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Runoff Curve Numbers from Partial Area Watersheds

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Introduction

Runoff curve numbers CN are coefficients used in a technique for estimating surface runoff depth from rainstorms. The technique was developed by and is still strongly identified with the U.S. Soil Conservation Service (SCS). While the empirical and practical sounding label of "curve number" has appeal to practitioners, it is usually of little interest to most scientific hydrologists. Thus, despite widespread usage, curve numbers are infrequent topics in hydrology literature, and much information is exchanged through what might be best described as an "applied hydrology underground." Unfortunately, most readings on the topic are authoritative rather than developmental, innovative, or critical.

The purpose of this paper is to suggest and examine an extension of the curve number method in a developmental, innovative, and critical light. Hopefully, users will find value in more enlightened application, in explaining observed variation from predictions, and in logical insights to runoff generation.

The relationships used spring from

$$\frac{Q}{P} = \frac{P - Q}{S} \qquad (1)$$

with symbols as given in Appendix II.

Although this starting point is of obscure origin the justification is pragmatic, i.e., it is simple and seems to work. It solves for Q to

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

Note.—Discussion open until May 1, 1980. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 105, No. IR4, December, 1979. Manuscript was submitted for review for possible publication on December 18, 1978.

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Then, by introducing initial abstraction I_a and its judged relationship to S as $I_a = 0.2S$, the relationship reduces to

$$Q = \frac{(P - I_a)^2}{P - I_a + S} = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{(3)}$$

which is valid for all $P \geq 0.2S$. It is of interest to point out the differences in the maximum possible loss, ($P - Q$, as $P \rightarrow \infty$) in the two preceding expressions. Synthetic division shows that in Eq. 2 this is S, but that with the introduction

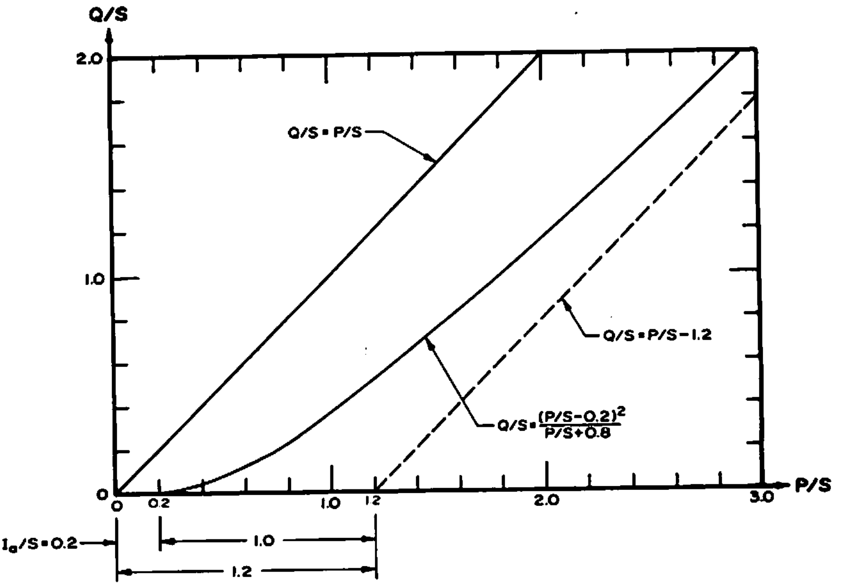

FIG. 1.—SCS Rainfall-Runoff Relationship Standardized on Retention Parameter S

of $I_a = 0.2S$ in Eq. 3 the maximum possible loss enlarges to $1.2S$. Parameter S is then further transformed by the relationship

$$\text{CN} = \frac{1{,}000}{10 + S} \quad \text{(4)}$$

in which CN is called the "curve number," which is 0 at $S \rightarrow \infty$ and 100 at $S = 0$. Any watershed condition that can be defined by a value of S can then be described by a CN with its value between 0 and 100.

Eq. 3 represents a family of curves of Q on P for a range of values of S from 0 to ∞. The SCS *National Engineering Handbook*, Section 4, Hydrology (12), hereafter referred to simply as "NEH-4," presents a well-known figure of rainfall P and runoff Q, for a wide variety of curve numbers. However, the relationships can be simplified to a single curve by standardizing P and Q on watershed retention parameter S. The resulting relationship becomes

$$\frac{Q}{S} = \frac{\left(\frac{P}{S} - 0.2\right)^2}{\frac{P}{S} + 0.8} \qquad (5)$$

This is shown in Fig. 1. Note that it is valid for all $P/S \geq 0.2$, and that the value of Q/S approaches $(P/S) - 1.2$ assymptotically.

In the original references and in numerous subsequent agency documents,

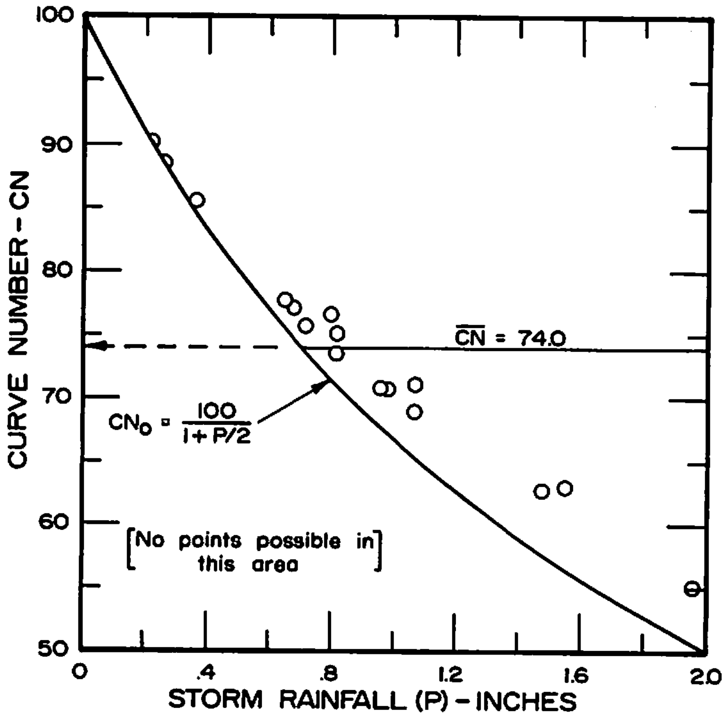

FIG. 2.—Threshold Curve Number, CN_o = 100/(1 + P/2), and Experienced Curve Numbers for Storms on West Branch of Chicken Creek, Davis County, Utah (1 in. = 25.4 mm)

CN for different soil and vegetative combinations were suggested, and a means of dealing with antecedent soil moisture was offered. Thus, insofar as CN is variable with land condition, the connection can be made in surface-runoff calculations. A rainstorm of design duration, distribution, and frequency can be used with a CN defined by present or expected future soil and vegetation to calculate surface runoff depth Q and this then incorporated in a unit hydrograph procedure for flood peak or routing calculations, or both.

The formulas shown operate in English units only (i.e., inches), although conversion to metric units is certainly possible. Since P and Q are in inches, S should likewise be in inches. Thus, the 10 and 1,000 in Eq. 4 should include

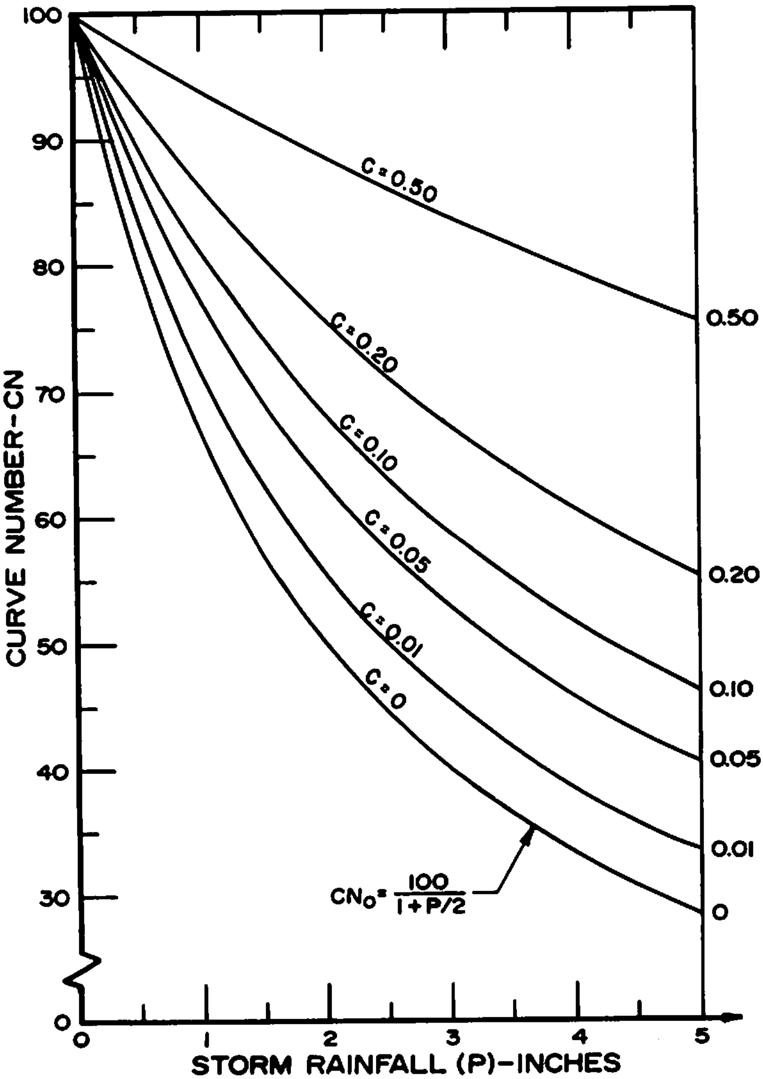

FIG. 3.—Runoff Curve Number as Function of Runoff Ratio C (= Q/P) and Storm Size (1 in. = 25.4 mm)

the inch dimension, and CN is dimensionless. Also, there is a CN for which any P less than threshold P will yield no runoff. By substituting $S = 5P$ in Eq. 4 this relationship is

$$CN_o = \frac{100}{1 + \frac{P}{2}} \quad \text{(6)}$$

In Eq. 6, then, a CN (CN_o) is defined for a given P for which the initial abstraction is just satisfied. Any smaller P for that CN will give no runoff, and likewise any CN smaller than CN_o will give no runoff for the same P. This threshold relationship is shown in Fig. 2, which indicates the area below the CN_o line as a domain of no runoff. (The average curve number for the

TABLE 1.—Watershed and Data Summary

Watershed (1)	Abbreviation[a] (2)	Location (3)	Area, in acres (4)	Average elevation, in feet (5)	Period of record (6)	N (7)	Data source (8)
Missouri Gulch	MOG	Colorado	4,200	8,580	59–59	14	Ref. 3[b]
Alpine Meadows	ALP	Utah	376	10,100	51–61	10	Ref. 14[c]
Morris Creek	MOR	Utah	156	7,195	40–65	17	Ref. 14[c]
Halfway Creek	HWY	Utah	484	7,680	40–65	14	Ref. 14[c]
East Chicken Creek	ECK	Utah	137	7,890	68–11	12	Ref. 9[c]
West Chicken Creek	WCK	Utah	217	7,975	67–72	16	Ref. 9[c]
Seven Springs West	SSW	Arizona	482	9,284	64–69	20	Ref. 6[b]
Seven Springs East	SSE	Arizona	748	9,472	64–69	26	Ref. 6[b]
North Thomas Creek	TCN	Arizona	441	8,600	65–74	9	Ref. 6[b]
South Thomas Creek	TCS	Arizona	601	8,600	65–74	12	Ref. 6[b]
Wayne Creek	WAY	Wyoming	60	9,500	62–65	14	Ref. 11

[a]Identification used in Figs. 4–7.
[b]Data from Rocky Mountain Forest and Range Experiment Station, United States Forest Service.
[c]Data from Intermountain Forest and Range Experiment Station, United States Forest Service.
Note: 1 ft = 0.305 m.

TABLE 2.—Curve-Fitting Summary

Watershed (1)	Abbreviation[a] (2)	N (3)	C (4)	r^2 (5)	Se(CN) (6)
Missouri Gulch	MOG	14	0.0031	0.99+	0.6
Alpine Meadows	ALP	10	0.0635	0.68	2.0
Morris Creek	MOR	17	0.0029	0.99	0.6
Halfway Creek	HWY	14	0.0105	0.99	0.9
East Chicken Creek	ECK	12	0.0045	0.99	0.6
West Chicken Creek	WCK	16	0.0075	0.97	1.1
Seven Springs West	SSW	20	0.0059	0.94	1.9
Seven Springs East	SSE	26	0.0161	0.94	0.8
North Thomas Creek	TCN	10	0.0006	0.99+	0.4
South Thomas Creek	TCS	13	0.0006	0.99	0.8
Wayne Creek	WAY	14	0.0075	0.93	1.8

[a]Identification used in Figs. 4–7.

points, CN = 74.0, is also shown. The points were calculated by Eq. 8 from representative storm-rainfall and storm-runoff data.) Also shown in Fig. 2 are some representative data points taken from a small instrumented watershed. Their variation with total storm depth has also been shown and, as pointed out in Ref. 4, is not uncommon. The average curve number defined by this data set is also shown. This is *not* a design curve number selected from NEH-4 tables by considering soil and vegetation characteristics of the particular watershed.

While not formally stated, it seems obvious than CN must be taken as a constant for a given soil, vegetation, and moisture condition. Indeed, all definitions of a CN variety end with these considerations. Because the strength of the methodology resides in the capability to reflect changes of land condition in hydrologic reasoning, this assumption of consistency is important. If it is not valid, then the mechanics for variation of CN with other important associated

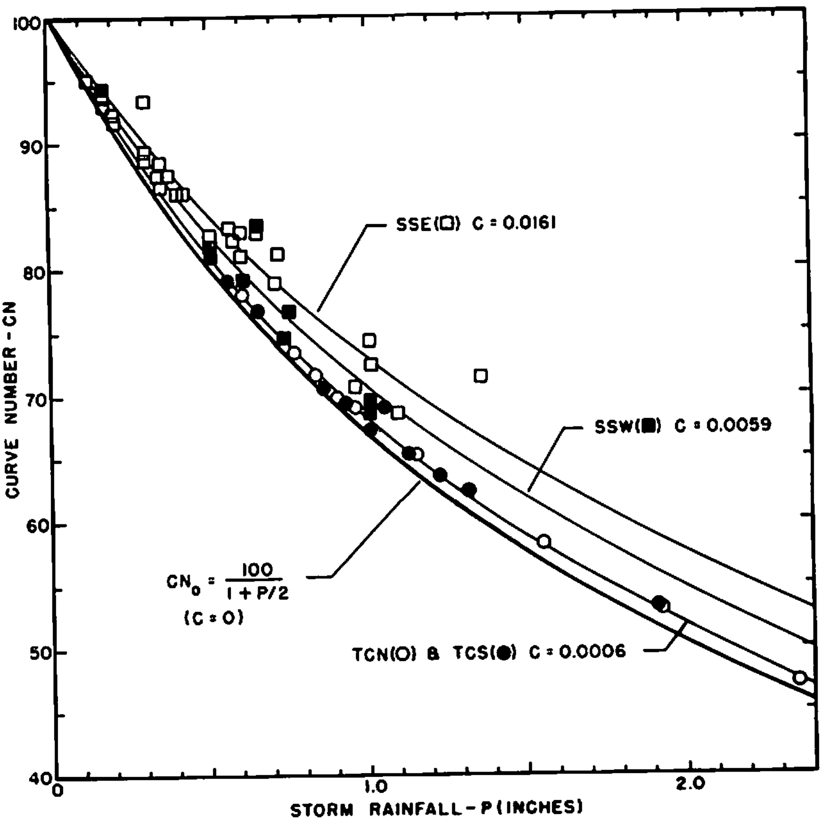

FIG. 4.—Observed Runoff Curve Number as Function of Storm Size for Thomas Creek and Seven Springs Watersheds (1 in. = 25.4 mm)

factors should be known. This paper will point out observed variation of CN with storm size and hypothesize some causes of such behavior.

The choice of the appropriate CN is left to the professional judgment of the hydrologist. For much of the range of experienced rainfalls, the output value of Q calculated is more sensitive to CN than to rainfall (5). Catalog and handbook tables of CN are available for different soil types and vegetative and land conditions, and semiobjective field techniques have been developed for some situations. The ultimate means of CN identification, however, should be the use of real data from small local watersheds. Such information can then be used as a basis for CN judgments on similar or nearby situations.

In dealing with individual storm data and hydrograph analysis, a direct algebraic solution for curve number is possible. Eq. 3 is solved for S by the quadratic formula to

$$S = 5(P + 2Q - \sqrt{4Q^2 + 5PQ}) \quad (7)$$

and that is substituted into Eq. 4 and further simplified to

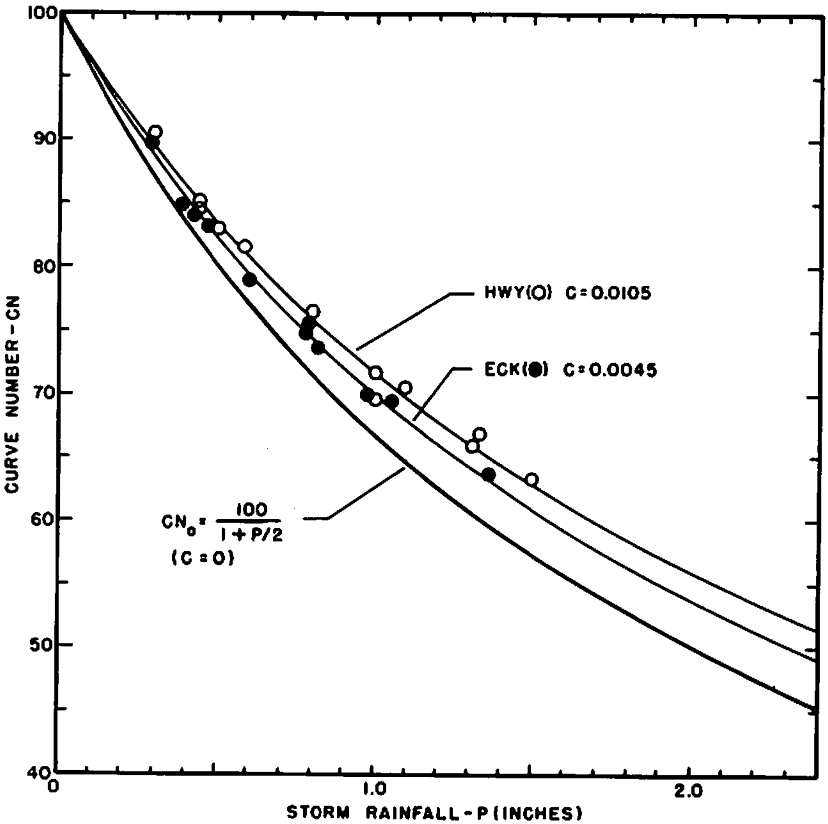

FIG. 5.—Observed Runoff Curve Numbers as Function of Storm Size for East Branch of Chicken Creek and Halfway Creek, Davis County, Utah (1 in. = 25.4 mm)

$$CN = \frac{100}{1 + \frac{1}{2}(P + 2Q - \sqrt{4Q^2 + 5PQ})} \quad (8)$$

Eq. 8 contains only P and Q; thus any real P-Q data pair can be used to calculate what must have been the CN for that particular rainfall-runoff event. This result might be thought of as the actual, historical, observed, or "realized" curve number that was necessary to generate the observed Q from the observed P. It carries with it any variation due to watershed wetness, cover condition, or physically important local factors, or all, not included in the NEH-4 technology such as storm intensity and duration.

Variation with Storm Volume

In an earlier paper (4), the writer demonstrated, with data from several small western forested watersheds, a strong empirical (curve fitting) relationship

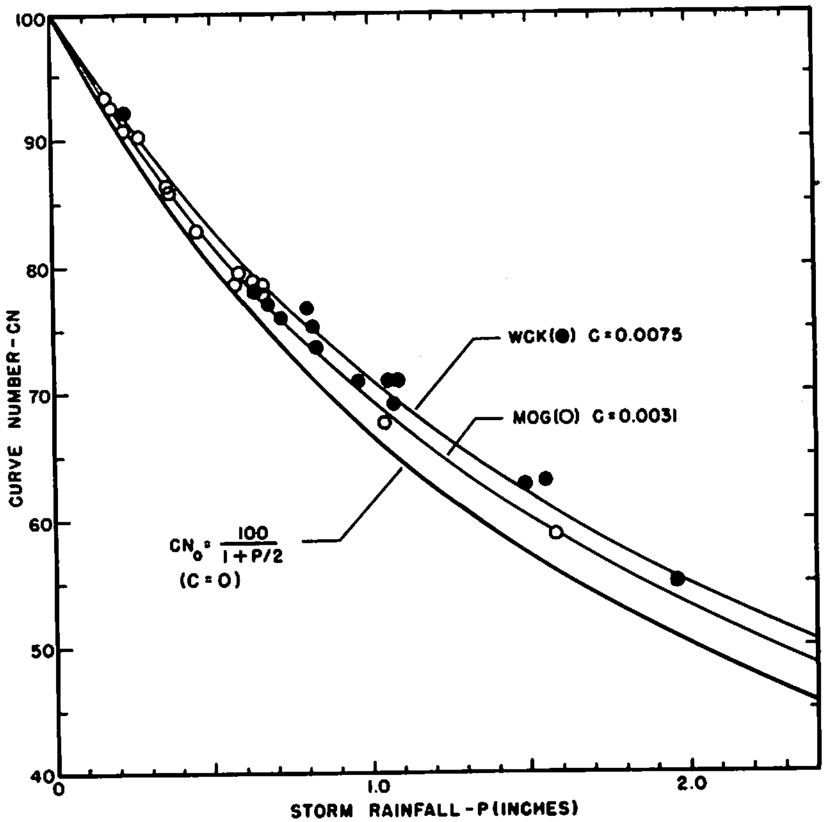

FIG. 6.—Observed Runoff Curve Numbers as Function of Storm Size for West Branch of Chicken Creek, Davis County, Utah, and for Missouri Gulch, Colo. (1 in. = 25.4 mm)

between observed CN and storm size. The objective of this paper is to test the hypothesis that this may be the simple natural consequence of a constant (or near constant) impervious source area for storm flows.

Assuming an impervious contributing area, a, for storm runoff from a watershed of area A, the runoff would then be a simple fraction $a/A = C$ of the storm rainfall. Then, simply stated

$$Q = CP \qquad (9)$$

While this may be a strong premise to accept, the notion of no or very little overland flow from upland watersheds is well entrenched and often documented (8). Eq. 9 might be taken as an expression of the well-known "rational" formula. However, C is usually simply called the "runoff ratio."

Substituting Eq. 9 into Eq. 8 yields, with some algebra

$$\text{CN} = \frac{100}{1 + \frac{Pf(c)}{2}} \qquad (10)$$

in which $f(c) = 1 + 2C - \sqrt{4C^2 + 5C} \qquad (11)$

A family of curves representing Eq. 10 is given in Fig. 3 for a series of values of C. Also, note the similarity among Eqs. 10, 8, and 6. Where storm runoff does arise simply from fixed impervious sources, observed field data should follow the trends shown in Fig. 3.

Fits to Small Watershed Data

As suggested previously, if runoff is a fraction of rainfall, data from research watersheds where this occurs should coincide with Fig. 3 and fit the functions given in Eqs. 10 and 11. This hypothesis was tested for the watersheds summarized in Table 1. The events were all summer rainstorms and represent almost a complete inventory of the usable data available for the period of record. Separation of storm runoff from baseflow was done by a variation of Hewlett's method (7); usually the storm hydrograph was a major portion of the total streamflow during the storm event. Storm rainfall, with one exception, was determined by Thiessen polygons. As shown in Table 1, the period of record is as long as 26 yr; thus, the inclusion of extreme events in the sample is highly probable.

Each of the data sets was fit to Eqs. 10 and 11 by an iterative least-squares procedure to determine coefficient C. These values, the standard errors, and r^2 are shown in Table 2 and presented graphically in Figs. 4–7. (In Fig. 4 the Thomas Creek fitted lines are essentially identical; only a single plot is shown. Because of overlap and crowding many points for Seven Springs West are not shown. The abbreviations used in Figs. 4–7 are as given in Tables 1 and 2.) This experience fails to reject the hypothesis that this curve number behavior results from a small runoff source area on the watershed. Also, for the conditions encountered, it is obvious that a better data fit is obtained than with a "constant" curve number value implicit in NEH-4.

A more severe test of the hypothesis would be a comparison of the C factors in Table 2 with actual measures of watershed areal imperviousness. Unfortunately, budgetary and information restrictions discourage these determinations here, although such would no doubt be a fruitful future endeavor. However, informal comparisons, on the general information available are encouraging. The Alpine Meadows watershed, with the highest C (0.0635), is known to include a substantial area of swampy bottomlands. The smallest C values (0.0006) are for the Thomas Creek watersheds, which have a heavy conifer cover and a meagre stream outlet. Each of the watersheds is thought to be drained by a near-permanent "live" streams.

Analysis

Application.—The relationships observed in the preceding can only be reasonably expected in situations where a constant source area (or nearly so) is the sole source of runoff. This can be hypothesized as physically arising from the stream-channel surface, from roads and near channel impervious areas, and from swamps, bogs, lakes, etc., and in the absence of other (and variable) sources. Furthermore, as observed, initial soil moisture or recent rainfall history

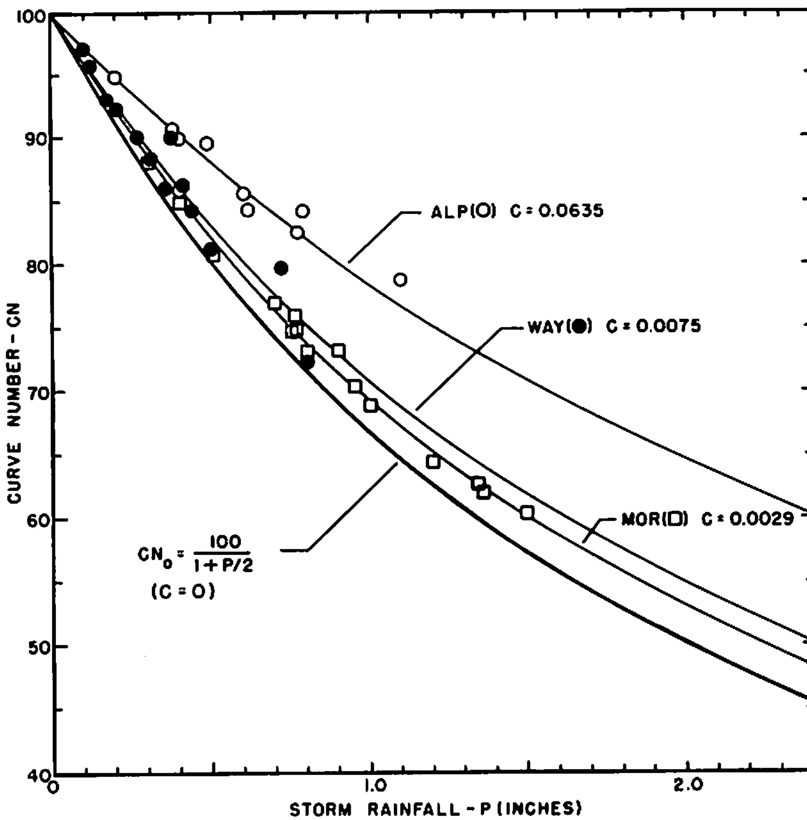

FIG. 7.—Observed Runoff Curve Numbers as Function of Storm Size for Alpine Meadows and Morris Creek, Utah and for Wayne Creek, Wyo. (1 in. = 25.4 mm)

should be inconsequential: the small standard errors indicate that storm rainfall alone is important. These conditions could well be present on the watersheds studied: porous soils of high infiltration capacity and, thus, only infrequent overland flow; semiarid summer conditions resulting in uniform low soil moisture; and the presence of live streams. While these are not common conditions nationally, they do exist over much of the mountainous western United States. Before application of such reasoning, the user should be confident that these conditions exist and that the design storm does not indeed create rainfall excess and overland flow.

A reasonable estimate of C is also needed. Depending upon the objectives of the calculation, a detailed survey, either on site, or from available photos, or from land-use data might be justified. If the determined source areas are assumed to be completely impervious, then C is simply their fraction of the total watershed area. It would be assumed that the soil and vegetation conditions are sufficient to store all rain falling on the land surface itself.

Limitations.—The phenomenon is certainly not universal. As an example of a situation where it does not prevail, a sampling of points from an agricultural watershed in west-central Illinois is shown in Fig. 8. [Data are excerpted from Minshall (10). Points for $P < 2$ in. (50.8 mm) were sampled (every fifth point

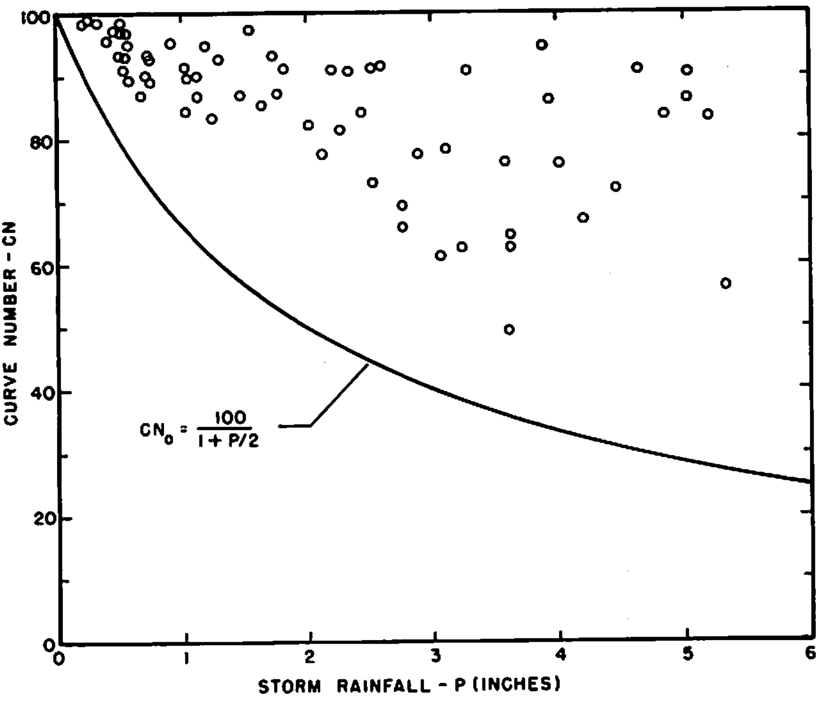

FIG. 8.—Effect of Storm Rainfall on Observed Curve Number for Edwardsville, Ill., Watershed W-4 (1 in. = 25.4 mm)

used), and all events for $P > 2$ in. (50.8 mm) are shown. The gap between the plotted points and CN_0 is due to the omission of events in Minshall's data summary in which $Q < 0.10$ in. (2.5 mm).] Note the confusion of points throughout: curve number is variable but clearly not dependent on rainfall alone. Here, as shown by Minshall (10), soil moisture is an important occuring influence.

Combinations and borderline cases can also be found, with exceptions that suggest cause and effect or exercise the processes, or both. Fig. 9 shows data from a pine-covered watershed in northern Arizona (6). [Note that, with a single exception, a strong relationship exists for storms of up to approx 2 in. (50.8 mm). The aberrant point was an event that occured under exceptional

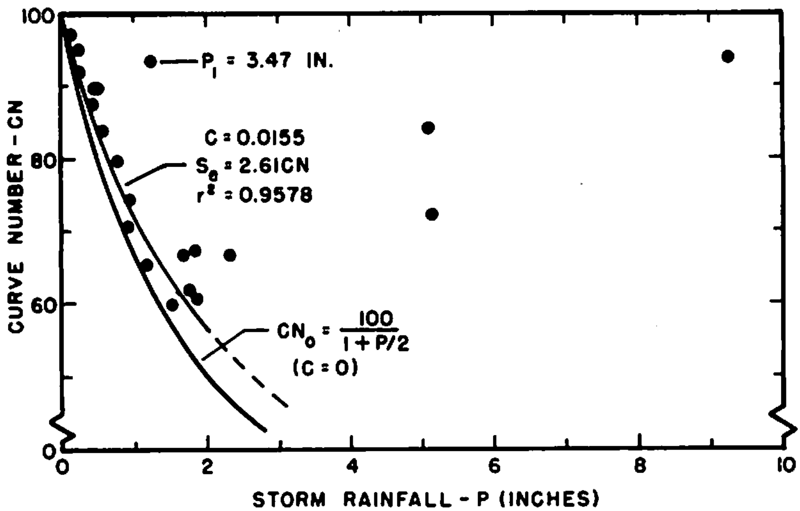

FIG. 9.—Effect of Storm Rainfall on Observed Curve Number for Beaver Creek, Ariz., Watershed 17 (1 in. = 25.4 mm)

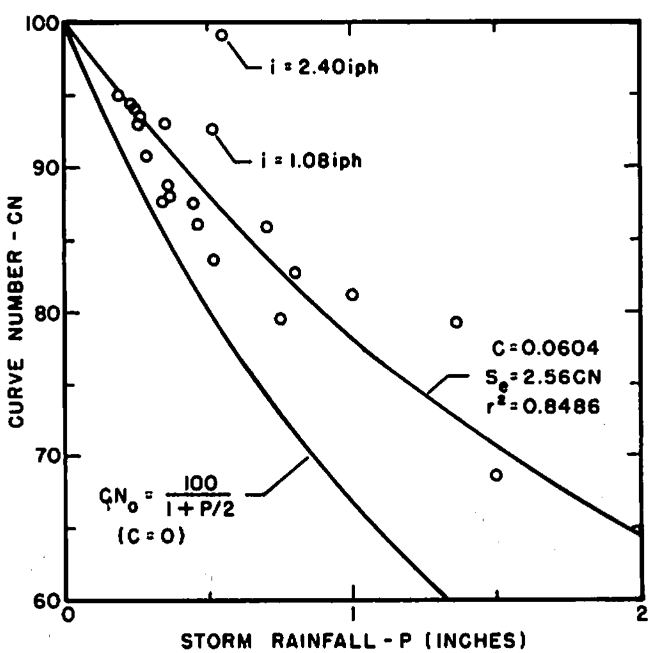

FIG. 10.—Storm Rainfall and Observed Curve Number for Ephriam Watershed A (1 in. = 25.4 mm)

antecedent moisture conditions, 3.47 in. (88.1 mm) of rain the previous day; the highest such value by a factor of approx 3 in the data set. The fitted line was for all points less than $P = 2$ in. (50.8 mm) and excluded the identified storm.] With a single exception, all points below about $P = 2.0$ in. (50.8 mm) follow the form of Figs. 4–7. The exception occured with the wettest antecedent condition in the data set (by a factor of 3). Over about $P = 2$ in. (50.4 mm) storms are apparently sufficiently large or intense to induce other processes, possibly overland flow. Fig. 10 shows data from Ephriam, Utah, watershed A where, again, a retreating curve number with storm size is observed, except for two instances of exceptional intensity. (The 5-min intensities for the exceptional points are shown, which were the highest in the data set. The points are summer events from 1915–1919 while the watershed was grazed. The fitted line excluded the identified points. The data are from Ref. 2.) In these cases a constant source may be hypothesized, except when either rain intensity or soil wetness is sufficient to develop the operation of other runoff-source processes. For the 11 watersheds and data shown in Table 1, this apparently did not occur.

On the other hand, applying a constant-runoff fraction to such as the 11 watersheds studied in Table 1 would be safe only within the limits sampled. Extrapolation would present the danger of encountering higher intensities and lower infiltrations, thus possibly exceeding the sample runoff conditions by orders of magnitudes, e.g., the exceptional event identified in Fig. 9 produced a runoff volume 268 times greater than a companion event with almost identical total rainfall depth. This illustrates the threat of either underestimation or overestimation by either ignoring or overanticipating, respectively, the specific storm and watershed conditions. In order to observe these profound differences, the critical threshholds of watershed performance need to be identified and appreciated by the user. Either extreme—high or low—could be significant errors in different situations.

Rainfall Depth Perspective.—The data sets used herein are extracted from carefully tended reaearch installations, and the storm rainfall depths encountered are a legitimate representative sample of a population for the sites studied. On a national basis they may appear unnaturally small. Comparatively, they are only a fraction of Midwestern and Southern storm rainfalls, but this is the scale at which they naturally occur over much of the Intermountain and Rocky Mountain areas of the western United States. To that extent, the rainfall-runoff relationships demonstrated are valid, however peculiar they may appear.

As an example, the 6-hr 50-yr rainfall for the Wasatch Plateau of Central Utah (Alpine Meadows watershed) is only about 1.1 in. (26.9 mm) (1). For the Edwardsville, Ill., watersheds, the 6-hr 50-yr rainfall is about 4.5 in. (114.3 mm) (13). The extensive area sampled by the study watersheds in Table 2 is found in a trough of low design rainfalls. Thus, for this area low rainfalls are not exceptional, and the aberrated rainfall-runoff relationships may be expected with some regularity. Rainstorm runoff processes in this area simply do not become fully exercised as commonly as in wetter locations.

Future Directions.—The prospect of enormous error as a result of innocent routine assumptions places the hydrologist in an uncomfortable position. Thus, there is an obvious need to identify watersheds and site situations where such responses may occur and the necessary parameters to properly account for them, i.e., the dynamic processes governing the contribution of variable runoff-source areas need to be identified and understood. Information with high priority would then be: (1) Effective watershed infiltration rates; (2) critical site-moisture levels; (3) the fraction of the catchment in channels; and (4) the fraction of the catchment with impervious areas near channel-supply zones. For example, correlation of the *C* values in Table 2 with inventoried watershed drainage densities could lead to valuable relationships for estimating *C* in ungaged watersheds. The comparison of experienced loss rates for different land types with expected rainfall intensities would lend insight to the importance and frequency of overland flow as a runoff generating process. This latter consideration seems especially relevant insofar as the NEH-4 Curve-Number method assumes that overland flow does occur. This difficulty is aggravated by the fact that the CN procedure is applied in areas such as those described herein, where overland flow source areas are active only in the "intense storm-wet watershed" circumstances, as well as in areas where source areas are variable and overland flow in fact predominates.

Conclusions

A constant CN independent of storm size is not appropriate for all situations. In some instances, runoff is a simple fraction of the storm rainfall. This strongly suggests a constant "impervious" runoff-source area, like channel interception, accompanied by high infiltration rates relative to rainstorm intensity and a constant role for antecedent moisture (uniformly dry). Extremes in storm intensity or watershed wetness, or both, may invoke other processes; thus departures from the preceding may occur. Application of this idea to extreme events should be made only if it can be assured that these suspended causative conditions are not violated. Definition of the critical watershed threshholds is thus important for enlightened applied hydrology.

Acknowledgments

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Appendix II.—Notation

The following symbols are used in this paper:

C = runoff coefficient, associated with runoff ratio Q/P;
CN = runoff curve number, defined as $1{,}000/(10 + S)$;
CN_o = critical curve number necessary to initiate runoff for given P;
$I_a = 0.2S$ = initial abstraction;
P = storm rainfall;
Q = direct storm runoff; and
S = index of potential site retention.

15024 RUNOFF CURVE NUMBERS FROM WATERSHEDS

KEY WORDS: Hydrology; **Rainfall-runoff relationships**; Runoff; **Storm runoff; Watershed management**; Watersheds; **Wildlife habitats**

ABSTRACT: A previously observed relationship between runoff curve numbers and storm rainfall is further examined. Under some wildland conditions the runoff curve numbers have been observed to decrease with increasing storm size. The existence of a relatively constant runoff source area is hypothesized to produce this relationship. For the high elevation wildland watershed studied this hypothesis appears valid.

REFERENCE: Hawkins, Richard H., "Runoff Curve Numbers form Partial Area Watersheds," *Journal of the Irrigation and Drainage Division*, ASCE, Vol. 105, No. IR4, **Proc. Paper 15024**, December, 1979, pp. 375-389