

Stochastic–conceptual analysis of near-surface hydrological response

Keith Loague* and Robert H. Abrams

Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305, USA

Abstract:

The stochastic–conceptual rainfall–runoff simulator (SCRRS) developed by R. A. Freeze in 1980 was used in this study to demonstrate quantitatively the interplay of the factors that control the occurrence of overland flow by the Horton and Dunne mechanisms. The simulation domain and input data for the SCRRS simulations reported here were abstracted from the R-5 catchment (Chickasha, OK) data sets. The results illustrate that the identification of a dominant hydrological response process may not be as simple as a singular Horton or Dunne characterization. The SCRRS simulations show that the Horton and Dunne processes can (i) occur simultaneously at different locations during a given rainfall event, (ii) change from one process to the other with time depending on the characteristics of the rainfall event, and (iii) be strongly dependent on the initial conditions. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS Dunne overland flow; Horton overland flow; near-surface hydrological response; R-5 catchment; spatial variability; stochastic–conceptual simulation

INTRODUCTION

The stochastic–conceptual rainfall–runoff simulator (SCRRS) developed by Freeze (1980) was used in this study, in the spirit of the ‘game’ pioneered by Freeze, to investigate hydrological response at and near the surface. The SCRRS was designed to both (i) generate conceptually sound near-surface hydrological systems and (ii) analyse the response of these hypothetical realities to different inputs. The calculations that comprise a given SCRRS experiment are made up of analytical and numerical solutions to a specified near-surface boundary-value problem. Freeze (1980) used SCRRS to investigate the influence of spatial stochastic properties on the statistical properties of simulated rainfall–runoff events at the hillslope scale (also see Loague and Freeze, 1988). Following Freeze’s original application, there have been two more applications of SCRRS: Loague (1988a) used SCRRS to investigate the worth of hydrological data in simulating rainfall–runoff events; and Loague (1988b) used SCRRS to investigate the impact of equally likely realizations of a single stochastic process in characterizing hydrological response. Each of the prior applications of SCRRS were for generic hillslopes constructed with information gleaned from several sources.

The objective of the study reported here was to characterize quantitatively the factors controlling the occurrence of overland flow using SCRRS. In contrast with previous SCRRS efforts, the purpose of this study was to base the simulations on a well-studied field site. The information used to drive the SCRRS in this study was from the R-5 catchment, Chickasha, OK.

Overland flow

Overland flow is generated after surface ponding has occurred. Based upon careful field experiments (e.g. Horton, 1933; Dunne and Black, 1970a, b) and heuristic simulations (e.g. Freeze, 1972a, b; VanderKwaak

*Correspondence to: K. Loague, Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305, USA.
E-mail: keith@pangea.stanford.edu

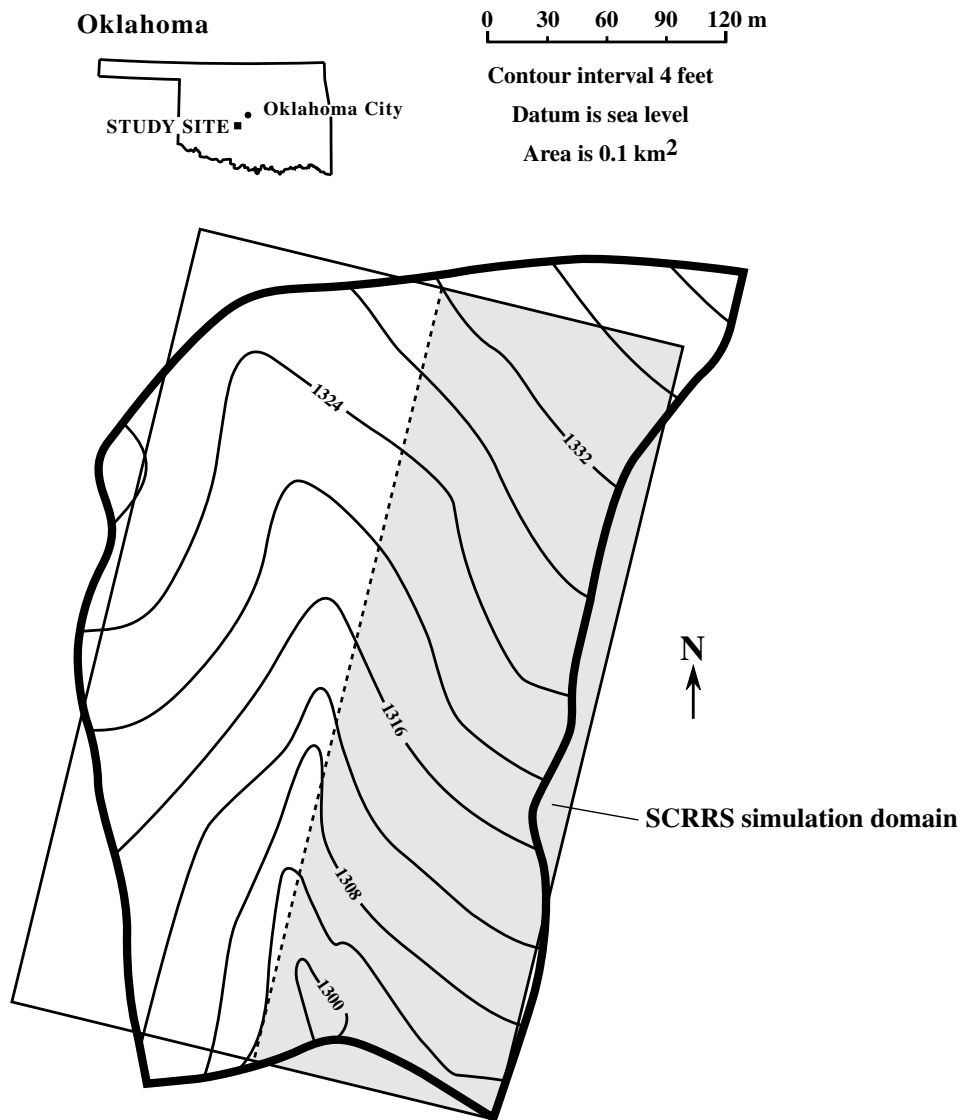


Figure 1. The R-5 catchment showing the SCRRS simulation domain

and Loague, 2001), it is now well known that overland flow resulting from surface saturation can occur by two distinct mechanisms: Horton and Dunne. For the Horton mechanism, the rainfall intensity must exceed the saturated hydraulic conductivity of the surface soil for a period of time long enough for ponding to occur. For the Dunne mechanism, the duration of rainfall, at an intensity less than the saturated hydraulic conductivity, must exceed the period of time necessary for an initially shallow water table to rise to the surface. In general, Horton overland flow is more common on the upslope areas within a catchment (generated from areas where infiltration rates are the lowest), whereas Dunne overland flow is more common in near-channel lowlands (originating from areas where the water table is shallowest). Both the Horton and Dunne mechanisms can lead to variable source areas that expand and contract through wet and dry periods.

The R-5 catchment

The 0.1 km² R-5 catchment (Figure 1) is located approximately 18 km north-east of Chickasha, OK in rolling prairie grassland that has been subjected to continuous, well-managed grazing for many decades. The combined data sets for the R-5 catchment contain a significant amount of spatial and temporal information [e.g. infiltration (Sharma *et al.*, 1980; Loague and Gander, 1990; Loague and Kyriakidis, 1997); soil-water content (Jackson *et al.*, 1981; Loague, 1992a); soil texture (Loague, 1992b); porosity (Loague, 1986); vegetation (Loague and Gander, 1990); and rainfall, runoff, sediment yield, and temperature (Loague, 1990; Loague and Freeze, 1985; USDA-ARS, 1983)]. Loague *et al.* (2000a) provide a summary of the research that has been conducted at R-5 (also see Loague *et al.*, 2000b). The selection of R-5 as the source of information for the SCRRS simulations reported here was ideal as both the Horton and Dunne mechanisms are now believed (see VanderKwaak and Loague, 2001; Loague and VanderKwaak, in press to be important hydrological response processes for the catchment).

STOCHASTIC-CONCEPTUAL RAINFALL-RUNOFF SIMULATOR

Overview

The overview in this section is a summary of the complete description of the stochastic-conceptual rainfall-runoff simulator (SCRRS) given by Freeze (1980). To ease any cross-referencing between the current study and past efforts, the notation in this presentation is carried over from the earlier papers. A SCRRS simulation in the study reported here involves tracking a rainfall event across the region of interest and calculating the resulting hydrological response. One complete synthetic data set involves the simulation of an ensemble of rainfall-runoff events. The region of interest is discretized into a set of square elements. The time-independent, spatially variable parameters (e.g. saturated hydraulic conductivity) and the time- and space-dependent variables (e.g. rainfall intensity) are generated from a set of simulated stochastic processes. Hydrological response, in the form of the Horton and Dunne mechanisms, is calculated on the basis of a distributed set of physically based equations that represent the processes for the region of interest.

To explain the application of SCRRS it is necessary first to introduce both time-independent porous media parameters and time-dependent porous media and rainfall variables. The time-independent parameters are defined on a two-dimensional spatial grid (Figure 2) with subscripts $i = 1, 2, \dots, I$ in the x direction and $j = 1, 2, \dots, J$ in the y direction. The space increments in the x and y directions are Δx and Δy . The time-dependent variables that are calculated at each time-step of each rainfall event are defined over time intervals with superscripts $m = 1, 2, \dots, M$. The time interval is Δt . The algorithm used by SCRRS to generate all of the two-dimensional fields of autocorrelated variables and parameters utilizes a random variable with a distribution that is the radial spectral distribution function. The statistical parameters used to generate the autocorrelated values are the mean μ , the standard deviation σ , and the autocorrelation parameter α . The two-dimensional fields generated in this study are assumed to represent element-scale properties rather than point measured properties. The topographic elevation z_{ij} (L) for the region of interest has an average slope a (L/L). The average initial water table configuration z'_{ij} (L) is assumed to be elliptical in shape, with an average slope b (L/L). The unsaturated soil depth z''_{ij} (L) for the region of interest is given by $z''_{ij} = z_{ij} - z'_{ij}$. The proportion of annual rainfall recharging the saturated zone is denoted as c (0).

The SCRRS utilizes a stochastic rainfall generator and allows for the generation of overland flow by both the Horton and Dunne mechanisms. The rainfall generation scheme produces a storm that moves laterally across the region of interest, parallel to the stream channel. The storm velocity U (L/T) is constrained in this study to the x (upstream) direction. The infiltration algorithm is for time-varying rainfall. In past applications of SCRRS (Freeze, 1980; Loague, 1988a,b), the routing of overland flow (from the element in which it is generated to the channel) was treated as a simple stochastic travel time, with base flow taken as constant, based upon Dupuit-Forchheimer theory, for the duration of each runoff event. For the effort reported here,

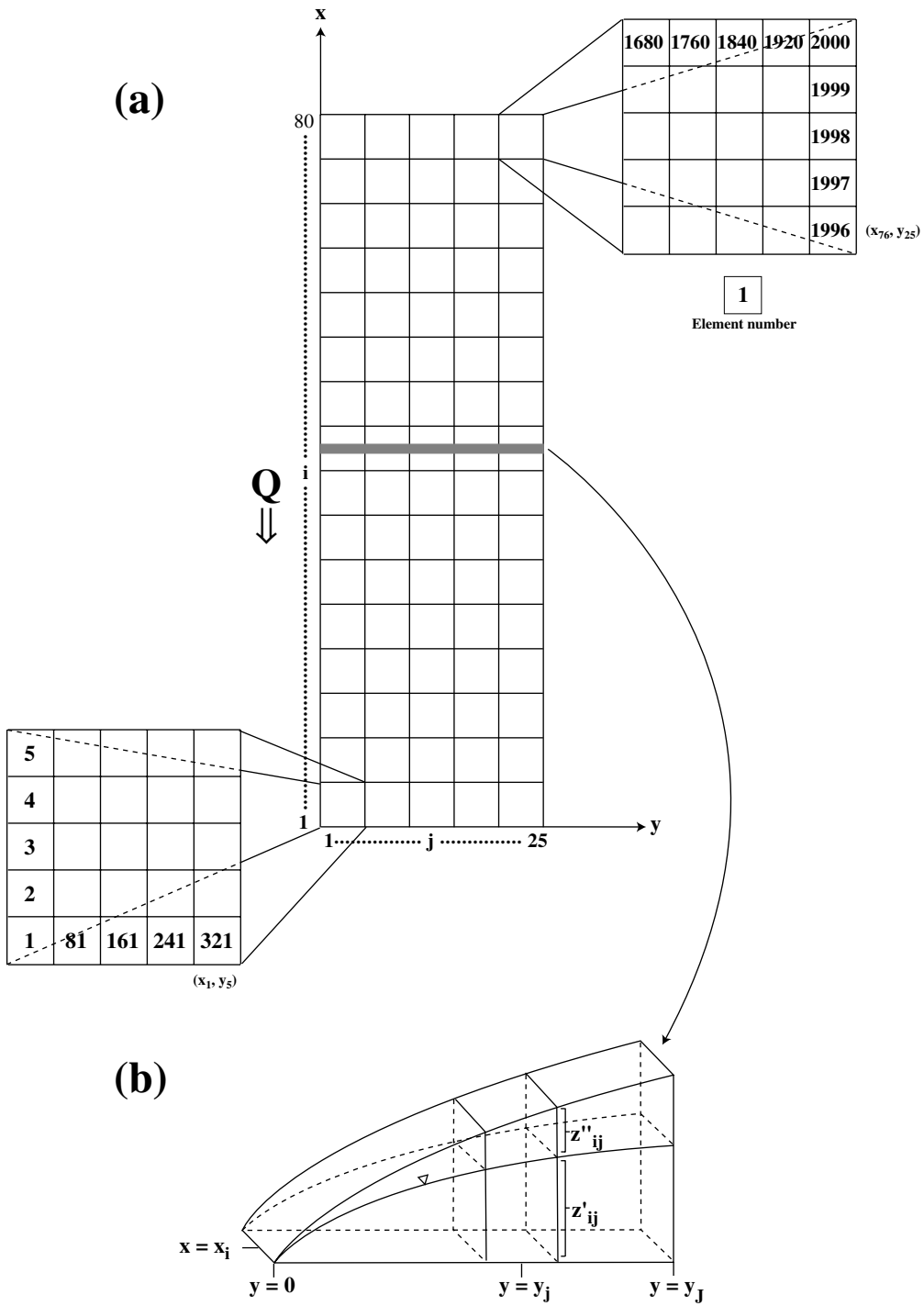


Figure 2. The SCRRS representation of one half of the R-5 catchment (see Figure 1). (a) Two-dimensional grid ($\Delta x = \Delta y = 5$ m) with 2000 elements. (b) Vertical cross-section, perpendicular to the stream channel as indicated by the stripe in (a)

the routing of overland flow (the weakest component of SCRRS) was not considered. The elements within the grid are independent of each other in this study. Once the region of interest is generated, SCRRS treats the water balance calculations for each element individually.

Overland flow

The calculation of rainfall excess with SCRRS under the Dunne mechanism is straightforward. The calculation of rainfall excess with SCRRS under the Horton mechanism follows the methodological approach of Smith and Parlange (1978). The calculations used to determine if Horton or Dunne overland flows occur in a SCRRS simulation are carried out sequentially with the following five-step procedure:

1. The first step is to check if the ponding time has been exceeded at (x_i, y_j) at time t^m owing to the Dunne mechanism; for $t^m > t_{ij}^p$, where t^m is the current time-step in the simulation and the variable t_{ij}^p (T) is the time until ponding at (x_i, y_j) , this condition is given by

$$\Delta x \times \Delta y \times \int_0^{t^m} p_{ij}(t) dt > S_{ij}^0 \quad (1)$$

where p_{ij} (L/T) is the rainfall intensity and S_{ij}^0 (L^3) is the initial soil-water content.

2. If $t^m > t_{ij}^p$ owing to the Dunne mechanism, the rainfall excess r_{ij}^m (L^3) is given by

$$r_{ij}^m = p_{ij}^m \times \Delta x \times \Delta y \times \Delta t \quad (2)$$

3. If $t^m < t_{ij}^p$ owing to the Dunne mechanism, SCRRS checks to see if the ponding time has been exceeded as a result of the Horton mechanism; for $t^m > t_{ij}^p$, two conditions must be met

$$p_{ij}^m > K_{ij}^s \quad (3)$$

and

$$\int_0^{t^m} p_{ij}(t) dt > B_{ij} \times (n_{ij} - \theta_{ij}^0) \times \ln \left[\frac{p_{ij}^m}{p_{ij}^m - K_{ij}^s} \right] \quad (4)$$

where K_{ij}^s (L/T) is the saturated hydraulic conductivity, n_{ij} (L^3/L^3) is the porosity, θ_{ij}^0 (L^3/L^3) is the initial soil-water content (assumed to hold throughout the depth z_{ij}'' and to decline exponentially from the maximum soil-water content), and B_{ij} (L) is the soil-water storage parameter, given by

$$B_{ij} = G_{ij}(n_{ij} - \theta_{ij}^0) \quad (5)$$

where G_{ij} (L) is the net capillary drive (an intrinsic property of the soil), given by

$$G_{ij} = \frac{s_{ij}^2}{2K_{ij}^s(n_{ij} - \theta_{ij}^0)} \quad (6)$$

where s_{ij} ($L/T^{1/2}$) is Philip's (1969) sorptivity.

4. If $t^m < t_{ij}^p$ for both mechanisms, the rainfall excess is given by

$$r_{ij}^m = 0 \quad (7)$$

5. If $t^m > t_{ij}^p$ owing to the Horton mechanism but not the Dunne mechanism, the rainfall excess is given by

$$r_{ij}^m = (p_{ij}^m - f_{ij}^m)\Delta x \times \Delta y \times \Delta t \quad \text{for } p_{ij}^m > f_{ij}^m \quad (8)$$

and

$$r_{ij}^m = 0 \quad \text{for } p_{ij}^m < f_{ij}^m \quad (9)$$

where f_{ij}^m (L/T) is the infiltration rate at (x_i, y_j) at time t^m , given by

$$f_{ij}^m = C_{ij}(t^m - t_{ij}^0)^{-1/2} + K_{ij}^s \quad (10)$$

where C_{ij} (L/T^{1/2}) is the infiltration coefficient (similar to s_{ij}), given by

$$C_{ij} = 0.3[2K_{ij}^s \times B_{ij} \times (n_{ij} - \theta_{ij}^0)]^{1/2} \quad (11)$$

and t_{ij}^0 (T) (which can be viewed as the vertical asymptote of the infiltration curve) is given by

$$t_{ij}^0 = t_{ij}^p - \left[\frac{C_{ij}}{p_{ij}^p - K_{ij}^s} \right]^2 \quad (12)$$

Summary

The application of SCRRS as used in this study is represented, in general, by the five-stage procedure outlined in Table I. With this five-stage procedure, N near-surface hydrological response realizations are simulated with SCRRS, using a Monte Carlo approach, for the region of interest. The values of z_{ij} , z'_{ij} , z''_{ij} , θ_{ij}^0 , K_{ij}^s , n_{ij} , B_{ij} and S_{ij}^0 are known for each element of the region of interest, and the values of p_{ij}^m , f_{ij}^m and r_{ij}^m are known for each element for each time-step of each event.

The simplifying assumptions upon which the SCRRS simulations reported here are based lead to some underlying deficiencies in the approach. The principal shortcomings of SCRRS related to this study are listed

Table I. Five-stage procedure for the application of SCRRS in this study (after Freeze, 1980)

Stage	Procedure
I	Generate the time-independent hillslope parameters. These are the topographic elevation z_{ij} , the saturated hydraulic conductivity K_{ij}^s (L/T), the porosity n_{ij} (L ³ /L ³) and the soil-water storage parameter B_{ij} (L)
II	Generate the external properties for each rainfall event. These are the time since the previous storm τ (T), the storm duration D (T), the storm velocity U (L/T) and the total storm rainfall depth H (L)
III	Generate the initial hillslope conditions for each event. These are the water table elevation z'_{ij} (L), the unsaturated soil depth z''_{ij} (L), the initial soil-water content θ_{ij}^0 (L ³ /L ³) and the initial soil-water deficit S_{ij}^0 (L ³)
IV	Generate the internal rainfall intensity pattern p_{ij}^m (L/T) for each time step of each event
V	Calculate the infiltration rate f_{ij}^m (L/T) and the rainfall excess r_{ij}^m (L ³) for each time step of each event

Table II. Shortcoming of SCRRS as related to this study

The analyses are event-based in which the events are independent
There is no evapotranspiration algorithm
The representation of the water-table configuration does not include consideration of a seepage face
The position of the water table during an event is not tracked
There is no accounting for reinfiltration (run-on) losses, that might occur for the microchannels that deliver overland flow to the stream
The treatment of topography is limited to convex hillslopes
The hydrological parameters are not generated with a multivariate process
There is no accounting for stream bank-to-hilltop variations in geological deposition patterns, soil morphology, or soil-vegetal interactions

in Table II. Assuming one is willing to accept the representativeness of SCRRS, the approach can provide great insight into the non-intuitive interplay between the factors that control the generation of Horton and Dunne overland flow.

INPUT PARAMETERS

The region of interest (i.e. the simulation domain in Figure 1) for the SCRRS simulations in this study is an abstraction of one-half of the R-5 catchment. The control parameters for the SCRRS simulations in this

Table III. Information used for the SCRRS simulations in this study

Input parameters	Symbol ^a	Dimensions	Values	Sources of information
Hillslope :				
Topographic slope	a	L/L	0.03	R-5 ^b
Topographic residual (standard deviation)	σ_z	L	0.05	Freeze (1980)
Topographic residual (autocorrelation parameter)	α_z	0	0.03	Freeze (1980)
Log hydraulic conductivity (mean)	μ_Y	log L/T	-4.93 m s ⁻¹	R-5
Log hydraulic conductivity (standard deviation)	σ_Y	log L/T	0.37 m s ⁻¹	R-5
Log hydraulic conductivity (autocorrelation parameter)	α_Y	0	1.0	R-5
Porosity (mean)	μ_n	L ³ /L ³	0.48	R-5
Porosity (standard deviation)	σ_n	L ³ /L ³	0.03	R-5
Porosity (autocorrelation parameter)	α_n	0	1.0	R-5
Soil-water content storage (mean)	μ_B	L	0.07 m	R-5
Soil-water content storage (standard deviation)	σ_B	L	0.03 m	R-5
Soil-water content storage (autocorrelation parameter)	α_B	0	1.0	R-5
Initial soil-water content conditions:				
Initial soil-water content, decay parameter	d_1	1/L	3.0 × 10 ⁻¹ m ⁻¹	Freeze (1980)
Initial soil-water content, decay parameter	d_2	1/T	6.0 × 10 ⁻⁷ s ⁻¹	Freeze (1980)
Initial soil-water content residual (standard deviation)	σ_θ	L ³ /L ³	0.02	Freeze (1980)
Storm and rainfall:				
Time between storms (mean)	μ_τ	T	3.61 × 10 ⁶ s	R-5
Storm duration (mean)	μ_D	T	2.10 × 10 ³ s	Fit
Total storm rainfall depth (mean)	μ_H	L	3.07 × 10 ⁻² m	R-5
Storm velocity (mean)	μ_u	L/T	0.1 m s ⁻¹	Freeze (1980)
Storm velocity (standard deviation)	σ_u	L/T	0.02 m s ⁻¹	Freeze (1980)
Depth-duration relationship	$\mu_a(t), \sigma_a(t)$	0	see Figure 7 ^c	Freeze (1980)
Rainfall intensity pattern (autocorrelation parameter)	α_ρ	0	0.15	Freeze (1980)

^a The same notation was used by Freeze (1980), Loague and Freeze (1988) and Loague (1988a,b).

^b The source of most of information (listed here as R-5) is from, or abstracted from, the first author's past efforts with the R-5 catchment (see Loague, 1990, 1992a,b; Loague and Freeze, 1985; Loague and Gander, 1990; and Loague and Kyriakidis, 1997). Note, some of the information used in this study has not been published previously.

^c Freeze (1980).

study are set as follows: $N = 100$; $\Delta t = 100$ s; $M = 1000$; $I = 80$; $J = 25$; and $\Delta x = \Delta y = 5$ m. The input parameters for the SCRRES simulations in this study are given in Table III. The input data for the SCRRES simulations in this study were, whenever possible, from R-5 data sets. The information needed for the SCRRES simulations in this study that was not available from the R-5 data sets was taken from Freeze (1980).

Eleven different values of c , the proportion of annual rainfall recharging the saturated zone, were used for the SCRRES simulations in this study (i.e. $c = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$ and 1.0). The spatial distribution of the initial soil-water content for the simulation domain for five different values of c is shown in Figure 3a. The relationship between c and the initial soil-water content of the simulation domain is straightforward; higher recharge, greater initial soil-water content.

For each of the 11 values of c , 100 SCRRES simulations were performed (i.e. a total of 1100 simulations). The SCRRES simulations in this study were fit to the average observed R-5 storm rainfall depth by adjusting the mean and maximum storm duration. For the 1100 SCRRES simulations, the storm trajectory on the R-5-like catchment was in the upstream direction with the maximum storm velocity set at 0.2 m s^{-1} (after Freeze, 1980).

RESULTS

The results from 1100 SCRRES simulated events, using the same realizations of near-surface soil-hydraulic properties (e.g. K_{ij}^s , n_{ij} , B_{ij}), are summarized in Figures 3 to 5 and Table IV. Figures 3 to 5, for SCRRES simulated events with different values of c , show overland flow source summaries (Figure 3b), elements with Horton (Figure 4a) or Dunne (Figure 4b) overland flow, elements with no overland flow (Figure 4c), and a summary of the dominant overland flow response for each element within the simulation domain (Figure 5a). Perusal of the results in Figures 3 to 5 leads to the following eight generalized comments, related to the SCRRES simulations of near-surface hydrological response for the region of interest based upon information from the R-5 catchment.

1. The spatial variability of near-surface soil-hydraulic properties (over a relatively small range of values) and the position of the water table controlled the simulated hydrologic response.
2. The number of elements with overland flow increased as the depth to the water table decreased (see Figure 3b).
3. The number of elements with Horton overland flow decreased as the depth to the water table increased (see Figure 4a).
4. The number of elements with Dunne overland flow increased as the depth to the water table decreased (see Figure 4b).
5. The number of events generating Dunne overland flow was greater for elements closer to the channel (see Figure 4b).
6. The number of elements not generating overland flow was greater as the depth to the water table increased (see Figure 4c).
7. The dominant overland flow mechanism changed from Horton to Dunne as the depth to the water table decreased (see Figures 4a, 4b and 5a).
8. The placement of the initial water table is extremely important for separating the contributions of Horton versus Dunne overland flow (see Figures 4a, 4b and 5a).

Figure 5b illustrates, for three SCRRES simulated events (numbers 11, 33, 88), that for the same simulation domain (i.e. K_{ij}^s , n_{ij} , B_{ij} and $c = 0.5$) the hydrological response can be dominated by Horton overland flow (event 11), Dunne overland flow (event 88), or no overland flow response at all (event 33). Depending upon the rainfall intensity and the duration of the storm the dominant overland flow process could change from, for example, Horton to Dunne, within a single event. The occurrence and dominance of one overland flow

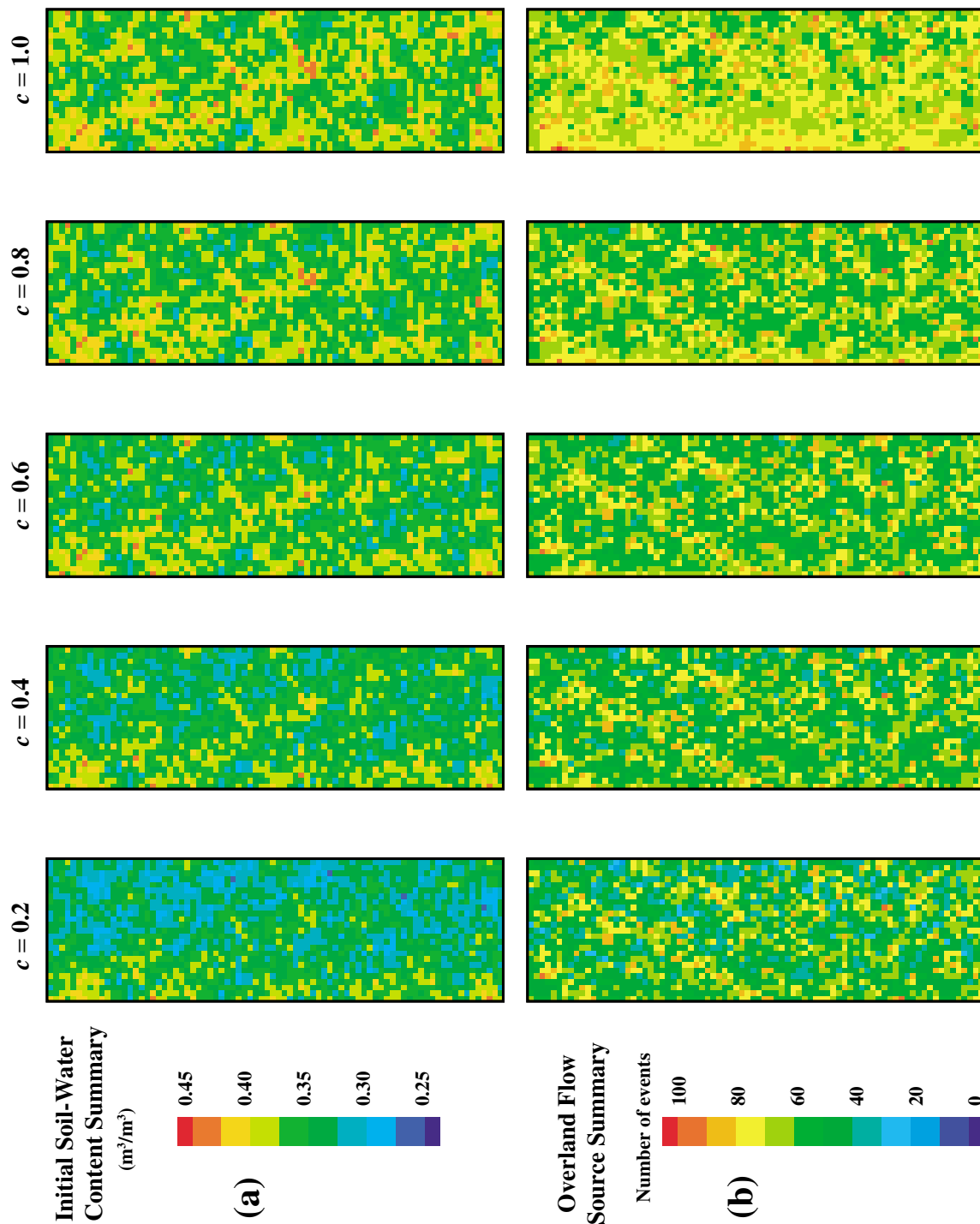


Figure 3. (a) Initial soil-water content (θ_{ij}^0) summary within the simulation domain for different values of c . (b) Overland flow source summary for 100 SCRRS events across the simulation domain with different values of c

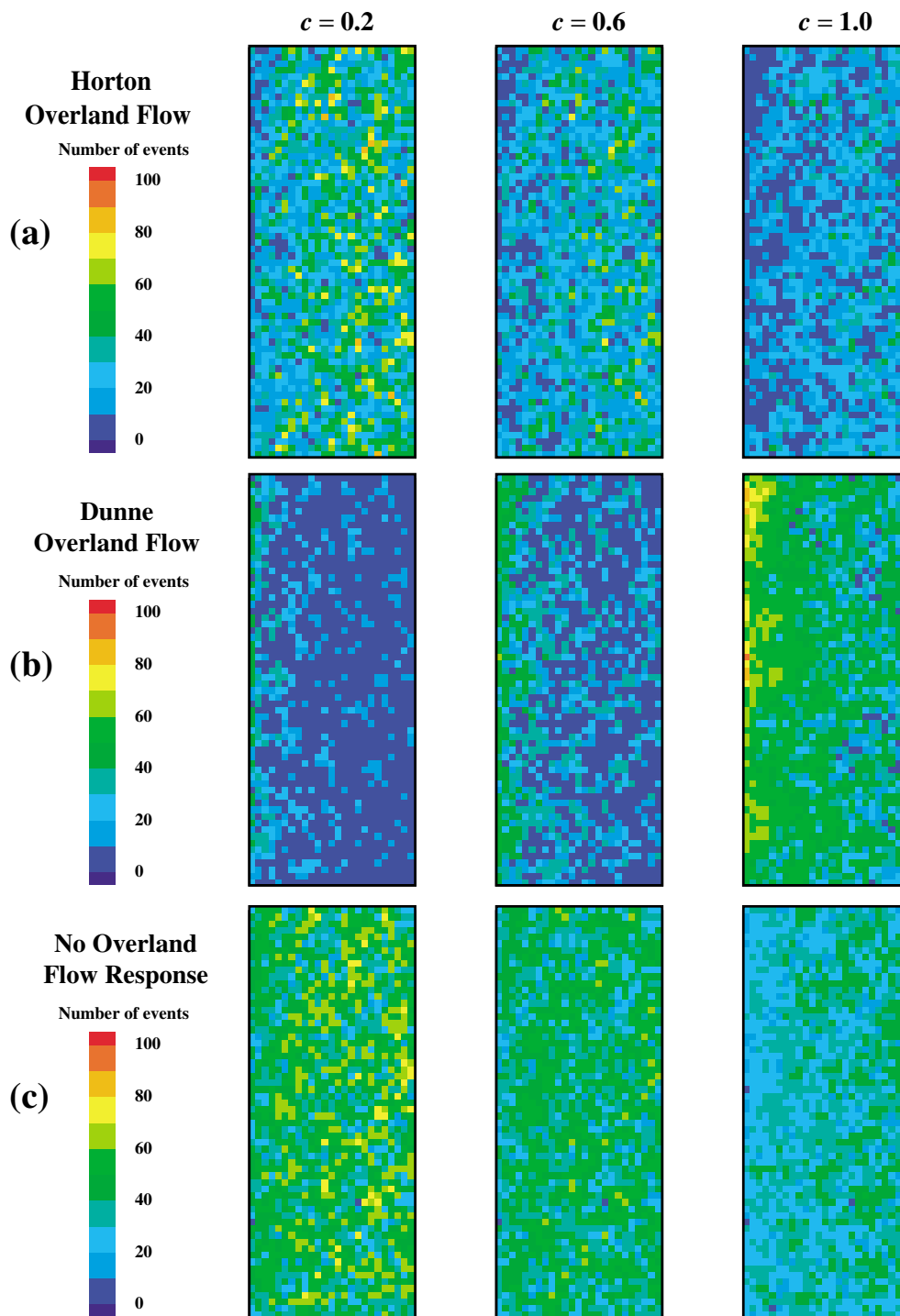


Figure 4. Summary of elements across the simulation domain with (a) Horton overland flow, (b) Dunne overland flow, and (c) no overland flow for different values of c (i.e. based upon 100 SCRRS simulated rainfall–runoff events for each value of c)

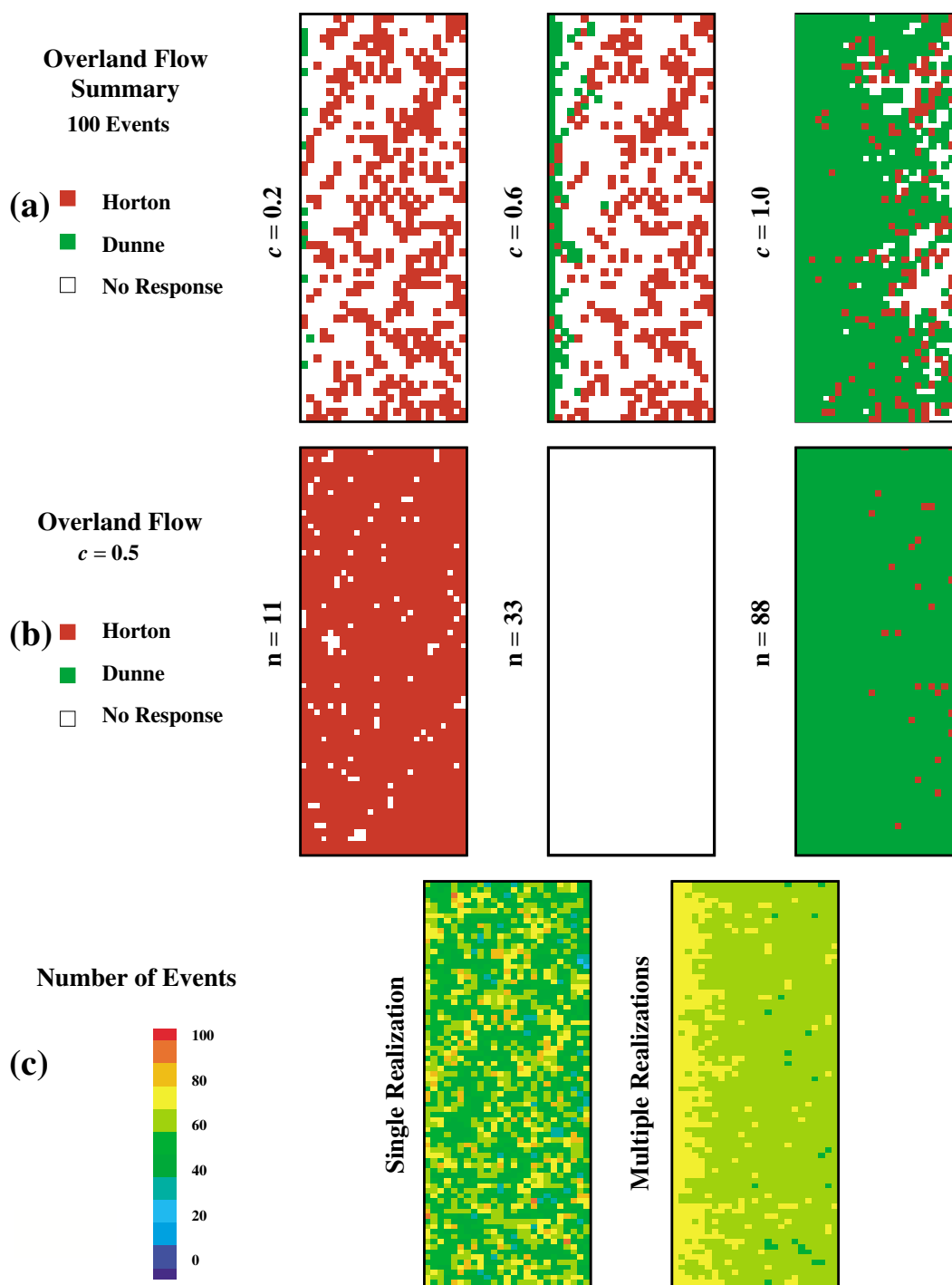


Figure 5. (a) Summary of the dominant overland flow response (i.e. Horton, Dunne, or no response) across the simulation domain for different values of c (i.e. based upon 100 SCRRS events for each value of c). (b) Overland flow summary for three of the 100 events (numbers 11, 33 and 88) across the simulation domain with c set at 0.5. (c) Overland flow source summary for 100 SCRRS events across the simulation domain for a single realization of near-surface soil-hydraulic properties with c set at 0.5, and for 100 equally-likely realizations of near-surface soil-hydraulic properties with c set at 0.5

Table IV. Comparison of the observed R-5 average initial soil-water content with the SCRRS simulations in this study with different values of c

	Number of events N	Average initial soil-water content θ_i (%)
Observed, R-5	72	73.6
SCRRS simulations		
$c = 0.0$	100	60.0
$c = 0.1$	100	66.7
$c = 0.2$	100	68.8
$c = 0.3$	100	70.8
$c = 0.4$	100	70.8
$c = 0.5$	100	72.9
$c = 0.6$	100	72.9
$c = 0.7$	100	75.0
$c = 0.8$	100	75.0
$c = 0.9$	100	75.0
$c = 1.0$	100	75.0

process over another depends upon both the initial soil-water content θ_{ij}^0 and the rainfall intensity p_{ij}^m for each of the individual events. Obviously, both the Horton and Dunne mechanisms could occur simultaneously (see VanderKwaak and Loague, 2001; Loague and VanderKwaak, in press).

It could be argued that some of the generalized results from the SCRRS simulations are either well known or follow directly from the assumptions in the methodological approach used in this study. It should be pointed out, however, that the catchment-scale concept-development simulations reported here illustrate effectively the many nuances of hydrological response. The results reported here demonstrate clearly that the spatially variable near-surface soil-hydraulic properties, initial conditions, and spatially/temporally variable rainfall inputs (both intensity and duration) interact to create non-intuitive spatial patterns of overland flow generation.

DISCUSSION

Linking the SCRRS simulations to the 'real' R-5 catchment

The proportion c of annual rainfall recharging the saturated zone is given by

$$c = 1 - \frac{ET}{P} \quad (16)$$

where ET (L^3) is evapotranspiration and P (L^3) is rainfall. For the R-5 catchment, the value of c ranges, based upon the monthly water balance estimates of Sharma and Luxmoore (1979), between 0.0 and 0.88, with an average value of 0.33. Table IV compares the average initial soil-water content estimates from the SCRRS simulations (for different values of c) with observed values for R-5 events. Inspection of Table IV reveals that the best (on average) estimate of c , from the SCRRS simulations, is either 0.5 or 0.6 corresponding, respectively, to average water table slopes b of 0.016 and 0.018. The maximum SCRRS simulated unsaturated zone thickness for the simulation domain (shown in Figure 1) for the c values of 0.5 and 0.6 are, respectively, 1.7 m and 1.5 m.

Equally likely realizations of near-surface soil-hydraulic properties

The SCRRS simulations discussed up until this point have all been for the same single realizations of three (time-independent) near-surface soil-hydraulic properties (i.e. K_{ij}^s , n_{ij} , B_{ij}). To investigate the issue of

time invariance, an additional set of SCRRES simulations was conducted in which the spatial distributions of K^s , n and B varied in each simulation. Figure 5c shows overland flow source summaries for 100 SCRRES events across the simulation domain with c set at 0.5, for a single realization and equally likely realizations of the three near-surface soil-hydraulic properties. Close inspection of Figure 5c reveals that the equally-likely realizations (versus the single realization) of near-surface soil-hydraulic properties produced a much more uniform runoff response, a demonstration of the Central Limit Theorem for the Monte Carlo simulations reported here. Even with the smoothing of the spatially variable near-surface hydrological impacts resulting from equally likely realizations of K^s , n and B , the Dunne mechanism is clearly still simulated to be a very important process near the channel, demonstrating that even for the most smoothed out case, more than one overland flow mechanism can operate. The near-surface soil-hydraulic properties for the R-5 catchment are not time invariant (see Loague and Gander, 1990; Loague and Kyriakidis, 1997), but they do not change randomly with time.

CONCLUSIONS

The objective of this study was to apply the stochastic-conceptual rainfall-runoff simulator (SCRRES) developed by Freeze (1980) to quantitatively demonstrate the interplay of the factors that control the occurrence of overland flow by the Horton and Dunne mechanisms. The focus of the effort reported here was on the generation of overland flow and not on routing surface runoff. The SCRRES simulation domain for the effort reported here was based upon the general characteristics of the R-5 catchment. Information gleaned from R-5 data sets (e.g. spatially variable near-surface soil-hydraulic properties and the characteristics of observed rainfall events) was used for the SCRRES simulations. It is important to recognize that the SCRRES simulations reported here were not intended to represent individual R-5 events, rather they were conducted to provide a general probabilistic interpretation of near-surface hydrological response based upon data sets from a real catchment.

The results presented here clearly illustrate that the identification of a dominant hydrological response process may not be as simple as a singular Horton or Dunne characterization. The hydrological response of a realistic near-surface system at the catchment scale can be complex and non-intuitive. The SCRRES simulations, using data from the relatively simple R-5 catchment, show that the Horton and Dunne processes can (i) occur simultaneously at different locations during a given rainfall event, (ii) change from one process to the other with time depending on the characteristics of the rainfall event, and (iii) be strongly dependent on the initial conditions (i.e. soil-water content at the surface and the location of the water table).

ACKNOWLEDGMENTS

The effort reported here is a Center for Earth Science Information Research (CESIR) contribution. The presentation benefited from the review comments of Steve Burges. The computing facilities used in this study were provided by an equipment grant to Steve Gorelick and the first author from the National Science Foundation.

REFERENCES

- Dunne T, Black RD. 1970a. An experimental investigation of runoff production in permeable soils. *Water Resources Research* **6**: 478–490.
- Dunne T, Black RD. 1970b. Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research* **6**: 1296–1311.
- Freeze RA. 1972a. Role of subsurface flow in generating surface runoff, 1. Base flow contributions to channel flow. *Water Resources Research* **8**: 609–623.
- Freeze RA. 1972b. Role of subsurface flow in generating surface runoff, 2. Upstream source areas. *Water Resources Research* **8**: 1272–1283.
- Freeze RA. 1980. A stochastic-conceptual analysis of rainfall-runoff processes on a hillslope. *Water Resources Research* **16**: 391–408.

- Horton RE. 1933. The role of infiltration in the hydrologic cycle. *Eos (Transactions of the American Geophysical Union)* **14**: 446–460.
- Jackson TJ, Schmutge TJ, Nicks AD, Coleman GA, Engman ET. 1981. Soil moisture updating and microwave remote sensing for hydrologic simulation. *Hydrologic Sciences Bulletin* **26**: 305–319.
- Loague KM. 1986. *An assessment of rainfall–runoff modeling methodology*. PhD dissertation, University of British Columbia, Vancouver.
- Loague KM. 1988a. Impact of rainfall and soil hydraulic property information on runoff predictions at the hillslope scale. *Water Resources Research* **24**: 1501–1510.
- Loague KM. 1988b. Streamflow generation: equally likely realizations of a single stochastic process. *Proceedings of International Symposium on Modeling Agricultural, Forest, and Rangeland Hydrology*, American Society of Agricultural Engineers, St Joseph, Michigan; 420–426.
- Loague K. 1990. R-5 revisited: 2. Re-evaluation of a quasi-physically based rainfall–runoff model with supplemental information. *Water Resources Research* **26**: 973–987.
- Loague K. 1992a. Soil-water content at R-5: 1. Spatial and temporal variability. *Journal of Hydrology* **139**: 233–261.
- Loague K. 1992b. Using soil texture to estimate saturated hydraulic conductivity and the impact on rainfall–runoff simulations. *Water Resources Bulletin* **28**: 687–693.
- Loague KM, Freeze RA. 1985. A comparison of rainfall–runoff modeling techniques on small upland catchments. *Water Resources Research* **21**: 229–248.
- Loague KM, Freeze RA. 1988. Correction to ‘A stochastic–conceptual analysis of rainfall–runoff processes on hillslope’ by R. Allan Freeze. *Water Resources Research* **24**: 630–632.
- Loague K, Gander GA. 1990. R-5 revisited: 1. Spatial variability of infiltration on a small rangeland catchment. *Water Resources Research* **26**: 957–971.
- Loague K, Kyriakidis PC. 1997. Spatial and temporal variability in the R-5 infiltration data set: *Deja vu* and rainfall–runoff simulations. *Water Resources Research* **33**: 2883–2895.
- Loague K, VanderKwaak JE. In press. Simulating hydrologic response for the R-5 catchment: comparison of two models and the impact of the roads. *Hydrological Processes*.
- Loague K, Gander GA, VanderKwaak JE, Abrams RH, Kyriakidis PC. 2000a. Simulating hydrologic response for the R-5 catchment: a never ending story. *Floodplain Management* **1**: 57–83.
- Loague K, Gander GA, VanderKwaak JE, Abrams RH, Kyriakidis PC. 2000b. Technical addendum for simulating hydrologic response for the R-5 catchment: a never ending story. *Floodplain Management* **2**: 57–64.
- Philip JR. 1969. The theory of infiltration. *Advances in Hydroscience* **5**: 215–296.
- Sharma ML, Luxmoore PJ. 1979. Soil spatial variability and its consequences on simulated water balance. *Water Resources Research* **15**: 1567–1573.
- Sharma ML, Gander GA, Hunt CG. 1980. Spatial variability of infiltration in a watershed. *Journal of Hydrology* **45**: 101–122.
- Smith RE, Parlange JY. 1978. A parameter-efficient hydrologic infiltration model. *Water Resources Research* **14**: 533–538.
- USDA-ARS New Orleans, LA. 1983. *Hydrology, Erosion, and Water Quality Studies in the Southern Great Plains Research Watershed, Southwestern Oklahoma, 1961–78*. Agricultural Reviews and Manuals, ARM-S-29, U.S. Department of Agricultural, Agricultural Research Service New Orleans, LA.
- VanderKwaak JE, Loague K. 2001. Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model. *Water Resources Research* **37**: 999–1013.