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Evaluating Shuttle radar and interpolated DEMs for slope gradient and soil erosion estimation in low relief terrain

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A B S T R A C T

The error in slope gradient estimates provided by digital elevation models propagates to spatial modelling of erosion and other environmental attributes, potentially impacting land management priorities. This study compared the slope estimates of Shuttle Radar Topographic Mission (SRTM) DEMs with those generated by interpolation of topographic contours, at two grid cell resolutions. The magnitude and spatial patterns of error in DEM slope, and derived erosion estimates using the Revised Universal Soil Loss Equation (RUSLE), were evaluated at three sites in eastern Australia. The sites have low-relief terrain and slope gradients less than 15%, characteristics which dominate the global land surface by area and are often highly utilised. Relative to a reference DEM resampled to the same resolution (a measure of DEM 'quality'), the 90 m (3-s) SRTM DEM provided the best estimates of slopes, being within 20% for each 5% slope class outside alluvial floodplains where it over-predicted by up to 220%. Relative to a hillslope scale 10 m reference DEM, the 30 m (1-s) SRTM-derived DEM-S, provided slope gradient estimates slightly less biased towards under-prediction than the 90 m SRTM and significantly less biased on alluvial floodplains. In contrast, the 20 m vertical contour intervals underpinning the interpolated DEMs resulted in under-prediction of slope gradient by more than a factor of 5 over large contiguous areas (>1 km^2). The 30 m DEM-S product provided the best estimate of hillslope erosion, being 3–4% better than the 90 m SRTM. The slope errors in the interpolated DEMs translated into generally poorer and less consistent erosion estimates than SRTM. From this study it is concluded that the SRTM DEM products, in particular the 30 m SRTM-derived DEM-S, provide estimates of slope gradient and erosion which are more accurate, and more consistent within and between low relief study sites, than interpolated DEMs.

1. Introduction

Low relief terrain dominates many areas of the world; for example over 90% of the Australian continent (based on SRTM evaluation) and over 50% of the continental US (Guth, 2006) have slope gradients of less than 5%. Low relief terrain is often highly utilised and, as such, has been identified as a potentially major source of erosion (Lu et al., 2003; Menke and Eric, 1992; Scanlan et al., 1996). With continued land use intensification and climate change affecting many parts of the world, there is increasingly a need to assess erosion and sediment delivery over large river catchments to ensure agricultural productivity and sustainability (Biggelaar et al., 2003; Montgomery, 2007) and to protect the integrity of downstream aquatic ecosystems (Allan et al., 1997). The need for quantitative assessments of erosion rates, and modelling the effects of future land management scenarios has become an imperative through federal policies such as the European Water Framework Directive and the U.S. EPA source water protection program (U.S. EPA, 1997). In Australia the Caring for Our Country program targeted a 10% reduction in sediment delivery to the Great Barrier Reef (Commonwealth of Australia, 2008). Slope gradient is an essential input for erosion estimation (e.g; Renard et al., 1997) and gridded DEMs generally provide that slope gradient information.

Much of Australia is covered by DEMs derived from two different data sources; those interpolated from topographic contours ("interpolated DEMs") and more recently those derived from remote sensing, the most common being the Shuttle Radar Topographic mission DEMs ("SRTM DEMs") derived from

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interferometric synthetic aperture radar data collected aboard the NASA Space Shuttle mission STS-99 (Farr et al., 2007; Rabus et al., 2003). Both types of DEM have known but different spatial patterns of errors which have potential to affect slope gradient estimation. For contour interpolated DEMs, terracing, where slope is flatter in the vicinity of contour lines, is often noted (Fisher and Tate, 2006; Guth, 1999; Wood, 1996; Wood and Fisher, 1993) and can be detected as adjacent peaks and troughs in the histograms of DEM height (Wood and Fisher, 1993). Splining techniques such as ANUDEM (Hutchinson, 1988, 1989; Hutchinson and Gallant, 1999, 2000) are considered one of the best methods of interpolation (Desmet, 1997) especially in areas of low sampling density and weak spatial structure (Chaplot et al., 2006). However, splines are not entirely immune from the terracing phenomena (Wilson et al., 2000) and can also result in overshoots (Aguilar et al., 2005). SRTM DEMs contain both structured errors relating to instrument position, platform orientation and ground control as well as random errors related mostly to radar speckling (Farr et al., 2007; Rabus et al., 2003). Random errors result in SRTM DEMs over-predicting slope gradient, particularly in areas of less than 5% slope (Falorni et al., 2005; Guth, 2006). Other sources of error in SRTM DEMs include vegetation (Carabajal and Harding, 2006), and rounding of elevation to integer values in the 90 m SRTM resolution product. A recently released 1 s (approximately 30 m) SRTM-derived DEM-S product is available for Australia (Gallant, 2011b; Gallant et al., 2011a,b). The DEM-S has been subjected to de-striping, vegetation correction and adaptive smoothing in an attempt to reduce some of the well recognised SRTM DEM errors noted above. The effect of these adjustments on DEM-S derivatives has not yet been quantitatively evaluated (Gallant, 2011a).

Evaluation of slope gradient error in DEMs has received much less attention than evaluation of DEM height errors and is rarely reported as more than a single statistical measure. DEM height errors generally increase with increasing terrain complexity and decreasing data density (Aguilar et al., 2005; Chaplot et al., 2006). And slope gradient error estimates are known to be highly sensitive to DEM height errors regardless of DEM resolution or type (Carter, 1992; Erdogan, 2009; Gao, 1998; Toutin, 2002; Ziadat, 2007). However, height error statistics such as root mean squared error or mean error commonly provided in DEM height error studies (and for DEM metadata generally) cannot be directly translated into slope gradient errors, as errors in slope gradient result from relative height differences between adjacent cells. Very little is known about the localised (pixel by pixel) spatial structure of height errors, and in particular how it varies between methods of DEM generation, although it is generally acknowledged that DEM height error is often moderately to highly spatially correlated outside of areas of high terrain complexity, being dominated by systematic errors more than by random noise (Heuvelink, 1998; Hunter and Goodchild, 1997; Wood and Fisher, 1993). Systematic errors include errors in the original stereo modeller and, in the case of interpolated DEMs, undershoots in the DEM approximation (Oksanen and Sarjakoski, 2006). A number of studies have investigated the propagation of DEM height errors into the slope gradient (Heuvelink, 1998; Holmes et al., 2000; Oksanen and Sarjakoski, 2005; Raaflaub and Collins, 2006; Wood and Fisher, 1993). However, these studies relied on global or regionalised assumptions about the structure of such error, e.g. via semivariograms functions. As such, they offer only broad insight into the spatial patterns of slope gradient errors.

There is general agreement that hillslope erosion rates predicted in models such as SWAT, AGNPS, and RUSLE are highly sensitive to DEM quality (e.g. Chaplot, 2005; Wang et al., 2011). But DEM quality is almost invariably considered in terms of grid resolution. The dependency of slope gradient estimates on DEM grid resolution is well recognised (Chang and Tsai, 1991; Thieken et al., 1999), with coarser resolution DEMs (greater than 30–50 m) resulting in significantly lower slope gradient estimates that inevitably resulting in lower erosion estimates. For RUSLE, the slope gradient (S) and cover (C) factors have the largest influences on erosion estimates (Risse et al., 1993), with S and C typically showing localised (within catchment) variations of at least two orders of magnitude variations. Whereas, other RUSLE factors typically vary by less than one order of magnitude over the same area. As RUSLE is simply a product of these factors, error in any individual factor translates directly into the estimate of RUSLE. An illustration of the effect of DEM resolution on erosion modelling is given by Wang et al. (2011) who find that an increase in resolution from 100 m to 30 m in an interpolated DEM resulted in a 50% increase in average slope gradient, minimal effect on runoff, but a five-fold increase in RUSLE-based sediment load estimates. Thus there is a high potential for DEM quality to adversely affect estimates of hillslope erosion. However the equating of DEM quality to DEM resolution neglects to address the fact that other aspect of DEM quality (such as poor representation of terrain) may also be have an equally and potentially less predictable influence on hillslope erosion estimates.

This study utilised high resolution DEMs as a reference data set against which to evaluate the spatial patterns of slope gradient errors on a cell-by-cell basis in catchment DEMs for three low relief rangeland sites in eastern Australia. We use slope gradient errors based on reference DEM resampled to the stated resolution of each catchment DEM to assess the 'quality' of the DEM. We use the term 'quality' (in quotes) to refer specifically to *the ability of the catchment DEM to represent terrain features at its stated grid cell resolution*. We then consider the additional effects of DEM resolution on slope gradient errors by comparing the catchment DEM slope gradients to those based on a standardised reference DEM grid cell resolution of 10 m. Finally we examine the impact of the propagation of these slope gradient errors into estimates of RUSLE-based hillslope erosion.

2. Materials and methods

2.1. Study sites and reference DEMs

The study sites presented in this paper represent low relief, sparsely vegetated regions typical of much of eastern Australia and capture a range of terrain structure climatic and geological settings (Fig. 1 and Table 1). The mean and median slopes of these sites are typical of slopes for the eastern Australian States.

Reference DEMs at each site were derived from high density measured heights gridded by the suppliers at a resolution that included several measured heights within each grid cell. The Reference DEMs for Blue Range and Station Creek were generated by autocorrelation of high resolution scanned air photo stereo pairs with vertical accuracy estimated by the supplier to be 1 m and 0.5 m respectively. The Reference DEM at Simmons Creek was generated from a dense cloud (2.3 m average raw point separation) of spot heights measured using airborne Lidar (Light Detection And Ranging) with vertical standard error assessed by the supplier to be 0.14 m. For both types of reference DEM, vegetation was detected and removed from the raw point cloud before DEM grid generation - for photogrammetry, a mix of automated and manual vegetation detection was used, while with Lidar the vegetation detection technique was proprietary.

2.2. Catchment DEMs

The catchment DEMs in this study are publicly available products, developed to be used for broad scale landscape assessments and catchment modelling. Two resolutions of each were studied (Table 2). Interpolated DEMs utilised the best available State Government topographic mapping, at 1:50,000 (Simmons Creek) and 1:100,000 scale (Blue Range and Station Creek). Contour interval at both scales is 20 m and is typical of that available over much of the rangeland areas of eastern Australia. Spot heights, mostly on hilltops, were utilised in the interpolation, but were very sparse. Drainage lines were used to reinforce flow direction in the DEM. Both coarse and fine resolution interpolated DEMs were based on the same topographic mapping. Version 4 of ANUDEM, similar to that coded into the latest release (Version 9) of ArcGIS software as the GRID-based TOPOGRID command (ESRI, 2009b) was used to generate the catchment DEMs evaluated in this study. ANUDEM is based on a thin-plate spline technique with stream line enforcement (Hutchinson, 1988, 1989, 1996;