93	1.90	.38	44	25	64	12.7	2.54
83	67	93	2.05	.41	43	25	63	13.2	2.64
82	66	92	2.20	.44	42	24	62	13.8	2.76
81	64	92	2.34	.47	41	23	61	14.4	2.88
80	63	91	2.50	.50	40	22	60	15.0	3.00
79	62	91	2.66	.53	39	21	59	15.6	3.12
78	60	90	2.82	.56	38	21	58	16.3	3.26
77	59	89	2.99	.60	37	20	57	17.0	3.40
76	58	89	3.16	.63	36	19	56	17.8	3.56
75	57	88	3.33	.67	35	18	55	18.6	3.72
74	55	88	3.51	.70	34	18	54	19.4	3.88
73	54	87	3.70	.74	33	17	53	20.3	4.06
72	53	86	3.89	.78	32	16	52	21.2	4.24
71	52	86	4.08	.82	31	16	51	22.2	4.44
70	51	85	4.28	.86	30	15	50	23.3	4.66
69	50	84	4.49	.90					
68	48	84	4.70	.94	25	12	43	30.0	6.00
67	47	83	4.92	.98	20	9	37	40.0	8.00
66	46	82	5.15	1.03	15	6	30	56.7	11.34
65	45	82	5.38	1.08	10	4	22	90.0	18.00
64	44	81	5.62	1.12	5	2	13	190.0	38.00
63	43	80	5.87	1.17	0	0	0	infinity	infinity
62	42	79	6.13	1.23					
61	41	78	6.39	1.28					

*For CN in column 1.

Applications

The examples in this part mainly illustrate the use of tables 4.2, 9.1, and 10.1 and figure 10.1. Records from gaged watersheds are used in some examples to compare computed with actual runoffs. The errors in a runoff estimate are due to one or more of the following: empiricisms of table 4.2 or figure 4.9, or table 9.1 and similar tables in chapter 9, of the relation between AMC (columns 1, 2, and 3 of table 10.1), and of equation 10.9; and errors in determinations of average watershed rainfall (chap. 4), soil groups, (chap. 7), land use and treatment (chap. 8), and related computations. Consequently it is impossible to state a standard error of estimate for equation 10.10; comparisons of computed and actual runoffs indicate only the algebraic sums of errors from various sources.

SINGLE STORMS. The first example is a typical routine application of the estimation method when there is no question regarding the accuracy of rainfall, land use and treatment, and soil group determinations.

> Example 10.1.- During a storm an average depth of 4.3 inches of rain fell over a watershed with a cover of good pasture, soils in the C group, and an AMC-II. Estimate the direct runoff.
>
> 1. Determine the CN. In table 9.1 at "Pasture, good" and under soil group C read a CN of 74, which is for AMC-II.
>
> 2. Estimate the runoff. Enter figure 10.1 with the rainfall of 4.3 inches and at CN = 74 (by interpolation) find Q = 1.83 inches.

In practice the estimate of Q is carried to two decimal places to avoid confusing different estimates. Except for such needs the estimate should generally be rounded to one decimal place; in example 10.1 the rounded estimate is 1.8 inches. If the storm rainfall amount is not accurately known the estimate is rounded even further or the range of the estimate is given as in the following example.

> Example 10.2.--During a thunderstorm a rain of 6.0 inches was measured at a rain gage 5.0 miles from the center of a watershed that had a flood from this storm. The drainage area of the watershed is 840 acres, cover is fair pasture, soils are in the D group, and AMC-II applies. Estimate the direct runoff.

1. Determine the average watershed rainfall. Enter figure 4.4 with the distance of 5.0 miles and at line for a rain of 6.0 inches read a plus-error of 2.8 inches. The minus-error is half this, or 1.4 inches. The watershed is small enough that no "areal correction" of rainfall is necessary (see figure 21.-- and related discussion in chapter 21), therefore the average watershed rainfall ranges from 8.8 to 4.6 inches.

2. Determine the CN. In table 9.1 the CN is 84 for fair pasture in the D soil group.

3. Estimate the direct runoff. Enter figure 10.1 with the rainfall of 8.8 inches and at CN = 84 (by interpolation) read an estimated runoff of 6.87 inches; also enter with the rainfall of 4.6 inches and read a runoff of 2.91 inches. After rounding, the estimate of direct runoff is given as being between 2.9 and 6.9 inches or, better yet, between 3 and 7 inches. The probability level of figure 4.4 can also be used with the runoff estimate.

Table 10.1 is used when it is necessary to estimate runoff for a watershed in a dry or wet condition before a storm:

Example 10.3.--For the watershed of example 10.1, estimate the direct runoff for AMC-I and AMC-III and compare with the estimate for AMC-II.

1. Determine the CN for AMC-II. This is done in step 1 of example 10.1; the CN is 74.

2. Determine CN for other AMC. Enter table 10.1 at CN = 74 in column 1 and in columns 2 and 3 read CN = 55 for AMC-I and CN = 88 for AMC-III.

3. Estimate the runoffs. Enter figure 10.1 with the rainfall of 4.3 inches (from ex. 10.1) and at CN = 55, 74, and 88 read (by interpolation as necessary) that Q = 0.65, 1.83, and 3.00 inches, respectively. The comparison in terms of AMC-II runoff is as follows:

AMC	CN	Direct runoff, Q		
		Inches	As percent of rainfall	As percent of Q for AMC-II
I	55	0.65	15.1	35.6
II	74	1.83	42.5	100
III	88	3.00	69.8	164

Note that the runoff in inches or percents is not simply proportional to the CN so that the procedure does not allow for a short cut.

ALTERNATE METHODS OF ESTIMATION FOR MULTIPLE COMPLEXES. The direct runoff for watersheds having more than one hydrologic soil-cover complex can be estimated in either of two ways: in example 10.4 the runoff is estimated for each complex and weighted to get the watershed estimate; in example 10.5 the CN are weighted to get a watershed CN and the runoff is estimated using it.

Example 10.4.--A watershed of 630 acres has 400 acres in "Row crop, contoured, good rotation" and 230 acres in "Rotation meadow, contoured, good rotation." All soils are in the B group. Find the direct runoff for a rain of 5.1 inches when the watershed is in AMC-II.

1. Determine the CN. Table 9.1 shows that the CN are 75 for the row crop and 69 for the meadow.

2. Estimate runoff for each complex. Enter figure 10.1 with the rain of 5.1 inches and at CN of 75 and 69 read Q's of 2.52 and 2.03 inches respectively.

3. Compute the weighted runoff. The following table shows the work.

Hydrologic soil-cover complex	Acres	Q(inches)	Acres X Q
Row crop etc.	400	2.52	1,008
Meadow etc.	230	2.03	467
Totals:	630		1,475

The weighted Q is 1475/630 = 2.34 inches.

Example 10.5.--Use the watershed and rain data of example 10.4 and make the runoff estimate using a weighted CN.

1. Determine the CN. Table 9.1 shows that the CN are 75 for the row crop and 69 for the meadow.

2. Compute the weighted CN. The following table shows the work.

Hydrologic soil-cover complex	Acres	CN	Acres X CN
Row crop etc.	400	75	30,000
Meadow etc.	230	69	15,870
Totals:	630		45,870

The weighted CN is 45,870/630 = 72.8. Use 73.

3. Estimate the runoff. Enter figure 10.1 with the rain of 5.1 inches and at CN = 73 (by interpolation) read Q = 2.36 inches. (Note: Q is 2.34 inches just as in example 10.4 if the unrounded CN is used.)

Without the rounding in step 2 of example 10.5, both methods of weighting give the same Q to three significant figures, and there appears to be no reason for choosing one method over the other. But each method has its advantages and disadvantages. The method of weighted-Q always gives the correct result (in terms of the given data) but it required more work than the weighted-CN method especially when a watershed has many complexes. The method of weighted-CN is easier to use with many complexes or with a series of storms, but when there are large differences in CN for a watershed this method will under- or over-estimate Q, depending on the size of the storm rainfall. For example an urban watershed with 20 acres of impervious area (CN = 100) and 175 acres of lawn classed as good pasture on a B soil (CN = 61) will have the following Q's by the two methods (all entries in inches):

Storm rainfall:	1	2	4	8	16	32
Q (weighted-Q method):	0.10	0.27	1.14	3.91	10.85	26.10
Q (weighted-CN method):	0	.13	1.03	3.89	10.97	26.34

This comparison shows that the method of weighted-Q is preferable when small rainfalls are used and there are two or more widely differing CN on a watershed. For conditions other than these the method of weighted-CN is less time-consuming and almost as accurate.

MULTIPLE-DAY STORMS AND STORM SERIES. Data from a gaged small watershed will be used in the following example to illustrate (i) an application of the method of estimation to a storm series such as used in evaluation of a floodwater-retarding project, (ii) treatment of multiple-day storms, which differs from that of design storms in chapter 21, and (iii) the amount of error generally to be expected from use of the method. The data to be used are taken from:

Reference 1. "The Agriculture, Soils, Geology, and Topography of the Blacklands Experimental Watershed, Waco, Texas," Hydrologic Bulletin 5, U.S. Soil Conservation Service, 1942.

Reference 2. "Summary of Rainfall and Runoff, 1940-1951, at Blacklands Experimental Watershed, Waco, Texas," U.S. Soil Conservation Service, 1952.

The watershed is W-1 with an area of 176 acres, average annual rainfall of 34.95 inches for the period 1940-1952 inclusive, and average storm rainfall depths determined from amounts at four gages on or very near the watershed. According to figure 4.6 (its scales must be extended for so small a watershed) the storm rainfall amounts will have a negligible error. With this exception the data to be used are equivalent to those ordinarily obtained for ungaged watersheds.

Example 10.6.--Estimate the runoff amounts from storms that produced the maximum annual peak rates of flow at watershed W-1, Waco, Texas, for the period 1940-1952 inclusive.

1. Determine the soil groups. Reference 1 shows that the soils are Houston Black Clay or equivalents. Table 7.1 in chapter 7 shows these soils are in the D group.

2. Determine the average land use and treatment for the period 1940-1952. Reference 2 gives information from which the average land use and treatment is determined to be:

Land use and treatment	Percent of area
Row crop, straight row, poor rotation	58
Small grain, straight row, poor rotation	25
Pasture (including hay), fair condition	15
Farmsteads and roads	2

3. Tabulate the storm dates, total rainfall for each date, and the 5-day antecedent rainfall. Reference 2 gives the information shown in columns 1 through 5 of table 10.2.

4. Determine the CN for AMC-I, -II, and -III. Table 9.1 gives the CN for each complex; the computation of the weighted CN for AMC-II is:

Hydrologic soil-cover complex	Percent/100	CN	Product
Row crop etc.	0.58	91	52.7
Small grain etc.	.25	88	22.0
Pasture etc.	.15	84	12.6
Farmsteads etc.	.02	94	1.9
Totals	1.00		89.2

No division of the product is necessary because "percent/100" is used. The CN is rounded to 89. CN for the other two AMC are obtained from table 10.1 and are:

AMC:	I	II	III
CN:	76	89	96

Table 10.2.--Working table for a storm series.

Year	Month	Day	Storm rainfall	Antecedent rainfall	AMC	CN	Estimated runoff		Actual runoff		Differences	
							By days	Storm totals	By days	Storm totals	By days	Storm totals
			(in.)	(in.)			(in.)	(in.)	(in.)	(in.)	(in.)	(in.)
1940	Nov.	22	4.74	0.18	I	76	2.32		2.32		0	
		23	2.20		III	96	1.77		2.02		- .25	
		24	2.03		III	96	1.61		1.39		.22	
		25	.38		III	96	.13	5.83	.26	5.99	- .13	- 0.16
1941	June	10	2.39	1.38	III	96	1.96	1.96	2.05	2.05	- .09	- .09
1942	Sept.	7	3.89	.22	I	76	1.65		.35		1.30	
		8	3.36		III	96	2.91		2.02		.89	
		9	.78		III	96	.44	5.00	.46	2.83	- .02	2.17
1943	June	5	1.58	.09	I	76	.22	.22	.51	.51	- .29	- .29
1944	April	29	3.63	0	I	76	1.45		1.56		- .11	
		30	2.64		III	96	2.21		2.15		.06	
	May	1	6.37		III	96	5.90		6.92		- 1.02	
		2	1.10		III	96	.73	10.29	.13	10.76	.60	- .47
1945	March	2	.77	.41	I	76	0		.23		- .23	
		3	2.50		III	96	2.07	2.07	2.15	2.38	- .08	- .31
1946	May	12	2.90	1.08	III	96	2.46		2.11		.35	
		13	.95		III	96	.59	3.05	.84	2.95	- .25	.10
1947	March	18	1.74	0	I	76	.29	.29	.85	.85	- .56	- .56
1948	April	25	3.10	.05	I	76	1.08	1.08	1.17	1.17	- .09	- .09
1949	July	4	2.86	.03	I	76	.92	.92	1.07	1.07	- .15	- .15
1950	Feb.	12	1.94	1.08	III	96	1.52	1.52	1.09	1.09	.43	.43
1951	June	16	1.64	1.28	II	89	.74	.74	.19	.19	.55	.55

5. Determine which AMC applies for each rain in column 4, table 10.2. The AMC for the first day of a multiple-day storm is obtained by use of dates in columns 2 and 3 (to get the season), antecedent rainfall in column 5, and figure 4.9. The AMC for succeeding days in a multiple-day storm is similarly obtained but with the previous day's rain (from column 4) added to the antecedent rainfall. The results are shown in column 6. The CN for the AMC are shown in column 7.

6. Estimate the runoff for each day. Enter figure 10.1 with the rainfall in column 4 and the CN in column 7 and estimate the runoff. The results are tabulated in column 8.

7. Add the daily runoffs in a storm period to get the storm total. The totals are shown in column 9. This step completes the example.

Actual runoffs for W-1, taken from reference 2, are given in columns 10 and 11 for comparison with the estimates in columns 8 and 9. Differences between computed and actual runoffs are shown in columns 12 and 13. For some estimates the differences (or estimation errors) are fairly large; the errors may be due to one or more of several causes, of which the most obvious is applying an average land use and treatment to all years and all seasons in a year. The quality of land use and treatment varies (that is, the CN varies from the average) from year to year because of rainfall and temperature excesses or deficiencies and during the seasons of a year because of stages in crop growth as well. In practice the magnitudes of the variations are generally unknown so that the method of this example is usually followed; if they are known, the CN are increased or decreased on the basis of the hydrologic condition as described in the next section. A comparison made later in this chapter illustrates that errors of estimate, even when fairly large, do not adversely affect frequency lines constructed from the estimates as long as the errors are not all of one type.

SEASONAL OR ANNUAL VARIATIONS. The average CN in table 9.1 apply to average crop conditions for a growing season. If seasonal variations in the CN are desired, the stages of growth of the particular crop in the complex indicate how much and when to modify the average CN.

For cultivated crops in a normal growing season the CN at plowing or planting time is the same as the CN for fallow in the same soil group of table 9.1; midway between planting and harvest or cutting times the CN is the average in table 9.1; and at the time of normal peak growth or height (usually before harvest) the CN is:

$$CN_{\text{normal peak growth}} = 2\,(CN_{\text{average}}) - (CN_{\text{fallow}}) \qquad (10.13)$$

Thus, if the average CN is 85 and the fallow CN is 91, the normal peak growth CN is 79. After harvest the CN varies between those for fallow and normal peak growth, depending on the effectiveness of the plant residues as ground cover. In general, if 2/3 of the soil surface is exposed, the fallow CN applies; if 1/3 is exposed, the average CN applies; and if practically none is exposed the normal peak growth CN applies.

For pasture, range, and meadow, the seasonal variation of CN can be estimated by means of tables 8.1 and 8.2; for woods or forest, the Forest Service method in chapter 9 is applicable.

Changes in CN because of above- or below-normal rainfall or temperature occur not only from year to year but also within a year. They are more difficult to evaluate than changes from normal crop growth because detailed soil and crop histories are necessary but seldom available; climate records are a poor substitute even for estimating gross departures from normal. Runoff records from a nearby streamflow station are a better substitute because they provide a means of relating CN to a runoff parameter (for an example see figure 5.6(a)) and approximating the variations of CN.

The CN of table 9.1 do not apply for that portion of the year when snowmelt contributes to runoff. The methods of chapter 11 apply for melt periods. Chapter 12 contains a discussion of snow or freezing in relation to land use and treatment.

VARIATION OF RUNOFF DURING A STORM. The variation of runoff during the progress of a storm is found by the method of the following example. This method is also used for design storms in chapter 21.

> Example 10.7.--Estimate the hourly pattern of runoff for a watershed having a CN of 80 and condition AMC-II before a storm of 20 hours' duration, using rainfall amounts recorded at a rain gage.
>
> 1. Tabulate the accumulated rainfalls at the accumulated times. Accumulated times are shown in column 1, rainfalls in column 2, of table 10.3
>
> 2. Estimate the accumulated runoff at each accumulated time. Use the CN and the rainfalls of column 2 to estimate the runoffs by means of figure 10.1. The runoffs are given in column 3.
>
> 3. Compute the increments of runoff. The increments are the differences given in column 4. Plotting these increments shows the pattern of runoff (the plotting is not given).

Table 10.3.--Incremental runoffs for a storm of long duration

Time	Accumulated rainfall	Accumulated runoff	ΔQ
	(inches)	(inches)	(inches)
1:00 a.m.	0	0	
			0
2:00	.15	0	
			0
3:00	.30	0	
			0
4:00	.62	0	
			.08
5:00	1.01	.08	
			.10
6:00	1.27	.18	
			.04
7:00	1.36	.22	
			0
8:00	1.36	.22	
			.01
9:00	1.38	.23	
			0
10:00	1.38	.23	
			.09
11:00	1.55	.32	
			.16
12:00 noon	1.87	.48	
			.24
1:00 p.m.	2.25	.72	
			.25
2:00	2.61	.97	
			.03
3:00	2.66	1.00	
			.01
4:00	2.68	1.01	
			.41
5:00	3.22	1.42	
			.76
6:00	4.17	2.18	
			.56
7:00	4.82	2.74	
			.09
8:00	4.93	2.83	
			.06
9:00	5.00	2.89	

RUNOFF FROM URBAN AREAS. Whether a conversion of farmlands to urban area causes larger amounts of storm runoff than before depends on the soil-cover complexes existing before and after the conversion; determination of the "before" and "after" CN is sufficient for a decision. A comparison of runoffs, using real or assumed rainfalls, gives a quantitative answer. Impervious surfaces of an urban area cause runoff when the remainder of the area does not so that the method of example 10.4 is best used. But these surfaces may not contribute runoff in direct ratio to their proportion in the area as the following case illustrates.

Figure 10.3 shows storm rainfall amounts plotted versus runoff amounts for Red Run, a fully urbanized watershed of 36.5 square miles' drainage area, near Royal Oak, Michigan. The data are from "Some Aspects of the Effect of Urban and Suburban Development upon Runoff" by S. W. Wiitla; open-file report, U.S. Geological Survey, Lansing, Michigan; August 1961. This watershed has 25 percent of its area in impervious surfaces and presumably runoff amounts should never be less than those shown by the 25-percent line on the figure. But the data show that the surfaces are only about half effective in generating runoff. The report does not state why this deficiency occurs but does state that "Flood peaks on the urban basin were found to be about three times the magnitude of those for natural basins of comparable size." Determination of the effects of urbanization may therefore require as much use of the methods in chapters 16 and 17 as of those in this chapter.

APPLICATIONS TO RIVER BASINS OR OTHER LARGE AREA. The runoff-estimation method is not restricted to use for small watersheds. It applies equally well to river basins or other large areas providing the geographical variations of storm rainfall and soil-cover complex are taken into account; this is best accomplished by working with hydrologic units (chap. 6) of the basin. After runoff is estimated for each unit the average runoff at any river location is found by the area-runoff weighting method of example 10.4.

INDEXES FOR MULTIPLE REGRESSION ANALYSES. The parameter CN is not a desirable index of watershed characteristics in a multiple regression analysis (chap. 18) because there is generally insufficient variation in the CN to provide a statistically significant result. The parameter S is the preferred index. It is used without change if it is an independent variable in a regression equation with the final form of:

$$Y = a + b X_1 + c X_2 \ldots\ldots \qquad (10.14)$$

where Y is the dependent variable; a, b, c, etc. are constants; and the subscripted X's are the independent variables. But if the final form is

$$Y = a X_1^b X_2^c \ldots\ldots \qquad (10.15)$$

it is necessary to use (S + 1) instead of S to avoid the possibility of division or multiplication by zero. The equation for lag used to develop figure 15-3 uses (S + 1) for this reason; otherwise the graph would give a lag of zero time for an impervious surface (because S is zero when CN is 100) no matter how large an area it might be.

ACCURACY. Major sources of error in the runoff-estimation method are the determinations of rainfall and CN. Chapter 4 provides graphs for estimating the errors in rainfall. There is no comparable means of estimating the errors in CN of ungaged watersheds; only comparisons of estimated and actual runoffs indicate how well estimates of CN are being made. But comparisons for gaged watersheds, though not directly applicable to ungaged watersheds, are useful as guides to judgment in estimating CN and as sources of methodology for reducing estimation errors.

A comparison of storm totals in example 10.6 shows that estimated amounts are fairly close to recorded amounts in 7 out of 12 years, despite the use of a CN for average land use and treatment. On the whole, this is acceptable estimation in view of the limitation on the CN. But the results are better if the storm totals are used as data in a frequency analysis (chap. 18). Figure 10.4(a) shows data from columns 9 and 11, table 10.2, arranged in order of magnitude in their respective groups, and plotted versus their sample percent-chance values. Solid or broken lines connecting the points identify the groups. It is evident from the plotting that one frequency line serves equally well for either group. Thus the estimation errors, though large for some estimates, do not preclude the construction of an adequate frequency relationship. The reason is that the errors are random, being neither all plus or all minus nor all confined to a particular range of magnitudes.

The example of W-1 at Waco demonstrates that estimation errors should be kept random. One way of accomplishing this is to apply the CN for AMC-II to all storms in a series. A second example illustrates this.

Storm runoffs and rainfalls for Amicalola creek, Georgia, are given in columns 5 and 6 of figure 5.5. The CN is 65 for AMC-II, as determined in example 5.4. This CN and the rainfalls give the following estimates of runoff (actual runoffs are shown for comparison):

Year	Runoff (in.)		Year	Runoff (in.)	
	Estimated	Actual		Estimated	Actual
1940	1.64	0.81	1947	1.06	1.59
1941	2.15	1.40	1948	2.13	1.36
1942	1.81	1.74	1949	2.06	1.85
1943	1.22	1.65	1950	.89	1.15
1944	.91	1.16	1951	1.46	1.33
1945	.12	.36	1952	.93	2.01
1946	1.92	2.33			

In a plotting of estimated versus actual runoff the scatter of points indicates a moderately low degree of correlation, but the scatter also indicates that the errors are randomly distributed, which means that a reasonably good result on probability paper can be expected. Figure 10.4(b) substantiates this: again a single frequency line will do for either group. The curvature of the plottings signifies only that 13 years of record on this watershed are insufficient for an adequate frequency line (chap. 18); discrepancies in the lower half of the plotting come from this insufficiency.

In practice the CN for an ungaged watershed cannot be estimated by means of runoff data, as the CN for Amicalola Creek was, but it can be estimated from watershed data at least as well as that for W-1 at Waco. It will take correct identification of soil-cover complexes, especially if there are few complexes in a watershed or they differ little from each other or one of them dominates the area. But if there are many complexes of about equal area and in a wide range of CN, it is likely that misjudgment of several will not adversely affect the estimate of the average CN. Using complexes that are properly identified and rainfall data that are adequate, runoff estimates are made accurately enough for practical purposes.

* * * *

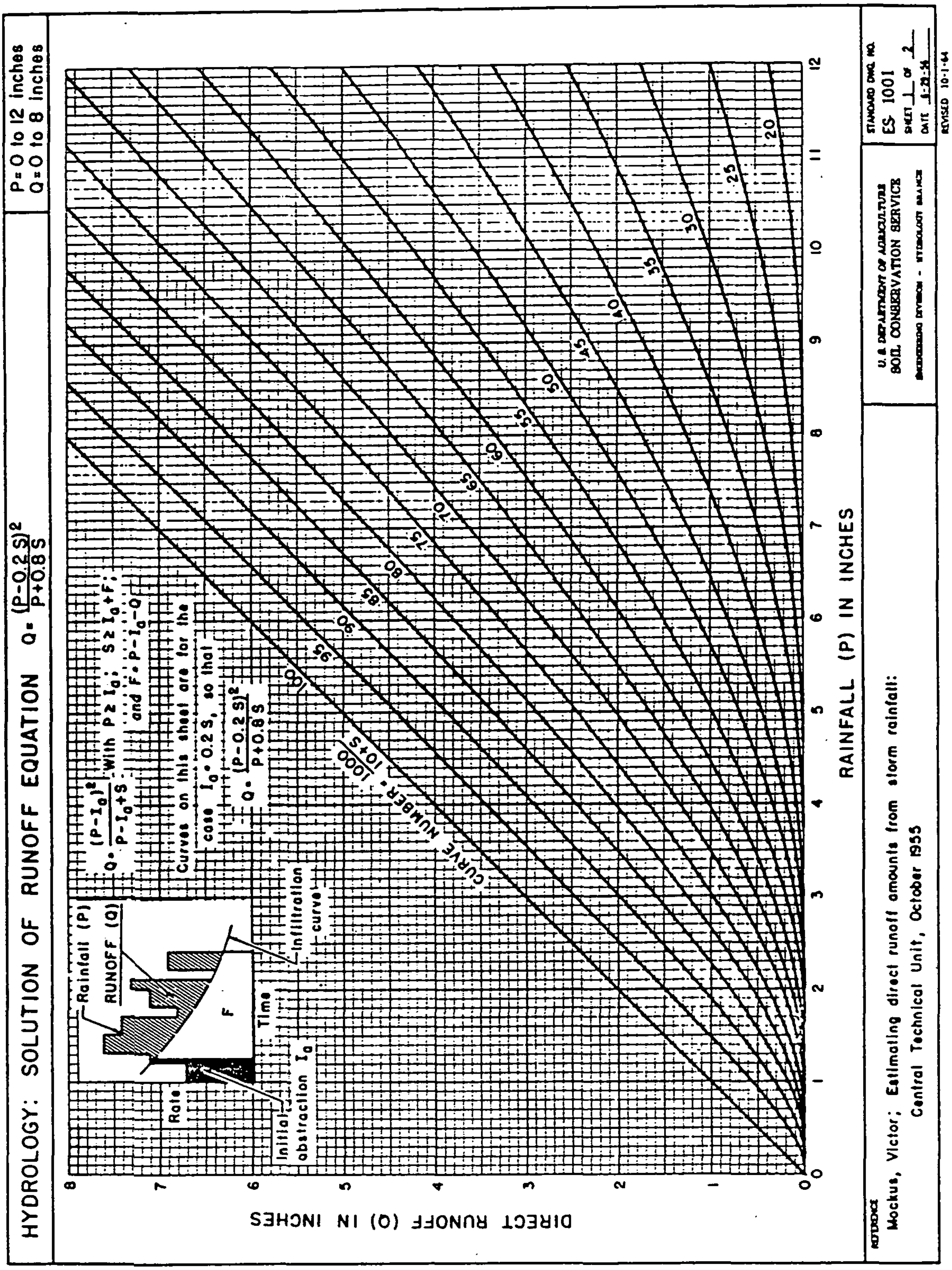

Figure - 10.1 (1 of 2)

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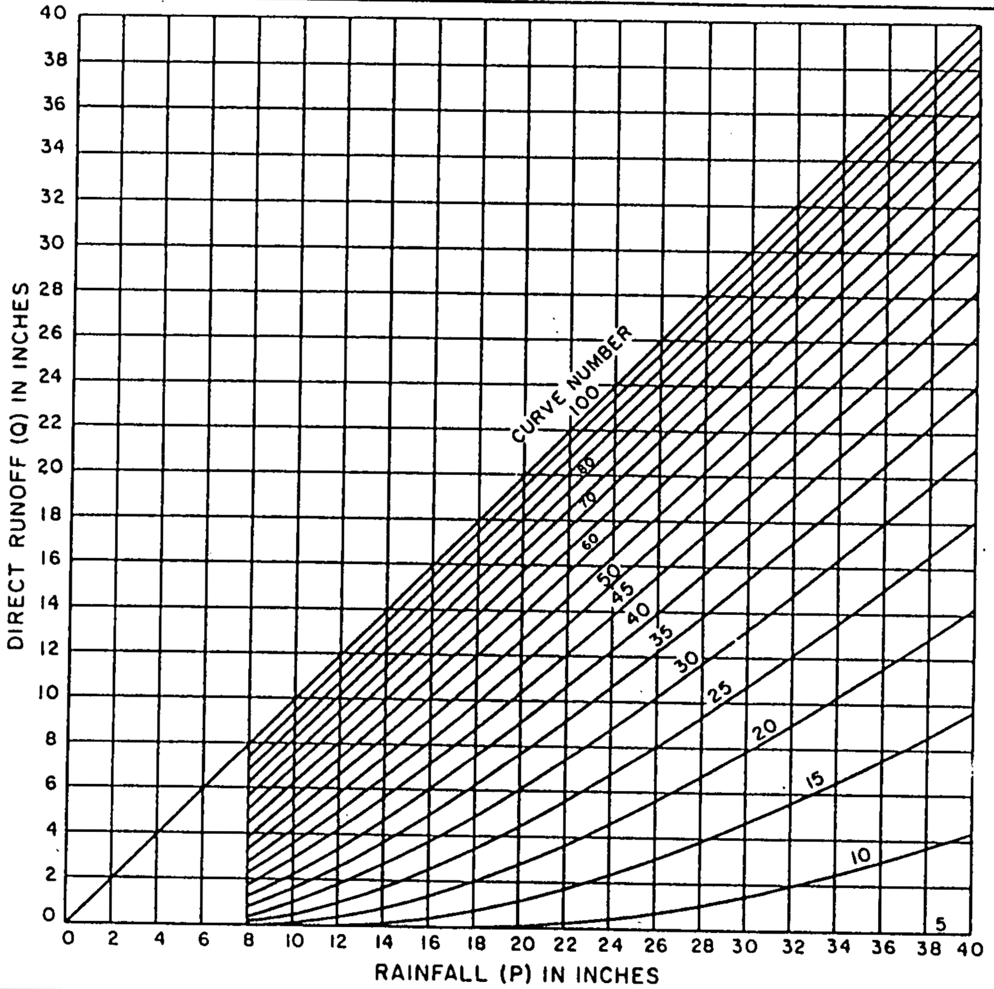
HYDROLOGY: SOLUTION OF RUNOFF EQUATION $Q=\frac{(P-0.2S)^2}{(P+0.8S)}$

P=8 to 40 inches
Q=0. to 40 inches



REFERENCE
Mockus, Victor; Estimating direct runoff amounts from storm rainfall:
Central Technical Unit, October 1955.

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Figure 10.1 (2 of 2)

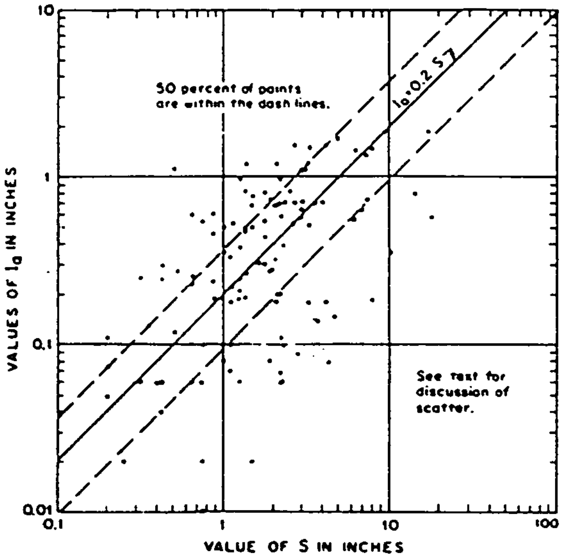

Figure 10.2.--Relationship of I_a and S. Plotted points are derived from experimental watershed data.

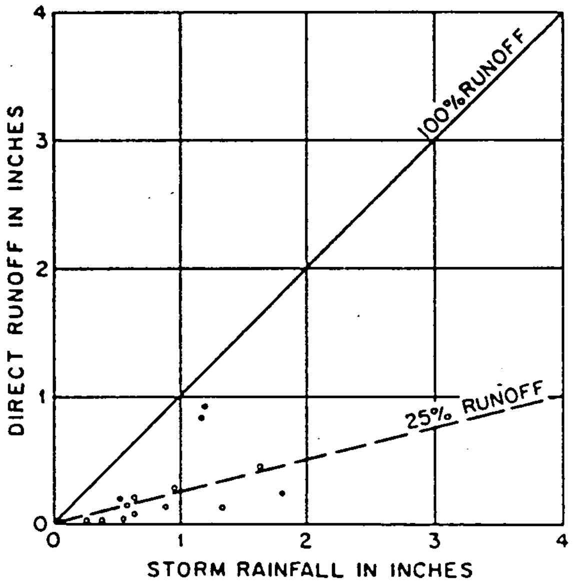

Figure 10.3.--Expected minimum runoff (dashed line) and actual runoff (plotted points) for an urbanized watershed.

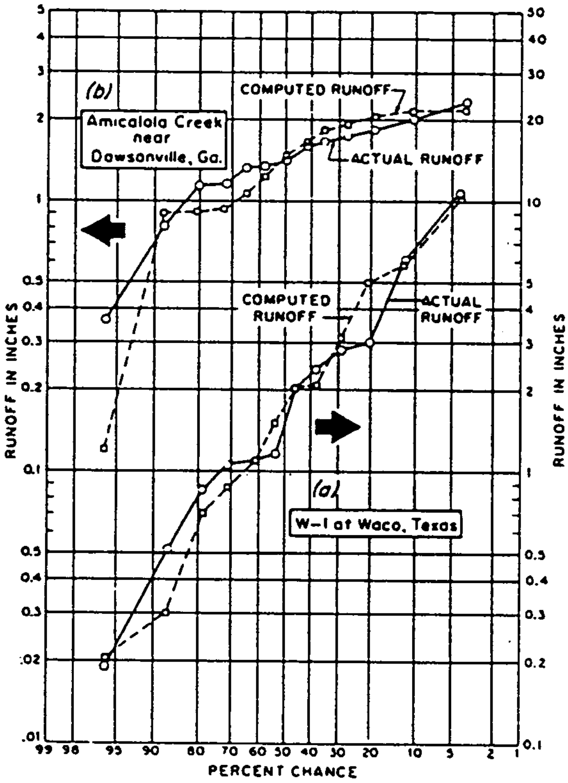

Figure 10.4.--Comparisons of computed with actual runoff on a frequency basis.