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TOPOGRAPHIC CONTROLS ON SUBSURFACE STORM FLOW AT THE HILLSLOPE SCALE FOR TWO HYDROLOGICALLY DISTINCT SMALL CATCHMENTS

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INTRODUCTION

Controls on hillslope flow pathways are still not well understood, despite the many different studies reported since the pioneering work of Hewlett (1961). In a wide range of recent modelling studies it has been assumed that flow directions can be related to hydraulic gradients derived from surface topography. This assumption leads to believable maps of predictions of soil saturation and is convenient because of the increasing availability of digital terrain maps (DTMs). The validity of the resulting spatial patterns throughout the watershed, however, have not been fully assessed [although see the discussion in Beven *et al.* (1995) and the recent studies of Nyberg (1996) and Crave and Gascuel-Odoux (1997)]. This results from the difficulty of obtaining adequate spatial coverage of hydrological variables and the scale problem of relating point measurements to predictions at the DTM grid scale.

Recent hillslope analyses of soil moisture distributions have identified that flow paths do not necessarily converge to hollow regions (Anderson, 1982), that they may require dynamic spatial representations (Barling *et al.*, 1994) and that their prediction using topographically derived indices have had mixed results (Burt and Butcher, 1986; Moore and Thompson, 1996).

Spatial representations of topographically driven indices, therefore, need further exploration. A possible way forward is to conduct more detailed studies of the dynamics of subsurface flow at the hillslope scale. Analysis of a natural hillslope combines integrated (trench flow) and point-scale (soil moisture) measurements coupled with a detailed understanding of surface and subsurface features. Such data provide a more comprehensive assessment of the assumption, used in many modelling studies, that hillslope flow is controlled by surface topography.

In this letter we address the question of whether it is appropriate to use surface topography to describe hillslope flow paths or if it is not more appropriate to use subsurface gradients relating to the soil/bedrock interface or the hydrologically impeding layer. We present examples for two hillslopes in different hydrogeological–climatic settings. Analyses of the distribution of topographic index patterns derived from digital terrain analysis for both surface and subsurface topography are related to observational patterns of subsurface storm flow along artificial trench face sections.

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STUDY SITES

Maimai

Hydrological research work at the 10 ha Maimai catchment in New Zealand (Rowe *et al*., 1994) has been considerable and active since 1974. Much of this work has focused on understanding the contributions of subsurface storm flow at different scales and exploring the use of different measurement techniques (Brammer and McDonnell, 1996). Since 1992 a subsurface runoff collection system along the base of a 30 m wide by 60 m upslope hillslope section has been studied (Woods and Rowe, 1996). Maimai receives an average annual rainfall of (2600 mm) with little seasonal variation. Slopes are short (30 m) and steep (average 34°) with highly weathered soils.

Panola

The Panola Mountain Research Watershed is a 41 ha forested catchment 25 km south-east of Atlanta, USA, and has been described in detail by Huntington *et al*. (1993). Research has focused primarily on understanding the geochemical mass balance budgets and element cycling throughout the watershed. Recent intensive studies in the upper 10 ha watershed have gained insight into the hydrological response of the saturated valley bottom zone and its linkages to the hillslopes (Ratcliffe *et al*., 1996; Peters and Ratcliffe, 1997). In 1995 a 20 m long trench was excavated to bedrock at the bottom of a 48 m long planar forested hillslope. In contrast to Maimai, Panola receives 1200 mm of rainfall annually and has a marked summer dry period.

Trench instrumentation

At each site, the hillslope trench systems collect subsurface flows for several individual 2 m wide trench sections (30 at Maimai with 15 in the main subcatchment, and 10 at Panola). Panola also included separate macropore collections owing to the high volume of flow produced by these features. Both sites are assumed to have a subsurface, hydrologically impermeable layer. At Maimai this interface is the Old Man Gravels (compacted conglomerate) and at Panola a granitic bedrock surface. Flows from both sites were routed via pipes to continuously monitored tipping-bucket gauges of similar design.

TOPOGRAPHIC ANALYSIS

This study will consider one of the more popular topographic indices, the $\ln(a/\tan\beta)$ index of Kirkby (1976), where a is the upslope accumulated area and $\tan\beta$ is the local slope angle. The calculation of this index, often associated with TOPMODEL (see Beven *et al*., 1995), is based on the multiflow direction algorithm of Quinn *et al*. (1991). The index is one of hydrological similarity, for which the likelihood that surface or subsurface saturation will occur at that point increases with increasing values of the index. In terms of local discharges this would be consistent with a higher rate of flow (given homogeneous soil characteristics). To avoid bias in the accumulated area calculations caused by the presence of the trench instrumentation, no downslope area accumulations were shared between adjacent trench cells.

Digital terrain maps were produced at a 1 m grid scale for both sites based on detailed topographic surveys (Maimai irregular survey 756 points, Panola 2 m grid of points). A further ground survey mapped the bedrock topography. At Maimai, an aluminium wading rod was used to measure depth at 181 irregularly spaced points and at Panola a soil corer was forced to refusal (if depth was greater than 1·25 m a small hand auger was used to complete the measurement) at a 2 m grid scale (288 points). At Maimai, greater bedrock depths correspond to the topographic hollow in the centre of the trench site. Depths ranged from 0·15–0·30 m on ridge tops and 0·60–2·0 m along the midslopes and central hollow. At Panola, depth to bedrock, which was highly variable (0–1·86 m), did not correspond with the more planar hillslope topography. Maps of the spatial patterns of the two indices at Panola are shown in McDonnell *et al*. (1996).

Table I. Predictions of total subsurface storm flow volumes and total bromide recovery using the elevation and bedrock derived indices at the Maimai catchment (r^2 values in bold italics show significantly better correlations)

Event	Precipitation (mm)	Total trench storm flow (l)	Elevation surface $\ln(a/\tan\beta)$ index r^2 relationship	Bedrock surface $\ln(a/\tan\beta)$ index r^2 relationship
#1, 25–26 March	41·5	21 866	0·76	0·77
#2, 1–2 April	30·2	1788	***0·55***	0·47
#3, 7–8 April	24·4	304	***0·69***	0·55
#4, 9–12 April	83·0	45 480	0·77	0·80
#5, 19–20 April	62·0	27 893	***0·91***	0·76
#6, 24–27 April	74·0	34 395	***0·81***	0·75
#7, 5–6 May	61·0	21 107	0·71	***0·76***
Bromide recovery	n/a	169 353[a]	0·76	***0·86***

[a] Total flow for the study period

RESULTS

Summary r^2 statistics for the following results are derived from linear correlations between the individual indices and the cumulative storm flow at each of the trench face sections.

Maimai

Data were evaluated from a three month study from March to May 1995, which included seven major rainstorms (Table I). At the beginning of the study, a bromide line injection source was added 35 m upslope of the trench face as part of a tracer study (D. Brammer pers. comm., 1996).

Each index predicted the cumulative trench flow patterns well. Contributions from individual trench sections varied significantly between events, this variability was greater than that shown by the difference between the patterns predicted by the two indices. Overall the average r^2 correlations for the two surfaces were equivalent (0·74 compared with 0·71), although total bromide recovery (94% of source input) for the period was more highly correlated with the bedrock index, an indicator of longer term flow dynamics. Predictions were significantly worse for discharge data from smaller precipitation events (Table I). The spatial correlation between the two indices for the entire hillslope is very high ($r^2 = 0{\cdot}97$). The high correlation reflects the occurrence of the surface topographic low with the deepest soil depths, which produces similar trench face index patterns (Figure 1).

Panola

Three rainstorms in the hydrologically active season were studied. Figure 2 shows the distribution of total accumulations and peak flows for the largest of these events (95 mm of precipitation), and the results of corresponding digital terrain analysis for the trench face sections for both elevation and bedrock surfaces. Clearly the discharge and peak flow patterns are more strongly correlated with the bedrock index ($r^2 = 0{\cdot}65$) than the topographic index ($r^2 = 0{\cdot}01$). The spatial correlation between the two indices for the entire hillslope is insignificant ($r^2 = 0{\cdot}08$). By accounting for the bedrock topography, the major flow paths are completely altered, modifying patterns along the trench face, resulting in the much higher correlation with the observed trench outflows.

Analysis of the other events shows a considerable reduction in the significance of the index/trench flow accumulation relationship with the decreasing size of the event. For the 4 February event ($P = 65$ mm) r^2 values were 0·07 for the topographic index and 0·47 for the bedrock index, and for the 26 March event ($P = 25$ mm), which had relatively dry antecedent conditions, r^2 for each index was less than 0·2. However, total flow from the 26 March event was only 1·5% of the total flow from the 6 March event, reflecting the need for connected downslope flow pathways to become established before major flows at the trench face will occur.

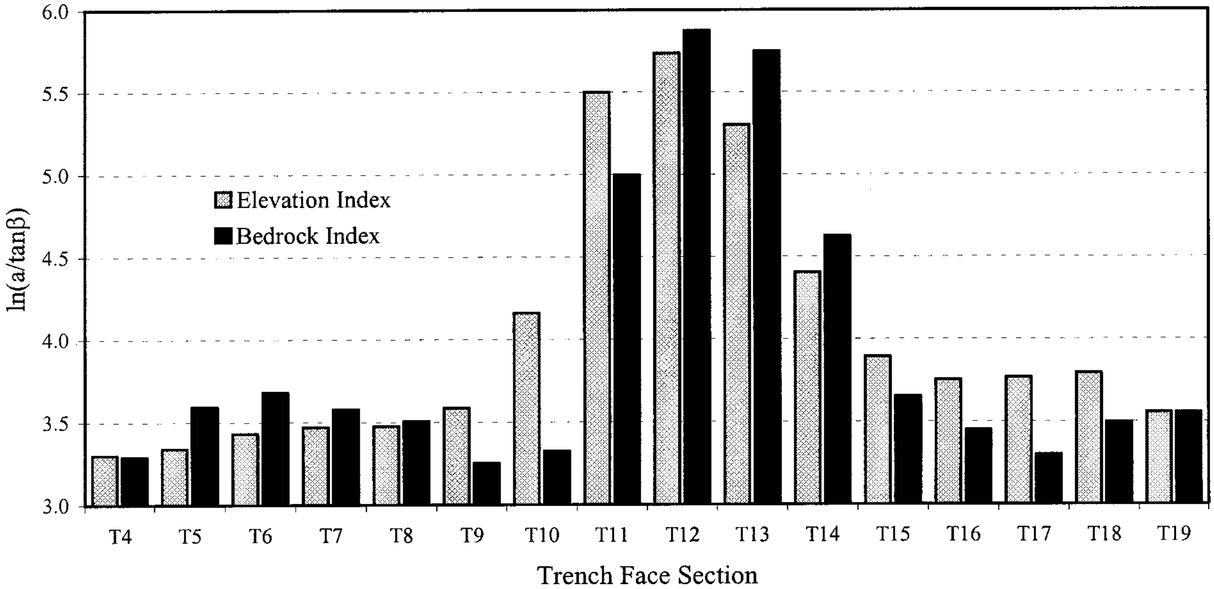

Figure 1. Maimai trench face, distribution of topographic indices for both the elevation (surface topography) and bedrock-derived surfaces

CONCLUSIONS

1. The topographic index has been shown to be of value in determining the patterns of trench flow for two catchments, differing in climate and topography. Where bedrock topography is distinctly different from surficial topography, the bedrock surface has a considerable influence on local hydrological gradients and therefore the dominant flow path directions, as shown at Panola. If, as is the case at Maimai, these gradients and flow paths between the surface and subsurface are highly correlated, then it is not necessary to document the subsurface topography. In this case the underlying TOPMODEL assumptions of hydrological gradients being parallel to the surface topography are reasonable at the hillslope scale.

2. The correlation between each index and cumulative flow volume is lower as the magnitudes of the events decrease at either catchment. This finding suggests that the indices are a poorer indication of downslope flux under drier conditions owing to the implicit assumption of steady state flow throughout the slope. Results might be improved for the smaller events if the dynamics of the upslope accumulated area could be estimated and related to current soil moisture status. This presents difficulties, however, in determining an initial pre-storm soil moisture distribution and upslope contributing area, especially in a soil having significant macropore development.

3. This research highlights the importance of understanding the dominant downslope hydraulic gradients at the hillslope scale, which may not necessarily be represented by surface topography. Clearly, this is important for any evaluation of spatial model predictions where the underlying subsurface topography is significantly different from the elevation surface and, therefore, would significantly alter the spatial pattern of any topographic indices derived from DTMs.

FUTURE DIRECTIONS

The results from this study are preliminary, representing two catchments where appropriate data are available. The results suggest that an analysis of bedrock topography may be critical to understanding the flow processes on hillslopes. Further data sets from other sites should be considered to evaluate the necessity of such an analysis.

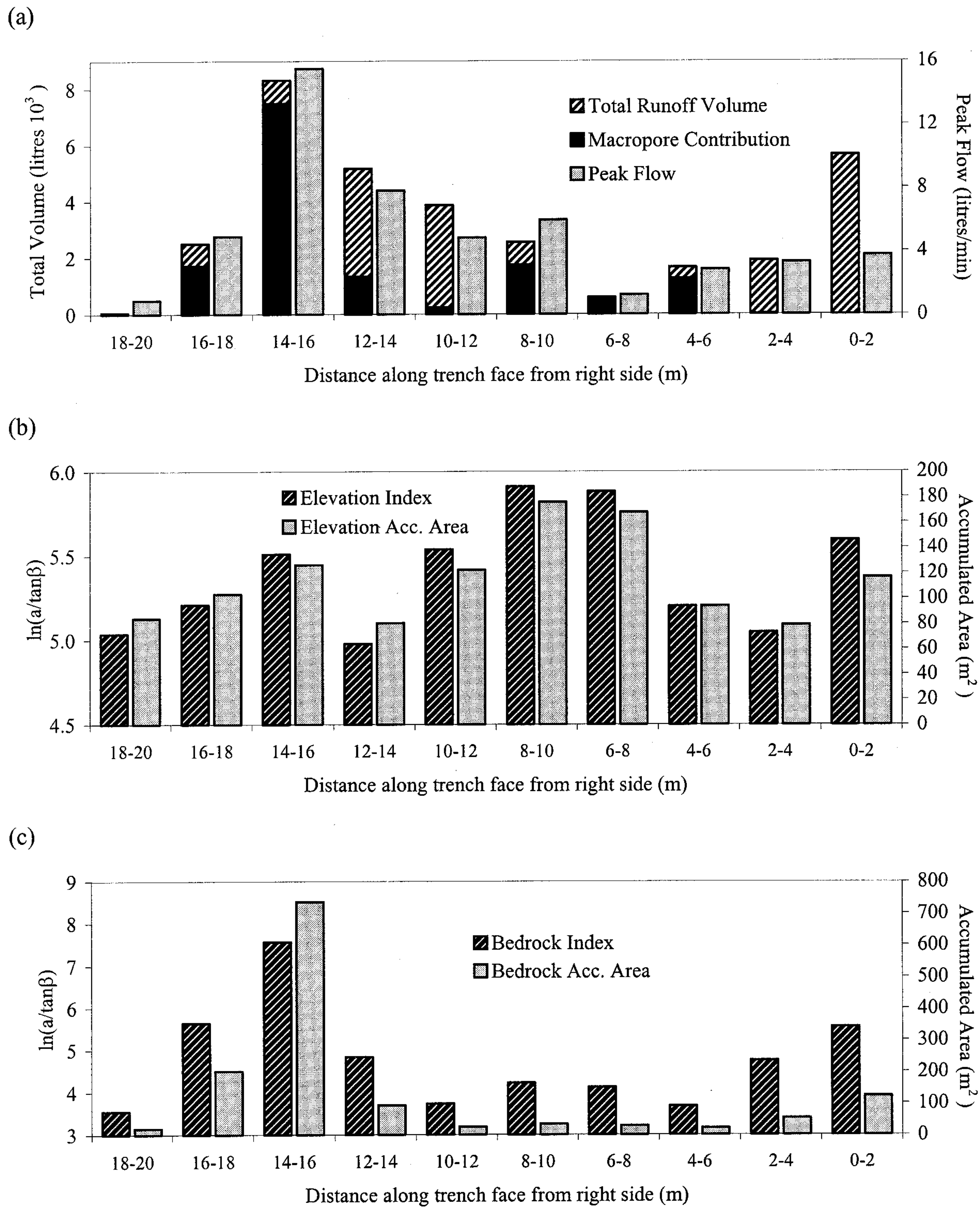

Figure 2. Panola trench face, comparison of digital terrain analysis results with observed cumulative flow for the 6 March event. (a) Observed cumulative volume and peak flow. (b) Elevation (surface topography) and (c) bedrock derived indices

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