Predicting Hydrologic Effects of Urbanization by Using Soil Conservation Service Methods

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A recent study by the Water Resources Council indicated that the methods of the Soil Conservation Service (SCS) are among the most widely used hydrologic design methods. The TR-55 graphical and chart methods are used to predict peak discharge. The TR-55 tabular method and the TR-20 computer package can be used to generate entire storm hydrographs. Because the methods are widely used for design in urban areas, it is important to understand exactly how the effects of urbanization should be assessed by using the SCS methods. Changes in land use affect the flood runoff through both the time of concentration and the SCS methods is compared with the effect indicated by SCS methods.

Hydrologists have demonstrated major concern over the hydrologic effects of urbanization for at least three decades. During this period, a wide array of hydrologic models has been developed to predict the effects of urbanization on runoff characteristics. Even in 1983 more models are being developed. It appears reasonable, therefore, to examine some of these models and to assess the range of predicted effects of urbanization on runoff characteristics.

Urbanization is a process that affects a number of components of the hydrologic cycle. The clearing of vegetated land cover reduces the interception storage. Often, development of land involves significant amounts of grading. The grading usually causes significant decreases in the depression storage. After clearing and grading, parts of the developing area are covered with impervious surfaces. In addition, the previously sinuous drainageways are straightened; the result is a decrease in both the roughness and natural storage. The impervious surfaces decrease the potential for infiltration, and the modifications to the drainageways change the storage effects on runoff. In many localities, storm-water detention facilities are required to compensate for the natural storage that is lost during urbanization; however, studies have shown that detention storage does not return the runoff and storage characteristics to their predevelopment status (1,2).

The hydrologic effects of urbanization are most often assessed by using the change in peak discharge as the sole criterion. Nevertheless, other runoff characteristics are important. In addition to peak discharge, urbanization causes changes in both the volume of direct runoff and the various time characteristics of the runoff, including the time of concentration, the time to peak, and the duration of flow at various flood stages. These other runoff characteristics are recognized as being important, especially because of their effects on water quality. In summary, when the hydrologic effects of urbanization are evaluated, it is important to view the problem from a multicriterion standpoint.

Although the hydrologic concepts used by the Soil Conservation Service (SCS) (3, 4) have been in existence for some time, their use gained widespread acceptance when SCS TR-55 was published in 1975 (5). The TR-55 methods have been included in the design sections of many drainage and storm-water management policies and are widely used. In many states, the TR-55 methods are replacing the rational formula as the recommended technique for peakdischarge estimation on small watersheds.

The objective of this paper is to demonstrate how

the SCS methods can be used to evaluate the hydrologic effects of urbanization and to compare the predicted effects with the results of other studies.

EFFECT ON RUNOFF VOLUMES

The reductions in interception storage, depression storage, and infiltration that accompany urbanization cause increases in runoff volumes. The increased volume of direct runoff is partly responsible for both the degradation of channels and the decreases in groundwater recharge. In recognition of the detrimental effects of increases in runoff volume, one purpose of storm-water management is to replace the natural storage that is lost due to urbanization.

The SCS methods use the following equation to compute the depth of runoff (Q) in inches that results from a 24-hr rainfall depth (P) in inches:

$$Q = (P - 0.2S)^2 / (P + 0.8S)$$
(1)

in which S is the potential maximum retention,

$$S = (1,000/CN) - 10$$
 (2)

where CN is the SCS curve number for runoff. The rainfall depth is for a specified return period. The SCS methods are most often applied by using the 24-hr rainfall depth.

The runoff CN is an index that reflects the land use, treatment, hydrologic condition, and hydrologic soil group. CN increases as the pervious land covers are changed to impervious land covers. SCS assumes a CN of 98 for impervious surfaces. Thus, a composite CN can be obtained by weighting the impervious and pervious land cover CNs by using the fraction of the total area in each land cover:

$$CN = 98f + (1 - f)CN_P$$
 (3)

where f is the fraction of imperviousness and CN_P is the CN for the pervious portion of the watershed. Because the CN is a function of f, the change in the runoff volume (Q) due to a change in f is obtained as follows:

 $\partial Q/\partial f = (\partial Q/\partial S) \cdot (dS/dCN) \cdot (\partial CN/\partial f)$ (4a)

$$\partial Q/\partial f = \{(98 - CN_P)[400(P - 0.2S) + 800Q]\}/[(CN)^2(P + 0.8S)]$$
 (4b)

Equation 4 indicates that the sensitivity of Q to changes in f is a direct function of Q and is inversely related to the pervious-area CN. Figure 1 shows the relationship between the rate of change of the runoff and the fraction of imperviousness for the pervious surface CNs of 60, 70, 80, and 90 and a rainfall of 5 in. To illustrate the use of Equation 4b, if P is 5 in., CNp is 70, and f is 0.9, then $\partial Q/\partial f = 3.15$. If a proposed development would increase the fraction of imperviousness by 0.05, the change in the runoff volume would be 3.15 (0.05) = 0.16 in., which is the product of $\partial Q/\partial f$ and Δf .

Figure 1. Sensitivity of runoff volume to fraction of imperviousness for selected pervious area CNs.



EFFECT ON TIME PARAMETERS

Time is an important parameter in most hydrologic models, including the SCS methods. The time of concentration (t_C) and the lag time (L) are the two most frequently used time parameters. SCS computes the lag time as follows:

$$L = \ell^{0.8} (S+1)^{0.7} / 1,900 Y^{0.5}$$
(5)

where

L = lag time (hr),

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- l = watershed length (ft),
- Y = watershed slope (%), and
- S = potential maximum retention, which is defined by Equation 2.

SCS provides the following relationship between L and to:

$$t_c = 1.67L$$
 (6)

SCS provides a second method, which is called the velocity method, for computing the time of concentration. Although the lag equation (Equation 5) is recommended only for small rural drainage areas, the velocity method can be used with all land covers. When the velocity method is used, the time of concentration is defined as follows:

$$t_{c} = \left[\sum_{i=1}^{n} (k_{i}/V_{i})\right]/3,600$$
(7)

in which l_i is the length of the ith flow segment in feet, V_i is the velocity in feet per second of flow through flow segment i, and n is the number of flow segments. The velocity for overland flow segments can be estimated by using a graph of the watershed slope and the velocity; different relationships are given for different surface types. Manning's equation can be used to estimate the velocity of flow in channels.

When the lag method is used and part of the watershed is urbanized, SCS provides two graphs of lag

factors for correcting the lag estimated with Equation 5. In one graph the percentage of imperviousness is related to a lag correction factor, which can vary from 0 to 1. In the other graph the percentage of the hydraulic length modified is related to a lag correction factor. The lag factor in both graphs is a function of CN. These lag factors are approximations of the effect of urbanization on the time parameters.

If the more exact evaluation of the effect of urbanization on the time of runoff cannot be evaluated by using the velocity method, the effect can be estimated by examining the change in the lag time with respect to change in the fraction of the watershed that is impervious. By using Equations 5, 2, and 3, it can be shown that <code>@L/@f</code> is given as follows:

$$\partial L/\partial f = (\partial L/\partial S) \cdot (dS/dCN) \cdot (\partial CN/\partial f)$$
(8)

From Equation 5, the partial differential of L with respect to S is

$$\partial L/\partial S = 0.7 \ell^{0.8} (S+1)^{-0.3} / 1,900 Y^{0.5}$$
 (9)

From Equation 2, the differential of S with respect to CN is

$$dS/dCN = -1,000/(CN)^2$$
 (10)

From Equation 3, the partial differential of CN with respect to f is

$$\partial CN/\partial f = 98 - CN_P \tag{11}$$

Therefore, the following expression results for the partial differential of Equation 8:

$$\partial L/\partial f = [-700\xi^{0.8}(98 - CN_P)]/[1,900(S + 1)^{0.3}(CN)^2 Y^{0.5}]$$
 (12)

The second derivative is

$$\frac{\partial^2 L}{\partial f^2} = \left\{ 700\ell^{0.8} (98 - CN_P)^2 \left[2CN(S+1)^{0.3} - 300(S+1)^{-0.7} \right] \right\}$$

+ $\left[1,900(S+1)^{0.6}CN^4 Y^{0.5} \right]$ (13)

The change in the lag time due to change in the percentage of imperviousness can be evaluated by using a Taylor expansion:

$$\begin{aligned} L_{a} &= L + (\partial L/\partial f) \cdot df + (1/2!)(\partial^{2} L/\partial f^{2}) \cdot df^{2} \\ &+ (1/3!)(\partial^{3} L/\partial f^{3}) \cdot df^{3} + \dots \end{aligned} \tag{14}$$

in which L is the lag time at f = 0, and L_a is the lag time at f = df. The lag factor can be obtained by dividing Equation 14 by L:

$$L_{a}/L = 1 + (\partial L/\partial f) \cdot (df/L) + (1/2!)(\partial^{2} L/\partial f^{2}) \cdot (df^{2}/L) + (1/3!)(\partial^{3} L/\partial f^{3}) \cdot (df^{3}/L) + \dots$$
(15)

For the range of values for CN and f that are usually of interest, the second-order Taylor series is sufficient. Then Equation 15 reduces to the following:

$$L_{a}/L = 1 + (\partial L/\partial f) \cdot (df/L) + (1/2!)(\partial^{2} L/\partial f^{2}) \cdot (df^{2}/L)$$
(16)

The first-order Taylor series is acceptable when CN is greater than 85 and f is less than 0.3. For a CN of 70 and an f of 0.6, the error in using the second-order Taylor series (Equation 16) is about 0.05. Figure 2 shows the peak-factor relationships obtained by using the second-order Taylor series (solid lines) and the peak-factor relationships of TR-55 (broken lines). The noticeable differences between the two sets of lines indicate that the lag formula, which was derived for use on rural waterFigure 2. Variation of lag factor with CN and fraction of imperviousness.



sheds, should not be used with the lag factors of TR-55 for even moderate levels of imperviousness, for example, greater than 30 percent; i.e., f = 0.3. Beyond this value, which actually varies with CN, the sensitivity of the lag formula to changes in imperviousness may not be rational. When the percentage of imperviousness exceeds this value, the velocity method should be used to examine the effect of urbanization on time parameters.

To illustrate the use of Equation 12 for evaluating the effect of urbanization on the timing of runoff, the effect of a change in imperviousness on the time of concentration can be computed by multiplying the constant 1.67 from Equation 6 by Equation 12 to give $\partial t_c/\partial f$. For a watershed with a flow length of 1,000 ft, a pervious-area CN of 70, and a slope of 2 percent, $\partial t_c/\partial f = 0.379$ when f = 0. Therefore, if development were to increase f to 10 percent, the time of concentration would decrease by 0.379 (0.1) = 0.038 hr, which is the product of the change in f and $\partial t_c/\partial f$.

SCS METHODS

The SCS has developed an array of hydrologic methods. The simplified methods described in TR-55 can be used to compute either a peak discharge or an entire hydrograph. Two peak-discharge methods are provided in TR-55--the graphical method and the chart method. When an entire hydrograph is needed, the TR-55 tabular method can be used. A simplified method for determining the required volume of detention storage is also given in TR-55.

The TR-20 computer program $(\underline{4})$ can be used for more complex watershed analyses. TR-20 can be used to generate runoff hydrographs, route the hydrographs through either channel reaches or reservoirs, and combine hydrographs at stream confluences.

Graphical Method

Chapter 5 in TR-55 describes a method for estimating the peak discharge. The method, which is referred to as the graphical method, derives its name from a graph that relates the time of concentration in hours and the unit peak discharge inch cubic feet per second per square mile per inch of runoff. The input data requirements, which are minimal, are the return period in years (T); the 24-hr, T-yr precipitation in inches (P); the CN; the drainage area in square miles (A); and the time of concentration in hours (t_c) .

The procedure requires the volume runoff to be estimated by using P and CN as input to Equation 1. The time of concentration can be estimated by using either the lag method or the velocity method; however, the velocity method is preferred for the graphical method. The unit peak discharge is estimated from Figure 5-2 of TR-55, which relates the unit peak discharge and the time of concentration. The peak discharge equals the product of the unit peak discharge, the drainage area, and the volume of runoff.

The graphical method is recommended (a) where valley routing is not required; (b) for watersheds where land use, soil, and cover are uniformly distributed throughout the watershed; and (c) where runoff can be represented by one CN. Also, the graphical method should not be used when runoff volumes are less than about 1.5 in. for CNs less than 60 and the drainage area should be less than 20 miles². These limitations are given in TR-55.

Chart Method

Another procedure for computing the peak discharge, which is called the chart method, is described in TR-55. The chart method was designed for use in estimating the effect of development on the peakdischarge rate. The input data are the same as those for the graphical method (except for t_c) with the addition of the hydraulic length in feet, the percentage of ponds and swampy area, the watershed slope in percent, and the percentage of both the impervious area and the hydraulic length modified. Not all the data are necessary for all cases because some of the options are not mandatory. Application of the method is limited to watersheds from 1 acre to 2,000 acres. The method is based on a 24-hr storm volume and a SCS type II storm distribution.

The hydraulic length (HL) is used when it is desired to make a shape adjustment. The hydraulic length is entered and used to compute the effective area (EA):

EA = 0.00013586HL^{3/5}

If a watershed shape adjustment is not desired, the HL is not necessary and EA should be set equal to the drainage area (A).

If a significant portion of the watershed is swampy or in ponds or both, the pond and swamp adjustment factor can be obtained from a table. The value depends on the location of the ponds or swampy area within the watershed, the return period (T) (or storm frequency), and the percentage of ponding and swampy area.

The unit peak discharge, which will be discussed below, is obtained from charts designed for index slopes of 1, 4, and 16 percent. For slopes other than those for these three index values, a slopeadjustment factor can be obtained from a table. The following table indicates the slope designations:

Index Slope Slope Range		
(%)	(%)	
1	SP < 2.5	
4	2.5 < SP < 7.5	
16	7.5 < SP -	
	Index Slope (%) 1 4 16	

The effective area and slope are used as input to the appropriate part of a table in TR-55, and the slope-adjustment factor is obtained.

The unit peak discharge is then obtained from one of three figures in TR-55, which is separated on the basis of the three index slopes. The unit peak discharges are given in units of cubic feet per second per inch of runoff. The figures define the unit peak discharges for the SCS type II storm. The CN is used with the effective area to get the unit peak discharge.

By using the depth of precipitation and the CN, the volume of runoff (in inches) can be determined. If an adjustment is to be made for the percentage of imperviousness, the peak-adjustment factor (FIMP) is obtained from a figure. The percentage of imperviousness (IMP) and the CN are used as input. A similar adjustment is used when the hydraulic flow pattern has been or will be modified. The percentage of the hydraulic length modified (HLM) and the CN are used as input to a figure from which the peak-adjustment factor (HLMF) is obtained.

Tabular Method of TR-55

The tabular method, which is discussed in Chapter 5 of TR-55, was designed for use in the following circumstances:

 For developing composite flood hydrographs at any point within a watershed,

2. For measuring the effects of changes in land use of one or more subwatersheds, and

3. For assessing the effects of structures or combinations of structures.

In general, the procedure was intended for measuring the effect on the composite flood hydrograph of changes within subwatersheds of a larger drainage area.

The input requirements for the tabular method for each subwatershed are the same as those needed in the graphical method. In addition, the travel time for each channel reach is necessary.

Before the method is applied, the user should be familiar with several constraints. The constraints that were used in developing the method are important when applying the method. The tabular method was developed by making numerous computer runs with the TR-20 program. In each case, a CN of 75 was used and the rainfall volumes were selected to yield 3 in. of runoff. When the tabular method is applied to cases having characteristics that are significantly different from the conditions used in developing the method, the resulting hydrograph may not provide close agreement with the hydrograph that would result from a TR-20 analysis. These assumptions are not considered to be critical when the sole purpose in using the method is to assess the effect of changes in a watershed, such as land use or structure changes. The difference in the before and after hydrographs is relatively insensitive to the assumption of a CN of 75.

In order to make accurate assessments of watershed changes, there are certain limitations that should be adhered to in applying the method. First, within any subwatershed there should be little variation in CN; this does not mean that subwatersheds should have similar CNs but that each subwatershed should have little variation in soil and land use characteristics. Second, the area of each subwatershed should be less than 20 miles². Third, the precipitation should be sufficient to yield runoff volumes greater than 1.5 in., especially when CNs are less than 60.

The solution methodology centers about the tabu-

lar discharge values, which are given in a set of tables in TR-55. A table segment is given for selected times of concentration $(t_c): 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.25, 1.5, and 2.0 hr. For values other than these, the closest value can be used; further precision can be achieved through interpolation.$

Each table segment is further subdivided by the total travel time (T_t) from the subwatershed outlet to the design point. For each t_c and T_t , discharge rates are given in cubic feet per second per square mile per inch of runoff for hydrograph times (i.e., the time from the beginning of precipitation) ranging from 11.0 to 20.0 hr in various time increments; these hydrograph times correspond to time in the 24-hr SCS type II rainfall distribution.

The procedure used in solving problems with the tabular discharge hydrograph method is to segment the watershed into appropriate subareas and identify the necessary input for each subarea and channel reach. The hydrograph at the design point due to runoff from any subarea is determined by entering the tables for the subarea t_c and the total travel time from the outlet of the subarea to the design point. The total hydrograph is determined by summing the subarea hydrographs.

SCS TR-20 Computer Program

TR-20 is a computerized method for solving hydrologic problems by using the concepts outlined in Section 4 of the SCS National Engineering Handbook. The program was formulated to develop runoff hydrographs, to route hydrographs through both channel reaches and reservoirs, and to combine or separate hydrographs at confluences. The program is designed to make multiple analyses in a single run so that various alternatives can be evaluated in one pass through the program; this leads to more efficient use of computer time.

Even though a computer is used to solve problems, the input data requirements are surprisingly minimal; the amount of data depends on the complexity of the problem to be solved. If actual rainfall events are not going to be used, the total depth of precipitation is the only meteorological input. For each subarea, A, CN, and t_c are required; the SCS antecedent soil moisture condition (I, II, or III) must also be specified. For each channel reach, the length is required along with the channel crosssection description, which includes the elevation, discharge, and end-area data; although it is optional, a routing coefficient may also be used as input. If the streamflow routing coefficient is not given as input, it will be computed by using the cross-section data. For each structure it is necessary to describe the outflow characteristics with the elevation-discharge-storage relationship. The time increment for all computations must be specified, and any baseflow in a channel reach must be identified.

EFFECT ON PEAK DISCHARGES COMPUTED WITH SCS METHODS

When SCS hydrologic methods are used, the effect of urbanization on peak discharges is assessed by the joint effect of urbanization on t_c and CN. For the chart method, the computed peak discharge will increase as either the runoff volume or the peak factors increase. The peak factors are a function of CN and the percentage of change in either the imperviousness or the hydraulic length modified. The tabular method will show an increase in the peak discharge when either the runoff volume increases or the time of concentration or the channel-reach

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IMPA (%)	CN	Q (in.)	q _u [(ft ³ /sec)in.]	F1MP	QP (ft ³ /sec)	∆QP/QP ₀ (%)	∆Q/Q ₀ (%)	∆q _u /q _{uo} (%)	∆IMPF (%)
0	60	1.30	42	1.00	54.6	-	-	-	-
10	64	1.58	46	1.06	77.0	41.0	21.5	9.5	6
20	68	1.88	50	1.13	106.2	94.5	44.6	19.0	13
30	71	2.12	54	1.20	137.4	151.6	63.1	28.6	20

travel time or both decrease. For the RUNOFF subprogram of the TR-20 program, changes in urbanization will be reflected by changes in CN and t_c , both of which are necessary input.

The chart method is easily used to demonstrate the effect of urbanization on peak discharge. For a 100-acre, wooded (fair condition) watershed with a slope of 4 percent and type-B soil, CN is 60. The 10-yr 24-hr rainfall depth is assumed to be 5 in. The results in Table 1 show the effect of increases in the percentage of imperviousness on the 10-yr peak discharge. By using Equation 2 to compute CN, the change in CN is a prime input to each of the steps. CN is used to obtain the runoff volume (Q), the unit peak discharge (q_u), and the peak factor (FIMP). The change in peak discharge is 151.6 percent for a change of 30 percent in imperviousness.

The effect of a change in the fraction of imperviousness on the peak discharge can be computed analytically for the graphical method. The peak discharge will change in accordance with the changes to t_c and Q; the change in the runoff volume results from a change in CN. The graph in TR-55 that relates the unit peak discharge in cubic feet per second per square mile per inch of runoff can be represented by a function having the following form:

 $q_u = b_0 t_c^{b_1}$ (18)

in which ${\bf b}_0$ and ${\bf b}_1$ are coefficients that must be determined for small ranges of ${\bf t}_c$. The peak discharge $({\bf q}_p)$ is computed by

$$q_{n} = q_{u} A Q \tag{19}$$

The effect of urbanization is then determined analytically by

$$\partial q_{p} / \partial f = \left[\left(d q_{u} / d t_{c} \right) \left(\partial t_{c} / \partial f \right) \right] A Q + q_{u} A \left(\partial Q / \partial f \right)$$
(20)

The derivative $dq_{\rm U}/dt_{\rm C}$ can be obtained by differentiating Equation 18 as follows:

$$dq_{u}/dt_{c} = b_{1}b_{0}t_{c}^{b_{1}-1} = b_{1}q_{u}/t_{c}$$
(21)

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The partial derivative $\partial t_c/\partial f$ equals 1.67 times the value of Equation 12, and the partial derivative $\partial Q/\partial f$ is computed with Equation 4. The first term on the right-hand side of Equation 20 represents the effect of change in f on q_p because of the effect of change in f on t_c ; the second term represents the effect of change in q_p due to the effect of f on Q.

ADVANTAGES AND DISADVANTAGES OF SCS METHODS

As have all hydrologic methods, the SCS methods have been criticized. A major concern of practicing engineers has been the inadequate form of the documentation of the methods. Before worksheets were made available in 1981 for the TR-55 methods, many applications were incorrectly made. The TR-20 documentation is not a good learning tool for someone interested in making a first application of the computer program. Also, the documentation does not make the limitations of the methods sufficiently clear. These problems are currently being addressed. Revised manuals will be available in the near future.

Several elements of the methods have been criticized as not being rational; however, this is to be expected for any simplified method. The two most frequent criticisms appear to be the assumed initial abstraction relationship and the infiltration relationship that is imbedded within the methods. Although these elements are criticized, it is not clear that they contribute to any inaccuracies; that is, these assumptions may not affect the accuracy of the methods when the methods are used for the purposes for which they were intended.

The methods have also been criticized because of the apparent lack of an empirical basis. Although some effort has been made to document the empirical as well as the conceptual basis for the SCS methods ($\underline{6}$, pp. 353-364), recent empirical studies have shown the accuracy of the methods to be similar to that of other widely used hydrologic methods. The most recent study ($\underline{7}$) comparing hydrologic methods on small urban watersheds indicated that the TR-55 methods were relatively unbiased but showed slightly more error variation than both the rational method and the new USGS urban-peak formula.

In spite of these criticisms, the SCS hydrologic methods have numerous advantages. First, they have been widely used and no major problems have been reported. Second, the input data are easily obtained, and the methods are simple to apply. Recent studies (8,9) have shown that reasonably accurate estimates of the input can be obtained by using remotely sensed data. Third, the SCS methods represent an array of procedures, including peakdischarge methods, simple hydrograph methods, methods for analyzing complex watersheds, and methods for sizing storm-water detention facilities. The array of procedures enables the planner and designer to solve various elements of a problem by using procedures based on the same concepts. Such integrated design eliminates problems associated with the use of different methods. Also, the methods can be used for analyzing runoff problems The SCS for both urban and rural land covers. methods are also popular because they have eliminated the reproducibility problem that is associated with many of the empirical formulas such as the rational method; regulatory agencies that must review and approve design plans are often confronted with the problems created by the range of values provided with empirical coefficients such as the runoff coefficient of the rational method.

An important advantage of the SCS methods is the continued research that is being undertaken to improve and diversify the methods. For example, a two-stage riser design method was developed because hydrologists recognized that one-stage risers in detention ponds did not adequately control the runoff frequency curve. Similarly, CNs were developed for new agricultural practices. PEAK DISCHARGE: COMPARISON OF SCS METHODS WITH OTHER MODELS

Leopold (10, pp. B9-B11) provided a graph of the ratio of the mean annual discharges after and before development versus the percentage of the area served by storm sewers and percentage of the area that was urbanized (according to Leopold, 100 percent urbanization corresponds to 50 percent imperviousness). The values of the ratio ranged from 1 to 6. As an example, when 50 percent of the area was served by sewers and 50 percent was urbanized, the ratio value was about 2.85.

Dunne and Leopold (11), after Carter (12) and Anderson (13), provided the following relationship between the percentage of imperviousness (I) and the ratio of the after- to the before-urbanization peak discharges:

 Q_{q} (after urbanization)/ Q_{p} (before urbanization) = (0.30 + 0.0045I)/0.30 (22)

Thus, the ratio would vary from 1 to 2.5 for values of I from 0 to 100 percent.

Sarma, Delleur, and Rao (14) provided the following relationship for computing peak discharges on urban basins:

$$Q_{\rm p} = 484.1 {\rm A}^{0.723} (1 + {\rm I}/100)^{1.516} {\rm P}_{\rm E}^{1.113} {\rm T}_{\rm R}^{-0.403}$$
(23)

where

- $\Omega_p = \text{peak discharge (ft³/sec),}$ A = drainage area (miles²),
- I = percentage of imperviousness,
- P_E = volume of excess rainfall (in.), and
- $T_R = duration of excess rainfall (hr).$

It is evident that the effect of urbanization will vary with the values of A, P_E , and T_R . For example, for a 1-mile² watershed in which 1 in. of precipitation excess occurs during 1 hr, the ratio of the after-urbanization to the before-urbanization peak discharges ranged from 1.0 at I equal to zero to 2.86 at I equal to 100 percent. This range agrees favorably with the range resulting from Equation 22.

The USGS urban peak-flow formula (14) has the following form:

$$UQ_{T} = b_{0}A^{b_{1}}SL^{b_{2}}(RI2 + 3)^{b_{3}}(ST + 8)^{b_{4}}(13 - BDF)^{b_{5}}I^{b_{6}}RQ_{T}^{b_{7}}$$
(24)

where

- UQ_T = urban peak discharge for return perried T (ft³/sec),
 - A = drainage area (miles²),
- SL = channel slope (ft/mile) with a
- maximum value of 70 ft/mile,
- RI2 = 2-yr, 2-hr rainfall intensity (in.),
- ST = basin storage (%),
- BDF = basin development factor,
- I = percentage of imperviousness,
- RQ_T = rural watershed peak discharge (ft²/sec) for the T-yr event (i.e., before development peak discharge), and

$$b_{i} (i = 0,$$

 $1, \ldots, 7$ = regression coefficients, which vary with the return period of the discharge.

Assuming that A, SL, RI2, and ST remain constant with development, the increase in peak discharge due to urbanization is a function of BDF and I. Sauer and others (15) indicated that the ratio of peak discharges after to those before development will range from 1 to 4.5 for the 2-yr event and from 1 to 2.7 for the 100-yr event as the value of BDF varies from 0 to 12 and I varies from 0 to 100 percent.

Although the SCS peak-discharge methods use CN and the percentages of imperviousness and hydraulic length modified to account for the effects of urbanization on peak discharge, other methods use either the imperviousness alone or a combination of other factors. Methods that use more than one factor, such as the SCS methods, the USGS urban equations, and Leopold's relation between percentage of area served by sewers and percentage urbanized, are certainly more flexible and provide more opportunity to adapt the procedures for different watershed modifications than methods based solely on the percentage of imperviousness. Urbanization of a watershed can take many forms, from land cover changes such as residential development to the installation of a sewer system and modification of the channel system. Because the hydrologic effects of each of these factors are different, it is important to have a model that is sensitive to the type of urbanization and will reflect the hydrologic effects of the watershed change. However, as the number of factors in a model that relate to a specific process, such as urbanization, increases, it becomes increasingly difficult to calibrate the model and separate the effects of the factors. The problem is compounded because the change of the peak discharge results from changes to various factors such as the level of natural storage, the timing of the runoff, the volume of runoff, and the drainage density. Conceptual models attempt to reflect the effect of changes in each of these factors on the runoff.

DISCUSSION

A variety of hydrologic models has been developed to represent each of the components of the hydrologic cycle. Models of groundwater flow, evapotranspiration, channel flow, and infiltration are used for decision making; surface-runoff models are probably the most widely used. Because of the diversity of surface-runoff regimes, several surface-runoff models have been developed. In many cases, the models have been fitted with measured data from the site or region where the model was intended to be used. Other models have been developed without fitting to measured data and are recommended for general use at all sites within a large region. Such uncalibrated models are widely used because of the generality of their conceptual framework and their operational simplicity.

The SCS concepts were initially developed for estimating surface runoff from agricultural areas. TR-55, which was published in 1975, provided methods for estimating surface runoff from urban watersheds. The methods recognize the effect of urbanization on all elements of surface runoff, including the peak discharge, the runoff volume, and the time characteristics of both surface runoff and channel flow. Thus, the methods permit the evaluation of the effects of urbanization on all of the major aspects of surface runoff in urban areas. Because of this flexibility and the computational simplicity of the methods, TR-55 has been widely adopted as part of drainage and storm-water management policies.

The true hydrologic impact of urbanization cannot be known because the processes involved and their interaction are too complex to be represented mathematically, especially when one considers the diversity in urban watersheds. This has led to the development of a number of urban surface-runoff models. Problems are created when different models are used by different hydrologists at the same site. This is sufficient reason for adopting one

method, even when we recognize that if we knew the true effect of urbanization, the model selected might not be the most accurate. What criteria should be used in selecting one design method? First, the conceptual framework of the model should be rational. Second, the model should be flexible so that it can be used for a variety of design problems. Third, the model should be applicable to large regions, not just sites within a single county. Fourth, the input data requirements should be minimal and easily obtainable. Fifth, the method should be highly reproducible; that is, different hydrologists should get the same design at a given location. Sixth, a model should be simple to apply.

In summary, the SCS methods appear to satisfy the six criteria for model selection (i.e., conceptually rational, flexible in design, widely applicable, requiring minimal input, highly reproducible, and computationally simple). Studies have also shown that the methods are reasonably accurate and relatively unbiased when they are applied under the conditions for which they were developed.

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Simple Methods to Evaluate Relative Effects of Longitudinal Encroachments

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To aid highway planners and others who must site structures and fills in natural floodplains, simplified graphical solutions were developed that provide short-cut methods for easy assessment of encroachment impacts. Changes in stage (water-surface elevation) and hydrograph peak discharge due to encroachments were determined. The discussion is limited to encroachments that parallel the channel.

Construction in floodplains of highway fills and other types of built-up areas with alignments generally parallel to the main channel of a river or stream constitutes longitudinal or lateral encroachment. Such encroachments usually reduce storage and conveyance available for passing flood flows and generally alter the characteristics of flooding at the affected site.

The impact of encroachments can be determined by using existing techniques that include an assortment of computer models and other methods. These techniques are complex, however, require costly and time-consuming field data collection and preparation, and are therefore unsuitable at the preliminary design phase for assessing relative impact of encroachment alternatives on flooding. In this paper results are presented from a study that developed simple procedures to evaluate impacts of encroachment options on flood depths and peak-discharge rates. Sample problems are presented to illustrate the procedures developed.

RESEARCH APPROACH

To develop the simplified procedures, representative channel cross sections were selected and a controlled series of tests with existing mathematical models produced a set of predicted changes that were used to develop the graphic plots of relationships among groups of significant variables. The entire range of graphs developed and step-by-step proce-