Modelling Spatial Patterns of Runoff on a Hillslope: Implications for Fine Sediment Delivery

Kinsey-Henderson, A. E.[1], Post, D. A.[1,3], Bartley, R.[2], and Hawdon, A. H.[1]

anne.henderson@csiro.au, david.post@csiro.au

[1]*CSIRO Land and Water, Davies Laboratory, Townsville, QLD 4811 Australia.*
[2]*CSIRO Land and Water, Tropical Forests Research Centre, Atherton, QLD 4883 Australia.*
[3]*Integrated Catchment Assessment Management Centre, Australian National University, Canberra.*

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EXTENDED ABSTRACT: In this study we use modelling techniques to consider the effects of hillslope configuration and condition on both the magnitude and spatial variability of runoff from a 1.2 ha hillslope in the semi-arid Burdekin Catchment of North Queensland, Australia. We then discuss how these runoff predictions might influence suspended sediment yield.

The Burdekin catchment at 130,000 km^2, is the second largest catchment draining to the Great Barrier Reef World Heritage Area (GBRWHA). Ninety percent of the catchment is utilized for grazing and loss of sediment from these grazing lands is a potentially serious issue not just at the source, but in regard to downstream water quality and the effects on the GBRWHA.

A hydrological model, LISEM, was calibrated using results from a field monitoring campaign carried out in the Weany Creek sub-catchment, a tributary of the Burdekin. A number of scenarios were modelled on a 1.2 ha flume site in the Weany Creek catchment, examining the impact of slope, vegetation cover and vegetation distribution (including patch size) on runoff.

The results indicate that runoff is very sensitive to changes in both vegetation cover and distribution, The 'riparian good' scenario yielded 136 m^3 (35%) more water than current conditions while the 'riparian poor' scenario resulted in 384 m^3 (98%) more runoff (i.e. almost double current conditions). This is despite both scenarios having the same proportion of good, average, and poor cover as current conditions. When all of the cover was changed to 'good', runoff decreased to 0.4 m^3, and when it was all 'poor', it increased to 1422 m^3 – more than tripling current conditions.

In addition to total vegetation cover, the patchiness of the vegetation also seems to have a significant impact on total water yield. When the good, average and poor cover was distributed evenly across the hillslope in 16 by 16 metre random patches, the runoff was 83 m^3 (21%) more than current conditions, compared to 30 m^3 (8%) less when it was distributed in 4 by 4 metre patches.

Conversely, changes in slope had very little impact on runoff, with a doubling in slope leading to an increase of only 19 m^3 (5%) over current conditions, and a halving of slope leading to a decrease of 24 m^3 (6%). Similarly, turning a planar slope into a convex one decreased runoff by 9 m^3 (2%) while a concave slope decreased it by 50 m^3 (13%).

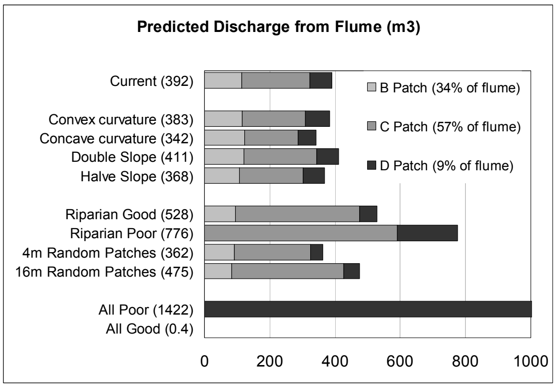

Figure 1: Modelled runoff from a 1.2 ha flume for a 230mm rainfall event in January, 2005. B, C and D patches represent good, medium, and poor condition respectively.

When attempting to predict spatial patterns of runoff, our modelling suggests the need to consider not only the dependence on vegetation patterns (and to a lesser extent slope), but also the often subtle patterns of flow concentration that may develop at the scale of a typical hillslope.

Preliminary predictions of fine sediment yield, derived by combining predicted hillslope runoff patterns with measures of sediment concentrations at patch scale, suggest the dependence on spatial patterns of vegetation and terrain at the hillslope scale may be even stronger for suspended sediment yield than for runoff..

1. INTRODUCTION

Tropical rangelands in North Queensland are characterised by open Eucalypt woodlands and grassland vegetation. They receive most of their annual rainfall in the four months between December and March. The extreme wet-dry climate regime experienced by these systems results in a naturally 'patchy' arrangement of vegetation in the landscape. Pressures from grazing make these lands highly vulnerable to land degradation.

There has been a concerted research effort on the relationship between ground cover and runoff (Connolly *et al.*, 1997; McIvor *et al.*, 1995a and b; Pressland *et al.*, 1991) and sediment loss (McIvor *et al.,* 1995a and b; Scanlan *et al.,* 1996) in savanna rangelands. However, the influence of vegetation patterns and their distribution in the landscape has been less explored. Field studies by Bartley *et al.* (2005) suggests that runoff and sediment loss is very sensitive to not only average cover levels, but equally to the pattern and patchiness of vegetation on hillslopes.

The Burdekin Catchment is 130,000 km^2 and is the second largest catchment draining into the Great Barrier Reef World Heritage Area (GBRWHA). It is characterised by Eucalypt savanna woodlands, and apart from the rainforest-dominated humid fringe in the northeast, has a mean annual rainfall of 400 - 650 mm. Ninety percent of the catchment is utilised for beef production. Although these grazing areas are situated inland, and the runoff is potentially buffered by the Burdekin Dam and coastal floodplains, the volume and quality of the runoff generated in large events has potential to impact significantly on downstream and offshore water quality. The reasons for this work are twofold; firstly, loss of soil and nutrients is detrimental for the long term sustainability of the grazing industry. Secondly, excess sediment and nutrients from the grazing lands may be having detrimental impacts on the Great Barrier Reef Lagoon (GBRL).

In this study we have modelled total runoff and runoff patterns for a 1.2 ha flume site located in the Weany Creek catchment within the Burdekin. This site has been the focus of six years of monitoring and field measurements (Roth *et al.*, 2003 and Bartley *et al.,* 2005), and more recently models have been used to simulate runoff and sediment loads (Liedloff *et al.*, 2005, Ludwig *et al.*, 2005, and Kinsey-Henderson *et al.*, 2005).

Weany Creek is located on a cattle property that has been grazed for the past 100 years. It is representative of the highly erodible 'gold-fields' country between Townsville and Charters Towers. Large bare scald patches are present on the slopes adjacent to many gully and stream networks. The canopy vegetation is composed primarily of narrow-leafed ironbark (*Eucalyptus creba*) and red bloodwood (*Eucalyptus papuana*) and the ground cover is dominated by the exotic, but naturalised stoloniferous grass Indian couch (*Bothriochloa pertusa*).

For this modelling study, we focused on the fate of runoff at the hillslope scale. We used modelling to investigate the impact of hillslope configurations of vegetation on runoff response and spatial patterns of runoff on the hillslope. Combining these predicted runoff patterns with measurements of suspended sediment concentrations from each of the patch types gives us a preliminary estimate of sediment yield from the hillslope. This analysis is needed to support the development of landscape specific spatially distributed hillslope runoff and sediment delivery ratios. These ratios reflect the ability of the hillslope to capture eroded sediment before it reaches a stream. Such ratios are used in conjunction with RUSLE-based (Renard, 1997) predictions of erosion in catchment models such as SedNet and EMSS. Previous approaches to HSDR within these modelling frameworks assumed a constant value everywhere (eg. Prosser *et al.*, 2002). However, there is a need to consider the sensitivities of HSDR to hillslope characteristics, particularly as the spatial resolution of these models increases.

2. MODEL PARAMETRISATION, CALIBRATION AND VALIDATION

2.1. The Model

LISEM (the Limburg Soil Erosion Model), is a physically based hydrological and soil erosion model developed in the Netherlands. It routes water and sediment over terrain surfaces using a grid-based routing scheme. We identified certain advantages in LISEM over other hydrological modelling frameworks in that (1) it is flexible and simple in its handling of input parameters, (2) it has the capability of dealing with surface texture and channelisation (eg. for representing flow partitioning), and (3) the modelling outputs (two-dimensional PC-Raster grids) can be further analysed in a Geographic Information System in terms of spatial patterns such as relative contributions to runoff at the flume. A more complete description of LISEM can be found in Jetten (2003).

While the hydrological modelling environment of LISEM is highly relevant to our study, the erosional modelling is not. The output grids of LISEM do not differentiate between splash erosion and flow detachment, nor do they differentiate between fine and coarse fractions. LISEM has two options for dealing with sediment transport. LISEM "Basic" uses transport equations developed by Govers (1990) which focus on the larger size fractions (silt to coarse sand), and are therefore not suitable for suspended clays. LISEM "Multiclass" has the potential to deal with several size fractions (including clays), however it is largely untested and was not therefore used here.

2.2. Parameterisation

LISEM requires landuse maps as the basis by which various hydrological parameters are assigned. The flume catchment has been extensively mapped over several years using the Hierarchical Patch Classification System (HPCS) which builds on the Landscape Function Analysis (LFA) methods of Tongway and Hindley (2004). There were 23 different patch classes recognized on this basis. However, for simplicity of modelling and scenario development we reduced the number of patch types to three classes of patch B, C and D as good, average, and poor condition respectively (see Figure 2). A thalweg in the hillslope was incorporated into the model as a small channel (0.25 to 0.5m wide and very flat (5 degrees)).

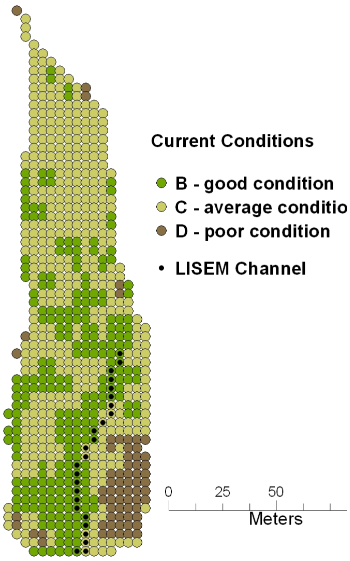

Figure 2: The existing arrangement of patches in the flume catchment (current conditions).

Each patch type was assigned hydrological parameters based on field observations, field data, or current literature. Parameters were then adjusted to calibrate the modelled hydrograph to the field measured hydrograph. Calibrated model parameters are shown in

Table 1. Initial soil moisture content, random roughness and percent cover were estimated from field measurements and observations. Saturated hydraulic conductivity (Ksat) and suction at the wetting front (Psi) were firstly estimated based on field observations then used as calibration terms to find a best fit of the time-dependent Green Ampt infiltration function in LISEM to the observed flume runoff. Hydraulic roughness (Mannings n) was estimated firstly from published work (Peugeot *et al.*, 2003) and then adjusted slightly to reproduce the runoff responses to rainfall observed at the flume.

Table 1: Hydrological parameters for LISEM.

Patch Type	B	C	D
Ksat (mm/h)	20	2	1
Psi (cm)	15	20	30
Init. moisture content (cm3/cm3)	0.04	0.1	0.06
Random Roughness (StdDev of relief cm)	0.33	0.32	0.16
Mannings (n)	0.17	0.1	0.03
%Cover (vegetation and litter)	0.8	0.47	0.02
% of flume	*34%*	*57%*	*9%*

2.3. Calibration and validation

We calibrated the LISEM model to a large (230 mm) rainfall event occurring over three days in January, 2005. The event encompassed 6 individual sub-events of varying total rainfalls, intensities, and antecedent moisture conditions. The LISEM model was able to model most of the sub-events to within 20% of the measured discharge and reproduced the hydrograph responses well. For the entire three-day event, the total discharge calculated from the LISEM model was within 4% of observed with an r^2 of 0.85 (See Figure 3).

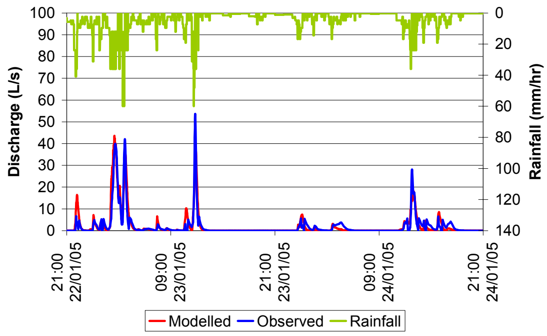

Figure 3: Calibration hydrograph for the January, 2004 event comparing observed and modelled discharge.

We only had a limited number of events with which to validate our calibrated model due to lack of events with substantial discharge rates (due to persistent drought conditions) and changes in patch condition and cover levels through time. A relatively large event was used for validation (60 mm over two days in January, 2004) and showed very good agreement to the observed hydrograph (Figure 4). The LISEM discharge estimate was within 6% of observed (with an r^2 of 0.91) and the 2 sub-events agreed with observed to within 7%.

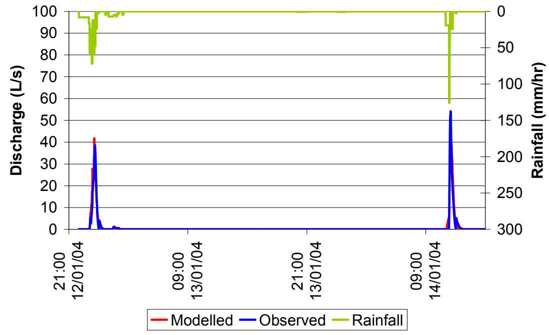

Figure 4: Validation hydrograph for the January 2004 event comparing observed and modelled discharge.

The contribution of each pixel to the total discharge from the hillslope can be seen in Figure 5. Concentrated flow, reflecting less opportunity for infiltration, is evidenced by the higher contributions to discharge (red grid cells) down the middle of the hillslope. The large yellow to red patch to the right reflects the poor infiltration properties of a scald (D-patch).

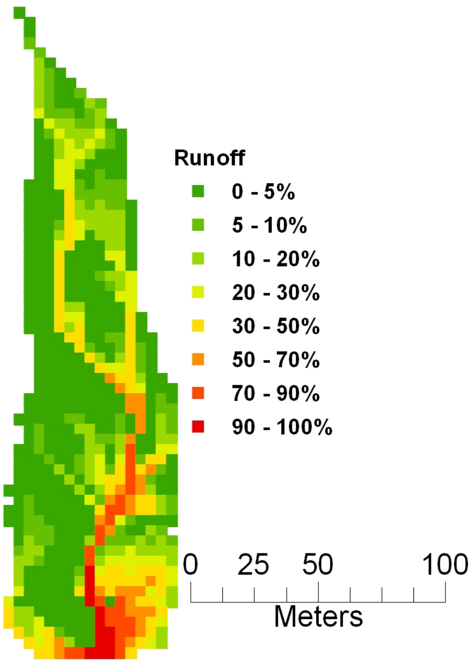

Figure 5: Proportion of discharge from each grid cell contributing to the total discharge at the flume for the January, 2005 event.

3. SCENARIOS

We used the January 2005 event to test the sensitivity of runoff to changes in terrain and vegetation patterns.

Scenarios fell into two broad categories – terrain-related and vegetation-related.

Terrain-related	***Vegetation-related***
Convex	*Riparian Good*
Concave	*Riparian Poor*
Double Slope	*All Good*
Halve Slope	*All Poor*
	4m Random Patches (10 repeats)
	16m Random Patches (10 repeats)

Figure 1 contains a summary of the results of all our scenario runs.

We maintained the existing patch configuration for scenarios relating to changes in terrain. For convex and concave scenarios, we compared height versus linear distance upslope from the flume for the DEM (see Figure 6). The result showed that the hillslope approximates quite closely to a planar slope. We applied a power function to height as a function of distance (1.5 for concave and 0.67 for convex) to impart curvature to the slope while maintaining the average slope conditions of the original. Doubling and halving of slope was accomplished by linearly scaling the DEM heights.

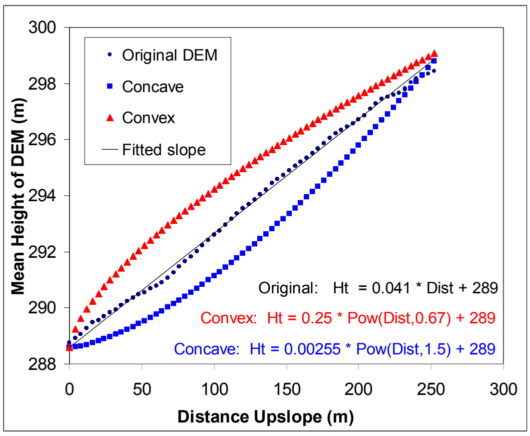

Figure 6: Adjustment of DEM to produce convex and concave curvature

Results (see Figure 1) suggest that terrain has only a minor effect on total runoff. The concave and convex hillslopes both yield less water than the planar slope (current conditions). For the convex slope, the increase in yield from the D patch (occurring mostly as a scald near the bottom of the slope) was countered by a larger decrease in yield from C patches that dominate the upper slopes. Doubling the slope increased runoff slightly while halving it decreased runoff slightly, with the relative proportions contributed from each patch type remaining similar to current conditions.

For vegetation-related scenarios, we rearranged the patches while maintaining the original proportions of each patch type within the hillslope (exceptions being where we were looking at extremes such as 'all good' or 'all poor'). Runoff predictions from each scenario are summarised in Figure 1.

Changes in vegetation had a much greater impact on runoff than changes in terrain, with the extreme examples of all B condition ('all good') reducing runoff to 0.4 m^3, and all D condition ('all poor') more than tripling it (to 1422 m^3).

When we rearranged patches such that cover decreased downslope ('riparian poor'), discharge almost doubled to 776 m^3. Conversely, when cover increased downslope ('riparian good'), runoff (unexpectedly) increased from that predicted under current conditions to 528 m^3 (up by 35%). The reason for this can be seen in Figure 7 which shows these two riparian scenarios and their resulting runoff patterns. For the 'riparian good' scenario, runoff from the large areas of D and C patches (which have poor infiltration properties) experiences concentration of flow before encountering the good condition B patches. As a result, runoff is offered little opportunity for infiltration as it exploits the concentrated flow path (the thalweg) through the large B patch downslope.

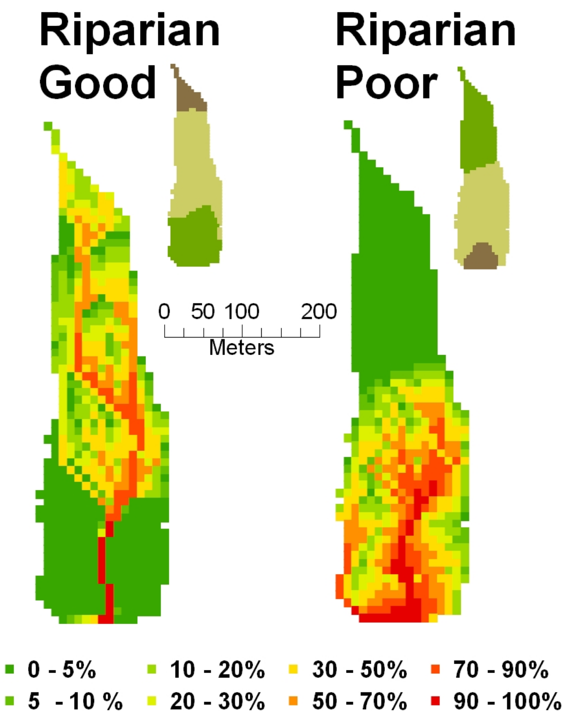

Figure 7: The effect of spatial arrangement of patches on the proportion of discharge from each grid cell contributing to the flume. Cover map inserts are as per Figure 2, i.e. dark green is B patch, light green is C, and brown is D.

The pattern of vegetation seen in current conditions (Figure 2), where B patches are closely associated with areas of concentrated flow, is most likely influenced by the fact that areas of concentrated flow have higher water availability at drier times. To some degree then, the naturally occurring patch patterns are better equipped to self-regulate runoff than the 'riparian good' scenario. Also, improvements to riparian zone management, while increasing the cover levels at the bottom of the hillslope, should continue to *maintain* the current condition of patches on the rest of the hillslope. Such conditions would certainly result in reductions in runoff compared to current conditions, and not the increase predicted in our model scenario.

16 by 16 m random patches yield more runoff (475 m^3 with a standard deviation of 27) than 4 by 4 m patches (362 m^3 with a standard deviation of 14). This suggests that smaller patch sizes provide more chance of water encountering well vegetated areas, thus allowing more opportunities for infiltration. If we consider the riparian scenarios to represent a further extreme of patch size, we see the very large patch systems becoming less efficient at capturing runoff, despite wider areas of good cover, due to their connectivity to concentrated flow paths.

The issue of patchiness *within* each 4m grid cell is suggested by Ludwig *et al.* (1999) to be important for understanding runoff in savanna landscapes. We recognize that such geometry affects the flow efficiency and preferential flow paths within each patch, and attempted to account for these effects by our choice of Mannings and random roughness. However, a more comprehensive study would be required to understand how these processes could be effectively simulated.

In summary, runoff seems to be more sensitive to changes in vegetation patterns and overall cover than changes in slope. While this is not surprising, considering the close link vegetation cover has to infiltration and hydraulic roughness, the degree of sensitivity to cover *distribution* as opposed to average cover, is. Runoff can almost double, without any change in average hillslope cover, depending on the size and distribution of vegetation patches.

4. IMPLICATIONS FOR SUSPENDED SEDIMENT

The modelling presented in this paper is part of a larger study designed to investigate the sensitivity of sediment delivery to hillslope configuration. Future work will concentrate on how observations such as those in this study might 1) translate into sensitivities with respect to sediment loads and 2) scale up for catchment models which currently assume a very simplistic spatial representation of hillslope delivery of sediments.

As a first estimate for item 1) we translated our runoff results into suspended sediment yield data, based on measurements from an extensive set of field experiments from microplots carried out in Weany Creek from 1999-2003 (Roth *et al.*, 2003 and Roth, 2004). The relationship between suspended sediment generation from the microplots and percent cover (as vegetation plus litter) is shown in Figure 8. The three points corresponding to the average cover conditions for the three patch types are also shown. Note that these field results would reflect erosion dominated by splash detachment (rather than overland flow), given the small size (0.6 m^2) of the plots.

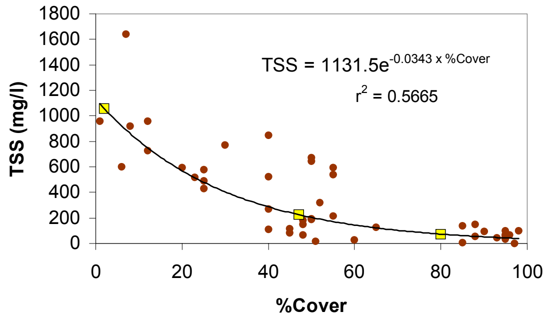

Figure 8: Percent cover versus total suspended sediment concentration (TSS) based on microplot data (Roth *et al.*, 2003).Yellow squares indicate predicted concentrations for our 3 patch types.

Table 2 illustrates the effects of superimposing the suspended sediment concentrations from Figure 8 onto our modelled patterns of runoff. Although this only accounts for one source of hillslope erosion (splash detachment) and ignores others such as overland flow detachment, we felt it well represented the conditions of our particular hillslope on the following basis:

The 230mm January, 2005 event had an actual measured load of 87kg (based on calculations used in Bartley *et al.*, 2005). Compared to our modelled load of 128kg this is an over-prediction of 47%. We consider this to be a reasonable result, given that:

- The microplot data were from smaller events than modelled here. During larger events, it is observed that suspended sediment concentration reduces through time (Bartley *et al.*, 2005).
- Depth of flow in areas of runon and concentration of flow would act to reduce splash erosion.
- The high clay content and stripped nature of the soils (up to 70% clay at the surface) gives them a tendency to hard-set and form pavements resulting in abnormally low (i.e compared to Figure 8) sediment concentrations in runoff from these areas (Roth et al., 2004).

Table 2: Comparison of the sensitivity of runoff and suspended sediment loads to changes in hillslope configuration

scenario	Predicted discharge at Flume (m3) from LISEM	Predicted Sediment Load at Flume (kg)	Proportion of Predicted Current Discharge	Proportion of Predicted Current Sediment
Current	392	128	1.0	1.0
Convex curvature	383	130	1.0	1.0
Concave curvature	342	104	0.9	0.8
Double Slope	411	132	1.0	1.0
Halve Slope	368	122	0.9	1.0
Riparian Good	528	149	1.3	1.2
Riparian Poor	776	330	2.0	2.6
4m Random Patches	362	100	0.9	0.8
(st dev)	*14*	*10*		
16m Random Patches	475	144	1.2	1.1
(st dev)	*27*	*15*		
All Good patches	0.4	0	0.0	0.0
All Poor patches	1422	1504	3.6	11.8

Our over-prediction might also suggest that overland flow detachment, at least in relation to fine sediment capable of remaining in suspension, is not a major process in these erosionally mature landscapes. Cryptogams and the cohesive nature of high clay soils will also tend to reduce flow detachment.

The last two columns of Table 2 suggest that cover levels and arrangement of patches have the potential to significantly exaggerate (eg ‘riparian poor’ and ‘all poor’ scenarios) the sensitivities to vegetation already noted with runoff. If overland flow detachment is in fact a significant source of suspended sediment, its effect on sediment yield would be to further exaggerate these sensitivities, as it would tend to occur in those areas where flow is concentrated and contribution to total hillslope runoff is high.

5. CONCLUSIONS

Our results highlight not only the dependence of runoff on vegetation and terrain configuration at the hillslope scale, but also the need to account for the often subtle patterns of flow concentration occurring within a hillslope when attempting to interpret spatial patterns of runoff.

Preliminary work also suggests that the sensitivities observed for runoff may be further exaggerated when looking at suspended sediment yields. This is important when interpreting hillslope vegetation conditions and terrain configurations for the purposes of assessing impacts on water quality.

Future work will focus further on the translation of spatial patterns of runoff into patterns for sediment yield. This will allow us to develop simple hillslope metrics for use in estimating spatially explicit hillslope delivery ratios. Such estimations will significantly improve our prediction capability in catchment scale water quality modelling.

6. ACKNOWLEDGEMENTS

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