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Use of the Connectivity of Runoff Model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas

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Abstract:

Much attention has been given to the surface controls on the generation and transmission of runoff in semi-arid areas. However, the surface controls form only one part of the system; hence, it is important to consider the effect that the characteristics of the storm event have on the generation of runoff and the transmission of flow across the slope. The impact of storm characteristics has been investigated using the Connectivity of Runoff Model (CRUM). This is a distributed, dynamic hydrology model that considers the hydrological processes relevant to semi-arid environments at the temporal scale of a single storm event. The key storm characteristics that have been investigated are the storm duration, rainfall intensity, rainfall variability and temporal structure. This has been achieved through the use of a series of defined storm hydrographs and stochastic rainfall. Results show that the temporal fragmentation of high-intensity rainfall is important for determining the travel distances of overland flow and, hence, the amount of runoff that leaves the slope as discharge. If the high-intensity rainfall is fragmented, then the runoff infiltrates a short distance downslope. Longer periods of high-intensity rainfall allow the runoff to travel further and, hence, become discharge. Therefore, storms with similar amounts of high-intensity rainfall can produce very different amounts of discharge depending on the storm characteristics. The response of the hydrological system to changes in the rainfall characteristics can be explained using a four-stage model of the runoff generation process. These stages are: (1) all water infiltrating, (2) the surface depression store filling or emptying without runoff occurring, (3) the generation and transmission of runoff and (4) the transmission of runoff without new runoff being generated. The storm event will move the system between the four stages and the nature of the rainfall required to move between the stages is determined by the surface characteristics. This research shows the importance of the variable-intensity rainfall when modelling semi-arid runoff generation. The amount of discharge may be greater or less than the amount that would have been produced if constant rainfall intensity is used in the model. Copyright © 2006 John Wiley & Sons, Ltd.

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INTRODUCTION

It is well known that high-magnitude flood events in arid and semi-arid environments are caused by a combination of precipitation characteristics, including amount, intensity, duration and spatial distribution (Wolman and Gerson, 1978; Costa, 1987; Hirschboek, 1991; Enzel *et al.*, 1993; Greenbaum *et al.*, 1998). It is also accepted that rainfall intensities are of prime importance for flood generation in all catchment sizes (Costa, 1987; Schick, 1988; Pitlick, 1994). At the small scale, many investigations have been dedicated to producing an extensive knowledge of factors influencing runoff at the plot scale, such as vegetation (Imeson *et al.*, 1992; Bergkamp *et al.*, 1996; Cammeraat and Imeson, 1998; Cerdà *et al.*, 1998; Cerdà, 1999), soils and slope (Parsons *et al.*, 1996, 1997; Martínez-Mena *et al.*, 1998, 1999; Lasanta *et al.*, 2000; Wainwright *et al.*, 2000). However, there have been a limited number of investigations into how the characteristics of rainfall input into semi-arid systems influence runoff. Hence, we do not know whether more runoff is produced if high-intensity rainfall occurs at the start of a storm, or later when the catchment has wetted up. If we are to realize the potential developments in understanding plot controls on runoff in semi-arid areas, then we need to develop our knowledge of the impact of storm rainfall pattern to be able to combine the two areas of research.

This study uses the Connectivity of Runoff Model (CRUM) to investigate how the characteristics of rainfall input to semi-arid areas influence the runoff produced at the base of a hillslope. This scale was chosen since previous relevant research tends to have been undertaken at the plot and catchment scales, but few investigations have been conducted at the hillslope scale. The hillslope scale is key to developing our understanding and prediction of runoff and flood generation, because landscape morphology has the ability either to encourage or discourage connection of runoff between source areas and main trunk channels. The strength and development of connectivity are also controlled by characteristics of the storm

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rainfall input into the semi-arid system, and hence this paper is vital to develop our understanding of how different rainfall inputs are transformed into hillslope output. This paper introduces the model developed to investigate semi-arid runoff generation, then details the different patterns of rainfall used to investigate the influence on hillslope runoff. The patterns of rainfall investigated are constant rainfall, variable rainfall, pulsed rainfall and stochastic rainfall. Natural rainfall is delivered in a series of pulses, and a much fuller understanding of the influence of rainfall inputs is established by considering when high-intensity rainfall occurs within a storm, the impact of spacing of pulses, and the nature of variation within storm events.

METHODOLOGY

This section introduces the CRUM, the test hillslope used in this research and the different methods of storm generation utilized.

The Connectivity of Runoff Model (CRUM)

The model developed to investigate the controls on runoff generation and flow dynamics in semi-arid environments is the CRUM. The model is divided into vertical and horizontal components and distributed on a grid structure. The model has been designed using an object-orientated approach to create a modular model that is simple to modify, to debug and to reuse. The vertical component represents interception, surface detention storage, surface depression storage, soil moisture storage and recharge (Figure 1). Each process represented in the model is discussed in turn.

Interception is modelled by a non-leaking store that covers a percentage of the horizontal area. Once this store fills and overflows, all of the rainfall will reach the soil surface. This approach has been applied in the Pattern[lite] model (Mulligan and Reaney, 2000) and the CASC2D model (Johnson *et al*., 2000). The size of the canopy store and the percentage intercepted is related to the vegetation type and amount of biomass. This approach is able to capture the key dynamics of the process with a minimal amount of information.

The depth of the surface depression store is determined from the surface gradient and roughness using the following relationship established by Kirkby *et al.* (2002):

$$\frac{\mathrm{dp}}{\alpha} = 0{\cdot}11 \exp\left(\frac{-0{\cdot}02\beta}{\alpha}\right) \tag{1}$$

where dp (mm) is the surface depression storage, α is the surface roughness and β (degrees) is the slope gradient. The depth of the surface depression store is very important for determining the timing of runoff generation. The use of this equation enables the prediction of the depth of the surface depression store across the area being modelled.

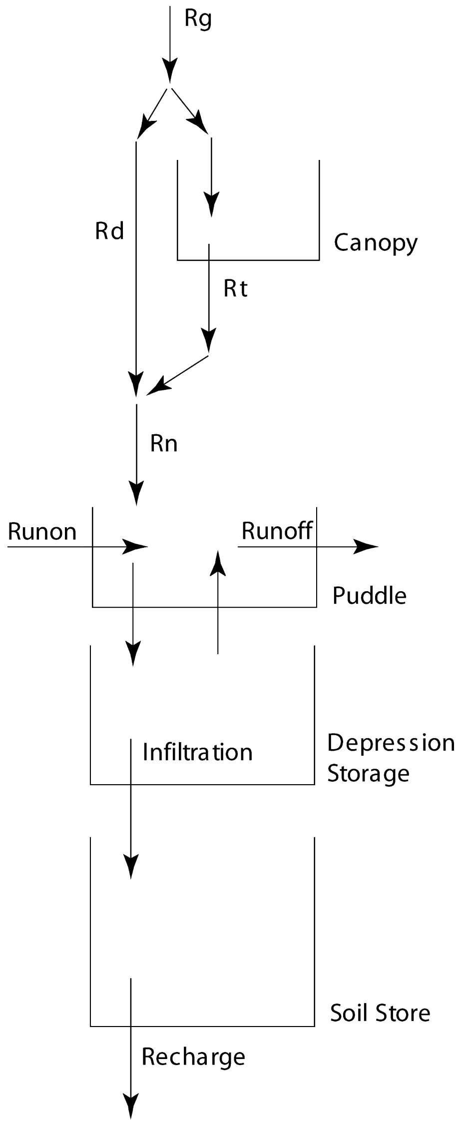

Figure 1. The vertical hydrological representation used in the CRUM

The infiltration rate is predicted by a soil moisture storage-based simplification of the Green and Ampt (1911) equation developed by Kirkby (1975, 1985):

$$i_{\mathrm{t}} = a + \frac{b}{\theta} \tag{2}$$

where a and b are coefficients and θ is the soil moisture. The use of the storage term in Equation (2) gives a number of advantages. It enables the equation to model the infiltration rate over areas rather than points. This is of great help in scaling the model, since the storage term can relate to an area of 1 cm^2 or 1 km^2 (Beven, 2000). The use of a changing soil moisture term, rather than a time-based model, allows the equation to be applied to irregular rainfall time-series. The storage term is required for the application of an infiltration equation to a distributed model to handle the influence of run on to a point in the landscape. The water that is not able to be infiltrated is first held in the surface depression store. Once this store overflows, runoff is generated.

The horizontal interactions occur only as overland flow because lateral flow through the soil is negligible in semi-arid environments (Bull and Kirkby, 2002). The flow routing between the grid cells uses the FD8 algorithm (Quinn *et al.*, 1991), which uses multiple flow directions and hence allows both the dispersion and concentration of flow. This is of great importance when modelling at the hillslope scale. The amount of flow assigned to each cell is determined on a slope-weighted basis as proposed by Quinn *et al.* (1991) and Freeman (1991). The fraction of flow given to neighbour i is

$$F_i = \frac{\beta_i^v}{\sum_{i=l}^{8} \beta_i^v} \tag{3}$$

where β_i is the slope from the central node to neighbour i and v is a positive constant.

The v constant is a flow concentration factor: the greater the value of v, the greater the flow concentration (Holmgren, 1994). Once runoff is generated, it may move across the soil surface until it either reaches the base of the hillslope or is infiltrated at a downslope location with a greater infiltration capacity. This infiltration of water results in the disconnection of parts of the hillslope from the channel network.

Overland flow may consist of a combination of laminar, transitional and turbulent flow (Abrahams *et al.*, 1986). In these situations, the Darcy–Weisbach equation (Equation (4)) is the most appropriate for the determination of flow velocity, since it is able to describe all of these flow conditions (Baird, 1997):

$$v = \sqrt{\frac{8gRs}{\mathrm{ff}}} \tag{4}$$

where v (m s^{-1}) is the flow velocity, ff is the friction factor, g is the acceleration due to gravity, R is the hydraulic radius and s is the slope of the energy gradient. Following Abrahams *et al.* (1992), the friction factor ff is related to the surface cover rather than the flow hydraulics.

The CRUM is able to capture the dynamics of semi-arid runoff generation and flow connectivity without being site specific or requiring a large amount of data. These characteristics make CRUM a powerful modelling tool for the investigation of the controls on runoff generation and overland flow connectivity.

Test hillslope

A simple test hillslope has been defined to simplify the rainfall–runoff relationship such that the effect of storm characteristics on the runoff generation and transmission processes can be investigated. The test hillslope consisted of a 50 m × 50 m grid using a 1 m^2 cell size and the simulations were run using a 1 s time step. The details of the test hillslope and storm are given in Table I, and Figure 2 shows the discharge hydrograph and the depression storage varying within an example storm event. This landscape has been created to be typical of many semi-arid areas. The slope length of 50 m at an angle of 6° represents typical slopes found in the field. The infiltration model parameters relate to results from a rainfall simulation experiment on a scrub area in Almeria, south-eastern Spain (Reaney, 2003).

Table I. Test hillslope model parameters

Parameter	Value
Slope size (m^2)	50 × 50
Cell size (m^2)	1 × 1
Slope gradient (°)	6
Surface roughness	Independent random elevations based on an exponential distribution with a mean of 1 mm
Soil depth	Related to slope, giving a depth of 0·288 m at 6°
Initial soil moisture (%)	45
Vegetation	None
Infiltration parameters (mm h^{-1})	$a = 11$, $b = 9$
Friction factor ff	75
Storm length (min)	5
Storm intensity (mm h^{-1})	75

Rainfall generation

Natural rainfall does not occur at a constant rainfall intensity; rather, it is highly variable on both spatial and temporal scales. At the spatial scale of a single slope, the spatial variations may be considered negligible, but the temporal variations will affect the generation and transmission of runoff across the slope. To investigate the influence of the storm characteristics on runoff generation and transmission, detailed rainfall sequences for defined storm lengths and intensities are required. With the available historical rainfall record, it is not possible to extract the required range of storm characteristics. To overcome this problem, rainfall time-series have been created using defined hydrographs, the Rectangular Pulse Model (RPM) and Monte Carlo-based storm generators.

Two sets of defined storm hydrographs have been developed. The first set consists of a series of defined storm hydrograph patterns that all deliver 80 mm of rainfall over a 2 h period (Figure 3). Although this is an extreme rainfall event, it is able to bring out the differences in the runoff generation resulting from the varying storm hydrograph forms. The second set of storms considers the effect of length of time between different rainfall pulses with a storm. The time between each pulse will influence the antecedent conditions at the start of the rainfall. This will be expressed in the depth of the surface depression storage and the soil moisture which controls the infiltration rate. A rainfall pulse of 75 mm h^{-1} for 5 min has been repeated five times with a varying gap of no rainfall.

The RPM approach uses constant rainfall intensity for a set period of time and has been used in many hydrological

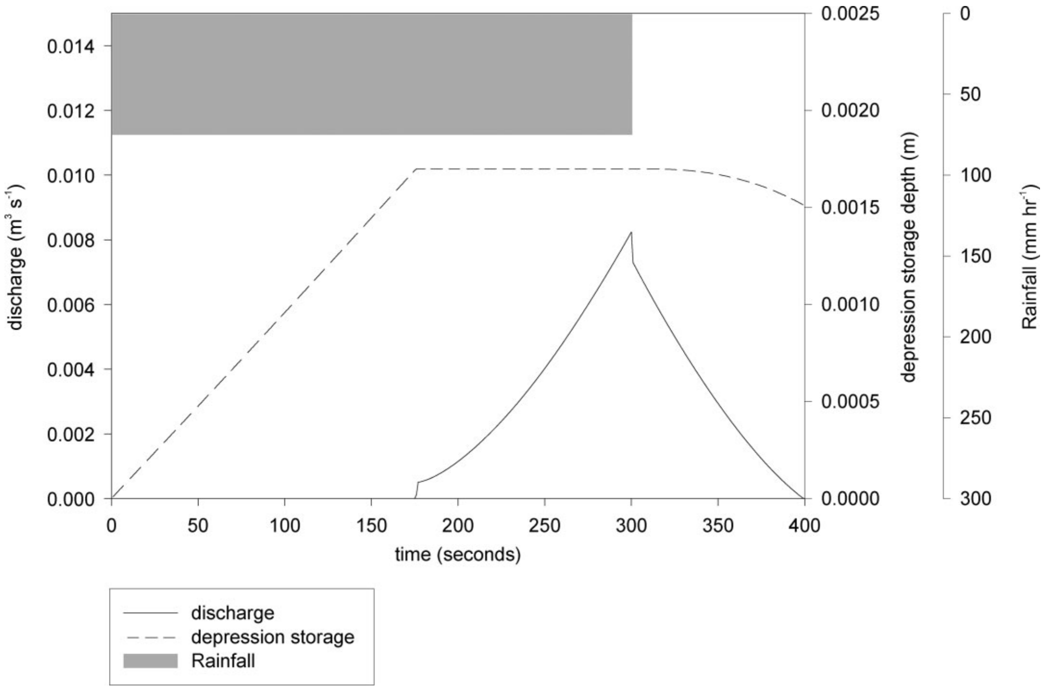

Figure 2. Input and output conditions of the test hillslope

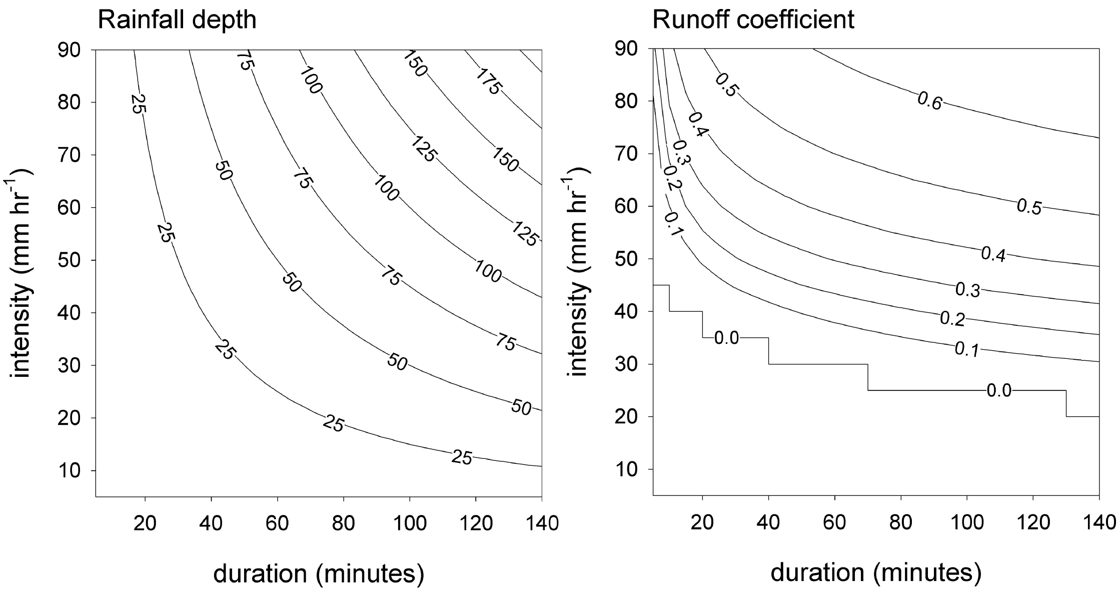

Figure 3. Effects of rainfall intensity and duration on the runoff coefficient from the test hillslope

applications (e.g. Khaliq and Cunnane, 1996; Cameron *et al*., 2000).

In contrast to the RPM, the Monte Carlo model selects random rainfall intensities from a distribution function. The Monte Carlo approach has been used for hydrological models of semi-arid environments (e.g. Mulligan, 1996). This type of model assumes that there is no temporal autocorrelation in the rainfall time-series. The Monte Carlo model uses a distribution function fitted to the intense rainfall sections of a measured time-series. This distribution function is given by

$$\mathrm{rf_i} = \left[\frac{1}{a}\ln(1-p)\right] \times 60 \tag{5}$$

where $\mathrm{rf_i}$ (mm $\mathrm{h^{-1}}$) is the rainfall intensity, $1/a$ is the mean per minute rainfall intensity and p is the probability of that rainfall intensity. For a measured tipping-bucket rainfall record from Almeria, southeastern Spain, for March 1997 to December 2000, $a = 1{\cdot}74$ ($R^2 = 0{\cdot}98$).

To investigate which properties of the rainfall pulse control the amount of discharge that leaves the slope, the test hillslope was subjected to 1000 storm realizations of varying intensity and duration. These storm pulses varied in duration from 1 to 20 min and with rainfall intensities from 40 to 90 mm $\mathrm{h^{-1}}$. Each storm realization has been characterized by a number of statistical properties relating both to the storm duration and intensity and to the

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variability of the rainfall within the storm pulse. In order to assess the importance of the different storm characteristics, the correlation coefficients between the characteristic and the peak discharge and the runoff coefficient have been calculated (see Table III). Owing to the high n value (1000), it is possible to use the Pearson correlation coefficient.

RESULTS

Constant rainfall

The constant rainfall intensity experiments used the RPM to generate rainfall intensities. This delivers rainfall at a constant intensity for a defined length of time. The range of intensities has been set as 10–90 mm h^{-1} and the duration from 5 to 140 min. These ranges cover the typical values encountered in semi-arid environments. The total rainfall depth and the runoff coefficients are shown in Figure 4.

There is a linear relationship between the rainfall duration, intensity and the rainfall depth. However, the runoff coefficient is more sensitive to changes in both the rainfall intensity and duration in different parts of the parameter space. The greatest sensitivity to the rainfall duration is over the range 5–20 min. The discharge is most sensitive to the rainfall intensity between runoff coefficients of 10 and 30% and is less sensitive above this region.

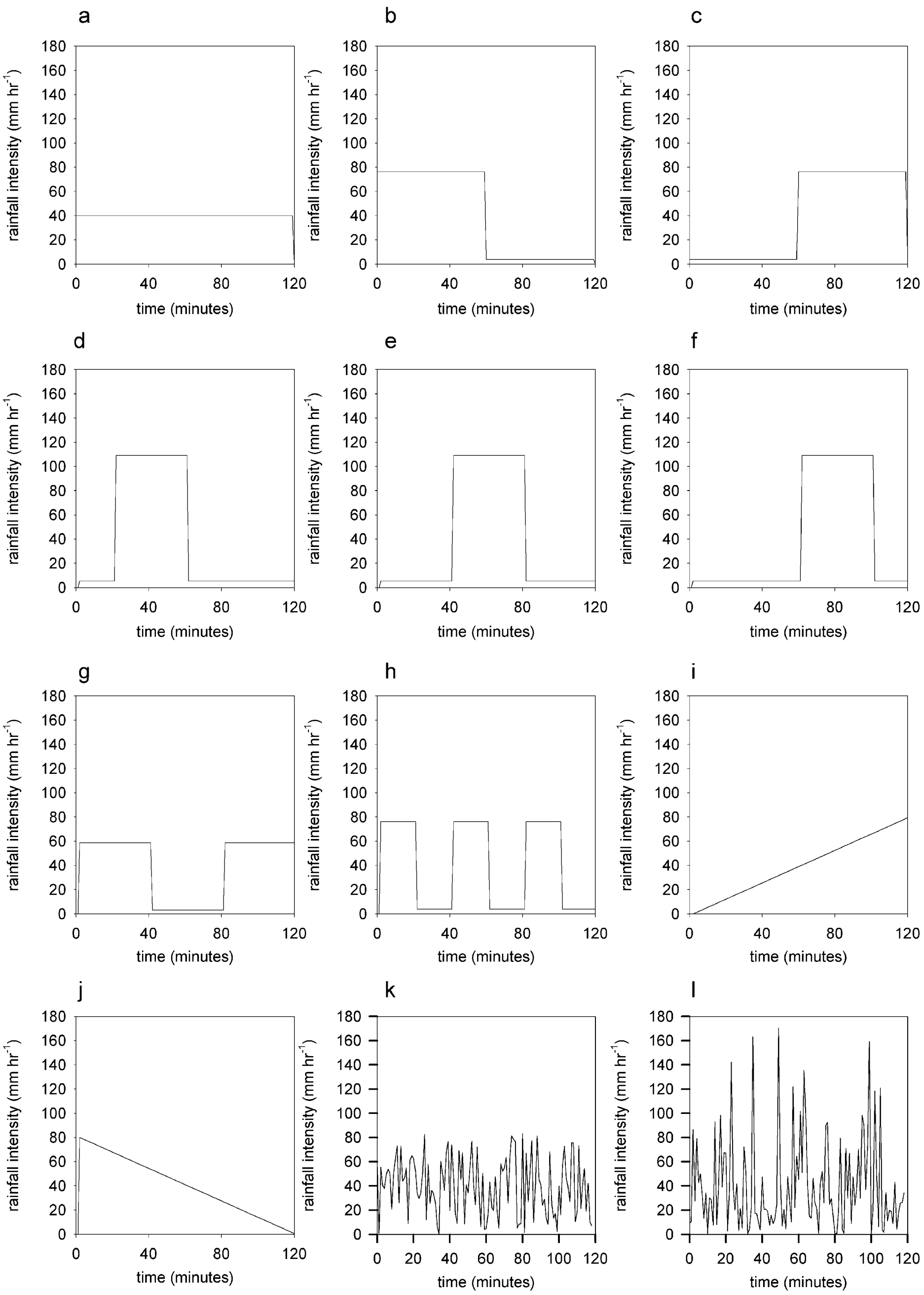

Figure 4. Defined storm hydrographs

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Part of the storm water is used to decrease the infiltration rate and to fill the surface depression store, and then a percentage of the remainder can be converted into runoff. The first part is a constant depth for a certain surface and, therefore, is not dependent upon the storm duration. As the storm duration increases, the percentage of the storm water that is able to be converted into runoff increases. For short storms, most of the storm water will be used to condition the surface for runoff generation. Therefore, the amount of runoff is very sensitive to changes over the range 5–20 min, but the sensitivity then decreases for longer duration pulses.

The response to changes in rainfall intensity is connected to the infiltration rate. Since the rainfall intensity has to be greater than the infiltration rate to initiate runoff, the slope will be sensitive to changes in the rainfall intensity. As the amount of water stored in the soil increases, the infiltration rate decreases and, hence, there is an increase in the runoff coefficient with increasing storm duration.

Storm hydrograph form

The storm characteristics and the runoff coefficients from the defined storm hydrographs are shown in Table II. Storm pattern 'a' has a constant rainfall of 40 mm h^{-1} and gives the lowest runoff coefficient at 25·3%. The initial infiltration rate is greater than 40 mm h^{-1}; therefore, a large percentage of the rainfall is being used to increase the soil moisture and, hence, decrease the infiltration rate. The maximum rainfall intensity in storms 'b' and 'c' increases to 76·2 mm h^{-1} and the runoff coefficient also increases to 51·4% for storm 'b' and 47·6% for storm 'c'. Storm 'b' gives slightly more discharge than storm 'c', and this can be related to the rainfall after the main pulse aiding the transmission of flow.

Storms 'd', 'e' and 'f' all have a maximum rainfall intensity of 109·1 mm h^{-1} and give runoff coefficients of over 55%. The difference between the storms is the location of the high-intensity rainfall pulse within the storm event. Storm 'd' has the high-intensity pulse at the start of the storm and has the highest runoff coefficient of the subset, whereas storm 'f' has the high-intensity pulse at the end of the storm and has the lowest runoff coefficient. The increase in runoff can be related to the rainfall after the main pulse aiding the transmission of flow.

Table II. Storm intensity characteristics and runoff coefficients

Storm	Intensity (mm h^{-1})		COV	Runoff coefficient (%)
	Max.	Mean		
a	40·0	40	0·00	25·3
b	76·2	40	0·91	51·4
c	76·2	40	0·91	47·6
d	109·1	40	1·23	57·9
e	109·1	40	1·23	56·9
f	109·1	40	1·23	55·8
g	58·5	40	0·66	39·4
h	76·2	40	0·91	44·8
i	80·0	40	0·58	37·1
j	80·0	40	0·58	35·2
k	83·2	40	0·60	26·2
l	170·3	40	0·95	26·9

Storm 'g' has two high-intensity rainfall pulses and a maximum rainfall intensity of 58·5 mm h^{-1}, and storm 'h' has three high-intensity rainfall pulses and a maximum rainfall intensity of 76·2 mm h^{-1}. Although storm 'g' has high-intensity rainfall for 66% of the storm events, it gives less runoff (rc = 39·4) than storm 'h' (rc = 44·8), which has high-intensity rainfall for 50% of the storm. The greater runoff coefficient can be related to the greater rainfall intensity in storm 'h'.

Storms 'I' and 'j' have a linear change in rainfall intensity, with a maximum intensity of 80 mm h^{-1}. Storm 'I' has a linear increase in intensity and storm 'j' has a linear decrease in rainfall intensity. Storm 'I' gives the higher runoff coefficient at 37·1%, opposed to 35·2%, and can be related to the wetting up of the soil before the higher intensity, runoff-generating rainfall.

Storms 'k' and 'l' are variable rainfall, with storm 'l' having the greater amount of variability. Storm 'k' has a maximum rainfall intensity of 83·2 mm h^{-1} and storm 'l' has a maximum intensity of 170·3 mm h^{-1}. Despite the large difference in the maximum intensities, they give similar runoff coefficients, with storm 'k' giving 26·2% and storm 'l' giving 26·9%. These values are only slightly greater than from storm 'a' with constant rainfall. This suggests that the runoff generated during the high-intensity rainfall is rapidly infiltrated during subsequent low-intensity rainfall periods. This shows the importance of the temporal structure of the storms.

The effects of the maximum rainfall intensity and the coefficient of variation (COV) of the per minute intensities on the runoff coefficient have been investigated using linear regression (Figure 5). Both the maximum rainfall intensity and the COV show a positive relationship with the runoff coefficient. However, COV is able to explain 64·18% of the variation in the runoff coefficient, whereas the maximum rainfall intensity is able to explain 1·48% of the variability (solid line). The outlier at a maximum intensity of 170·3 mm h^{-1} relates to storm 'l', where there is large variability in the rainfall intensity between consecutive minutes, thus allowing generated runoff to infiltrate. If the outlier is excluded, then the maximum rainfall intensity is able to explain 55·4% of the variability (dashed line). This suggests that the variability of the per minute intensities within the storm has a greater effect on the amount of discharge than the maximum rainfall intensity.

The position of a high-intensity rainfall pulse within the storm, therefore, influences the amount of discharge. The position of the pulse relates to the antecedent soil moisture conditions at the start of the storm and the conditions during the overland flow after the main rainfall pulse. Previous studies of semi-arid runoff generation have focused on the maximum or mean rainfall intensity. It is clear from the results presented above that the

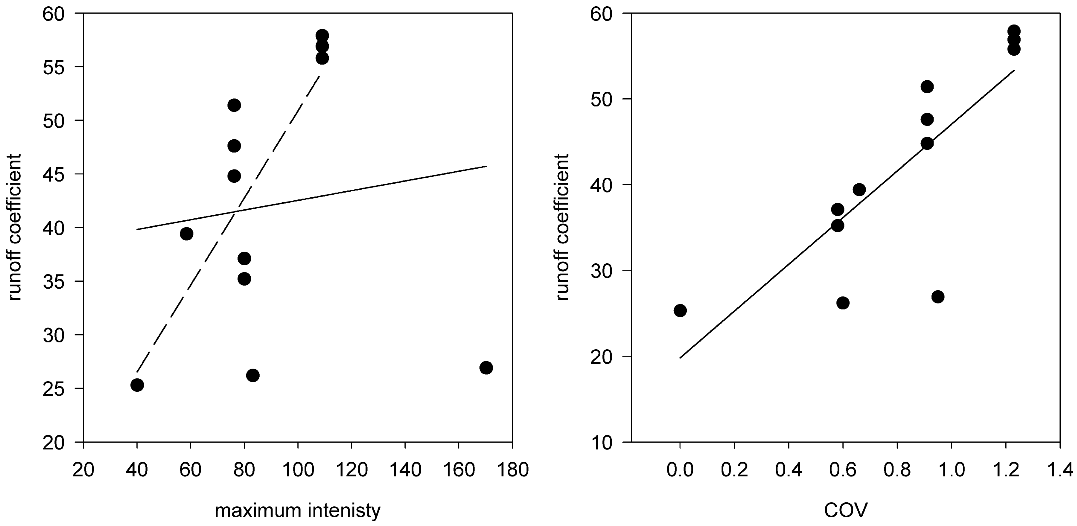

Figure 5. Effect of the maximum intensity and the COV on the runoff coefficient. The solid lines have been fitted to the whole dataset and the dashed line has been fitted to the dataset excluding the outlier at 175 mm h^{-1}

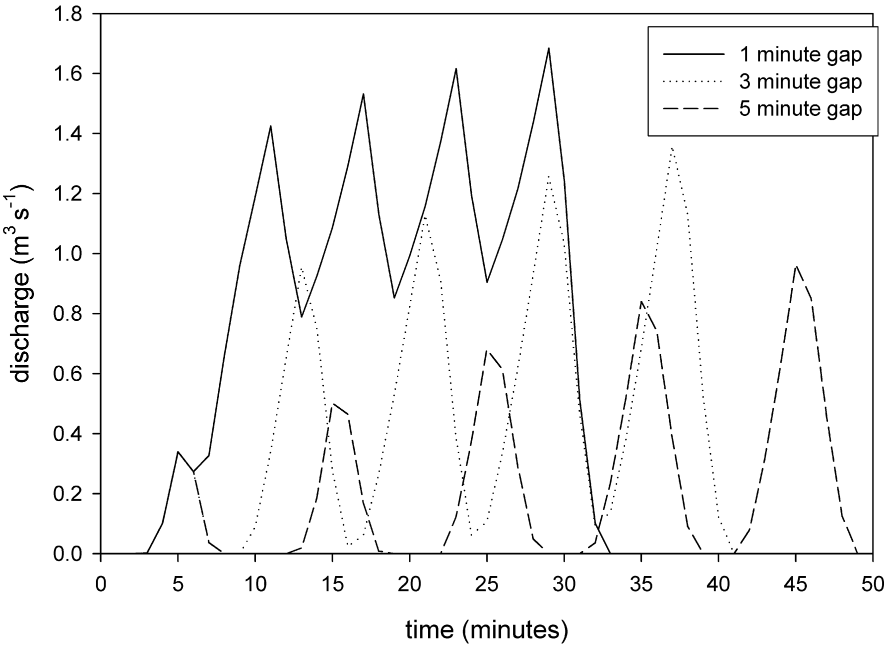

Figure 6. Effects of the length of the gap between storm pulses on discharge. Note: all three series have a peak at 5 min but are obscured by the 5 min gap line

temporal structure of the storm is a key control on the generation and transmission of runoff.

Series of pulses. The discharge hydrographs for gaps of 1, 3 and 5 min between the rainfall pulses are shown in Figure 6. Although the rainfall intensity in all of the rainfall pulses is constant between the different storms, the mean storm intensity decreases with the increasing gap between pulses. As the cumulative amount of rainfall increases, the runoff coefficient per rainfall pulse increases. This shows the importance of the antecedent soil moisture and soil surface conditions on the generation and transmission of runoff. As the total rainfall depth increases, the soil moisture increases, thus reducing the infiltration capacity. The reduction in the infiltration capacity decreases the time required for the surface depression store to fill and, hence, for runoff to be generated.

The discharge from the slope subjected to the rainstorm with 5 min between storm pulses always returns to zero before the next pulse of rainfall. There is sufficient time for the water on the surface to enter the surface depression store or to infiltrate and, hence, for runoff to stop. The amount and peak runoff increase with each successive pulse and can be related to the decrease in the infiltration rate with the cumulative infiltration. The rainfall time-series with 1 min between the pulses gives the maximum amount of discharge. Owing to the short time between the rainfall pulses, there is not enough time for the runoff-generating areas to become disconnected from the slope outflow. This, therefore, leads to the continuous discharge from the slope outflow.

Stochastic rainfall

The impact that variable rainfall has on discharge is shown in the box plots, presented in Figure 7. These plots compare the difference between the runoff leaving the slope from a rainfall pulse of 75 mm h^{-1} for five minutes delivered at constant and from 200 storm realizations with temporally varying rainfall intensities. Each of the storms has the same total rainfall depth with the varying intensity storms being generated with the Monte Carlo model.

For the total discharge, the introduction of variable rainfall leads to an increase in the median discharge. The maximum discharge volume simulated was 3·65 m^3; this is 480% greater than with constant rainfall. However, 25·9% of the simulations produced a discharge volume less than the constant rainfall, with the minimum simulated discharge at only 0·046 m^3. The median peak discharge is very similar between the constant and variable rainfall; hence, 51·2% of the simulations gave discharges less than the constant-intensity rainfall. There is a greater spread of values with the variable rainfall, to a maximum of 1·38 m^3 min^{-1}.

The relationship between the nature of the storm and the characteristics of the slope discharge are shown in Figure 8. This set of results considers the impact of the storm duration and depth on the runoff coefficient and peak discharge.

The total rainfall depth shows a positive relationship with both the peak discharge and the runoff coefficient. The increases in the peak discharge and the runoff coefficient are related to the decrease in infiltration rate with cumulative rainfall and, hence, the increase in runoff production. There is a large amount of scatter in the y-axis on both plots. For a total rainfall depth of 15 mm, the peak discharge varies from 0 to 4·8 m^3 min^{-1} and the runoff coefficient varies from 0 to 38%. This spread of values relates to the range of rainfall intensities within the pulse and the temporal structure of the storm pulse.

The maximum rainfall intensity shows threshold behaviour for both the peak discharge and the runoff coefficient. The maximum rainfall intensity must be greater than the infiltration rate of the soil to produce any runoff. The infiltration rate at the start of the simulation run is 55 mm h^{-1}, whereas the runoff threshold is at 84 mm h^{-1}. This difference relates to the infiltration excess required to fill the surface depression store. If only a small amount of water overflows from the depression store, it is likely that it will be infiltrated further downslope. This threshold, therefore, relates to the amount of infiltration excess required to form a connection between the runoff generating points and the outflow.

Above the threshold there is a positive relationship between the maximum rainfall intensity and both the peak discharge and the runoff coefficient. There is, however, a large amount of scatter, with many pulses with high maximum rainfall intensities giving no runoff. At a maximum rainfall intensity of 240 mm h^{-1}, the peak discharge varies from 0 to 5 m^3 min^{-1} and the runoff coefficient varies from 0 to 50%. The maximum rainfall intensity only describes a single minute within the rainfall pulse. This minute is expected to relate to the peak discharge, but not so well with the runoff coefficient, which is a pulse-scale measure. The response to the maximum intensity minute will be determined by the antecedent conditions, which are in turn related to the position of the high-intensity minute within the storm event.

As the pulse length increases, there is an increase in the range of runoff coefficients. The rate of increase in the maximum runoff coefficient rises above a pulse length of 5 min and levels off after 13 min. The increase at 5 min relates to the time required to fill the surface depression store and for the runoff to reach the outflow. The levelling off of the range of runoff coefficients at 13 min relates to the total travel times across the surface. With a slope length of 50 m, it will take approximately 8·5 min to reach the outflow from the top of the slope; hence, all of the hillslope is contributing runoff to the outflow. The remainder of the time is connected to the time required to generate runoff.

With the defined storm hydrograph patterns, the COV was found to be strongly related to the runoff coefficient. For the stochastic rainfall pulses, it does not show the

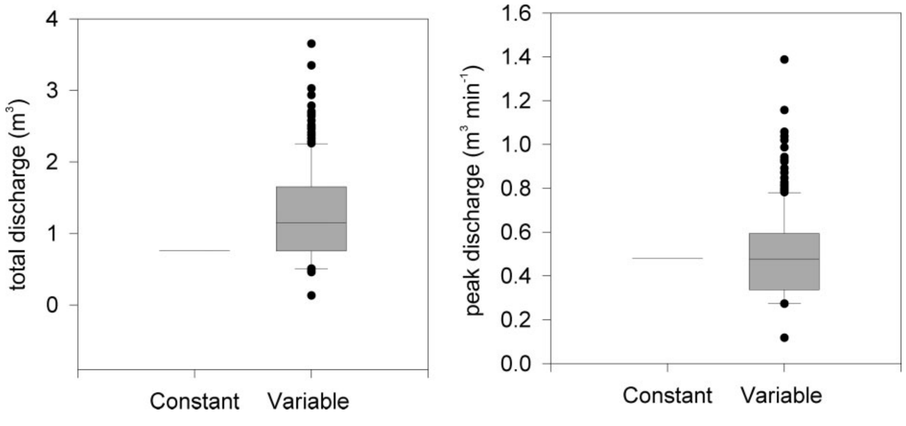

Figure 7. Box plots of the differences in runoff from variable and constant rainfall

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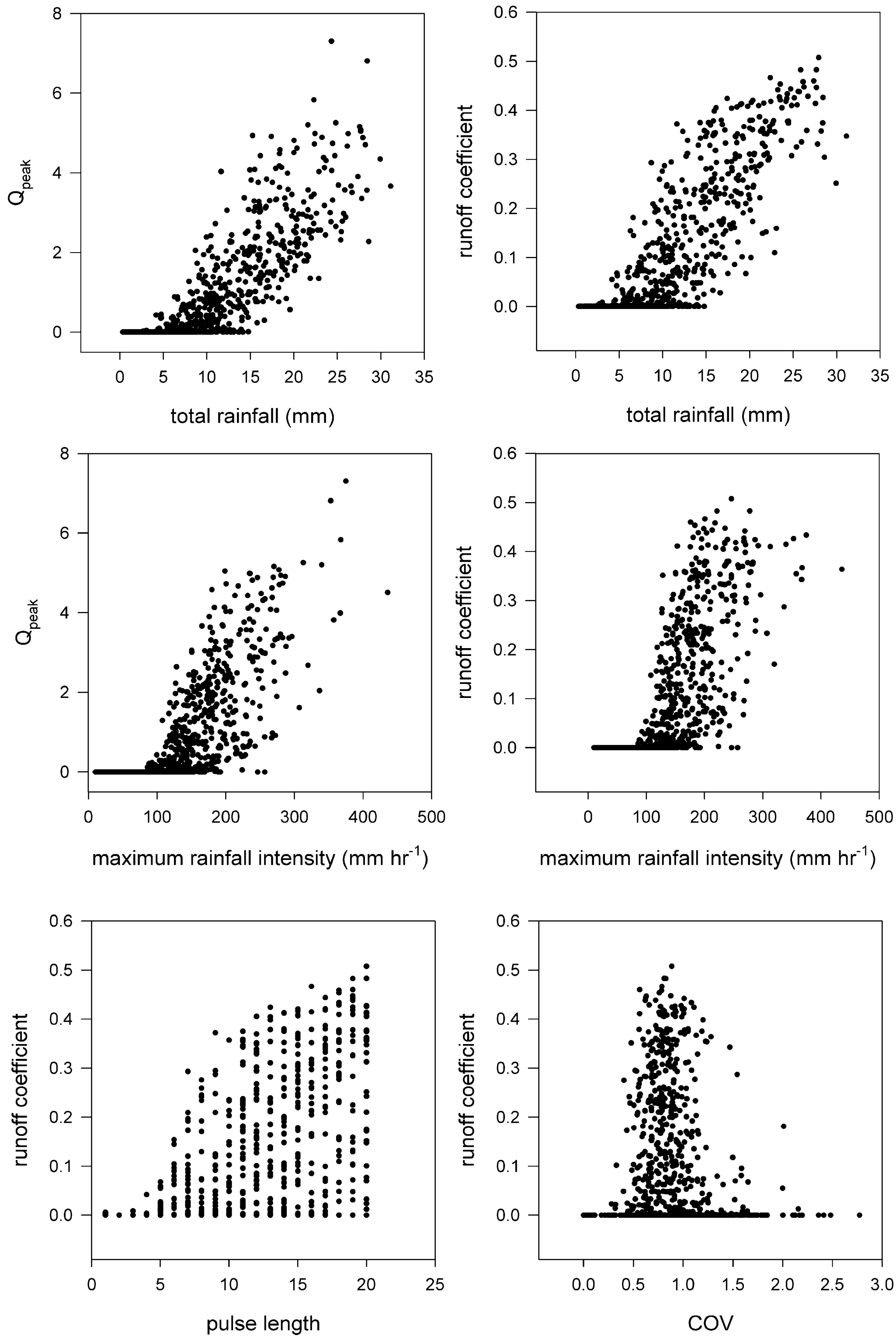

Figure 8. Effect of storm characteristics on the discharge characteristics

same behaviour. There are lower and upper limits beyond which there is minimal discharge from the slope. The lower limit is at 0·5 and the upper limit is at 1·25, although there are a number of outliers. Between these limits there is a large range of runoff coefficient values ranging from 0 to 50%. This, therefore, suggests that the temporal structure, as well as the variability, plays a significant role in the generation of runoff.

Storm statistical characteristics driving runoff generation

The statistical characteristics of the Monte Carlo-generated storm events have been related to the simulated runoff characteristics (Table III).

For the base slope, the rainfall pulse depth explains 72% of the variability in the runoff coefficient and 71% of the variability in the peak discharge. This is related to the

Table III. Correlations between storm characteristics and discharge for varying storms[a]

Statistical property	Peak discharge	Runoff coefficient
Pulse length	0·52*	0·53*
Range	0·73*	0·71*
Minimum intensity	−0·12*	−0·12*
Maximum intensity	0·75*	0·73*
Mean intensity	0·57*	0·58*
Pulse depth	0·84*	0·85*
Standard deviation	0·59*	0·58*
Skew	0·11*	0·08
Kurtosis	0·06	0·02
COV	−0·04	−0·06

[a] Correlations significant at the 99% level and above are marked with an asterisk.

conditioning of the soil to give runoff by the early section of the rainfall to give lower infiltration rates and, hence, higher runoff. The maximum rainfall intensity explains 56% of the variability in the peak discharge and 53% of the variability in the runoff coefficient. This is contrasted with the mean rainfall intensity only explaining 33% of the variability in the peak discharge and only 34% of the variability in the runoff coefficient.

Of the statistical moments related to the variability of the rainfall, the standard deviation is significantly related to the peak discharge, and the runoff coefficient and the skewness is only significantly related to the peak discharge. The kurtosis and the COV are not significantly related to either discharge hydrograph characteristic.

DISCUSSION

The modelling results show that there are two key storm characteristics that determine the runoff coefficient for individual storm events: the relationship between the rainfall intensity and surface conditions, and the temporal structure of the rainfall intensities within the storm event. It is helpful to consider the temporal dynamics of runoff generation as a four-stage process with the storm event moving the runoff-generating system sequentially between the different stages. The stages are:

1. The rainfall intensity is less than the infiltration capacity. During this stage, all the rainfall will infiltrate and the increase in soil moisture will cause a reduction in the infiltration capacity.
2. The rainfall intensity is greater than the infiltration capacity, but the amount of water held in surface detention is less than the depth of the surface depression store.
3. The rainfall intensity is greater than the infiltration capacity, and the amount of water held in surface detention is greater than the surface depression store capacity. During this stage, runoff is generated.
4. The rainfall intensity is less than the infiltration capacity, but the amount of water held in surface detention is greater than the surface depression store capacity. During this stage, no new runoff will be generated, but overland flow will continue.

The locations of the stages within the parameter phase space are shown in Figure 9. As a storm event progresses, it will create a path through this parameter phase space. The characteristics of the path taken through the phase space will determine the amount of runoff generated, the time available for the transmission of runoff across the surface and, hence, the amount of runoff that is able to leave the slope as discharge. The path that the storm takes through the phase space will be determined by both the surface characteristics and the nature of the storm. The amount of discharge from the slope will be determined by both the amount of time spent in stages 3 and 4 and the structure of the rainfall during this period. The structure of the rainfall will determine whether the storm will move between stages or remain in stages 3 and 4 for a long time.

The time taken to move through stage 2 is dependent upon the depth of the surface depression store and the fragmentation of high-intensity rainfall. This is related to the soil roughness and the local slope gradient. As the slope gradient increases, the depression storage decreases, reducing the amount of water required to pass through stage 2. The time required for the system to leave stage 1 will be strongly related to the antecedent soil moisture. With wetter conditions, the infiltration capacity will be lower; hence, less rainfall will be required to move the system into stage 2. When a high-intensity pulse of rainfall occurs in a system that is already in stage 2, 3 or 4, almost all of the water in the pulse will be converted into runoff. If a similar pulse falls on a dry, stage 1 soil surface, then much of the rainfall enters the soil and/or surface depression store before moving the system into stage 3, when runoff is generated.

The temporal structure of the rainfall time-series determines the amount of time that the runoff-generating system spends in stages 3 and 4 of the runoff generation phase space. Therefore, the temporal structure of the rainfall time-series is a key control on the development of connectivity across a slope and, hence, the amount of runoff able to reach the slope outflow. This is supported by the field results reported by Van de Giesen *et al*. (2000), who found that the runoff coefficient varied between storms with different temporal dynamics.

This importance of the timing of a high-intensity pulse is clearly shown in the investigations of the effect of the storm hydrograph form. The highest runoff coefficient was obtained by a high-intensity pulse followed by a long period of low-intensity rainfall. The low-intensity rainfall helps to keep the system in stage 4, hence allowing greater flow. For the experiments utilizing a series of rainfall pulses, the length of the gap between pulses determines how much the system can dry out or how many stages back that the system is able to move. For the series with a 1 min gap, once the system has reached stage 3 it oscillates betweens stages 3 and 4 until the end of the rainfall. The gap is insufficient to allow the system

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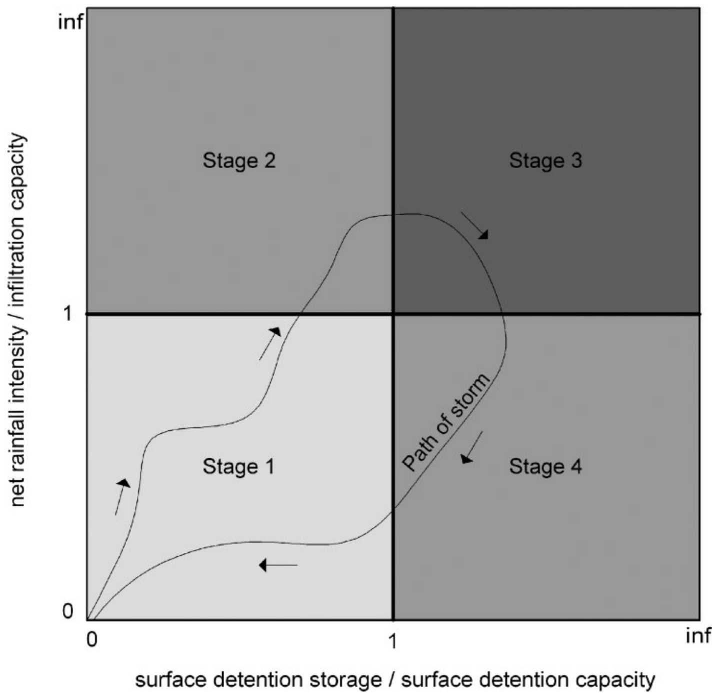

Figure 9. The location of the four stages of runoff generation within the parameter phase space

to move back into stage 2. The series with a 5 min gap always returns to stage 2 before the next storm pulse. This is shown by the cessation of discharge during the gap. This clearly shows the importance of the antecedent conditions at the time of the main rainfall pulse within a storm. If the land surface is conditioned for runoff generation, then the runoff-generation system can rapidly move into stage 3 and, hence, a greater amount of runoff can be generated.

The importance of the temporal structure of the rainfall time-series is clearly demonstrated by the Monte Carlo-based simulation results. From the Monte Carlo generation of 200 storms with the same rainfall depth and duration, it was found that the amount of runoff leaving a slope with a length of 50 m was highly variable. The majority of the realizations gave a greater runoff coefficient than the constant rainfall intensity. However, 25·9% of the realizations gave a lower total discharge, and 51·2% of the realizations gave a lower peak discharge. These results contrasts with the findings of Wainwright and Parsons (2002), who found that the use of variable-intensity rainfall always resulted in an increase in the amount of runoff leaving a slope. The results presented here show that the temporal structure can both increase and decrease the amount of runoff leaving a slope during a storm event. This difference may be due to the different range of storm characteristics considered in this research.

The investigations into which factors of the rainfall series have the greatest control on the runoff coefficient are presented. The modelling results showed that, although many statistical properties of the time-series are related to the runoff coefficient, no one statistical property was able to explain the variations in the runoff coefficients. The statistical properties do not directly consider the temporal structure of the rainfall time-series. The variability of the per minute rainfall intensities, expressed by the standard deviation, is able to explain 33·6% of the variability in the runoff coefficient. With more variable rainfall, the periods with runoff-generating rainfall become more fragmented. This allows the system to move back into stage 2 or stage. This finding suggests that the temporal structure, as well as the variability, plays a significant role in the determination of the runoff coefficient.

The variability of the 1–5 min rainfall intensities is important when considering the significance of convective-driven rainfall events as opposed to frontal-driven events. Convective events have short bursts of high - intensity rainfall with little build up, whereas frontal storms have rainfall over many days, which conditions the ground surface for runoff generation. The frontal storms, therefore, produce relatively more runoff and discharge at lower rainfall intensities.

These findings regarding the temporal structure of the rainfall intensities within the storm event support the comments of Yair and Lavee (1985), who found that the properties of the rainfall time-series were able to explain the observed discontinuities in the runoff from arid and semi-arid catchments in Israel. The importance of the variability in rainfall intensities was shown in the work by Wainwright and Parsons (2002). The Monte Carlo analysis suggests that many simple statistical properties of the time-series can be related to the amount of discharge. However, each of these relationships contains a large amount of scatter, thus indicating that there is a complex interplay between the parameters driving runoff generation and the runoff–run-on processes occurring across the hillslope. The nature of these relationships will be further complicated if variable land surface properties are also considered.

CONCLUSIONS

The response of the hydrological system to changes in the rainfall characteristics can be explained using a four-stage model of the runoff-generation process. These stages are: (1) all water infiltrating, (2) the surface depression store filling or emptying without runoff occurring, (3) the generation and transmission of runoff and (4) the transmission of runoff without new runoff being generated. The storm event will move the system between the four stages, and the nature of the rainfall required to move between the stages is determined by the surface characteristics.

The runoff coefficient is very sensitive to changes in the duration over the range 1–20 min. This sensitivity relates to the time required to move the system into the runoff-generating stage described above. It is most sensitive to changes in the rainfall intensity over the 10–30% runoff coefficient region of the parameter space and is less sensitive above this region. The change in sensitivity relates to the interaction between the infiltration rate and the rainfall intensity. In the 10–30% region, the infiltration rate and the rainfall intensity are similar; thus, a small change in the rainfall intensity results in a large change in discharge. Above this region, the rainfall intensity is much greater than the infiltration rate and, hence, a small change does not give such a large change in the discharge.

The temporal fragmentation of high-intensity rainfall is important for determining the flow distances and, hence, the amount of runoff that leaves the slope as discharge. If the high-intensity rainfall is fragmented, then the runoff will be infiltrated a short distance downslope. Longer periods of unbroken high-intensity rainfall allow the runoff to travel further and, hence, become discharge. Therefore, storms may have the same amount of high-intensity rainfall, but produce very different amounts of discharge. This shows the importance of the variable-intensity rainfall when modelling semi-arid runoff generation. The amount of discharge may be greater or less than the amount that would have been produced if constant rainfall intensity were used in the model. Therefore, much attention must be paid to the temporal structure of rainfall events in studies of semi-arid hydrological systems, since the temporal structure plays a key role in determining the hydrological response.

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