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Storm Runoff Generation at La Cuenca

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10.1 INTRODUCTION

Dynamic, spatially-explicit models of storm runoff generation are needed to underpin the prediction of particulate and solute movement through catchments. When such runoff models are applied to these problems, the spatial pattern, frequency and magnitude of overland flow must be simulated faithfully. Remarkably, there are few studies reported in the literature that compare model predictions and field observations of overland flow patterns at the catchment scale. This seems to be partly due to the fact that overland flow within catchments is notoriously variable in time and space, and is thus problematic to measure. However, it is also true that model predictions of overland flow patterns are rarely flattering when compared to reality, and this partly explains why few studies have reported such results. In this chapter we illustrate that part of the key to getting good spatial predictions of overland flow is properly representing spatial variability in soil hydraulic properties.

There is considerable debate in the literature regarding the need and manner in which to represent spatial variability of soil properties in runoff models. Smith and Hebbert (1979) compared storm runoff generation on a simple plane in which saturated hydraulic conductivity \( K_s \) values were either held uniform in space, systematically distributed or randomly distributed. The various parameter sets they compared produced very different results, though they noted some situations where a uniform \( K_s \) value produced similar runoff results as a randomly allocated log-normal distribution of \( K_s \) values. Binley et al. (1989) also found that runoff predictions were affected by soil property representation in their model, though they emphasised that the differences were only significant for low-permeability soils, dominated by surface runoff processes. Grayson et al. (1992a) detected only minor differences in discharge hydrographs on a catchment dominated by saturated source area runoff when uniform and randomly distrib-
uted $K_s$ values were compared. Merz and Plate (1997) and Grayson et al. (1995) illustrated that the spatial pattern of soil properties had different effects on predicted hydrographs depending on the intensity and amount of rainfall relative to the soil hydraulic properties and antecedent condition (see also Figure 1.6). Smith and Hebbert (1979) and Grayson et al. (1992a) argued that spatial variation in $K_s$ should be, at least in part, deterministic. They recommended against allocating randomly variable $K_s$ values in space without being sure there was no deterministic component to the $K_s$ patterns.

What seems to be lacking in the literature is the coupling of deterministic and stochastic variation in soil properties and the joint representation of these in distributed hydrologic models. Many catchment surveys reveal considerable spatial variability in soil hydraulic properties (see for instance Loague and Kyriakidis, 1997), though the median and standard deviation of property values may still be distinguishable, statistically speaking, between different parts of these catchments. This is well illustrated in the field data discussed by Elsenbeer et al. (1992) for a tropical rainforest catchment in western Amazonia, where four different soil types are distinguished and each has its own distinctive internal variability. The superimposition of stochastic variation on top of deterministic patterns of soil hydraulic properties, or any other system property for that matter, appears to be an approach rarely employed in distributed hydrologic modelling. One of the few exceptions is the KINEROS model described in Chapter 6, where deterministic patterns of soil properties are imposed across the modelling domain, but grid-scale hydraulic conductivity varies stochastically within an element around its geometric mean.

Another key determinant in the success of any storm runoff modelling exercise can be the manner in which initial moisture conditions are set in the model. Stephenson and Freeze (1974) argued that the initial moisture state of the catchment is the factor most likely to determine the outcome of an event prediction, while Merz and Bárdossy (1998) have argued that initial conditions are less critical, particularly in the case of large events. These and other studies have demonstrated that the importance of initial conditions depends on the dominant runoff mechanisms. For saturated source area runoff, correct specification of the initial saturation deficit is critical to accurate storm modelling. In the case of infiltration excess runoff, the importance of initial conditions depends on the storm intensity relative to the infiltration characteristics of the soil. If the storm is very much larger or smaller than the infiltration rates of the soil, initial conditions are not critical. When these are of similar magnitude, predicted runoff becomes highly sensitive to initial conditions (see also discussion in Chapter 6, p. 155). A survey of the literature reveals significant variation in the manner in which modellers deal with initial moisture conditions in event-based simulations. For instance, Coles et al. (1997) treated initial moisture conditions as a “black box” parameter, freely adjusting it between events as a calibration parameter. Grayson et al. (1992a) used the $\ln(a/\tan \beta)$ index to spatially modulate a single known or estimated moisture value. Merz and Plate (1997) used actual soil moisture observations, interpolated in association with the $\ln(a/\tan \beta)$ index, to initiate their simulations.
In this chapter, we review our attempts to measure and simulate storm runoff generation patterns across a small tropical rainforest catchment in western Amazonia, La Cuenca. After many years of effort we have gained a thorough understanding of storm runoff generation mechanisms within this catchment, and have recognised the importance of spatial variability in soil hydraulic properties (Elsenbeer et al., 1992, 1995; Elsenbeer and Lack, 1996; Vertessy and Elsenbeer, 1999; Elsenbeer and Vertessy, 2000). We have used our field knowledge to develop and evaluate a simple, dynamic and spatially explicit storm runoff model called Topog_SBM (Vertessy and Elsenbeer, 1999). In our quest to predict the spatial distribution of overland flow, we have come to appreciate the importance of spatial variability in soil hydraulic properties and the manner in which this should be represented in distributed hydrologic models. We have also compared different ways of initialising soil moisture conditions for our event simulations and have shown that assuming steady-state drainage is an objective and adequate approach to simulating initial soil moisture patterns.

Below, we describe the La Cuenca catchment, focussing on the measured spatial variability in soil hydraulic conductivity across the catchment. We then discuss observed mechanisms of storm runoff generation within the catchment, yielded from a combination of hydrometric and hydrochemical studies. After describing the Topog_SBM model briefly, we discuss four different ways in which such a model can be parameterised in terms of soil hydraulic property representation. Running the model on La Cuenca with each of these four different parameter sets, we compare model performance in terms of outflow hydrographs and spatiotemporal patterns of overland flow occurrence. It is shown that the manner in which soil hydraulic properties are represented has modest consequences for outflow hydrographs, but a very significant impact on simulated spatial patterns of overland flow. We demonstrate that the best results are obtained when deterministic and stochastic variations in soil properties are represented in the modelling process.

10.2 THE LA CUENCA CATCHMENT

La Cuenca is located in the Rio Pichis Valley in the Selva Central of Peru (75°5’W, 10°13’S) at about 300 m above mean sea level (Figure 10.1). It is a small first-order basin, covering an area of 0.75 ha and spanning a relative relief of 28 m. La Cuenca is characterised by short, steep convexo-linear sideslopes (up to 40°), narrow valley floors, and deeply incised gullies near stream heads (Elsenbeer et al., 1992). The catchment is covered by an undisturbed multi-storied primary rainforest (Figure 10.2). Despite its very small size, the catchment includes at least 57 different plant species, belonging to 25 families (Elsenbeer et al., 1994).

Mean annual temperature for the study site is 25.5 °C and mean annual rainfall is 3300 mm. Monthly rainfall is highest during December–March (up to 900 mm) and lowest during June–September (below 110 mm). Daily rainfall rarely exceeds 100 mm. During our intensive study period, June 1987 to April 1989, the
maximum daily rainfall amount was 70.3 mm and the maximum five-minute rainfall intensity was 96.0 mm h\(^{-1}\) (Table 10.1).

Elsenbeer et al. (1992) defined three main land units in the catchment, differentiated by topography and soil properties. These were the steep lower sideslope (unit B), intermediate terrace (unit C), and gentle upper sideslope (unit D) (Figure 10.3). Ultisols, observed over extensive areas of western Amazonia (Buol et al., 1989), are the main soil type within the catchment, though Inceptisols are present in land unit B. Soil depth across the catchment averages
Figure 10.2(a). Photograph of the La Cuenca catchment.

Figure 10.2(b). Photograph of the overland flow detectors.
about 1.0 m, with only modest spatial variation. The soils tend to be slightly (< 30%) deeper in the valley bottom than on the sideslopes. Elsenbeer et al. (1992) measured saturated hydraulic conductivity \( K_s \) across the catchment at various depths in the soil, involving 740 undisturbed small cores. On the basis of a detailed statistical analysis, they were able to demonstrate statistically significant differences between the \( K_s \) value distributions measured in the various land units, despite the fact that each land unit contained huge variability within it. Hence, they observed random variation imposed on top of a deterministic spatial pattern of soil properties.

Table 10.1. Descriptive statistics pertaining to 214 individual rainfall events sampled at La Cuenca, June 1, 1987 – April 18, 1989. \( I_5 \) denotes maximum 5-minute rainfall intensity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Median</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall amount</td>
<td>mm</td>
<td>8.7</td>
<td>70.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Rainfall duration</td>
<td>min</td>
<td>170</td>
<td>960</td>
<td>10</td>
</tr>
<tr>
<td>( I_5 )</td>
<td>mm h(^{-1})</td>
<td>19.2</td>
<td>96.0</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 10.3. Position of land units B, C and D in the La Cuenca catchment, showing the location of major sub-surface pipes and the frequency of overland flow occurrence at 72 detector sites for 187 separate events, after Vertessy and Elsenbeer (1999).
Median values of $K_s$ at the surface varied by an order of magnitude between land units, with the highest values present in unit C and the lowest in unit B (Table 10.2). $K_s$ was found to decrease sharply with depth in all three land units, though most sharply in land unit B. This has been attributed to higher clay content at depth in the soils of this unit. In Figure 10.4, we show the cumulative frequency distribution of surface $K_s$ values for all three land units and for the catchment as a whole. Each of the four cumulative frequency distributions shown is approximately log-normally distributed. These distributions are used later in the modelling analysis reported in this chapter.

The spatial and temporal frequency of overland flow occurrence was measured at La Cuenca using 72 overland flow detectors, similar to those described

**Table 10.2.** Median $K_s$ values (m d$^{-1}$) for various soil layers in land units B, C and D, after Elsenbeer et al. (1992). Note that 1 m/d = 41.7 mm/hr

<table>
<thead>
<tr>
<th>Unit</th>
<th>0–0.1 m</th>
<th>0.1–0.2 m</th>
<th>0.2–0.3 m</th>
<th>0.3–0.4 m</th>
<th>0.4–1.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1.09</td>
<td>$9.50 \times 10^{-3}$</td>
<td>$2.16 \times 10^{-3}$</td>
<td>$3.46 \times 10^{-3}$</td>
<td>$4.58 \times 10^{-3}$</td>
</tr>
<tr>
<td>C</td>
<td>11.09</td>
<td>$8.98 \times 10^{-2}$</td>
<td>$1.99 \times 10^{-2}$</td>
<td>$2.50 \times 10^{-3}$</td>
<td>$2.40 \times 10^{-4}$</td>
</tr>
<tr>
<td>D</td>
<td>8.02</td>
<td>$2.59 \times 10^{-2}$</td>
<td>$1.30 \times 10^{-2}$</td>
<td>$3.46 \times 10^{-4}$</td>
<td>$2.40 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**Figure 10.4.** Various frequency distributions of surface saturated hydraulic conductivity, $K_0$, measured in the La Cuenca catchment; these pertain to land units B, C and D, and the catchment as a whole. The dashed lines highlight the median values. (From Vertessy and Elsenbeer, 1999; reproduced with permission.)
by Kirkby et al. (1976). The positions of the 72 detectors are shown in Figure 10.3, which also shows the observed frequency of overland flow occurrence at each of the installation sites. Each detector consisted of a 25 cm long, 5 cm diameter PVC tube, with one end sealed with a lid, and the other attached to a Y-junction (Figure 10.2b). The bottom end of this junction was sealed with a lid, serving as a collecting unit, the top end covered with a can. One third of the PVC tube’s circumference was perforated with some 200 1-mm diameter holes. The detectors were installed in such a way that the perforated portion was in good contact with the soil, and that any intercepted overland flow would drain towards the collecting unit. Overland flow was judged to have occurred if the bottom of the collecting unit was completely covered by standing water, not just by a thin film.

Overland flow was also monitored continuously at three sites. The monitoring system at sites S1 and S2 (see Figure 10.3) was designed according to Riley et al. (1981). A triangular layer of topsoil, about 5 cm thick and two metres wide at the upslope base parallel to the contour lines, was carefully removed. The resulting cavity was filled with concrete, and the upslope contact moulded in such a way as to fit the microtopography of the soil surface. Strips of sheet metal were attached to both sides so as to route any intercepted overland flow towards the downslope apex equipped with a pipe, and further on to a series of connected 55 gallon drums. One of these at each site was equipped with a float-operated water level recorder. At site S3 (see Figure 10.3), a concentrated-flow line was intercepted with a simple device fabricated out of sheet metal.

Three sets of observed rainfall events are used in this chapter. The first is a set of 187 events for which data from the overland flow detectors is available and frequency of occurrence of overland flow can be computed. The second is a set of 34 events that were used for runoff simulations. Thirdly, the 10 events from the second set that overlapped with the first set are used to compare both the simulated runoff and the simulated spatial patterns of runoff occurrence with the respective observations.

10.3 STORM RUNOFF PROCESSES OPERATING AT LA Cuenca

Storm runoff in steep, humid, forested landscapes has traditionally been viewed to occur primarily via subsurface pathways (Dunne et al., 1975). Overland flow in such environments is often presumed to occur only as saturation excess in preferred topographic locations, namely valley bottoms and hillslope hollows. The study of Bonell and Gilmour (1978) was one of the first to demonstrate that overland flow could be widespread in a tropical rainforest setting, and display patterns of occurrence not necessarily dictated by topography. Our findings at La Cuenca concur with their observations.

For the La Cuenca catchment, previous studies have concluded that:

1. overland flow is generated frequently, both in the spatial and temporal sense (Elsenbeer and Lack, 1996);
2. changes in the \( K/\text{SiO}_2 \) ratio in streamflow during storms indicate a significant volumetric contribution of overland flow to storm runoff (Elsenbeer and Lack, 1996);

3. overland flow is generated by infiltration excess (Hortonian), saturation excess, and return flow mechanisms (Elsenbeer and Vertessy, 2000); though the relative proportions of these are not known it has been assumed that Hortonian runoff is infrequent as surficial hydraulic conductivities almost always exceed the maximum five-minute rainfall intensities;

4. topography exerts only a mild control on overland flow generation in this catchment (Elsenbeer and Vertessy, 2000);

5. there is significant storm runoff generated through a shallow subsurface pipe network, which emerges at the surface as return flow (Elsenbeer and Vertessy, 2000).

The widespread occurrence of both overland and subsurface flow at La Cuenca, and the manner in which they are generated, can be explained by the interaction of catchment soil hydraulic properties and local rainfall characteristics. The \( K_s \) of the soil decreases so abruptly with depth (Elsenbeer et al., 1992) that even low-intensity rainfall is likely to generate shallow subsurface flow, if rain persists for long enough (Figure 10.5). Low-intensity rainfall, however, is the exception rather than the rule in this environment, which, together with a high-rainfall frequency, causes a perched water table to reach the soil surface in many places, thus producing extensive saturation excess overland flow (Elsenbeer and Vertessy, 2000).

By comparing surface \( K_s \) values with the observed maximum and median 5-minute duration rainfall intensities (96 and 25 mm h\(^{-1}\), respectively), it is evident that infiltration excess overland flow may also occur in this catchment (dashed lines in Figure 10.5). However, this tends to operate in small ‘partial areas’ only, usually

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**Figure 10.5.** Box plots indicating the relationship between soil hydraulic conductivity at four different depth intervals and rainfall intensity at La Cuenca, after Elsenbeer and Vertessy (2000). The dashed horizontal lines denote the maximum and median 5-minute duration rainfall intensities recorded during the study period (96 and 25 mm h\(^{-1}\), respectively).
confined to the steep lower sideslopes (unit B) where surficial $K_s$ values are lowest (Elsenbeer et al., 1992).

For several places within the catchment, overland flow can be clearly traced back to the outlets of soil pipes (Figure 10.3). Elsenbeer and Lack (1996) argued that this return-flow mechanism is at least as prevalent as saturation overland flow in the catchment, and a strong determinant of the observed overland flow pattern (Figure 10.3). As noted earlier, they measured overland flow continuously at the three sites marked S1, S2 and S3 in Figure 10.3, across six events of varying magnitude and duration. The total event overland flow volumes at sites S1 and S2 ranged between 0 and 33 litres, whereas the total event overland flow volumes from S3 (the only one of the three sites associated with a subsurface pipe) ranged between 103 and 500 litres. At least six pipes of similar dimensions have been detected across the catchments (Figure 10.3), though we have no knowledge of the volume of flow emerging from these. On the basis of the flow volumes emerging from the single pipe we have instrumented, it is conceivable that the total volumes of runoff emerging from pipes account for a large proportion of total runoff during storm events. It is also worth noting that because of its point-source origin, return flow from pipes tends to occur more in concentrated flow lines, although this is also often a consequence of the rough micro-topography of the forest floor. This has consequences for the ability of such flows to re-infiltrate further downslope.

Hydrochemical measurements provide further insights into how storm runoff is generated within the La Cuenca catchment. Elsenbeer et al. (1995) showed that the chemical “fingerprints” of saturation overland flow, return flow, and subsurface flow at La Cuenca were each distinctive with respect to certain elements, most notably potassium ($K$) and Silica ($SiO_2$). Elsenbeer and Lack (1996) showed how the fingerprints of stream discharge varied systematically throughout storms in response to varying inputs of water from different hydrologic compartments in the catchment. Invariably, the $K/SiO_2$ ratio of the stream water rose and fell in association with discharge, reflecting the importance of overland flow as a major contributor to storm runoff (Figure 10.6).

Several studies have used hydrochemical information to “separate” the discharge hydrograph into time-varying fractions of storm runoff generated via different hydrologic pathways in catchments (Turner and Maepherson, 1987; McDonnell et al., 1990). In conducting such separations, it is commonly assumed that the signatures of the various hydrologic compartments do not vary in space. Our field experience at La Cuenca tells us that such assumptions are invalid and result in erroneous separations. Figure 10.7 shows the result of a chemical hydrograph separation into groundwater and overland flow components for a single event at La Cuenca. By treating overland flow chemistry as a constant in space, an apparent dominant volumetric contribution of overland flow results in the separation for this event. However, by accounting for the measured spatial variability in overland flow chemistry, confidence limits may be attached to the separation. The shaded area in Figure 10.7 shows that, even in the generous case of a 90% confidence limit, uncertainty regarding the relative contribution of overland

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flow, especially near peak flow, is considerable. In the case of a 95% confidence level (not shown), the lower limit for the overland flow contribution at peak flow overlapped with the groundwater contribution. Such data highlight the importance of spatial variability in overland flow and its role in catchment storm runoff production at La Cuenca.

10.4 THE TOPOG_SBM MODEL

The Topog series of models are designed to predict the spatiotemporal hydrologic dynamics of small (< 10 km²) heterogeneous catchments. Topog_SBM is one of the several models in this series and was derived by hybridising elements of

Figure 10.6. Catchment discharge and K/SiO₂ chemograph for the November 27, 1988 event at La Cuenca, after Elsenbeer and Lack (1996). A-A’ denotes duration of net rainfall (throughfall), and B-B’ denotes duration of overland flow.

Figure 10.7. Hydrograph separation for a typical rainy-season event at La Cuenca, based on a three-component mixing model (for sake of clarity, the soil water component is not shown). The shaded area denotes the bounds of the 90% confidence limits for the overland flow estimate.
the spatially explicit, fully dynamic model, Topog_dynamic (Vertessy et al., 1993, 1996; Dawes and Short, 1994; Dawes et al., 1997) and the aspatial, quasi-
dynamic model, TOPMODEL (Beven and Kirkby, 1979; Beven, 1997). In
brief, Topog_SBM consists of:

- the contour-based “streamtube” network for surface and subsurface flow
  routing, common to all Topog applications (see Figure 10.8),
- a simple bucket model for handling soil water fluxes in and between each
  element (as opposed to the Darcy–Richards approach described for pre-
  viously reported versions of Topog), and
- a one-dimensional kinematic wave overland flow module for simulating
  surface runoff along the Topog “streamtubes”.

Full details of the various components of Topog_SBM are given in Vertessy and
Elsenbeer (1999). Figure 10.9 provides a schematic representation of the model,
illustrating that it is capable of simulating infiltration excess, saturation excess
and exfiltration (or return) overland flow, as well as lateral subsurface flow
through the soil matrix. An underlying assumption of the model (borrowed
from TOPMODEL) is that $K_s$ is greatest at the soil surface and declines expo-
nentially with depth through the soil profile. The model as used here does not
explicitly represent pipe flow.

Topog_SBM is a fully distributed model, meaning that each spatial unit (or
element) can be ascribed unique system properties if so desired. For each timestep
(a five minute interval was adopted here) and each catchment element, the model
computes water table depth, soil moisture storage, deep drainage loss, lateral
subsurface flow, and overland flow height, velocity and discharge. As the

Figure 10.8. Element network computed by Topog for the La Cuenca catchment. Catchment area is
0.68 ha and mean element area is 10.1 m$^2$. (From Vertessy and Elsenbeer, 1999; reproduced with
permission.)
model is typically run for discrete storm events only, evapotranspiration processes are ignored. Our choice of a five minute timestep was dictated by the temporal discretisation of our rainfall input series. For such a small catchment, a smaller timestep (say one or two minutes) may have been preferable.

Aside from a rainfall series to drive the simulation and the topographic data used to derive the flow net, six model inputs must be specified for each element. These are soil depth ($z$), saturated soil water content ($\theta_s$), residual soil water content ($\theta_r$), saturated hydraulic conductivity at the soil surface ($K_o$), the rate of $K_s$ decay through the soil profile ($m$) and the Manning roughness value ($n$). Each of these inputs may be considered to be uniform across the catchment, or ascribed on an element by element basis, to represent spatial variability across the catchment.

### 10.5 MODEL APPLICATION

The La Cuenca catchment was discretised into a network of 678 elements (Figure 10.8), resulting in a mean element area of 10.1 m$^2$ and a maximum element area of 35.9 m$^2$. The element slope averaged 0.43 m m$^{-1}$ and ranged between 0.02 m m$^{-1}$ on the floodplain and 1.92 m m$^{-1}$ on the gully sideslopes. We represented the catchment floodplain (about 9% of the catchment area) by allocating a low slope (0.02 m m$^{-1}$) to the bottom row of elements, which represent about 8% of the catchment area.
We compared four different ‘sets’ of parameter values, which were distinguished by the manner in which soil hydraulic properties were represented. In set 1 (the “uniform” case) we applied the median value of the master $K_o$ data distribution (2.3 m d$^{-1}$) to every element in the catchment. In set 2 (the “organised” case) we applied the median $K_o$ value for land units B, C and D (1.2, 10.6 and 8.1 m d$^{-1}$, respectively) to all elements lying within each of these units. In set 3 (the “random” case), we randomly allocated deciles of the master cumulative frequency distribution of $K_o$ values (see Figure 10.4d) across the whole catchment. In set 4 (the “random&organised” case), we randomly allocated deciles of the cumulative frequency distribution of $K_o$ values for land units B, C and D (see Figures 10.4a, 10.4b and 10.4c), to elements lying within each of these units, respectively. It should be noted that we used a single random realisation of $K_o$ values for sets 3 (random) and 4 (random&organised) rather than multiple realisations as has been used by, for example, Smith and Hebbert (1979), Freeze (1980) and Loague and Kyriakidis (1997). Because the measured variability of $K_o$ is at a small scale relative to the size of the catchment, we believe that multiple realisations would produce similar results to the single realisation used here. If the scale of variability were larger relative to catchment size (such as the case of rainfall patterns in Chapter 6, pp. 133–4) we would have to use multiple realisations.

In all sets, soil depth, $z$, was fixed at 1.0 m for the whole catchment, as field observations did not reveal any significant variation in this quantity. Similarly $\theta_s$ and $\theta_r$ were fixed at 0.4 and 0.05, respectively, for all sets, again because little variability was evident in the field data gathered from the site. Preliminary model sensitivity analyses we have conducted suggest that $\theta_s$ and $\theta_r$ values (when systematically changed across their natural range) have a minor impact on model behaviour. Soil depth has a more significant effect, but the < 30 % variation over the La Cuenca catchment has a minimal effect on simulated runoff behaviour.

For sets discriminating between land units (sets 2-organised and 4-random&organised), the $K_o$ decay parameter ($m$) was set to 0.07, 0.02 and 0.01 for land units B, C and D, respectively. For sets 1-uniform and 3-random, the mean of these three $m$ values (0.03) was adopted.

A single event (event 12) was used to calibrate the model for all four sets. All simulations were initiated with a catchment wetness pattern derived from a “warm-up” simulation. The warm-up simulations involved applying a steady rainfall input equivalent to the observed pre-storm runoff rate; the run was terminated after the model produced a steady rate of runoff, equivalent to the pre-storm rate. On average, the warm-up run lasted about 100 days.

For each of the four parameter sets, it was possible to “fit” the model discharge hydrograph well to event 12, despite the fact that the observed hydrograph had a fairly complex shape. The Manning roughness parameters ($n$) obtained from these calibrations were 1.2, 1.1, 0.7 and 1.1 for sets 1, 2, 3 and 4, respectively. These $n$ values are much higher than commonly reported in the literature, although Shen and Julien (1992) note that $n$ can exceed 1.0 for extremely dense vegetation (their Table 12.2.1, p. 12.15). Acceptable hydrograph recessions could only be obtained by adopting such high $n$ values. The model
fit for set 4 (random & organised) is shown in Figure 10.10, illustrating that the height and timing of both runoff peaks, and the shape of the runoff recessions were faithfully reproduced by the model; similar quality fits were obtained for the other three sets.

We simulated 34 individual events for La Cuenca, chosen to span a wide range of rainfall totals, intensities and durations, and associated with varying antecedent soil moisture conditions (Figure 10.11). Rainfall totals varied between 10.2 and 82.5 mm (Figure 10.11a), with maximum five-minute intensities ($I_5$) ranging between 31.2 and 82.8 mm h$^{-1}$ (Figure 10.11b). Pre-storm runoff rates varied between 0.005 and 0.37 mm h$^{-1}$ (Figure 10.11c). Runoff totals varied between 1.3 and 44.8 mm (Figure 10.9d), and peak runoff rates ranged between 1.3 and 17.5 mm h$^{-1}$ (Figure 10.11e). Times between the start and peak of runoff (time of rise) ranged between 20 and 125 min, and averaged 40 min (Figure 10.11f). The graphs showing the frequency distributions for rainfall and $I_5$ also display the distributions for a larger population of events (187 in total) which were associated with the overland flow frequency observations shown in Figure 10.3. This shows that the 34 events which we modelled were skewed towards higher rainfall magnitudes and intensities when compared to the larger population of storm events.

### 10.6 MODEL RESULTS

Below, we explore how the model, when calibrated on the single event, performed on the other 33 events using four different sets of input parameters.

#### 10.6.1 Hydrograph Predictions

Figures 10.12 and 10.13 compare observed and predicted values of total runoff, peak runoff and time of rise for all 34 events, with predictions shown for each of the four parameter sets. Figure 10.12 shows observed values plotted against
Table 10.3. Statistics for the 10 overlapping events for which observed and predicted overland flow frequencies were compared.

<table>
<thead>
<tr>
<th>Event</th>
<th>Duration (min)</th>
<th>Pre-storm runoff (mm h⁻¹)</th>
<th>Total rainfall (mm)</th>
<th>Maximum $I_5$ (mm h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>90</td>
<td>0.112</td>
<td>28.0</td>
<td>36.0</td>
</tr>
<tr>
<td>4b</td>
<td>110</td>
<td>0.267</td>
<td>34.2</td>
<td>64.0</td>
</tr>
<tr>
<td>4c</td>
<td>550</td>
<td>0.364</td>
<td>83.5</td>
<td>96.0</td>
</tr>
<tr>
<td>5</td>
<td>140</td>
<td>0.267</td>
<td>31.8</td>
<td>33.6</td>
</tr>
<tr>
<td>7</td>
<td>280</td>
<td>0.275</td>
<td>30.6</td>
<td>36.0</td>
</tr>
<tr>
<td>8</td>
<td>270</td>
<td>0.257</td>
<td>39.9</td>
<td>64.8</td>
</tr>
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<td>16</td>
<td>220</td>
<td>0.163</td>
<td>14.3</td>
<td>26.4</td>
</tr>
<tr>
<td>17</td>
<td>150</td>
<td>0.078</td>
<td>20.4</td>
<td>48.0</td>
</tr>
<tr>
<td>21</td>
<td>80</td>
<td>0.131</td>
<td>19.5</td>
<td>45.6</td>
</tr>
<tr>
<td>22</td>
<td>75</td>
<td>0.219</td>
<td>14.2</td>
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</tr>
<tr>
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<td>0.238</td>
<td>29.3</td>
<td>40.8</td>
</tr>
<tr>
<td>Median₃₄</td>
<td>128</td>
<td>0.125</td>
<td>31.4</td>
<td>51.4</td>
</tr>
</tbody>
</table>

The subscript 34 denotes that these are the median values for all 34 events which were simulated.

Figure 10.11. Hydrometric characteristics of the 34 events simulated in this study, highlighting the model calibration event (event 12). The dashed lines in (a) and (b) refer to the characteristics for the 187 events associated with the overland flow frequency analysis reported in Elsenbeer and Lack (1996).
predicted values, whereas Figure 10.13 compares the cumulative frequency distributions for the observed and predicted values. By examining Figure 10.12 we can gain a sense of model error for particular events and thus detect where the model fails. Figure 10.13 shows us how the frequency of predicted hydrograph properties compares to what was observed in the field; this is most relevant when considering the ability of the model to predict multiple events.

All four sets produced very good estimates of total runoff for most of the events, with $r^2$ values ranging between 0.95 and 0.97 (Figure 10.12a). The best total runoff estimates were obtained from set 4 (random&organised), particularly for the larger events. Figure 10.13a shows that all sets slightly underpredicted the distribution of runoff values for the smallest 65% of events. It also shows that set 4 (random&organised) yielded the best cumulative distribution of total runoff volumes for the largest 35% of events.

Peak runoff was simulated less well by all sets, with $r^2$ values ranging between 0.47 and 0.66 (Figure 10.12b). Generally, good peak runoff predictions were obtained for events with small runoff peaks ($< 6\text{ mm h}^{-1}$) and large runoff peaks ($> 12\text{ mm h}^{-1}$), though intermediate events were poorly simulated by all sets. For the larger events, peak runoff was predicted best by sets 3 (random) and

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**Figure 10.12.** Observed versus predicted total runoff, peak runoff, and time of rise for all 34 events, for sets 1 (uniform), 2 (organised), 3 (random) and 4 (random&organised). The diagonal line in each plot is the 1:1 line.

**Figure 10.13.** Cumulative frequency distributions of observed and predicted (a) total runoff, (b) peak runoff, and (c) time of rise, for all 34 events.
4 (random & organised), and worst by set 1 (uniform). Similar conclusions can be drawn from Figure 10.13b which shows that the predicted distribution of peak runoff values was always lower than observed, except for the largest 10% of events. The largest discrepancies occurred between the 20th and 40th percentiles. Figure 10.13b also shows that set 4 (random & organised) predicted the most accurate cumulative distribution of peak runoff values, and that set 1 (uniform) yielded the worst results, although differences between the sets were small.

The time of rise predictions were generally good for all sets, with \( r^2 \) values ranging between 0.58 and 0.81 (Figure 10.12c). Set 3 (random) yielded the best cumulative distribution of time of rise values, being quite close to the observed distribution across the range of events (Figure 10.13c). Set 4 (random & organised) predicted much greater times of rise than were observed for the largest 10% of events.

In summary, reasonable catchment outflow hydrographs could be obtained for 34 events of varying magnitude and duration, using four different parameterisations of the model. This was achieved in spite of the fact that the model was calibrated on a single event (event 12), and that fairly simplistic initial moisture conditions were adopted in the simulations. Overall, sets 3 (random) and 4 (random & organised) yielded the best results and set 1 (uniform) yielded the worst.

### 10.6.2 Overland Flow Predictions

As noted earlier, one of our main aims was to simulate credible spatiotemporal patterns of surface runoff generation across the La Cuenca catchment. Figure 10.3 showed the frequency of overland flow occurrence at 72 detector sites for a total of 187 events. In Figures 10.11a and 10.11b, we showed that the distributions of total and maximum \( I_5 \) values of rainfall for our 34 events were much more skewed to “big events” than in the 187 events associated with the observed overland flow data set. There are two reasons for this. First, when selecting events to simulate, we tended to choose events that generated significant streamflow. Many of the 187 events sampled for overland flow frequency simply did not generate streamflow. Second, most of the 187 overland flow events were sampled early in the field campaign when mild drought conditions were prevailing, resulting in a greater than normal percentage of low-rainfall events. Ultimately, overland flow frequency amongst the 72 detector sites was only measured for 10 of the 34 events we simulated. These 10 “overlapping” events were used as the basis to compare observed and predicted spatial patterns of overland flow. The median event characteristics for these 10 events varied only slightly from those for the full 34 modelled, the median event duration being 145 min as opposed to 128 min, the median event rainfall being 29.3 mm as opposed to 31.4 mm, and the median maximum \( I_5 \) value being 40.8 mm h\(^{-1}\) as opposed to 51.4 mm h\(^{-1}\).

Figure 10.14 compares observed and predicted frequency distributions of overland flow occurrence for the 10 “overlapping” events at La Cuenca, and illustrates the strong effect of soil property representation in the model. These
data show what percentage of the model elements was predicted to generate overland flow. Also shown is the observed frequency distribution of overland flow at 72 detector sites for the same 10 events. Associated spatial patterns of overland flow frequency for sets 1 (uniform), 2 (organised), 3 (random) and 4 (random&organised) are shown in Figure 10.15.

The observed overland flow frequency distribution shown in Figure 10.14 indicates a near-linear pattern, with overland flow being generated at half of the detector sites for about half of the events. Only the tails of the distribution diverged from this linear pattern.

Using set 1 (uniform), the predicted pattern of overland flow development is strongly influenced by topographic factors, as soil properties are assumed to be uniform across the catchment (Figure 10.15). In this case, overland flow is concentrated in valleys and along the bottom contour, which we have represented as a floodplain by allocating low slope values to it. According to Figure 10.14, for set 1 (uniform) overland flow is generated over much less of the catchment area than is observed for almost all events. Using set 2 (organised), the influence of spatially variable soil is evident (Figure 10.15), with widespread occurrence of overland flow in landscape unit B, which has the lowest median $K_o$ value (Figure 10.4). The associated frequency distribution for set 2 (organised) shown in Figure 10.14 indicates that overland flow occurs far more extensively than in set 1 (uniform).
Figure 10.15. Predicted spatial patterns of overland flow frequency across the catchment for 10 events, as predicted by set 1 (uniform), set 2 (organised), set 3 (random), and set 4 (random&organised). (From Vertessy and Elsenbeer, 1999; reproduced with permission.)
for events ranked between the 10th and 40th percentile, but is of a similar pattern for all other events. Again, this frequency distribution differs significantly from that which has been observed in the field. In the case of set 3 (random), overland flow is generated in a random pattern across the catchment (Figure 10.15), though subtle topographic control is still evident. The pattern of runoff occurrence for set 3 (random) is dominated by extremes with a lot of elements showing no runoff and a lot with almost always runoff. This is because the mean soil conductivity is of a similar value to the precipitation intensities so, when randomness is introduced, those elements with lower \( K \) tend to “switch on” while those with higher \( K \) tend to “switch off”. According to Figure 10.14, set 3 (random) predicts that overland flow is generated more widely than is observed for the smaller events (i.e. too many elements are “switched on”), and less widely than is observed for the wettest half of events (i.e. too many elements are “switched off”). A major failing of set 3 (random) is that it predicts overland flow to occur over at least 30% of the catchment area for all events. Set 4 (random&organised) also displays a random pattern of overland flow generation, but not the extreme pattern of set 3 (random). The frequency of runoff occurrence is generally highest in land unit B and lowest in land unit C (Figure 10.15). This is a consequence of the \( K_o \) values in land unit B being almost an order of magnitude lower than those in land unit C (Figures 10.4a and 10.4b). Figure 10.14 shows that set 4 (random&organised) predicts an overland flow frequency distribution which is very similar to the observed distribution, particularly in the interquartile region. Beyond this region the model slightly overpredicts the occurrence of overland flow for the wettest events, and underpredicts its occurrence for the driest events.

Figure 10.16 provides for a visual comparison of the spatial patterns of observed runoff occurrence with the simulations of Figure 10.15. It is clear

![Figure 10.16](image)

**Figure 10.16.** Observed pattern of overland flow frequency across the catchment for the 10 “overlapping” events.
that the observations do not display the topographic or soil-property induced spatial pattern seen in the simulations using set 1 (uniform) or set 2 (organised). The simulation for set 3 (random) is generally characterised by extremes of no runoff or always runoff being detected, but this pattern is not evident in the observations. The pattern of runoff occurrences in the observations is best matched by the pattern using set 4 (random&organised) where there is a full spectrum of occurrences simulated.

10.7 DISCUSSION AND CONCLUSIONS

Whilst La Cuenca is a tiny catchment by any standard, it is characterised by considerable spatial variability in soil hydraulic conductivity and complexity in storm runoff generation. A large body of hydrometric and hydrochemical data indicates that storm runoff production in this catchment is dominated by overland flow. The hydrometric evidence further indicates that the spatial pattern of overland flow is governed by the distribution of soil hydraulic properties and that subsurface pipe outlets are major point sources for overland flow generation. Hydrochemical evidence shows that the $K/\text{SiO}_2$ signature of overland flow is spatially variable, indicating that it arises from a variety of pathways. Again, subsurface pipes are believed to play an important role in overland flow generation and the chemical signature that overland flow assumes. As we showed earlier, the volumes of overland flow generated by a subsurface pipe pathway could be large, but this contention must be regarded as speculative because we only have direct volumetric measurements from a single pipe. In hindsight, it would have been wise to have continuously monitored flows emerging from the other five pipes noted within the catchment (Figure 10.3).

We have described a fully dynamic and distributed storm runoff generation model which was relatively simple to parameterise, but did not include the process of subsurface pipe flow. In fact, a pipe flow process could have been invoked in the model as such a capability exists in Topog_SBM. However, we chose to ignore this process for two reasons. First, whilst we knew of the locations of up to six pipe outlets, we had no knowledge of the pipe dimensions, nor their catchment area. Second, because we had flow data for only a single pipe, we had no means of evaluating model predictions of pipe flow dynamics.

Topog_SBM was applied to La Cuenca for a wide range of event conditions, using four different sets of soil hydraulic properties, each of which could be defended as legitimate representations of field data. In the simplest case, set 1 (uniform), we ascribed the median $K_o$ value to all elements within the catchment. In the most complicated case, set 4 (random&organised), we ascribed deciles from three different distributions of $K_o$ values, randomly, to elements residing within three different sub-areas (land units B, C and D). In this latter case we represented both the stochastic and deterministic variability in catchment soil properties, an approach rarely employed in distributed hydrologic modelling.
The four sets of model predictions of total runoff, peak runoff rate and the time of rise at the catchment outlet were compared against field observations for a total of 34 events. Relatively inferior hydrograph predictions were obtained when it was assumed that soil hydraulic properties did not vary in space and the median \( K_o \) value was ascribed to all catchment elements, set 1 (uniform). The best results were obtained using set 4 (random\&organised), in which the model represented the measured spatial variability of \( K_o \) values within and between land units.

The discharge hydrograph differences between the four sets were relatively subtle, when compared to the predicted differences in spatiotemporal patterns of overland flow occurrence between sets. By randomly varying \( K_o \) across the catchment as a whole, but assuming no deterministic pattern in that variability, set 3 (random), the simulated pattern of overland flow occurrence changed radically but did not improve relative to sets 1 (uniform) and 2 (organised). By far the best results were obtained using the parameterisation for set 4 (random\&organised), where measured spatial variability in \( K_o \) was represented within each individual land unit. Further modelling efforts at La Cuenca could compare multiple realisations of random \( K_o \) fields (e.g. Loague and Kyriakidis, 1997) to assess how much particular random patterns affect results, but given the small scale of variability in soil properties compared to the catchment scale, it is unlikely that the conclusions will differ appreciably.

From our results, we conclude that in order to get features of the spatial patterns of runoff occurrence correct, it is necessary to represent spatial variability in soil properties. Yet, it is rare to find such detailed soil property data as has been collected at La Cuenca, and in most modelling exercises of this kind the soil property inputs are probably guessed. In cases such as La Cuenca where the precipitation intensity is similar to the soil hydraulic conductivity, we suggest that it is still probably best to conduct the fitting with a randomised log-normal distribution of values such as those used in sets 3 (random) and 4 (random\&organised), even if the distribution is entirely synthetic. On the basis of our findings we recommend representing stochastic variation in soil hydraulic property values, imposed on a deterministic pattern if multiple soil types are present within the area of interest.

Our strategy for setting initial conditions warrants discussion. As noted earlier, all of our event simulations were initialised with a soil moisture pattern derived from a “warm-up” run, in which a steady rate of rainfall, equivalent to the pre-storm runoff rate, was applied to the catchment. This approach was predicated on an assumption that the catchment was small enough to have drained to a near steady state condition prior to each storm. While the low conductivity subsoils would require several days to drain to a near steady rate, the more active upper 30 cm of soil could drain in a matter of hours. In Figure 10.11c we showed that the observed pre-storm runoff rates ranged between 0.005 and 0.37 mm h\(^{-1}\), so our event simulations were based on a very broad range of initial moisture conditions. There were probably circumstances where the time interval between successive events was too short for adequate catchment drainage
to have occurred. There were four occasions where more than 10 mm of rain fell within the 24 hours preceding the event to be modelled; conditions that might invalidate our assumption of a well drained catchment prior to the storm. Two of these events were simulated poorly and the other two were simulated quite well, including one where 32 mm of rain fell only nine hours prior to the start of the event simulated. Hence, poor hydrograph predictions cannot necessarily be blamed on errors in assumed initial conditions. Ideally, we would have selected events preceded by significant periods of no rain, thus reducing the possibility of errors in initial conditions. However, as it rains at La Cuenca on most days during periods of significant runoff generation (i.e. the wet season) this criterion proved impossible to satisfy.

We now briefly describe three possible ways in which to improve the performance of Topog_SBM in predicting the spatial patterns and temporal characteristics of runoff for the La Cuenca data set. These include an alternative way to prescribe initial moisture conditions, the incorporation of a fast subsurface flow path, and modifications to the soil water accounting scheme we have used.

Firstly, more realistic initial soil moisture conditions might be obtainable by letting the catchment drain from saturation until the pre-storm runoff rate has been attained. This would probably yield a moisture pattern more like the one that would occur under natural drainage between storms. However, as noted earlier, only some of the model error we have detected is attributable to initial moisture conditions, and the tendency in error is not at all systematic.

Secondly, by incorporating a rapid subsurface flow path into the model, we could represent the pipe network that has been observed to operate at La Cuenca during storm events (Elsenbeer and Vertessy, 2000). To some extent, the random pattern of $K_o$ values adopted in sets 3 (random) and 4 (random&organised) have represented the effect of a pipe network by creating multiple point sources of overland flow generation in elements with low $K_o$ values. However, a rapid subsurface flow path would result in the persistence of fast runoff after rainfall has ceased and allow us to relax our dependence on unrealistic roughness parameter ($n$) values to model hydrograph recessions correctly. A simple algorithm has been described by Bronstert and Plate (1997) which is within the Topog_SBM model but was not invoked in this study. However, as argued earlier, the geometry of the subsurface pipe network is unknown, and the parameters underpinning this sub-model would thus need to be treated as “black box” or calibration parameters.

Thirdly, some gains could be made by modifying the expression for $K_s$ decay with depth, as has been advocated in recent TOPMODEL applications (Ambroise et al., 1996; Beven, 1997; Iorgulescu and Musy, 1997). The parabolic, linear and power function decay models that have been proposed as alternatives to the exponential decay model adopted in this study should be evaluated in Topog_SBM on La Cuenca for the same events studied here. It is possible that a more appropriate decay model would improve the hydrograph recession fits, thus permitting some relaxation of the high $n$ values we were forced to use.
Concluding, we see a useful role for pattern comparisons in testing predictions of storm runoff dynamics in heterogeneous catchments from distributed models such as Topog_SBM. There are less complicated, and probably more accurate, modelling methods available if one’s interests are confined to hydrograph generation. But, if the spatial pattern and magnitude of different runoff components must be ascertained, as is required in pollutant transport or landscape evolution modelling, then distributed models must be used. Though we regard it as virtually impossible to replicate the exact pattern and magnitude of overland flow across even the best parameterised and simple catchments, we do believe that it is possible to approximate their functional behaviour. To achieve this, we have argued that it is critical to represent spatial variability in soil hydraulic properties, both in a deterministic (pattern) sense and a random (variability) sense. Future research in storm runoff generation modelling should focus on improving ways of representing such variability as well as methods to prescribe initial moisture conditions.

ACKNOWLEDGEMENTS

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