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EFFECT OF ORIENTATION OF SPATIALLY DISTRIBUTED CURVE NUMBERS IN RUNOFF CALCULATIONS[1]

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ABSTRACT: The NRCS curve number approach to runoff estimation has traditionally been to average or "lump" spatial variability into a single number for purposes of expediency and simplicity in calculations. In contrast, the weighted runoff curve number approach, which handles each individual pixel within the watershed separately, tends to result in larger estimates of runoff than the lumped approach. This work proposes further enhancements that consider not only spatial variability, but also the orientation of this variability with respect to the flow aggregation pattern of the drainage network. Results show that the proposed enhancements lead to much reduced estimates of runoff production. A revised model that considers overland flow lengths, consistent with existing NRCS concepts is proposed, which leads to only mildly reduced runoff estimates. Although more physically-based, this revised model, which accounts directly for spatially distributed curve numbers and flow aggregation, leads to essentially the same results as the original, lumped runoff model when applied to three study watersheds. Philosophical issues and implications concerning the appropriateness of attempting to disaggregate lumped models are discussed.
(KEY TERMS: curve number; distributed modeling; infiltration; land use; spatial variability; surface water hydrology.)

INTRODUCTION

The Natural Resource Conservation Service (NRCS, formerly SCS) first developed the curve number in 1954 (Rallison, 1980; Rallison and Miller, 1981) as part of its project planning related to the Watershed Protection and Flood Prevention Act (Public Law 83-566). Since that time, the curve number and the hydrologic prediction methods associated with it have grown immensely in popularity and use. Initially an agriculturally-based model, it has also grown in ways that were never intended, or at least in ways not envisioned by the original authors of the method.

The NRCS curve number approach in today's parlance is representative of a "lumped" parameter model. In reality a basin usually possesses a range of land uses such as forest, residential, and commercial; and soils ranging from sands and gravels to clays. Such spatial variability, inherent to the natural world, is averaged (lumped) out and a single, representative or effective value is used to quantify the behavior of a basin.

The principles of calculus show that the "truth" can be understood as well as we like, provided we only take the time to add up a large number of infinitesimal contributions. This is the philosophy behind "spatially distributed" modeling, which has exploited the growing capacities of computers and the increased availability of high resolution spatial data. What happens to the NRCS methods if we endeavor to translate them into a spatially distributed model? Specifically, can we account for differing spatial orientations of curve numbers within the framework of the existing NRCS models? This paper explores these questions and provides some insight into the consequences and the appropriateness of such an undertaking.

BACKGROUND

The NRCS method for estimating runoff is an empirical set of equations based on experimental watersheds across the United States (Rallison, 1980). At the heart of this method is the curve number, a value ranging between 1 and 100 representing the

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tendency of the land to convert rainfall to direct runoff. The larger the curve number, the smaller the losses and therefore, the greater the runoff. The curve number is first converted to a storage index:

$$S = \frac{1000}{CN} - 10 \quad (1)$$

where S is the storage index in inches and CN is the curve number. When it rains, a certain fraction of the rainfall is immediately retained as an "initial abstraction," accounting for such things as leaf and litter interception, depression storage, and initial wetting. Initial abstraction is traditionally taken as a fraction of the storage index, usually 20 percent:

$$I_a = 0.2S \quad (2)$$

where I_a is the initial abstraction in inches. Direct runoff is a function of the volume (expressed as a depth) of rainfall, the storage, and the initial abstraction:

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

where Q is the runoff volume (also expressed as a depth) in inches. In the event that the rainfall, P, is smaller than the initial abstraction, $P < I_a$, then no runoff occurs, $Q = 0$.

In order to approach the problem of estimating runoff from a particular storm using NRCS methods, three sets of spatially distributed data are required: topography, land use, and hydrologic soil type. Especially with respect to the determination of the curve number distribution, the methods outlined here provide only an initial estimate. More accurate estimates are ultimately obtained through comparison with peak discharges determined from regional regression equations or ideally from actual rainfall/runoff data.

Topography

Spatially distributed topography generally takes the form of a digital elevation model (DEM) which is simply a regular grid of elevation values. Each grid element or pixel takes on a single value representative of the elevation over the extent of that element. The U.S. Geological Survey (USGS) provides such data, at 90 meter resolution for all locations in the continental United States (USGS, 2000). Moreover, the USGS also provides 30 meter resolution DEMs for many locations within the United States. Knowing elevation and applying basic rules allowing water to flow in the direction of the steepest downhill gradient, it is possible to infer flow directions, flow lengths, slopes, drainage area, and watersheds (O'Callaghan and Mark, 1984; Jenson, and Domingue, 1988; Tarboton *et al.,* 1991). Using a geographic information system (GIS), the process of determining from a DEM any of these quantities is a largely automated process (Moglen and Casey, 1998).

Land Use

In digital format, land use is often described by a series of polygons (vectors) over a region, with each polygon indicating a region of assumed homogeneous land use. Schemes to describe different land use applications vary, but a common one (Anderson *et al.,* 1976) divides land use into such broad categories as urban, agricultural, forest, and water/wetlands. Such digital representations of land use are available at relatively coarse resolution (about 200 meters) from the USGS (USGS, 2000) covering the entire United States. Other descriptions of land use may be found from state or regional organizations such as state planning offices or departments of the environment.

Hydrologic Soil Type

Hydrologic soil type, as defined by the NRCS, categorizes soils by their infiltration capacities as either A, B, C, or D. These categories define the spectrum of infiltration capacities allowed by soils where an A soil (generally sands and gravels) defines the high end of the infiltration capacity scale and D soil (generally clays) are at the low end of the scale. Digital representations of these data can be obtained directly from the NRCS (NRCS, 2000) at several resolutions: SSURGO, STATSGO, and NATSGO. SSURGO data is the highest available resolution, digitized at scales ranging from 1:12,000 to 1:31,680 which is quite appropriate for smaller watersheds on the order of a few square miles in size. STATSGO data is digitized at 1:250,000 scale and is useful when analyzing watersheds at the multi-county to state scale. NATSGO data describes variations in soil type at the multistate to regional scale and is not appropriate for the applications being discussed here.

Curve Number

Land use and soil type are combined to determine a curve number. This process is generally one of employing a handbook table (e.g., see SCS, 1985 and 1986) that associates a curve number with a given land use and soil type. Use of such a table is not unlike determining a channel roughness coefficient for use in Manning's equation. For instance, quarter-acre residential lots have curve numbers estimated at 61, 75, 83, and 87 for A, B, C, and D soils, respectively. The increase in curve number reflects the effect of decreasing infiltration capacities as soil type varies. Again, using a GIS, the process of inferring the spatial distribution of curve number, given the spatial distribution of land use and soil type is a process that is readily automated (Ragan, 1991; Moglen and Casey, 1998).

ANALYSES

The averaging procedure used to determine runoff necessarily has an effect on the derived result. Traditionally, an average curve number is determined for the watershed being analyzed and this value is then propagated through Equations (1), (2), and (3). An alternative (weighted runoff) procedure is to postpone the averaging step until after the spatially varied curve numbers have been converted to spatially varied runoff. The consequences of the use of the weighted runoff procedure were recently examined by Grove *et al.* (1998). These two procedures can be summarized as follows:

1. **Traditional Procedure:** Determine a lumped (weighted average) curve number (representative of n sub-areas with different curve numbers). Perform one calculation each for Equations (1), (2), and (3). The result from Equation (3) is the lumped runoff, Q_L, from the watershed.

2. **Weighted Runoff Procedure:** Determine n runoff values (representative of n sub-areas or pixels with different curve numbers) by performing n calculations each for Equations (1), (2), and (3). Determine a weighted average runoff from these n values. The result of this average is the distributed runoff, Q_D, from the watershed.

Because of the non-linearities in Equations (1), (2), and (3), a bias is observed such that

$$Q_L \leq Q_D \tag{4}$$

where the equality only applies if there is no variation in curve number within the basin.

New Procedure 1: Allow for Infiltration Infinitely Downstream (α method)

This paper proposes to continue along the spirit of the analysis undertaken by Grove *et al.* (1998) to account not only for spatial variability, but also the spatial organization of the varied curve number values. The runoff produced from Equation (3) for an arbitrarily chosen pixel will naturally proceed downhill, eventually finding its way to a location of concentrated flow (termed a swale or channel in NRCS methods). From the perspective of the downhill pixel, runoff and rainfall are the same: they are both sources of an input volume of water. Equation (3) can be modified to reflect this perspective,

$$R_d = \frac{\left[\left(\Sigma R_u + P\right) - I_a\right]^2}{\left(\Sigma R_u + P + S_d - I_a\right)} = \frac{\left[\left(\Sigma R_u + P\right) - 0.2S_d\right]^2}{\left(\Sigma R_u + P\right) + 0.8S_d} \tag{5}$$

where R_d is the runoff leaving the downstream pixel (in units of pixel-inches); ΣR_u is the summation of the runoff from all immediately upstream pixels (in pixel-inches); and S_d is the storage of the downstream pixel (in pixel-inches). This new unit of measure, the "pixel-inch" is necessitated by the flow accumulation nature of Equation (5). Pixel-inches are converted back to inches after the runoff of all pixels within the watershed has been determined. The runoff, R_d (in pixel-inches), is divided by the number of pixels draining respectively to each pixel within the watershed. The result is an areal average depth of runoff analogous to the NRCS, Q, at each pixel throughout the watershed. Most importantly, the areal average runoff depth at the outlet of the watershed reflects the net runoff produced by the watershed allowing for both spatially varied and oriented curve numbers.

Figure 1 illustrates how Equation (5) is applied. In Figure 1 a DEM has been used to determine that two pixels flow into the downstream pixel in question. In this case ΣR_u = 0.94 + 2.54 = 3.48 pixel-inches. This 3.48 pixel-inches of upstream runoff is added to the rainfall at the downstream pixel (P = 4.8 pixel-inches) to produce a net input of 3.48 + 4.8 = 8.28 pixel-inches of water. If the curve number is 60 at this downstream pixel, resulting in a storage, S_d, of 6.67 pixel-inches, then the downstream runoff, R_d, is 3.54 pixel-inches. If there are no other inputs to the three upstream pixels, then the area associated with the downstream pixel is 3 pixels (e.g., the number of pixels draining into downstream pixel plus the downstream pixel itself). The areal average runoff at the downstream pixel for this example is then

$$Q_a = \frac{R_d}{A_d} = \frac{[(3.48+4.8)-(0.2)(6.67)]^2}{(3.48+4.8)+0.8(6.67)} \Big/ 3 = 1.18 \text{ inches} \quad (6)$$

The reader should note that the symbol Q is used to indicate runoff in units of inches, and the symbol R is used to indicate runoff in units of pixel-inches. Additionally, the subscript α indicates the determination of Q given the method presented in Equation (5). An alternative (β method) will be presented later.

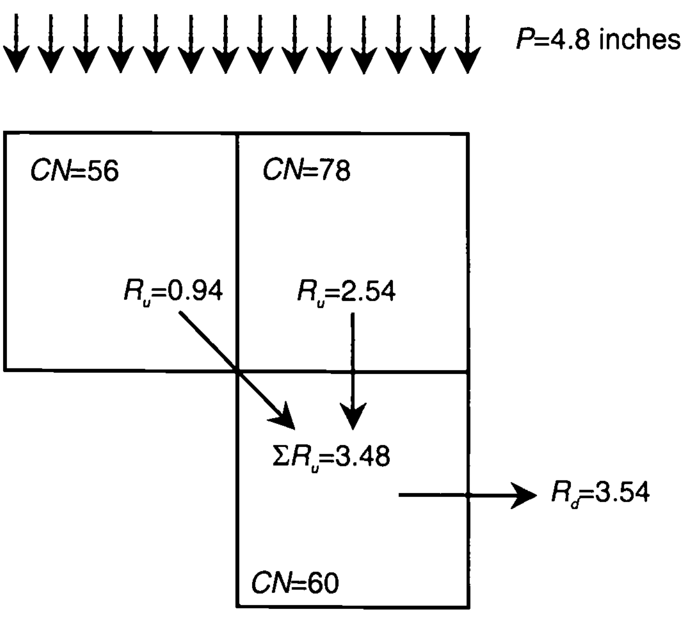

Figure 1. Schematic Diagram Illustrating Flow Aggregation and Accounting Structure Associated with Equation (5). The quantities R_u, ΣR_u, and R_d are in units of pixel-inches.

Consider the case where the runoff paths are exclusively parallel such that flow is accumulating in a strictly linear fashion (one-dimensional flow) moving downstream as illustrated in Figure 2. A 100 pixel flow path is divided into two 50-pixel sections and subjected to a rainfall, P = 3.0 inches. In "Case A," the upper 50 pixels are grassed (CN = 78) and the lower 50 pixels are paved (CN = 98). In "Case B," the order is reversed with the paved surface upstream of the grassed surface. Figures 3a and 3b present the runoff production of both systems as a function of position along the flow path. In both cases, the incremental runoff contributed by a single pixel is high for the paved surface as evidenced by the steep slope of the curves in Figure 3a. In Case A, the grassed surface produces relatively little incremental runoff as evidenced by the shallow positive slope in Figure 3a. In Case B, the grassed surface actually serves as a small net sink to runoff production indicated by the shallow negative slope in Figure 3a. At the downstream end of both systems, after 100 pixels of one-dimensional flow, Case A (149.9 pixel-inches) is observed to produce more runoff than Case B (121.5 pixel-inches) indicating that, although both systems have an identical land use make-up, the orientation does affect runoff produced. To obtain the net runoff for Cases A and B, divide by A_d = 100 pixels for each system resulting in Case A: $Q_{\alpha,A}$ = 149.9 pixel-inches/100 pixels = 1.50 inches or runoff and in Case B: $Q_{\alpha,B}$ =121.5 pixel-inches/100 pixels = 1.22 inches as indicated in Figure 3b. Note that the traditional, lumped procedure will produce an average CN_{avg} = (50 x 78 + 50 x 98) / 100 = 88. Therefore the storage, S, is 1000 / CN_{avg} – 10 = 1.36 inches. Using Equation (3), it is determined that Q_L = 1.81 inches. In contrast, from the weighted runoff procedure the grassed pixels have a CN = 78, which yields a storage, S = 2.82 inches, resulting in a runoff, Q = 1.13 inches. For the paved pixels CN = 98, S = 0.20 inches, and Q = 2.77 inches. Since orientation does not matter, the runoff for either case is a weighted average over 100 pixels evenly divided between the two runoff surfaces, producing Q_D = [50 pixels (1.13 inches) + 50 pixels (2.77 inches)] / 100 pixels = 1.94 inches. Note that $Q_D > Q_L > Q_{\alpha,A} > Q_{\alpha,B}$, which is consistent with Equation (4). A discussion of the relative magnitudes of $Q_{\alpha,A}$ and $Q_{\alpha,B}$ is postponed until later.

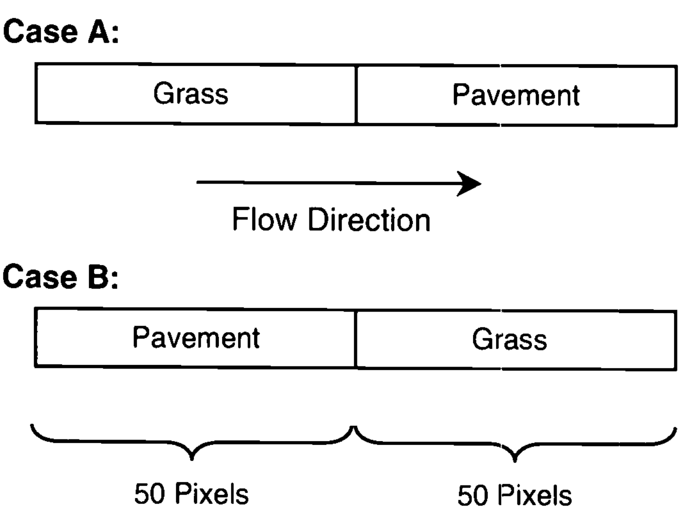

Figure 2. One-Dimensional Flow Study. In Case "A" grassed area is upstream of paved area. In Case "B" paved area is upstream of the grassed area.

Depending on the accumulated runoff (ΣR_u), the incremental runoff production (R_d - R_u = ΔR) for the grassed surface may be either positive (Case A) or negative (Case B) as shown in Figure 3. This suggests that a $CN = 78$ as used here for grass will result in a limiting condition where the runoff volume is no longer increasing as it moves from upstream pixel to downstream pixel. Under these conditions,

$$R_d = R_u \tag{7}$$

Note that $\Sigma R_u = R_u$ since this is the case of one-dimensional flow and by substituting from Equation (7) into Equation (5),

$$R_d = \frac{(P - 0.2S_d)^2}{1.2S_d - P} \tag{8}$$

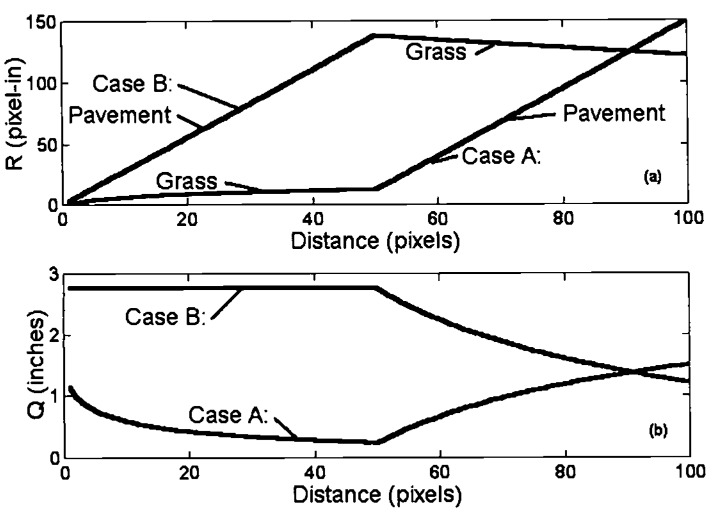

Figure 3. (a) Runoff, R (pixel-inches), Produced in One-Dimensional Flow Study; and (b) Runoff, Q (inches), Corresponding to R's in (a).

The numerator in Equation (8) is physically meaningful for $P > 0.2S$, which is the original condition for NRCS-defined runoff set forth in Equation (3). When $P < 1.2S_d$, Equation (8) predicts a positive value for R_d. For instance, for $P = 3.0$, and a curve number of 78, the limiting value of R_d is 15.4. In other words, an infinitely long overland flow plane under the specified conditions would produce 15.4 pixel-inches of runoff. Since the area drained at the downstream end of such an infinite plane would also approach infinity, the runoff volume would approach zero from Equation (6). This is the physical analog of the original NRCS equation which states that rainfall less than 20 percent of the storage results in no runoff. However, for this special limiting condition of flow aggregation (one-dimensional flow), P must be substantially greater than in the original NRCS equations (1.2S now versus 0.2S originally) for runoff to continue to grow as drainage area increases. If $P > 1.2S$, then Equation (8) yields a negative value indicating that R_d will grow linearly as water travels down an infinitely long plane. Since area, A_d, also grows linearly, the runoff, Q, will approach a constant (greater than zero) as can be seen by the horizontal curve in Figure 3b corresponding to the paved surface section of Case B.

Let us now move away from the simplified perspective of one-dimensional flow and examine the consequences of predicted runoff using the flow aggregation pattern of a real drainage network. This paper will continue to examine systems with only two curve numbers but now distribute these curve numbers in three different ways: (a) a "rectangular clearing" at the headwaters of the watershed; (b) the same clearing near the outlet of the watershed; and (c) the same area as the clearing dispersed randomly across the entire watershed. These three configurations are shown in Figure 4. Runoff will be calculated from these three configurations using the α approach. The curve number of the "clearing" is fixed at 98, while the curve number of the remaining (background) area varies from 35 to 65. A value of $P = 4.8$ inches will be used, which roughly corresponds to the 10-year, 24-hour storm in central Maryland.

Figure 5 shows the resulting runoff for the α method for each of the three configurations. The runoff from the lumped and distributed approaches is shown in dashed lines for reference. As in the one-dimensional flow case the lumped and distributed approaches predict the same runoff regardless of configuration. This is so because neither method is sensitive to orientation of the curve number field with respect to the flow paths. This experiment illustrates how Equation (5) captures the effect of spatial orientation of varied curve numbers. The proximity of the clearing to the outlet in configuration "b" leads this configuration to produce the greatest runoff across all background curve numbers. The clearing in the watershed headwaters (configuration "a") initially produces little runoff when the background curve number is small, but then approaches the runoff for the configuration "b" system for the larger values of background curve number examined. Configuration "c" produces the smallest amount of runoff because the runoff from its dispersed clearings is lost in the background areas downstream much as the runoff was lost in the "pavement to grass" transition of Case B in the one-dimensional example illustrated in Figures 2 and 3. The "memory" of upstream conditions in configuration "a" is longer lived as the curve number increases. In other words, the runoff produced at the headwater clearing is significant at the basin outlet only when the background curve number is high

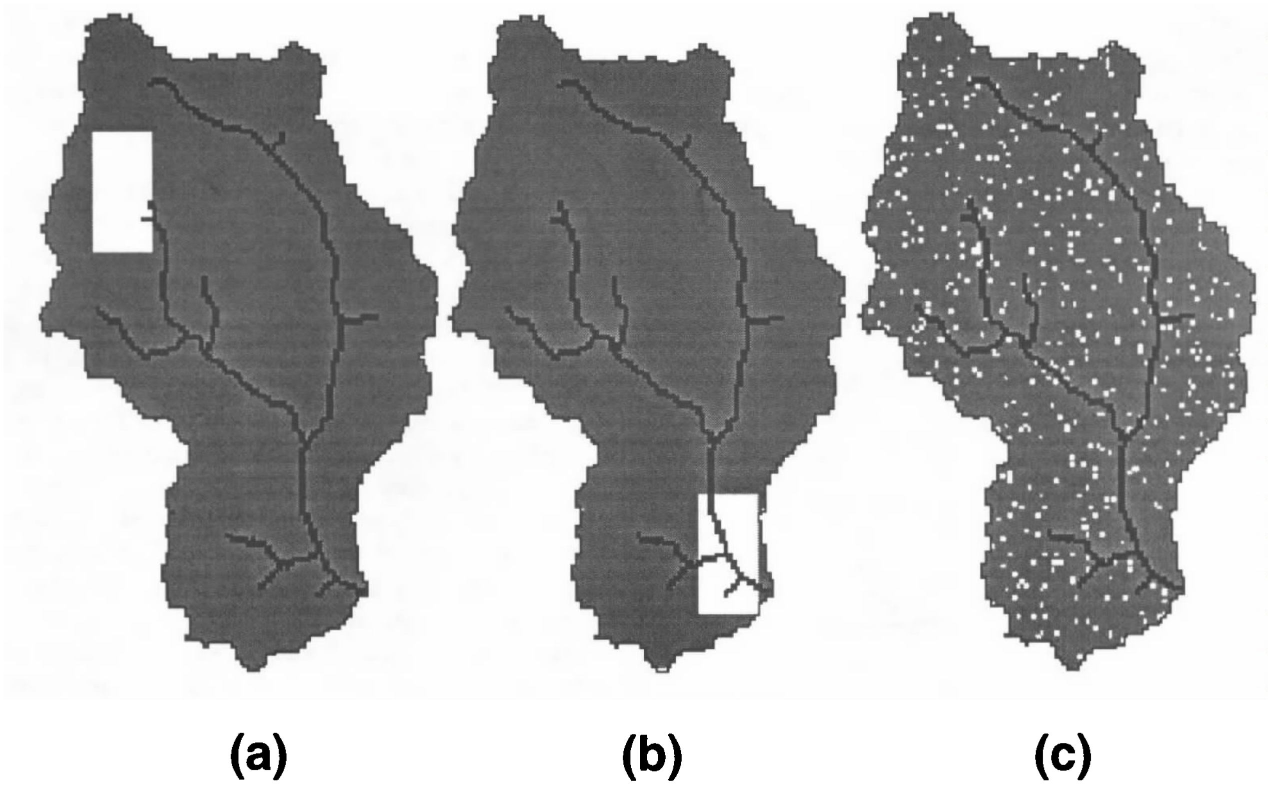

Figure 4. Configurations a, b, and c for Two-Dimensional Flow Aggregation Study. Dark areas have the background curve number. Light areas represent "clearings" with a fixed curve number of 98.

enough to sufficiently restrict infiltration of this runoff downstream of the clearing.

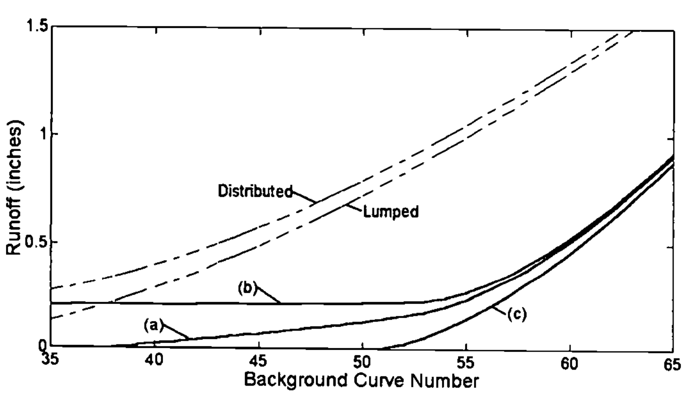

Figure 5. Runoff (inches) From Two-Dimensional Flow Study. Distributed and lumped runoff are shown for reference in dashed lines.

A limiting condition similar to the one-dimensional flow case can be derived for this more general flow aggregation case, provided the curve number is constant along the downstream flowpath. This condition is determined by observing that far downstream the incremental contribution to flow from the rainfall is small relative to the accumulated runoff coming down the channel. Looking at the incremental contribution to flow at a pixel with a large drainage area (this corresponds physically to a pixel that lies along the channel network) one finds that:

$$\Delta R = \Sigma R_u - R_d = \Sigma R_u - \frac{\left[\left(\Sigma R_u + P\right) - 0.2S_d\right]^2}{\left(\Sigma R_u + P\right) + 0.8S_d} \cong P - 1.2S_d \qquad (9)$$

which holds provided that $\Sigma R_u >> P$. In this case no special provisions about the nature of the flow aggregation pattern have been made. The conclusion is the same, however. If $P < 1.2S_d$ then the incremental contribution to runoff from the pixel in question is negative indicating that flow is being lost due to infiltration. The limiting results and commentary surrounding Equations (8) and (9) can be summarized as follows (R. H. Hawkins, personal communication, 1999):

1. For $0 \le P \le 0.2S$, Q = 0 in all cases because the initial abstraction is greater than the depth of rainfall and no runoff is ever generated.

2. For $0.2S < S \leq 1.2S$, $Q \rightarrow 0$ as the downstream drainage area becomes large. This is a consequence of division by A_d to convert from R (in pixel-inches) to Q (in inches) in Equation (6).

3. For $1.2S < P$, $Q \rightarrow P - 1.2S$ as the downstream drainage area becomes large.

New Procedure 2: Allow for Infiltration Downstream Over a Specified Distance (β method)

The NRCS runoff model, TR-55 (SCS, 1986) allows for runoff generation and routing by identifying three fundamentally different flow regimes within the watershed. Over the first 100 to 300 feet from basin divide to the channel, overland sheet flow is assumed to dominate. Immediately downstream of this regime "shallow concentrated flow" (often called "swale flow") dominates. Once the channel is encountered, open channel flow conditions as characterized by Manning's equation are dominant.

This description of the progression of flow aggregation gives rise to a modification to the proposed α method. Equation (5) accounts for the possibility of runoff generated upstream infiltrating later somewhere downstream. Such downstream infiltration could physically occur only in the region of overland flow. Once flow has reached a swale or channel it is concentrated and infiltration is assumed minimal because saturated conditions have been encountered. For pixels in this concentrated flow region, it is appropriate to employ the original runoff generation model set forth in Equation (3). Together, Equations (3) and (5) amount to perhaps a more realistic model allowing for downhill infiltration only upstream of swales or channels and reverting to the classic NRCS runoff equation where swales or channels are present. The reader may find it instructive to compare the β model to the Steenhuis *et al.* (1995) interpretation where only spatially variable saturated source areas are able to produce runoff.

While the α method did not introduce any new parameters, this β method introduces the quantity, L, which characterizes the distance to the onset of swale flow. Note that this β method parameterization is convenient since it provides a bridge between the distributed case and the α method, since $Q_\beta(L = 0) = Q_D$ and $Q_\beta(L = \infty) = Q_\alpha$. This β method will be illustrated and compared to the other methods in the following section.

APPLICATION TO ACTUAL WATERSHEDS AND COMPARISON OF METHODS

It is instructive to compare the results of the methods described earlier with some real watersheds of varying size and composition. Three such watersheds were taken from several locations within the state of Maryland. The same quality of data coverages were used for all three: 30 meter resolution DEMs, 1994 land use (obtained from the Maryland Office of Planning) and SSURGO soils data that has recently come available for several counties within the state of Maryland. In all cases, curve numbers have been determined by meshing land use and soils data to obtain commonly used handbook values (SCS, 1985).

Qualitative Description of Watersheds

Urban Watershed. The Rock Creek watershed drains approximately 60 square miles as it crosses from Maryland into Washington, D.C. At this point the distribution in land uses is approximately 51 percent residential, 9 percent commercial/industrial, 16 percent forest, about 12 percent agriculture, and 12 percent miscellaneous other land use categories. This constitutes a roughly 30 percent degree of imperviousness at the D.C. line. Soil groups are predominantly "B" (76 percent), with 6 percent "C" soils, and 17 percent "D" soils. Approximately 1 percent of the soils remain unclassified due to lakes within the watershed. Curve numbers range from 56-100, with a mean value of 76.8.

Agricultural Watershed. The Pipe Creek watershed is roughly 38 square miles as it drains west near the town of Union Bridge in Carroll County, Maryland. Land use is predominantly agricultural (73 percent), the remainder being approximately 11 percent residential, 0.6 percent commercial/industrial, 12 percent forest, and about 3 percent miscellaneous other land use categories. At this outlet, the watershed is 4.6 percent impervious. The soil drains well: 42 percent "A"soils, 40 percent "B" soils, 16 percent "C" soils, and 2 percent "D" soils. Curve numbers range from 35-100, with a mean value of 71.7.

Forested/Agricultural Watershed. A small branch of the Seneca Creek watershed is roughly 5.3 square miles at its outlet, approximately 1.5 miles due north of the town of Boyds in Montgomery County, Maryland. Land use is evenly divided between forest (46 percent) and agriculture (45 percent), the remainder being approximately 4 percent residential, 2 percent commercial/industrial, and about 3 percent miscellaneous other land use categories. At this outlet, the watershed is 3.1 percent impervious. The soils are not so well drained: approximately 11 percent "B" soils, 24 percent "C" soils, and 65 percent "D" soils. Curve numbers range from 56 to 100 with a mean of 82.0.

Discussion

The results of runoff computations using the aforementioned methods are shown in Table 1 and Figure 6. These results are consistent with the themes presented earlier in this paper: (1) runoff calculated using the distributed method is always greater than the associated lumped runoff, and (2) calculations using the α approach of Equation (5) estimate far less runoff than from either the lumped or weighted approaches. The β method, which introduced the concept of a limited distance of potentially enhanced infiltration, produces a spectrum of results as illustrated in Figure 6. The horizontal axis represents the modeled overland flow distance. It is the physical analog of the SCS (1986) length of "sheet flow" and as such is traditionally assumed to be no more than 300 feet. Interestingly, if this length constraint is imposed on the β method, (see inset in Figure 6 emphasizing the first 500 feet of the horizontal axis) the β method results in smaller runoff depths than predicted by the weighted runoff method and that, in general the β method curve crosses the lumped method value somewhere between $Q_\beta(100)$ and $Q_\beta(300)$. As shown for the Rock Creek watershed, this distance is approximately 150 feet. This finding suggests that all the additional effort that entered into the β approach: the use of DEM data, the tracking of the flow aggregation pattern, and the bookkeeping associated with Equation (5) essentially cancels the increased runoff predictions that resulted from the weighted runoff approach espoused by Grove *et al.* (1998). Although based on only three sample watersheds, this analysis shows a strong agreement between the complex Q_β(100 to 300) and the simple use of the original lumped approach recommended by NRCS.

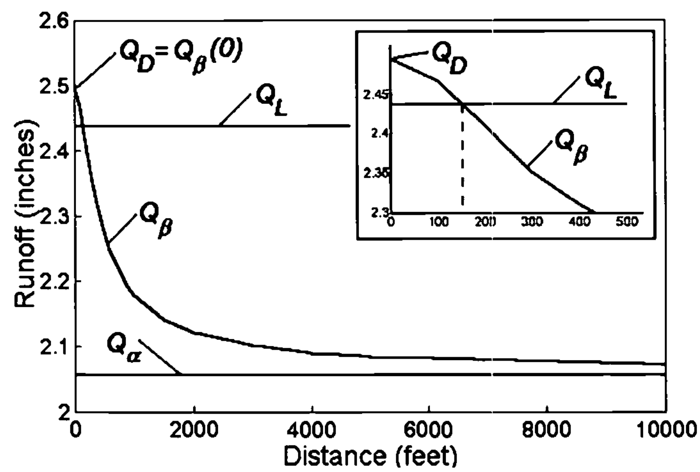

Figure 6. Predicted Runoff, Q_β, From the Rock Creek Watershed as a Function of Overland Flow Length. Note that $Q_\beta(0) = Q_L$, and $Q_\beta(\infty) = Q_\alpha$. Inset shows enlarged view for overland flow distance between 0 and 500 feet.

TABLE 1. Parameters for Study Watersheds.

	Urban Watershed	Agricultural Watershed	Forested/Agricultural Watershed
Drainage Area (mi^2)	59.7	38.2	5.3
Curve Number Range	56-100	35-100	56-100
Average Curve Number	76.8	71.7	82.0
Longest Flow Path (miles)	21.8	13.7	4.1
Lumped Runoff, Q_L (inches)	2.437	2.02	2.90
Distributed Runoff, Q_D (inches)	2.496	2.16	2.93
Procedure 1 Runoff, Q_α (inches)	2.057	1.63	2.61
Procedure 2 Runoff, Q_β (100) (inches)	2.468	2.14	2.91
Procedure 2 Runoff, Q_β (300) (inches)	2.350	2.01	2.81

NOTE: All runoff volumes are in inches and are based on a 24-hour rainfall depth of 4.8 inches. This rainfall depth corresponds roughly to the 10-year event in central Maryland.

PHILOSOPHICAL CONSIDERATIONS

Is it a worthy goal to propose a new or improved way to apply NRCS methods to the problem of hydrologic prediction? Exploiting the information contained in spatially distributed data and the power of GIS-based analyses is intuitively the direction that should lead to greater model accuracy. Conversely, the simplicity and widespread use and success of NRCS methods are not to be discounted. While the temptation to modernize NRCS methods is overwhelming, there is evidence that generalizing lumped models into a spatially distributed form is not a straightforward task (Finnerty *et al.,* 1997). There is also evidence that NRCS methods in their original incarnation can be interpreted to represent varying spatial distributions of curve number and varying runoff producing areas (Hawkins, 1982; Steenhuis *et al.,* 1995; Hawkins, 1996). To the extent that this is the case, the weighted runoff method and the flow aggregation procedures presented here may represent an over-accounting for spatial variability in curve number. Under these conditions, these procedures are an interpretation of NRCS methods taken at too fine a grain. If this is the case, what should be the fundamental scale for curve number determination?

Incorporating spatial variability into the NRCS runoff equation leads to clear biases between the spatially distributed and lumped predictions. Compared to the traditional lumped curve number approach, the analysis recently presented by Grove *et al.* (1998) illustrates a bias producing systematically larger runoff predictions. The new methods presented in this work produce a shift in hydrologic predictions in the opposite direction. Ironically, the two methods applied simultaneously predict runoff values quite similar to those associated with the original lumped model.

Do these modifications to the NRCS model represent a correct adaptation for a spatially distributed model? Is it appropriate at all to endeavor to modify the NRCS methods in this fashion? The results presented here illustrate the consequences of disaggregating a lumped model and attempting to account for spatial variability. One might be encouraged that the results from the β method for reasonable values of overland flow distances did not differ much from the original lumped values. Perhaps this is merely a coincidence. As Klemes (1986) would be quick to point out, it is risky to claim that all salient physics of the runoff production process have been captured in the approach presented here or in any approach. It is not clear whether extending the distributed and β methods to other locations or at higher resolutions will result in the same confluence of results with the lumped approach.

The mention of resolution gives rise to the troubling observation that the methods presented here were examined at a fixed pixel size of 30 meters (approximately 100 feet). The asymptotic relationships described by Equations (8) and (9) depend on repeated application of Equation (5) over many pixels. But if the pixel size were to be reduced from 30 meters to 30 centimeters, for example, these asymptotic relationships would apply 100 times faster even though the physical system is unchanged. This appropriately returns us to the question of existence of a fundamental modeling scale which depends largely on the scale at which the original NRCS curve numbers were developed and reported. As NRCS methods have propagated through time, the curve number tables (SCS, 1985) have persevered but documentation of such fundamental scales has been lost in most engineering texts. The likelihood is, correct or not, modeling will continue to take place at finer and finer scales as data resolution continues to increase.

The results presented in this paper show that attempting to disaggregate a lumped model is a tricky business. Depending on the methods used biases that diverge from the original answer may result. As illustrated by Grove *et al.* (1998) undertaking small "refinements" on existing models can lead to systematic biases in the results. If better data or methods lead to a systematic shift in the results, the approach needs to be questioned. New biases suggest that if the model was calibrated before these changes were instituted then the changes do not represent an improvement. Although an approach like that in Equation (5) contains some more realistic physics, the overall effect may be no more accurate than the original, much simplified approach.

CONCLUSIONS

Distributed modeling techniques applied to the existing curve number method allow for consideration of the orientation of high and low runoff producing areas when determining the runoff from a watershed. One- and two-dimensional examples illustrate how a small modification to the NRCS runoff equation can incorporate the effects of not just spatial variability but spatial orientation in runoff calculations. This modified equation leads to much reduced estimates of runoff depths owing to the possibility of infiltration at each pixel in the path of flow downstream. A constraint, consistent with the NRCS concept of sheet flow, was introduced that limited infiltration to only the first L feet of flow in the watershed where overland flow and infiltration processes dominate. When applied to actual watersheds spanning a range of sizes and land uses, the constrained model performs very similarly to the original, much simpler NRCS lumped model for accepted values of L.

These results suggest revisiting the original objective of modernizing the NRCS curve number method. Attempting to build a spatially distributed runoff model from a model originally conceived in a lumped fashion was shown to introduce biases in runoff prediction away from the original lumped runoff estimates. There is a need to be wary of the impact of changes in the modeling approach on the derived answer. Given a calibrated model, if a new approach systematically changes the answer in a single direction, the value of this new approach needs to be questioned. As presented here, refinements presented by two different groups led to systematic biases in opposite directions that tended to cancel each other out. Although more physically-based, the direct modeling of spatially distributed curve numbers and the incorporation of flow aggregation processes led to essentially the same results as the simplified, lumped approach.

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