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AREAL EFFECTIVE INFILTRATION DYNAMICS FOR RUNOFF OF SMALL CATCHMENTS

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INTRODUCTION

Soils of natural catchments are characterized by spatially variable infiltration properties, often with significant differences over relatively short distances. Because of the highly nonlinear nature of the infiltration process, the areal mean value of infiltration parameters cannot describe the net performance of a catchment. (Woolhiser and Goodrich, 1988; Binley et al., 1989).

We studied the net effective time pattern of infiltration of a small catchment with randomly distributed infiltration rate, subject to a spatially uniform but time varying rainfall. Important spatial interactions may be observed if areas with high infiltration rates lie downstream of areas with low infiltration rates. We examined these effects, and compared several methods to treat runoff from variably infiltrating catchments. Our objective is to compare several different methods used to represent a catchment with spatially variable runoff, in light of the interaction of rainfall intensity, mean infiltration, and variablity shown by previous investigators (Smith and Hebbert, 1979; Woolhiser and Goodrich, 1988)

METHODS

An experimental version of the runoff model KINEROS was employed for these studies (Woolhiser et al. 1990). Using this runoff model, the spatial variation of infiltration was treated in different ways, described below. KINEROS accurately reflects the surface hydraulics for cascaded networks of rectangular shaped surfaces, provided the criteria for kinematic hydraulics are met.

We assume that for any point on the area of interest the infiltration pattern is described by the analytically derived (Smith and Parlange, 1978) function

$$f = K_s \exp(I/G)/[\exp(I/G)-1] \qquad (1)$$

where f is infiltration flux, I is water depth infiltrated since the beginning of the event, K_s is effective saturated hydraulic conductivity, and G is a parameter reflecting capillary properties and initial water content. This study focuses on the effect of spatial variations in K_s, because it is the most sensitive infiltration parameter. The joint distribution of G and K_s is not considered, since Springer and Cundy(1987) showed for runoff from hillslopes with spatially-variable infiltration parameters that G could be set to mean values with essentially no effect if the variation in K_s is properly represented. Field measurements indicate that a lognormal distribution is acceptable for representing the spatial variability of K_s (Nielsen et al., 1973; Rogowski, 1972; Sharma et al., 1980)

<u>Composite (non-interactive) Analysis</u>. We can obtain analytic results if we assume that runoff from one area will not affect the effective infiltration at another. When a uniform rainfall rate, r, falls on a surface with K_s distributed with density function $p(K_s)$, part of the area will have $K_s > r$ and will have no runoff, and part will have runoff defined by Eq. (1). The expected value of K_s over the area is denoted by K_e, and is found as

$$K_e = [1-P_k(r)]r + P_k(r)E_r(K_s) \qquad (2)$$

in which P_k is the cumulative distribution of K_s, and E_r is the expected value of K_s over the region $r > K_s$. With $p(K_s)$ representing the probability density function of K_s, $E_r(K_s)$ is found to be

$$E_r(K_s) = \int_0^r p(K)KdK/ \ P_k(r) \qquad (3)$$

If Eq. (1) applies at each point, we can represent the net dynamic infiltration curve for the area with a Latin hypercube method. In this method, the ensemble net value is found as the sum of n parts, each represented by a value of the distributed variable which corresponds to the mean of a fraction 1/n of the cumulative distribution function. We define a scaled infiltration rate $f_* = (f-K_e)/(r-K_e)$. Then from the numerical results we find an ensemble effective value for f_* to be

$$f_* = \frac{f-K_e}{r-K_e} = \left\{ 1 - \left[\frac{(r-K_e)[\exp(I/G)-1]}{K_e} \right]^a \right\}^{-1/a} \qquad (4)$$

in which a is $1.5/c_v$, and c_v is the coefficient of variation of K_s. c_v cannot be zero, but Eq. (1) is the limit of Eq. (4) as c_v approaches zero. Figure 1 shows this curve for several values of c_v. Sivapalan and Wood (1986) obtain comparable results for uniform rain on variable soils using a modified version of Philip's infiltration relation. Some previous studies of variable runoff surfaces have taken local runoff directly to the stream with some time delay but without runon interaction (Binley, <u>et al.</u>, 1988, and Freeze, 1980). Those simple routing methods are related to this composite analysis, with the addition that the composite function Eq. 4 is effectively convoluted by a uniform distribution representing the probability of a given point being a certain distance from the bottom of the runoff area. Eq. (4) is not theoretically suitable for unsteady rainfall rates, and does not include runon interaction, so we do not expect it to compare favorably with methods applicable to variable rain patterns on a surface.

A runoff simulation method for spatially variable K_s which treats variable rain rates but does not simulate runon interaction was used by Woolhiser and Goodrich(1988). The Latin hypercube division of the cumulative distribution is used on the runoff surface to divide the flow surface into n equal strips, each exhibiting a homogeneous subvalue of K_s. Runoff from the surface is obtained by summing the runoff from each strip. This method, hereinafter referred to as W-G strips, effectively composites runoff after nonlinear surface routing, rather than at the point of production, as in Eq. (4). Using this method in a research version of KINEROS, we determined

that 10 strips is an adequate number to represent the distribu-
tion of K_s and is within a few percent of the results using 50
strips. The conceptual weakness of the W-G strip model of a
catchment surface is that it presumes homogeneity along flow
paths, such that the lowest K_s sites will be located along one
path, and conversely all the high K_s sites will be similarly
situated.

    Interactive Surface Runoff Simulation. In this model K_s
varies with the same distribution along the flow path as it
does across flow paths. KINEROS was modified to allow specifi-
cation of a lognormally distributed random K_s for each of as
many as 50 points along the length of surface flow, and using
as many as 20 strips to represent separate flow portions of a
catchment surface. The parallel strips are not required for
representing a distribution, as for the W-G method, but reduces
sampling statistical error. Provision was made to allow spatial
correlation along the flow path if desired. The same variabil-
ity of K_s can be applied to this model as to the W-G model for
comparison of a range of storms and relative values of storm
intensity. We wished to see if the result of Woolhiser and
Goodrich(1988), in which bias was inverted for relatively large
storms as compared with small ones, was true for interactive
model representations of variable f.

                              RESULTS

    We did not examine enough variables to make general conclu-
sions regarding treatment of variability in runoff modelling.
Some of the biases of simpler methods can nevertheless be il-
lustrated here. The following illustrations use two storms
measured on the Walnut Gulch, Arizona experimental watershed.
    Figure 2 shows comparison of hydrographs calculated using
the three methods of treating variability. The catchments used
here are hypothetical simple planes, divided into 10 strips for
the W-G strip method, and into 10 strips of 30 points each for
the runon model.
    Compared to the interactive model simulation, the uniform
model underestimates the runoff peak and the composite model
overestimates it. Because runon can effectively accelerate
ponding in high K_s zones from upslope zones of lower K_s, the
composite model cannot properly treat runoff from surfaces with
distributed infiltration. Use of the W-G strip model may
overemphasise the nonlinearity of the runoff production pro-
cess, and overestimate the peak and runoff volume from the
variable surface. The band of shading around the results from
the interactive model in Figure 2 illustrates the spread of
different results from 10 different realizations of the 600
points used on the surface. This shows that even with 20
strips, the sampling error for any random realization can ef-
fect the results when runoff is a small fraction of the rain-
fall.
    Woolhiser and Goodrich (1988) demonstrated a "crossover" ef-
fect when hydrographs obtained by the W-G method were compared
with uniform (c_v=0) surfaces. For some storms the uniform sur-
face produced higher peaks than the W-G method for low mean in-
filtration rates, and lower peaks when the infiltration rate
was increased. Figures 3 and 4 illustrate cases taken from
Figure 12 of Woolhiser and Goodrich (1988). The catchment
length is 91.4 m., and K_e was 3.4 or 0.35 mm/hr. In these fig-

ures, c_v is either 0 or 1 (in the earlier work, c_v was 0, 0.4, or 0.8). Note that the interactive method does not exhibit the "crossover" effect. In all cases the interactive method leads to higher peak rates than the uniform surface. In Figures 3 and 4 the W-G method uses 10 strips instead of 5 in the earlier work, and some modifications have been made in the infiltration algorithm. Although the "crossover" effect is still apparent, it is considerably reduced compared to the effect demonstrated in the earlier paper.

Another factor in the relation between spatial variability and runoff is the ratio of the surface length to the soil correlation length. The spatial interaction of runoff on a variably infiltrating plane serves to attenuate the differences in infiltration between points. Attenuation of peaks in slope hydrographs is also effected by plane length, so an interaction of plane length and variability would be expected. Further, the longer surface will exhibit a greater number of sample infiltrating points, given a constant soil correlation length, and thus have a greater probability of interactive attenuation. Figure 5 shows hydrographs obtained from uniform surfaces of 30.5 and 91.4 m. length, as well as variable infiltrating surfaces of the same length, using storm 4. These tests maintained an effective correlation length for the surface soil of 4.5 m, consistent with published values (Wagenet, 1981). Hydrograph peaks are considerably greater for the short planes, in either case. Addition of spatial variability, however, causes greater changes in hydrograph shape and peak location for the short planes than for the long ones.

CONCLUSIONS

We have extended somewhat our understanding of the role that spatially variable infiltration plays in watershed response, and its relation to slope length, and ratio of storm intensity to infiltration capacity. Earlier results, showing that effects of variability are greater for relatively lower intensity storms are confirmed by this work. Using a non-interactive runoff model is gives results considerably different from non-interacting models. Length of runoff surface interacts with correlation scale of K_s in determining the effect of variability on the hydrograph for a given storm. These results suggest the study of natural distributions of lengths of surface flow prior to flow concentration, as related to correlation scales of infiltation properties. Flow concentration, such as in small surface rills, should limit the runon type of interaction, and determine the extent to which catchment runoff is influenced by the interactive effects demonstrated here. We plan to pursue studies of such microtopographic influences, hoping to be able to characterise the significant variables involved in the role that small scale variability plays in shaping surface hydrology.

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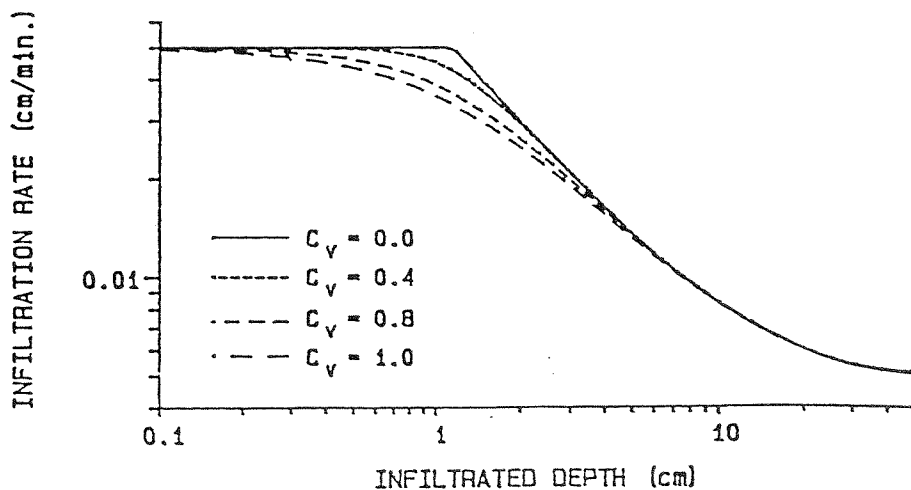
Figure 1. Example curves of composite infiltration for lognormally distributed K_s. c_v of K_s varies from 0. to 1.
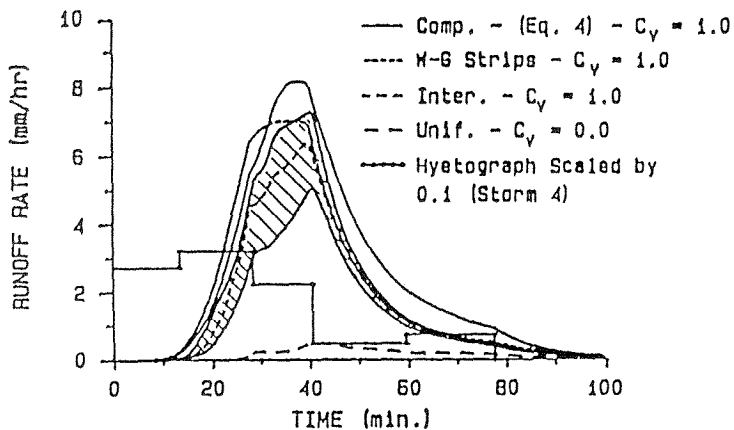
Fig. 2. Comparison of methods to simulate spatially variable infiltration in surface runoff.
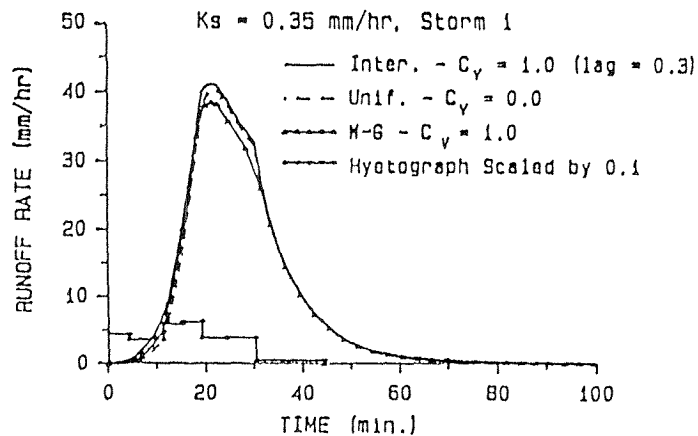

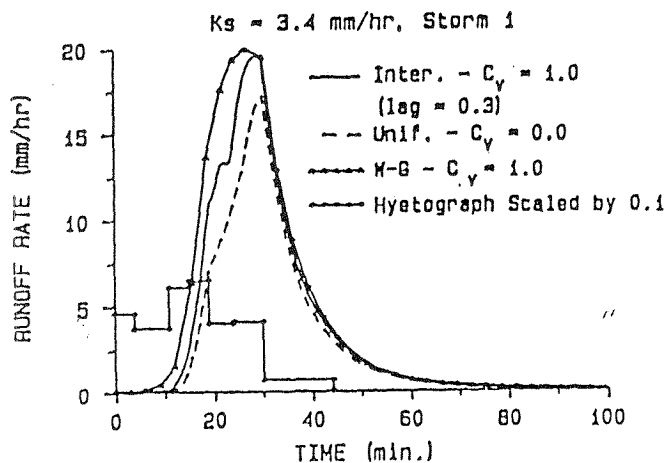Fig. 3. Effect of spatial variation for the Woolhiser-Goodrich (1988) case, with lower mean K_s.

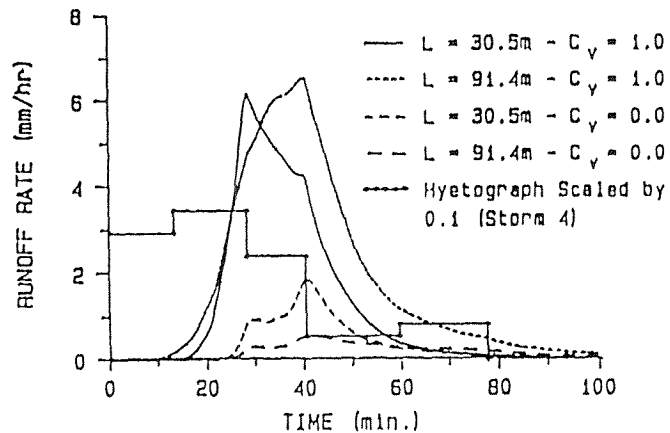Fig. 4. Same storm as Fig. 3, except that K_s is larger, and runoff is more sensitive.

Fig. 5. Comparitive effect of slope length and spatial variation on simple surface runoff.