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Evaluation of the scale dependence of a spatially-explicit hillslope sediment delivery ratio model

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Abstract: Approximately 90-95% of soil eroded on a hillslope is redeposited and does not enter a stream. However, sediment transport models such as SedNet require an estimate to be made of the actual delivery of sediment from a hillslope into a stream based on predictions of hillslope erosion. In a companion paper in this volume (Post *et al.* 2006) we have developed a spatially explicit hillslope delivery model based on travel time and applied it to erosion estimates (based on the Revised Universal Soil Loss Equation, RUSLE) for a small subcatchment of the Burdekin River, Weany Creek (13.5km²), at 5m grid size. In this paper we look at the effect of increasing grid spacing on the HSDR model's predictive capability at Weany Creek. We suggest that the model is only valid in the range of grid sizes up to 2500 m² (50 m grid size). For grid sizes between 50 -100 m (which equate to 1/4 and 1 channel threshold area), the model is unstable and should not be applied. For grid sizes beyond 100 m, the model is not applicable and a constant HSDR may be a suitable approximation. Our calibration term for HSDR, β , shows a strong dependency on grid size as it must compensate for the reduction in predicted erosion from the RUSLE with increasing grid size. The term γ , defining the decay rate of HSDR with hillslope travel time, appears to be grid size independent. The choice of channel threshold area is of critical importance in defining the spatial nature of HSDR and places very strong constraints on the range of grid sizes to which the model may be applied.

Keywords: Hillslope erosion; sediment delivery ratio; travel time.

1 INTRODUCTION

1.1 Background

In this paper, and the companion paper by Post *et al.* (2006) we build on previous work (Kinsey-Henderson *et al.*, 2005) based on a field trial and remotely sensed data in the Weany Creek subcatchment of the Burdekin River, Australia. In Kinsey-Henderson *et al.* (2005), the Revised Universal Soil Loss Equation (RUSLE) was used to estimate gross hillslope erosion in a 5m grid pattern and then a prediction was made of the proportion of this eroded sediment which contributes to suspended sediment stream loads by application of the concept of a spatially explicit hillslope sediment delivery ratio (HSDR).

Post *et al.* (2006) discussed an improved method for modelling HSDR based on travel time. In the current paper we explore how and why the patterns of hillslope erosion and stream delivery predicted in Post *et al.* (2006) change as the same calculation methods are applied at larger grid sizes. Such exploration will improve our understanding of the implications of applying such modelling techniques to whole of catchment scale, where a 5m grid framework is rarely an option.

Our estimates of hillslope erosion and delivery to stream will ultimately be used to better inform a relatively simple sediment transport model known as SedNet. SedNet is used widely in Australia to quantify and improve understanding of the sources of and downstream fate of sediments in river systems (Prosser *et al.*, 2001). As the Burdekin River catchment (of which Weany Creek is a small subcatchment) drains into the Great Barrier Reef World Heritage Area, understanding the fate of sediment (in particular suspended sediment and attached nutrients) is of importance.

The Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1997) is a widely used method of estimating soil loss;

$$\text{Soil Erosion (t/ha/yr)} = RKLSC \quad (1)$$

Where R , K and L are rainfall erosivity, soil erodibility, and slope length factors respectively, treated as constants within the Weany subcatchment, and S and C are slope and cover factors respectively, calculated explicitly at each grid point. The resultant grid shows a pattern of predicted localised erosion rates. The RUSLE estimates gross erosion. It does not discriminate between fine and coarse fractions.

The concept of sediment delivery is well recognised and much literature has been published on the subject (eg. Boyce (1975), Walling (1983), Lenhart *et al.* (2005) and Lu *et al.* (2005)). In SedNet applications, we talk about *hillslope* sediment delivery ratio (HSDR), to distinguish it from the more generic sediment delivery ratio (SDR) which may be applied from hillslope to catchment scale and may include other sources of sediment such as stream bank erosion. With HSDR, we only consider the proportion of sediment which reaches a stream, as the SedNet model explicitly deals with the sources and fate of sediment from the gully and stream network onwards. Also, as SedNet considers hillslope erosion contributions to stream to consist entirely of fine suspended sediment, the model we have developed for HSDR is focussed only on the fate of suspended sediment.

1.2 Previous work

In previous SedNet applications, HSDR has generally been accounted for by applying a constant ratio to the RUSLE erosion estimates throughout a catchment. Lu *et al.* (2006) explored the concept of subcatchment-scale variable hillslope delivery in terms of lumped hillslope and channel travel time, however, the detailed hydrological data analysis required makes it difficult to apply.

A series of papers by Ferro and Minacapilli (1995), Ferro (1997), and Ferro *et al.* (1998) attempt to quantify sediment delivery. Their conclusion is that SDR (at the scale of a morphological unit within a basin) can be related to the travel time of particles in water.

Jain and Kothyari (2000) adapted the concepts of Ferro to develop a spatially explicit HSDR model for use with gridded high resolution digital elevation models (DEMs) and vegetation mapping.

Our companion paper (Post, *et al.*, 2006) details how we adapted and calibrated the Jain and Kothyari (2000) approach to produce a spatially explicit model of HSDR for our 5 x 5 m gridded data at Weany Creek. To summarise the model:

- 1) A network of channel grid cells was defined based on the exceedance of a threshold channel formation area of one hectare. A one hectare threshold was chosen as it reproduces fairly closely the existing gullies. For the purposes of suspended sediment, we considered gullies to be the minimum hydrological unit for which complete transport downstream could be achieved. Each channel grid cell was assigned an HSDR of 1.
- 2) All other grid cells (i.e. hillslope grid cells) were assigned a travel time to the nearest channel along the path of steepest flow. Travel time

within each grid cell was estimated by relating it to distance, cover, and slope.

- 3) An uncalibrated grid of HSDR values was calculated using (2)

$$HSDR = \beta e^{(-\gamma t)} \quad (2)$$

where t is the travel time to the nearest channel

The decay term gamma (γ) had been estimated to be 0.002 for the catchment. And the calibration term beta (β) was set to 1.

- 4) The uncalibrated HSDR grid was combined cell for cell with the RUSLE erosion grid (calculated using (1)) to produce estimates of the *relative* contributions of each cell to the total eroded sediment in stream. Channel grid cells were assigned erosion rates of 0.
- 5) The calibration term beta (β) was then calculated to match the total relative contributions from 4) to the total suspended sediment load from hillslopes estimated to reach the mouth of Weany Creek (275 t/yr based on extrapolation of hillslope flume measurements).
- 6) A final grid of contributions to stream (as t/ha/yr of suspended sediment by grid cell) was calculated by

$$\text{Contribution to Stream} = HSDR \times RUSLE \quad (3)$$

See Post *et al.* (2006) for further details of the model. In this paper, we apply the Post *et al.* (2006) model to Weany Creek at increasingly large grid sizes. For these larger grid sizes, we have modified the method in one respect: channel pixels are no longer purely channel – we include a travel time component to account for time required to transit the grid cell before entering the channel thus allowing for an HSDR \neq 1 in channel pixels.

2 METHODS

Basic input grids used for the HSDR model at Weany Creek included a 5m grid of elevation (derived from aerial photography autocorrelation) and 2m cover mapping (as percent cover) derived from airphoto classification and ground truth. We re-sampled this data to grid sizes increasing by 5m intervals to 100 m, by 10 m up to 150 m, then by 25 m to 250 m. The grid values for each increase in grid size were determined by averaging the values in the equivalent area from the original high-resolution grids.

At each grid size, vegetation cover grids were used to derive both RUSLE cover factor (C) grids and grids of the cover coefficient a used in calculation of travel time (see Post *et al.*, 2006). The R , K and L factors had been set to constants for the determination of RUSLE for Weany creek, so no new grids were required. Elevation grids at each grid size were used to derive slope, RUSLE slope

factor (S), flow direction, and channel networks (based on the 1 hectare threshold flow accumulation area).

Travel time was estimated for each grid cell on a hillslope by relating velocity to cover and the square-root of slope (see Post *et al.*, 2006 for details) along a flow path to the nearest downslope channel cell. Internal travel times for channel cells were estimated by first calculating a nominal distance to channel. This was done by calculating the length of channel occurring within a channel pixel (L in m) and then applying the following formula, where D is the grid size (in m).

For $L > D$:

$$\text{HillslopeDist} = D^2 / (2L) \quad (4)$$

For $L < D$:

$$\text{HillslopeDist} = D - (L / 2)$$

This channel cell hillslope distance, combined with slope and cover allowed us to derive an internal travel time for channel cells that was then added to the travel time for all the grid cells on the hillslope either side of the channel.

Steps 4, 5 and 6 from Section 1.2 were then followed to derive our calibrated HSDR grids at each grid size.

3 RESULTS

3.1 Slope Grid

Figure 1 shows the effect of increasing grid size on the slope grid. As grid size increases, there is a decrease in both mean value and the range of values. This is a result of the tendency for flattening of terrain features at larger grid sizes. As both the RUSLE and travel time calculations utilise slope values, we expect to see these results influenced by grid size.

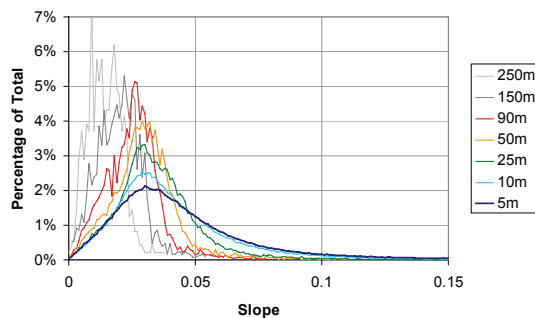


Figure 1: Histograms of slope at selected grid resolutions

3.2 Vegetation cover grid

Mean grid values for vegetation cover (and consequently RUSLE cover factor) remain constant at 50.9%, however the spread of values decreases and the value of the mode (peaks in Figure 2) increases with increasing grid size. This

is due to a change in the skewness of the distribution, with the skew towards higher values (eg individual trees) declining with increasing grid size.

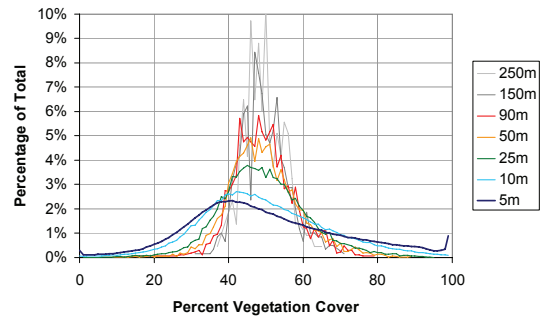


Figure 2: Histograms of percent cover at selected grid resolutions

3.3 Soil erosion rate grid

The RUSLE factors of rainfall erosivity (R), soil erodibility (K), and slope length (L) are assumed constant over the Weany Creek subcatchment, so the calculation of erosion rate is influenced solely by the combined effects of the slope and vegetation factors (S and C respectively). Thus, as we have already observed a drop in mean value for slope (Figure 1), we would predict the fall in mean erosion values with increasing grid size seen in Figure 3.

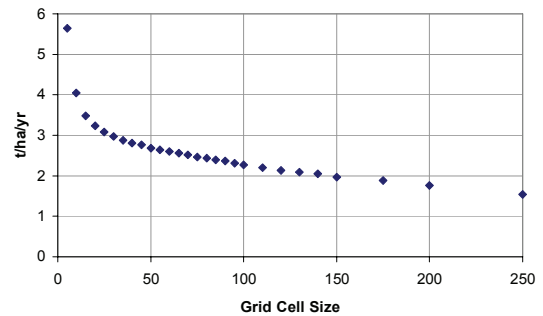


Figure 3: Mean erosion rate estimated from the RUSLE with increasing grid cell size

Although there is a smooth reduction in mean erosion with increasing grid cell size, if we look at the histograms for these erosion grids (Figure 4) we see a marked separation into two populations of values.

This separation of values is caused by spatial correlation between areas of high cover and low slope and areas of low cover and high slope. The lower erosion rates correspond to stream lines which have dense riparian vegetation combined with relatively flat slope. The overall lowering of values with increasing grid size in Figure 4 is the result of the decrease in slopes with increasing grid size noted in Figure 1.

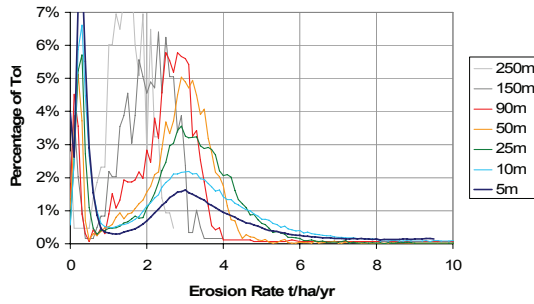


Figure 4: Histogram of RUSLE erosion rates at selected grid resolutions

3.4 Travel time grid

Figure 5 shows examples of the travel time grid derived from channel networks at various grid scales. The spatial patterns appear to remain reasonably similar up to grid sizes of 50 m.

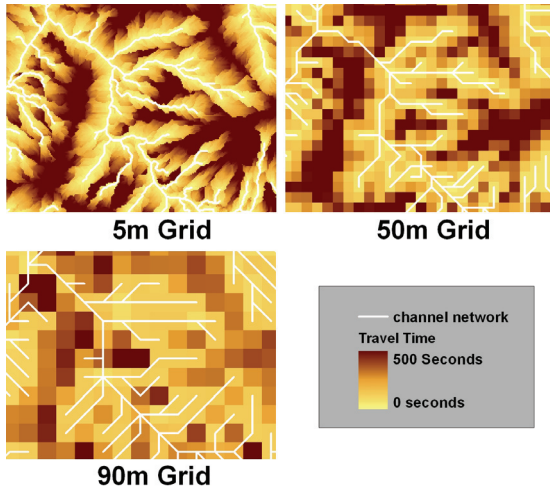


Figure 5: Travel time grids and channel networks as defined for various grid cell sizes.

However, if we look at the patterns of mean travel time with increasing grid size (Figure 6), we see that the mean starts to fluctuate systematically. If we compare total channel length in Figure 7 to travel times in Figure 6, we can see that the instability in mean value of travel time relates very well to an inability of the model to accurately predict the location and extent of the channel network with increasing grid size. Spatially, we can see the manifestation of this in the drainage network derived at 90 m compared with that from the 5 m grid in Figure 5.

The slight but steady drop in mean travel time between 5 m and 40 m grid sizes in Figure 6 cannot be entirely explained in terms of scaling of slope noted in Section 3.1, otherwise we might expect a slight *increase* in travel time (slopes flatten with increasing grid cell size, thus velocity would decrease) nor on the basis of decreasing total channel length (Figure 7), where we might expect less channels to result in longer travel times. However, by looking only at mean values,

we are not considering the potential effect of spatial correlations (eg like those observed in the erosion grid in section 3.3). This slight drop in mean travel time is minor and appears to have very little effect on the overall travel time predictions for grid sizes below 50 m as evidenced in Figure 5 and in the histograms in Figure 8.

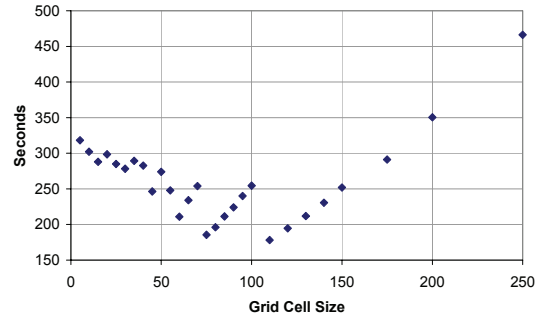


Figure 6: Mean value of travel time with increasing grid size.

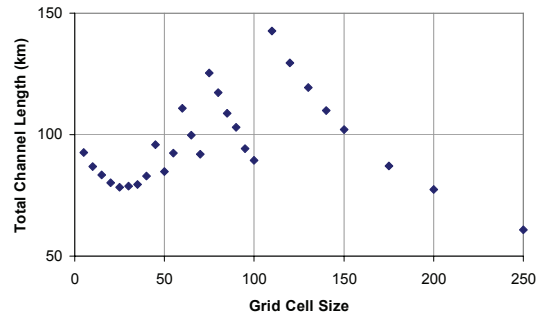


Figure 7: Total length of channel defined for each grid size.

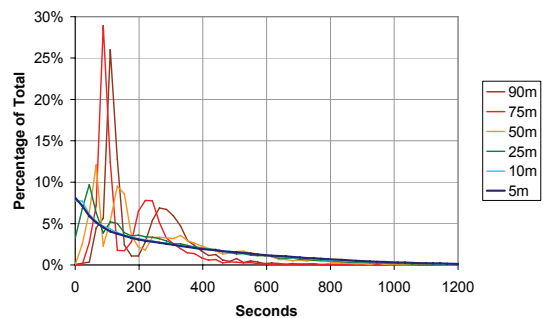


Figure 8: Histograms of travel time at selected grid resolutions

For grid cell sizes with area of greater than 1 hectare (i.e. 100 m or larger), our channel threshold value of 1 hectare necessitates that all grid cells contain a channel. However, as the grid size continues to increase beyond 100 m, it is impossible to maintain an appropriately dense channel network (one grid cell, one channel) thus the mean travel time starts to climb steadily once we exceed 100 m grid sizes (Figure 6). This

suggests the model should not be applied to grid resolutions where the grid cell area is greater than the threshold area for channels.

It is interesting to note that the same increase of mean values of travel time grids for grid sizes greater than 100 m is observed as a repeating pattern well below this size (Figure 6). In fact Figures 6 and 7 would suggest that grid resolutions larger than about 50 m are unable to reliably predict travel time. This observation is further reinforced by Figure 8 where, for grid sizes 50 m and above, the histogram increasingly breaks down into peaks and troughs due to the limited number of travel distances predictable at larger grids sizes: eg. for 90m grid cells, you may only make 1 or 2 grid cell “jumps” from hill crest to a channel, thus the travel times are constrained to a limited number of values.

3.5 HSDR grid

Although the spatial pattern of HSDR is stable (Figure 9) reflecting the relative stability of travel time for grid sizes up to 50 m, the mean value of the HSDR grids is significantly higher for larger grid sizes (Figure 10). This increase, generated by

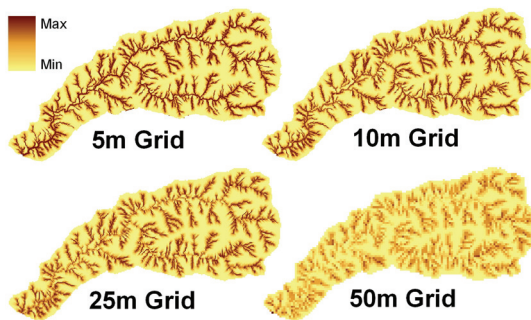


Figure 9: The spatial pattern of HSDR at increasing grid sizes

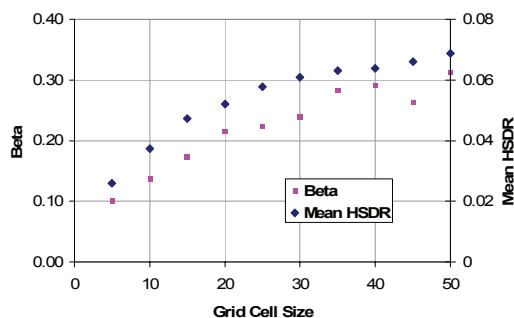


Figure 10: Calibration term (β) and the resultant mean value of the HSDR grids with increasing grid size.

the scaling of the calibration term β (also Figure 10), is compensating for the decrease in average erosion rates with increasing grid cell size (Figure 3).

The histograms of the HSDR grids (Figure 11) illustrate that predictions of HSDR are reasonably consistent with the 5 m grid up until about 50 m grid sizes, but then become unstable once we reach the grid resolution at which travel time estimates become unstable (i.e above 50 m).

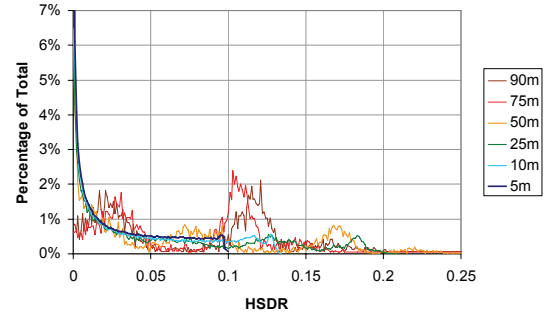


Figure 11: The effect of grid cell size on the distribution of HSDR values.

4 DISCUSSION

It is necessary that any spatial HSDR needs to recognise the change in hydrology from overland to channelised flow. In our model, we consider this change to occur very high in the landscape (at the 1 hectare threshold area). The definition of threshold area is a critically important component of the model. It not only places constraints on the grid sizes able to be used with the model (Section 3.4), but also implies the scale of spatial variability of HSDR (i.e. the grid size at which HSDR may be approximated to a constant value). Others may argue that a 1 hectare threshold is too small (eg Jain and Kothyari (2001) use 1:25,000 scale drainage lines). In the case of fine suspended sediment in event-driven climates such as in the Burdekin, even the smallest of drainage systems are potentially capable of fully transporting all suspended sediment. Whether such is the case in other regions should be the basis of further investigation, as should be the practical issues of implementation - i.e. are regional scale grids accurate enough to reproduce drainage patterns down to 1 hectare threshold areas.

Our HSDR model has two variables, γ and β , which, while modelled as constants for a particular subcatchment or grid scale, cannot be necessarily assumed to be constant throughout a catchment, nor as we have shown, at differing grid sizes. The Burdekin catchment consists of many varied terrain types, hydrological regimes and climates. Thus, if we are to apply this model to the whole of catchment, we not only need to understand the nature of the model from the point of view of grid size scaling, we need to understand the effect regional variations might have on the model.

This paper has demonstrated that β has a strong dependence on grid size, while Post *et al.* (2006),

suggests its value also implies certain characteristics of the soil composition and texture. At this point in time, it is not possible to separate the relative effects of these two factors, although, based on Figure 10, we would suggest that the dependence on grid size is likely to dominate.

For the valid grid size range of the model (up to 1/4 of the channel threshold area, i.e up to 50 m grid size), we have shown the decay term γ to have almost no dependence on grid size i.e. the same γ value produces similar patterns of HSDR. Post *et al.* (2006) relates the magnitude of γ to the volume of runoff (for the specific case of predicting fine suspended sediment). Thus we might expect γ to change if the infiltration rates are significantly different between one regime and another.

5 CONCLUSIONS

The work we have presented provides valuable information regarding the dependencies of our model on input data. It has also allowed us to place bounds on the use of the model – i.e. it should not be used with grid sizes above 1/4 the channel threshold area. For grid sizes above the threshold area, we suggest that a constant HSDR may be applicable. Between grid cells sizes of 1/4 and 1 the channel threshold area, the model is unstable and should not be used, unless improvements can be made.

As a result of this work we recommend areas for further study which may allow us to more confidently adapt the model to other regions with different terrain, hydrological regimes and climates. Such work includes inclusion of hydrological field data to better understand the variability of the decay constant γ and further consideration of the nature of channels and how to represent them in a model.

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