The Influence of the Type of Digital Elevation Models on Catchment Scale Slope Calculations and Erosion Modeling

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EXTENDED ABSTRACT

Slope is a major determining factor in the estimate of hillslope erosion rates. This paper investigates the performance of two whole-of-catchment digital elevation model (DEM) products in terms of representing slope for erosion estimates in catchment modelling for the Burdekin catchment ($120{,}000km^2$), Northern Australia. Performance is evaluated against a reference DEM produced by resampling a high resolution DEM covering a $400km^2$ study area (Blue Range) within the catchment. The two catchment-wide DEMs are the Shuttle RADAR Topographic Mission (SRTM) 3-sec arc (90m) DEM product and a 100m DEM from Queensland Department of Natural Resources and Water (NRW) interpolated from 1:100k topographic data using ANUDEM (Hutchinson (1996)).

Figure 1 shows the slope populations calculated from each DEM in the Blue Range study area. Blue Range was divided into three terrain types. Very flat alluvial areas (based on geological mapping) and two slope classes based on an observed break in the populations in **Figure 1**; i.e. high relief (>= 0.05 slope) and low relief (< 0.05 slope).

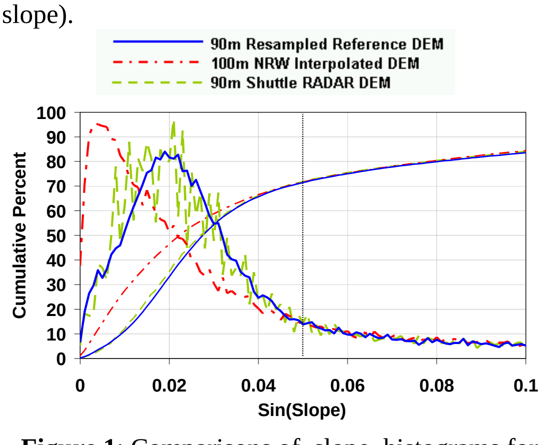


Figure 1: Comparisons of slope histograms for Blue Range. Sin(slope) ≈ slope for slopes < 0.2.

For alluvial areas, the SRTM over-predicted slopes by 24% due to amplification of noise effects on very flat terrain. The NRW interpolated grid appeared to better predict the histogram and mean value of slope, with only a 5% under-prediction in the mean. But spatial comparisons revealed a poor match with the reference DEM. As neither DEM performed well in these very flat areas, but the slope is predictably small and relatively invariant, we would recommend either patching of artificial values or smoothing of the DEM in these areas.

For high relief terrain, both DEMs performed well. The SRTM showed little difference in the mean value compared to the reference DEM, while the interpolated grid under-predicted slightly (5%) as would be predicted due to its coarser resolution. Spatial patterns supported the observed good statistical matches.

For low relief terrain (i.e. non-alluvial, but < 0.05 slope), the SRTM performed well (4% under-prediction) In contrast, the interpolated grid was unable to accurately predict slopes by up to an order of magnitude in areas where contours turned back upon themselves (eg on spurs and saddles), resulting in an overall under-prediction of slopes by 24%. Any interpolation technique would perform poorly in such areas, which are characterised by sparse data relative to the complexity of the terrain.

The impact of non-alluvial low relief areas on overall erosion estimates for Blue Range (**Table 1**) is high (contributing over 50% of the predicted eroded material) due to the large proportion (62%) of area in this terrain class. For the Burdekin catchment, with 70% low relief terrain, the impact would be even greater Thus, it is important to derive good estimates of slope in these low relief areas. This study suggests SRTM is a better solution than an interpolated grid.

Table 1: Mean hillslope erosion estimates (t/ha/yr) for Blue Range **Impact indicates relative contributions to total hillslope erosion*

DEM	Avg	Alluv	Low	High
Reference *Impact**	2.80	1.35 *5%*	2.35 *52%*	4.30 *43%*
NRW DEM *Rel. to Ref.*	2.39 *-15%*	1.31 *-3%*	1.81 *-23%*	3.80 *-12%*
SRTM *Rel. to Ref.*	2.80 *0%*	1.73 *+28%*	2.27 *-3%*	4.30 *-0%*

INTRODUCTION

1.1. Background

The Burdekin is a very large (120,000 km^2) catchment lying mostly within the dry tropics and draining into the Great Barrier Reef Lagoon (GBRL). It consists largely (90%) of open eucalypt woodlands under grazing management. The Burdekin has a few areas of steep terrain, while the majority of the area is low relief residual surfaces or, to a much lesser extent, transported alluvium.

Catchment scale sediment and nutrient transport models such as SedNet (Wilkinson *et al.* (2004)) have been used extensively in the Burdekin catchment, as well as throughout many areas of Australia, to assist natural resource mangers assess the impact of land management practices on water quality, both locally and downstream to the river mouth. Water quality is of particular concern for catchments draining into the GBRL because of the potential for offshore impacts on the World Heritage listed Great Barrier Reef.

1.2. The Issue

A major input to these catchment models is a spatially explicit grid of hillslope erosion rates. This is usually generated using the Revised Universal Soil Loss Equation (RUSLE) from Rosewell *et al.* (1993):

$$\boldsymbol{Erosion} = \boldsymbol{R} \times \boldsymbol{K} \times \boldsymbol{L} \times \boldsymbol{S} \times \boldsymbol{C} \qquad \textbf{(1)}$$

Erosion *is calculated in tonnes* $ha^{-1}\,y^{-1}$
R = *Rainfall Erosivity factor*
K= *Soil Erodibility factor*
L = *Slope Length factor*
S = *Slope Steepness (or just Slope) factor*
C = Cover factor

Each factor is represented in the model as a grid

The original hillslope erosion estimates for the Burdekin were developed as part of the National Land and Water Resources Audit (Lu (2001)). Since the Audit, there have been a number of studies aimed at improving the level of detail and accuracy of the models (Prosser *et al.* (2000); McKergow *et al.* (2005); Fentie *et al.* (2006)). The latter made improvements to a number of RUSLE factors (including C-factor) and noted in its companion volume, Cogle *et al.* (2006), the sensitivity of hillslope erosion prediction to slope and cover estimates. However, it still relied on the Audit S-factor.

The S-factor grid from the Audit was based on a 250m AUSLIG 9-sec DEM interpolated from 1:250,000 scale topographic mapping (Hutchinson (2001)). It predicted S-factor indirectly by applying statistical methods based on a selection of predictive variables and a limited number of high resolution DEMs (Gallant (2001).

1.3. The Opportunity

More recently, two DEMs covering the entire Burdekin region have become available offering the opportunity to improve significantly on slope and S-factor estimates from those of the Audit. The first was developed by the Queensland Department of Natural Resources and Water (NRW). It is an 100m interpolated grid based on 1:100,000 topographic data. The second DEM is the 3-second (90m) Shuttle RADAR SRTM. The SRTM DEM has already been used to estimate S-factor for a recent SedNet modelling study of the Burdekin Post *et al.* (2006).

A high resolution reference DEM, was available for Blue Range, a 22 km by 19 km (~400 km^2) study area in the Burdekin (Post *et al.* (2006)), see **Figure 2**.

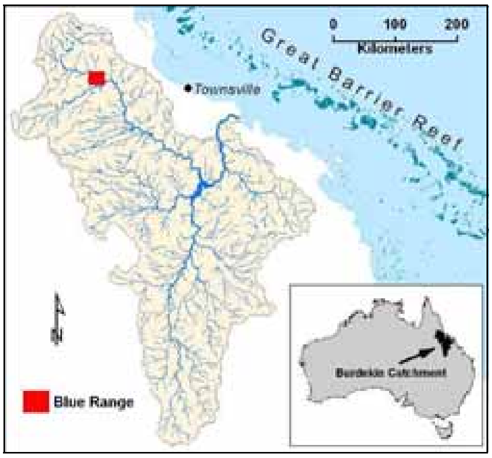


Figure 2: Map showing Blue Range DEM area in the Burdekin Catchment.

Blue Range contains a range of terrain types in similar proportions to the Burdekin (see **Table 2** at end of Section 1). It occurs in an area of open woodland under grazing management and has a mean foliage cover levels of 15%, with areas of steeper terrain averaging 30% - also typical of the Burdekin. Thus, the high resolution DEM for Blue Range offered an ideal reference from which to assess the two catchment-wide DEMs for use in hillslope erosion estimations for the Burdekin as a whole. There are many areas of Australia with similar terrain characteristics, vegetation cover, and DEM options available to them.

1.4. Objective of this Study

The objective of this study is to investigate the performance of the two regional DEMs in terms of representing slope for erosion estimates in catchment modelling for the Burdekin.

1.5. The DEMs

10m Reference DEM

The high resolution DEM over Blue Range was produced by Georeality Pty Ltd using semi-automated photogrammetric autocorrelation techniques. According to Georeality's quality statements, each 10m grid cell should contain several measured ground heights, where the measured heights have been manually filtered to remove spurious vegetation effects. The quoted accuracy of the DEM is 0.6m in the horizontal and 1.3m in the vertical for the 1:40,000 scale airphotography used.

100m Interpolated DEM (NRW)

A 100m resolution DEM was generated by Queensland's Department of Natural Resources and Water (NRW). Input data was 100,000 scale contours, spot heights and drainage captured for the whole Burdekin Catchment. Contour interval was 20m most places. Spot heights were scattered widely and provided only minimal additional data. ANUDEM 4.6.3, with stream line reinforcement (Hutchinson (1989); Hutchinson (1996)), was used to interpolate the DEM. The Burdekin DEM forms part of a set generated by the Department for use in modelling and were intended to capture both landscape characteristics and hydrological flow patterns (Smith and Brough (2006)). It was noted in the report that there was a "stepping" pattern in the final DEM surface, but suggested that there was no known solution to the issue.

3-second (90m) Shuttle RADAR (SRTM)

The 3-second (90m) Version 2 (Finished) DEM product from the Shuttle RADAR Topographic Mission (SRTM) Gesch *et al.* (2006)) is widely available. It is affected by systematic and random errors and missing data (Rodriguez (2005)), as well as pervasive effects from vegetation (Jarvis (2004)). Thus it has been regarded as an unreliable source of quantitative information. It's storage as integer values may also limit it's use, particularly in low relief terrain where noise or vegetation effects may be exaggerated. However, it is more data-rich than DEMs derived from topographic contours because almost every grid cell contains a measured value.

Table 2: Extents of different terrain types

Terrain Type	Burdekin	Blue Range
High relief (>= 5% slope)	20%	28%
Low relief (< 5% slope)	70%	62%
Alluvium (very flat)	10%	10%

2. METHODS

2.1. Resampling of the Reference DEM

Estimation of slope is heavily influenced by DEM grid resolution (Wilson and Gallant (2000); Thus the high resolution reference DEM had to be resampled to allow direct comparison of slopes with those derived from the whole-of-catchment DEMs. The resampling was accomplished by calculating an average value every 9 x 9 pixels, resulting in a 90m resolution DEM grid. Although the two whole-of-catchment DEMs were slightly different resolutions (90m and 100m), 90m was chosen as the resampling resolution for the reference DEM firstly because the reduction in slope estimates from 90m to 100m grid resolution was determined to be small and predictable (3%) and secondly because it is difficult to apply an averaging filter based on an even number of pixels.

Slope values were calculated for each pixel of the DEM grids using the ARC/INFO® GRID SLOPE command, which calculates slope using finite difference over the 8 adjacent grid cells. For 90 to 100m grid resolution, such a method effectively averages slope over a square area of dimensions 270 to 300m respectively. In the equation for the calculation of S-factor in the RUSLE **(2)**, the S-factor is directly proportional to Sin(slope). Slope and Sin(slope) are effectively the same below slopes of about 0.2 (i.e. 95% of the Blue Range study area). We have standardised on Sin(slope) in this paper, and use the term Slope interchangeably with Sin(slope).

$$
\begin{aligned}
S &= 10.8 * \sin\theta + 0.03 \qquad \sigma \le 9\% \\
S &= 16.8 * \sin\theta - 0.50 \qquad \sigma > 9\%
\end{aligned}
\qquad \textbf{(2)}
$$

Where σ is percent slope and θ is angular slope (Rosewell et al. (1993).

2.2. Hillslope erosion calculations

The R, K, L, & C-factor grids from the latest modelling study (Post *et al.* (2006)) were combined with the S-factor (**2**) for each DEM to produce predictions of hillslope erosion (**1**). A combined RKLC grid was dominated by high-magnitude (almost 2 orders) variations in the C-factor. And, although these four factors are invariant for the analysis, any spatial correlation between one of the four factors (eg. C) and the S-factors, may cause a bias in the resulting erosion estimates that would not have been predicted from analysis of the slopes alone.

2.3. Methods of Comparison

Mean values were used as a comparative measure of performance, as they has the most relevance in terms of mimicking the "lumping" of values that occurs in catchment models such as SedNet. However, it does not reveal potentially important differences in spatial and frequency distributions, which may detect other performance issues.

Frequency and cumulative histograms were analysed to reveal differences in populations of values that were not detectable based on such as simple statistical measure. Direct spatial (pixel by pixel) comparisons were used to help interpret the differences observed in the histograms and statistics of the DEM derivatives. Spatial comparisons were only interpreted qualitatively, as they had the potential to be adversely affected by mis-registration between the DEM grids, particularly at sharp changes of slope such as in steep or dissected terrain. Although, for this study mis-registration appeared to be generally small (less than 1 pixel).

2.4. Segmentation into terrain types

It was apparent from preliminary examination of the slope results in **Figure 1** that there were different performance characteristics in the DEM slope predictions depending on the terrain steepness, with the breakpoint occurring around 0.05 (5% slope). Additionally there were concerns about the performance of the DEMs in regions of extremely flat terrain associated with alluvial deposits on floodplains. Consequently, the Blue Range study area was divided into three terrain classes as shown in **Figure 3**.

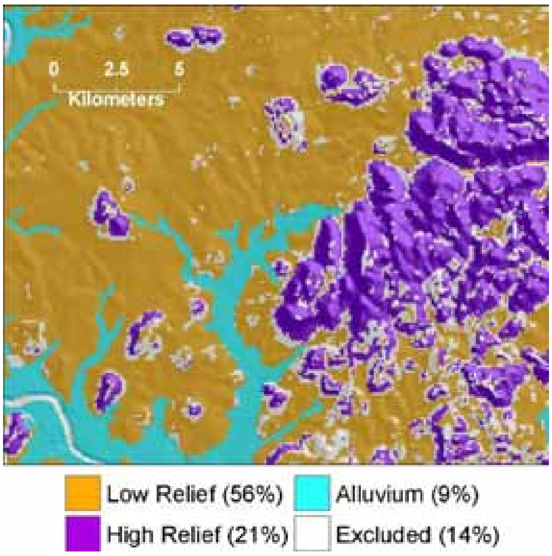


Figure 3: Extent and percentage of total area of each terrain type. Shaded relief backdrop is based on the 90m resampled reference DEM

High and low relief terrain was defined using the 0.05 (5%) slope breakpoint, where all corresponding pixels in the three DEMs had to have slope values in the same slope category i.e. all slopes < 0.05 or all slopes >= 0.05. Alluvial areas were identified from 1:250,000 scale geological mapping (QDME (2007)). Areas excluded from analysis were those of either (1) pixels of mixed slope classes (constituting approximately 6% each for both high and low relief classes, based on slopes from the reference DEM) or (2) mapped as water body (channel) in the 1:250,000 topographic mapping, and thus normally excluded from hillslope erosion analysis (constituting approximately 1% of alluvium).

3. RESULTS

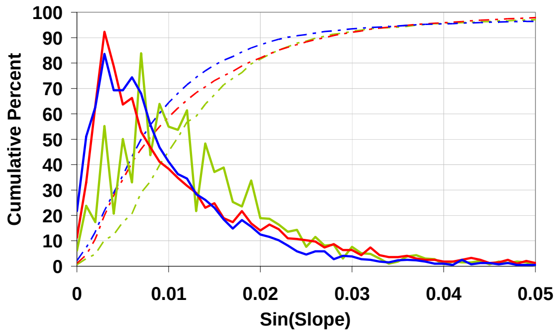
3.1. Slope comparisons

Histograms of slope values for each terrain type are shown in **Figure 4** and a comparison of mean slope values for each terrain type is shown in **Table 3**.

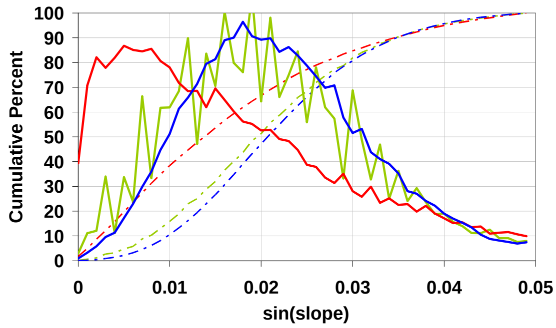
Figure 5 shows the spatial pattern of differences of predicted slopes to the reference DEM slope.

For alluvium, **Figure 5(a)** and **Table 3** show that the SRTM DEM over-estimates the slope significantly. This is to be expected for extremely flat terrain as the level of noise in SRTM becomes significant compared with the change in terrain elevation. **Figure 5(a)** illustrates that the over-estimation (brown tones) is largely restricted to the alluvium terrain class.

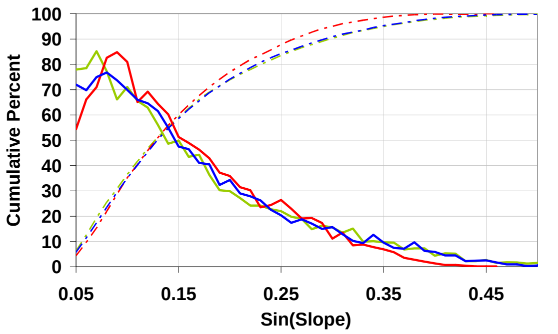
Despite its noisy reputation, there is a good overall match (5% under-prediction) between the SRTM and the reference DEM for low relief terrain. This is illustrated as well by the mostly pale tones in **Figure 5(a)**. This result contrasts with the relatively poor performance of the NRW interpolated DEM. **Figure 5(b)** illustrates why: There is a correlation between strong under-prediction (dark blue) and areas where contours bend back on themselves (i.e. along spurs and saddles). This phenomenon is also tending to "force" a general flattening (green tones) of the DEM immediately above contours (most likely the "stepping" observed by NRW). The overall effect is a large under-prediction (24%) of slope. Strong colouration in **Figure 5(b)** on alluvial areas suggests poor performance of the NRW interpolated DEM in these regions (possibly due to an inability of the sparse contour data to fully constrain the streamline reinforcement routine of ANUDEM). This observation is at odds with the apparent good performance results in **Table 3** and **Figure 5(a),** and suggests merely a fortuitous coincidence in slope populations that does not correspond spatially to the slopes observed in the reference DEM.



(a) alluvium



(b) low relief



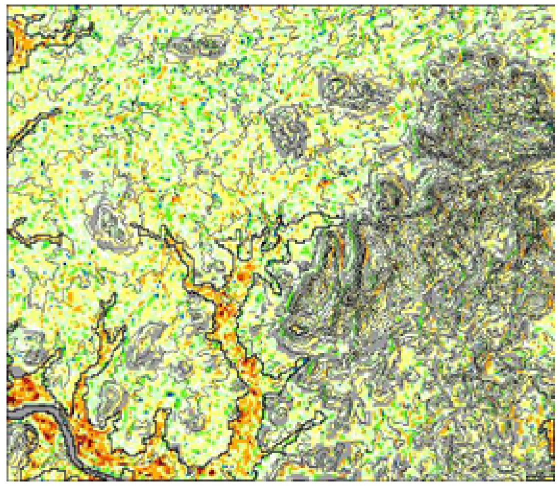
(c) high relief

Figure 4: Frequency and cumulative histograms of sin(slope) for each DEM (colours as per **Table 3**) based on terrain areas shown in **Figure 3**.

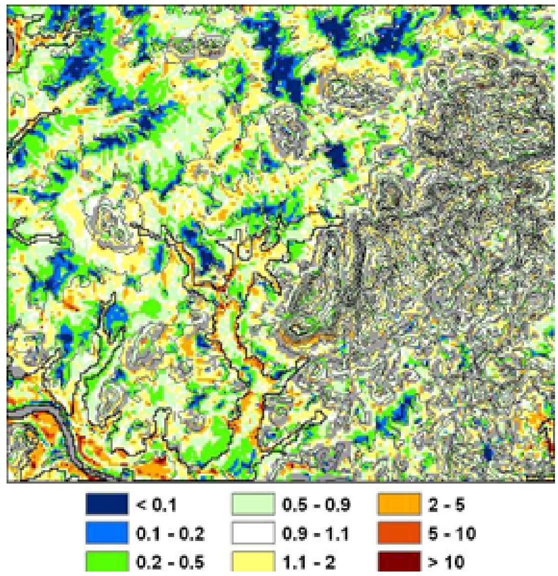
Table 3: Mean sin(slope) for Blue Range overall and for different terrain types.

DEM	Avg	Alluv	Low	High
Reference	0.058	0.012	0.022	0.159
NRW DEM *Rel. to Ref.*	0.050 *-13%*	0.013 *-6%*	0.017 *-24%*	0.151 *-5%*
SRTM *Rel. to Ref.*	0.055 -5%	0.015 *+24%*	0.021 *-5%*	0.159 *0%*

The histograms for high relief areas in **Figure 4(c)** suggest that both DEMs predict slopes reasonably well. The slight under-prediction of the NRW grid is accountable by the difference in grid resolution (section 2.1). The subdued colouration in **Figure 5(a)** and **Figure 5(b)** (despite high potential for



(a) SRTM



(b) NRM Interpolated DEM

Figure 5: Spatial pattern of the ratio of slopes for the two candidate DEMs to the reference DEM. Grey indicates excluded areas. Thick black lines delineate the extent of the alluvial areas. Thin black lines delineate 1:100,000 topographic contours.

mis-registration effects in high relief terrain (see section 2.3) provides supporting evidence for the good matches.

3.2. Implications for Hillslope Erosion

Table 1 shows the mean hillslope erosion values resulting from combining slopes (as S-factors - **(2)**) with the RKLC factors **(1)**. The variations in relative differences between **Table 3** and **Table 1** reflect slight biases resulting from spatial correlations between slope and the other factors (most likely C).

Of particular note in **Table 1** are the *impact* values which measure the relative contributions to total hillslope erosion of each terrain type. Impact values can be used to prioritise the relative importance of erosion prediction differences between the DEMs for various terrain types. For example, alluvium has a very low impact (5%) relative to the impacts from other terrain types. Thus, while SRTM doesn't perform particularly well (28% under-prediction) on alluvium, these areas have very low impact on erosion estimates for the Blue Range area as a whole.

4. DISCUSSION

ANUDEM has a newer version (5.2) (Hutchinson (2006)). And a test of the latest version over Blue Range, using the same data as the NRW grid and with options selected to minimize curvature, revealed a much reduced flattening above contours in the low relief areas. However, the model still under-predicted significantly where contours curve back on themselves, such as on saddles and spurs. Thus the slope predictions were still under by an average of 18% (albeit an improvement from 24%).

The inability of ANUDEM to accurately predict slopes in low relief non-alluvial terrain is not an inherent problem with ANUDEM, but is symptomatic of a more general problem when attempting to interpret sparse data in complex terrain. Any interpolation routine would have difficulties accurately representing such a landscape, unless done at such a coarse resolution as to be of little practical value. Thus SRTM, with its high density of measured values, offers a much more reliable solution.

For very flat terrain, such as alluvium, the apparently good statistical performance of the NRW interpolated grid is not matched by the observed spatial patterns (third paragraph in Section 3.1). SRTM is not a good alternative either due to the impact of noise when terrain is very flat. However, alluvial areas are characterised by predictably small and uniform slopes and thus it may be possible to simply "patch in" very low values of slope into the slope grid rather than trying to model them from DEM data. It may also be possible to improve SRTM slopes in these flat areas by using some form of smoothing algorithm.

Despite SRTM's poor reputation (See Section 1.5), it has performed well in our tests and should be given serious consideration for use in applications requiring accurate spatial representation of slope in both high and low relief terrain. It offers a particularly good option in Australia, where the landscape is dominated by complex but low relief terrain with low vegetation cover and where topographic mapping is often sparse.

One might argue that the absolute differences in slope estimates for low relief terrain are inherently small, but the potential for large *relative* differences (such as observed with the interpolated grid from NRW) to impact on hillslope erosion estimates in the Burdekin (and in Australia more generally) are greatly amplified due (1) to the extensive areas of low relief terrain and (2) the tendency for these area to have relatively low cover relatively to higher relief terrain (and thus increased impact on overall erosion estimates). In **Table 1**, low relief terrain accounts for over 50% of all the hillslope erosion estimated for Blue Range. For the Burdekin, which has a higher overall proportion of low terrain (70% of the area), the contribution of low-relief terrain would increase to over 60% of total hillslope erosion. Thus it is important to ensure these areas are represented as accurately as possible in catchments models.

5. CONCLUSIONS AND RECOMMENDATIONS

The use of terrain segmentation, histograms and spatial comparisons to interpret differences in performance of DEMs for slope representation has provided valuable insight into the appropriate use of DEMs for estimating slope and hillslope erosion:

- Both SRTM and the NRM interpolated DEM appeared to perform reasonable well in areas of slope > 5%.
- The impact of low relief terrain on overall erosion estimates in many parts of Australia can be significant, thus it is important to carefully explore the quality of the DEM options for this type of terrain
- Caution should be exercised if using DEM grids interpolated from topographic data to predict slopes in low relief terrain (characterised by sparse and convoluted contours). In these areas, SRTM is a better option.
- Very flat alluvial areas are problematic for calculation of slopes from either SRTM or DEMs interpolated from topographic data. But, "patching" or smoothing may offer simple solutions.

6. ACKNOWLEDGMENTS

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