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Digital elevation model error and its effect on modelling soil erosion and catchment geomorphology

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Abstract In many cases it is useful and appropriate to assess potential erosion risk both in the undisturbed environment and in catchments heavily disturbed by humans. One method for assessing risk, when modelling environmental processes, is to quantify the error(s) associated with model input parameters and include this in the modelling process. This study examines the impact of digital elevation model (DEM) error on the estimation of soil loss and geomorphological changes in a Northern Territory, Australia catchment. Multiple realizations (or versions) of the same catchment were created by including positional error in the DEM. The SIBERIA erosion model was run for a simulated 1000-year period, using these multiple catchment realizations as this is the expected minimum design life for rehabilitated uranium mines in the area. Examination of the area–slope relationship, hypsometric curve, and cumulative area distribution after 1000 years of simulated erosion demonstrates little geomorphological difference. Statistically significant differences occur when comparing channel network statistics. A probabilistic assessment allows an estimation of the statistical ranges of incision and average erosion.

Key words geomorphology; hydrology; risk assessment; SIBERIA; soil erosion modelling

INTRODUCTION

In many cases it is useful and appropriate to assess potential erosion risk both in the undisturbed environment and also in catchments heavily disturbed by humans (Evans, 2000). One method by which risk can be assessed is to quantify the error(s) associated with model input parameters, and include this error in the modelling process either as a sensitivity study using the range of possible parameter values, or a Monte Carlo analysis (Willgoose *et al.*, 2003). In many cases the variability surrounding input parameter data may be unknown or difficult to statistically quantify, thus providing further uncertainty in the results. Also, in the case of soil erosion and landscape evolution modelling, there is further uncertainty surrounding the initial conditions extant in the landscape being examined (Hancock, 2003; Willgoose *et al.*, 2003). In the case of landscape evolution models using DEMs as the catchment or hillslope input, questions remain as to the impact of errors in the coordinates on such outputs as soil erosion and catchment geomorphology.

This study examines the impact of DEM error on soil loss and the geomorphology of a thoroughly studied catchment in the Northern Territory, Australia. This catchment has uniform geology, soils, vegetation and, because of its small size, climate. The SIBERIA erosion and landscape evolution model is used to examine soil loss in the catchment, and how the catchment might geomorphologically evolve, over a 1000-year simulation, using calibrated erosion parameters.

STUDY SITE

Tin Camp Creek is a natural site in Arnhem Land, Northern Territory, Australia (Fig. 1) (Hancock *et al.*, 2002; Moliere *et al.*, 2002; Hancock 2003, 2004; Willgoose *et al.*, 2003).

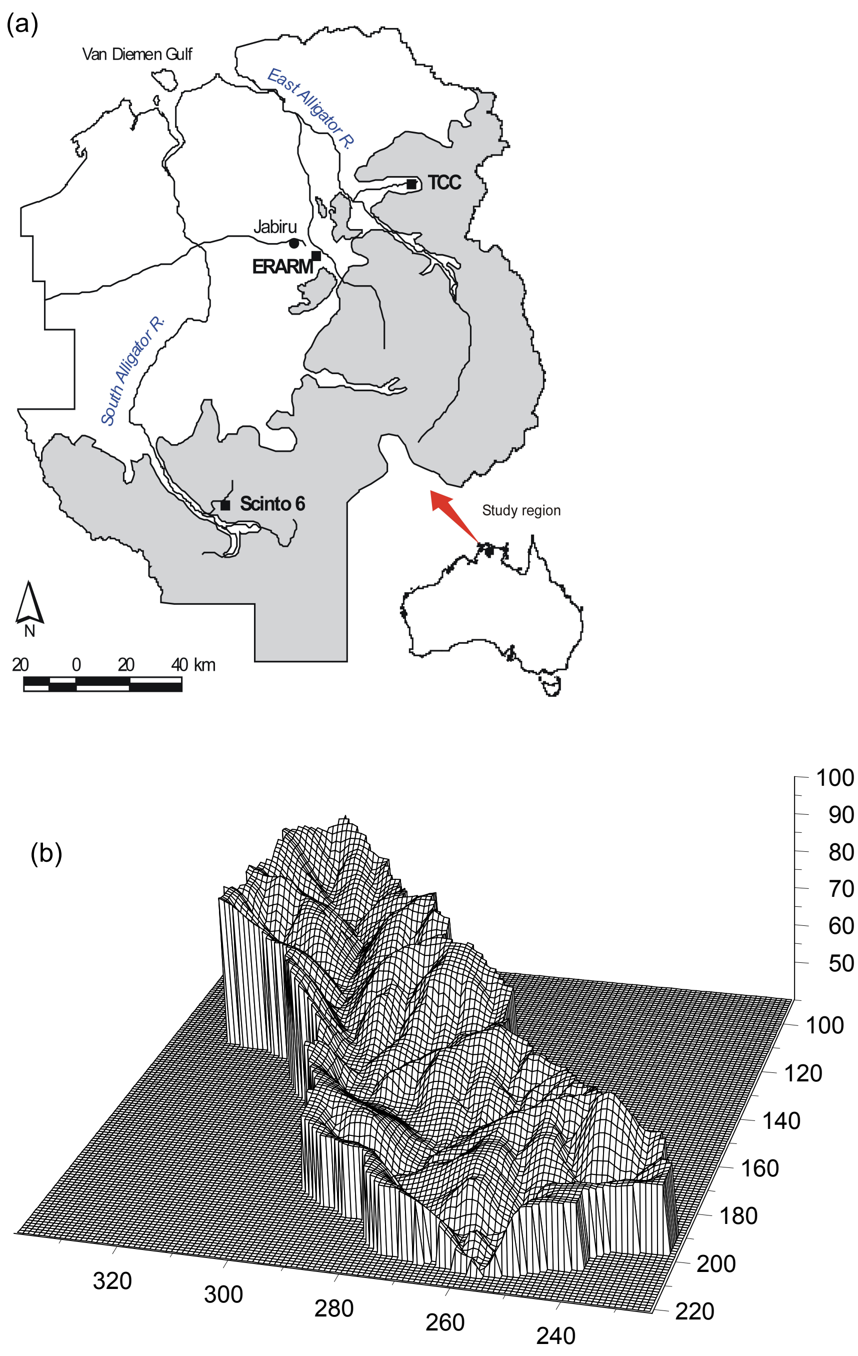

Fig. 1 Location of the (a) Tin Camp Creek (TCC) study site and (b) the Tin Camp Creek catchment.

There has been no intense grazing or other agricultural practices ongoing within the area, as a result of European settlement. The catchment has a very similar geology to that of the Energy Resources Australia Ranger Uranium Mine (ERARM), and is thought to be an analogue for the long-term rehabilitated post-mining landscape; therefore, it has undergone extensive examination in recent years (Moliere *et al.*, 2002; Hancock *et al.*, 2002; Hancock, 2003, 2004; Willgoose *et al.*, 2003). Other mine rehabilitation studies in the region have examined gully development on the waste rock dumps of the Scinto 6 former uranium mine (Hancock *et al.*, 2000) (Fig. 1).

The site is located in the seasonally wet/dry tropical environment of northern Australia, with an average annual rainfall of 1389 mm, mostly falling in the wet season from October to April. Short, high-intensity storms are common with fluvial erosion the primary soil-loss process. In this study a smaller geologically uniform 50 ha catchment was selected (Fig. 1). The soils are red loamy earths and shallow gravelly loam, with some micaceous silty yellow earths and minor solodic soils, on alluvial flats (Story *et al.*, 1976).

The native vegetation is open dry-sclerophyll forests and, although composed of a mixture of species, are dominated by *Eucalyptus* and *Acacia* species (Story *et al.*, 1976). *Melaleuca* spp. and *Pandanus spiralus* are also found in the low-lying riparian areas with an understorey dominated by *Heteropogon contortus* and *Sorghum* sp. There is vigorous growth of annual grasses during the early stages of the wet season. These grasses often fall over during the wet season, providing a thick mulch that causes high reductions in the erosion rates of bare soil.

THE SIBERIA LANDSCAPE EVOLUTION MODEL

SIBERIA is a physically-based mathematical model that simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion and mass transport processes. The sediment transport equation of SIBERIA is:

$$q_s = q_{sf} + q_{sd} \tag{1}$$

where q_s (m^3 s^{-1} m^{-1} width) is the sediment transport rate per unit width, q_{sf} is the fluvial sediment transport term, and q_{sd} is the diffusive transport term (both m^3 s^{-1} m^{-1} width).

The fluvial sediment transport term (q_{sf}), based on the Einstein–Brown equation, models incision of the land surface and can be expressed as:

$$q_{sf} = \beta_1 q^{m_1} S^{n_1} \tag{2}$$

where q is the discharge per unit width (m^3 s^{-1} m^{-1} width), S (m m^{-1}) the slope in the steepest downslope direction, and β_1, m_1 and n_1 are calibrated parameters.

The diffusive term, q_{sd}, is:

$$q_{sd} = DS \tag{3}$$

where D (m^3 s^{-1} m^{-1} width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface, and combines the effects of creep, rainsplash and landslides.

The SIBERIA model has recently been tested and evaluated for erosion assessment (both rate and method of erosion) of post-mining landforms (Boggs *et al.,* 2001; Hancock *et al.,* 2000, 2002; Hancock & Willgoose, 2003). A more detailed description of SIBERIA can be found in Willgoose *et al.* (1991).

Calibration of SIBERIA input parameters

Before SIBERIA can be used to simulate soil erosion and resultant landscape development, the sediment transport equation (1) requires independent calibration.

The fluvial sediment transport equation (2) in SIBERIA is parameterized using input from field sediment transport and hydrology data. This parameterization process is described in detail by Evans *et al.* (1998) and Hancock *et al.* (2000). For this study, the SIBERIA model was calibrated from field data collected at Tin Camp Creek from a series of natural rainfall events. The calibration of SIBERIA for Tin Camp Creek is described in detail elsewhere (Moliere *et al.*, 2002).

Two sub-catchments within the Tin Camp Creek Basin, 2032 and 2947 m^2, with average slopes of 19 and 22%, respectively, were instrumented during the wet season of 1990. Both sites are incised and channelized, and are representative of the overall 50 ha catchment. The study sites were monitored during rainfall events from December to January 1992. At this time, the catchments had a good covering of speargrass that quickly regenerated each wet season. To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall, and runoff for nine discrete events were collected, allowing calibration for the two individual catchments.

The rainfall–runoff monitoring data were used to calibrate the DISTFW (Field & Williams, 1983) rainfall–runoff model. The calibrated DISTFW model was used to derive long-term average hydrological parameters for SIBERIA. The parameters of SIBERIA represent average temporal properties of the runoff and erosion processes occurring on the landscapes (Table 1) (Moliere *et al.*, 2002).

METHODS

A DEM for Tin Camp Creek was created from digital photogrammetry of the area. Further DEMs of the catchment were created by incorporating error into each coordinate. This process is discussed below.

Table 1 Input parameters for SIBERIA determined from field data at Tin Camp Creek (Moliere *et al.*, 2002).

	Catchment 1	Catchment 2
m_1	1.70	1.69
n_1	0.69	0.69
β_3	0.000186	0.000144
m_3	0.79	0.83
β_1	1067	384

Tin Camp Creek digital elevation model

A high quality DEM of the Tin Camp Creek catchment exists, and has been used extensively in past studies (Hancock *et al.*, 2002; Hancock 2003, 2004; Willgoose *et al.*, 2003). The DEM was created by AIRESEARCH Pty Ltd, Darwin, and was supplied as 240 000 irregularly spaced data points within an irregularly shaped boundary. To place this data onto a regular grid, Delaunay triangulation (Sloan, 1987) was used to interpolate the landscape elevation data onto a 10 m × 10 m grid, producing a data set of approximately 82 000 points. All pits were removed from the DEM using the Tarboton *et al.* (1989) method. Hancock (2004) has demonstrated that a 10 m × 10 m DEM grid size is suitable (sufficient) to capture the catchment hillslope properties at Tin Camp Creek.

Creation of multiple digital elevation models

As with all coordinate systems, there is an error associated with each coordinate component. In this case the error associated with each point is uniformly distributed, with a maximum value of ±0.5 m in the x and y directions (axes), and ±0.5 m in elevation (personal communication, AIRESEARCH Pty Ltd). Using this information, a generator (Vetterling *et al.*, 1985) was used to create random numbers matching that of the error (±0.5 m), and was then added to each x, y and z component. As done for the original DEM, the data were plotted by Delaunay triangulation onto a 10 m × 10 m grid, and all pits removed using the Tarboton *et al.* (1989) method. Using this process, 10 individual DEMs, or catchment realisations were created, each representing a valid representation of the catchment. This provides eleven individual DEMs, if the original is included.

RESULTS

The catchment realizations for Tin Camp Creek were examined for their geomorphological properties. The DEMs were then input into SIBERIA and catchment geomorphology, together with soil erosion, examined after a 1000-year simulation period.

Initial catchment realizations

There are some small differences between catchment realizations with catchment area ranging from 5057 to 5115 pixels (Table 2). Comparison of the area–slope relationship (α value, or exponent on area in the area–slope relationship, Table 2) (Flint, 1974), cumulative area distribution (Perera & Willgoose, 1998), and hypsometric curve (Strahler, 1964) demonstrate that there is little variation between (among) different catchment realizations. There are some subtle differences in Strahler networking statistics (Strahler, 1964) (Table 2), and the width function (Naden, 1992). This is likely the result of flow path differences caused by variations in the surface roughness, and catchment size and shape, for each realization. Nevertheless, network convergence

Table 2 Geomorphic statistics for the 11 digital elevation model realisations for the Tin Camp Creek catchment, and the catchments after 1000-years of simulated erosion using Catchment 1 erosion parameters.

	Initial catchment		Initial catchment	
	Mean	SD	Mean	SD
Hypso. integral	0.475	0.0053	0.47	0.006
α	0.395	0.016	0.43	0.005
Bifurcation ratio	5.24	0.18	6.54	0.23
Slope ratio	1.31	0.022	1.23	0.002
Length ratio	1.23	0.03	1.43	0.048
Area ratio	4.95	0.38	5.85	0.46
Net. convergence	1.482	0.005	1.58	0.007
Area	5086	15.2	5086	15.2

SD: standard deviation.

(which is the average number of channels draining to a point) is nearly identical, indicating little difference in the networking properties of the catchments. The stability of the hypsometric integral (and area–slope data) demonstrates that the area–elevation properties of the catchments are similar. This data suggest that the eleven catchment realizations have strong geomorphological and hydrological similarity, yet have subtly different networking properties as a result of the small differences in catchment size and shape in conjunction with different estimates of surface roughness.

SIBERIA simulations

The SIBERIA erosion model was run for 1000 simulation years using the calibrated erosion parameters for the catchment (Table 1) as this is the expected minimum design life of the rehabilitated ERARM. Graphical comparison of the area–slope relationship, hypsometric curve, and cumulative area distribution after 1000 years of simulated erosion, using the 11 different catchment realisations demonstrates little geomorphologic difference.

Statistics derived from the eleven SIBERIA simulations demonstrate that there is no significant difference between the hypsometric curve, α (exponent on area of the area–slope relationship), nor Strahler area ratio, when compared to the initial catchment data (Table 2). This indicates no difference in the area–elevation or area–aggregation properties of the catchments after 1000 years of erosion. However, statistically significant differences do occur when comparing the Strahler bifurcation, slope and length ratios, and network convergence which, in conjunction with the width function, displays a less branched drainage network.

Erosion in the catchment was assessed from the 11 DEMs after using SIBERIA (Table 3). After 1000 simulated years, the mean maximum depth of erosion in the catchment is 3.74 m (range of 3.184–4.53 for mean ±2 SD) and 3.01 m (range of 2.24–3.65 m for mean ±2 SD) for the two different erosion parameter data sets. In both cases, erosion was concentrated in the major drainage lines. Average soil loss over the entire catchment was 3.57 t^{-1} ha^{-1} $year^{-1}$ (range of 3.54–3.87 t^{-1} ha^{-1} $year^{-1}$ for mean ±2 SD) and 1.65 t^{-1} ha^{-1} $year^{-1}$ (range of 1.47–1.83 t^{-1} ha^{-1} $year^{-1}$ for mean ±2 SD) for the two different erosion parameter data sets. The results demonstrate that Catchment 1 has a higher rate of erosion and sediment transport than Catchment 2.

DISCUSSION

Catchment soil erosion and geomorphology

Results from SIBERIA provide an erosion risk assessment over the catchment at two different spatial scales. The results are presented as both spatially averaged data over the catchment, and also as point-based values of maximum depth of incision (Table 3). Both data sets are statistically significantly different from each other for the 1000-year simulation. As both data sets have been determined for subcatchments within a single basin, both provide a range of expected erosion values.

Despite an average maximum and mean erosion depth in the catchment of 3.74 and 0.238 m, respectively, there is little change in geomorphological descriptors such as the hypsometric curve, cumulative area distribution, and area–slope relationship, indicating that the catchment is not likely to undergo any major change in area–elevation properties over the 1000-year simulation period. This suggests that any significant geomorphological change that might occur would require time periods in excess of 1000 years, assuming no significant climate changes. An increase or decrease in rainfall amount and/or intensity could change the erosion process and/or rate. This is an area where future climate modelling might be coupled to a probabilistic approach designed to further assess environmental risk.

The rates of erosion, predicted by SIBERIA in this study, have been validated by using the ^{137}Cs method for assessing soil erosion. Caesium-137 provides an integrative measure of catchment erosion and deposition for an approximately 50-year period, as a result of above-ground nuclear weapons tests (Hancock *et al.*, 2004). This study showed that soil loss in the catchment ranged from 2.9 to 14.1 t^{-1} ha^{-1} $year^{-1}$. Consequently, the soil erosion values obtained for the SIBERIA simulations compare very favourably to this independently determined soil loss data.

In this catchment, only the error that accompanies the derivation of the DEM has been evaluated; however, in the assessment of reconstructed landscapes, such as those in post-mining areas, other error(s), such as that expected from the vertical settling of fresh material, and construction activities (i.e. the inability of heavy-equipment operators to construct a landscape to pre-defined levels or design contours), also can be incorporated.

Table 3 Statistics for maximum depth (m) of erosion and average catchment erosion (t ha^{-1} $year^{-1}$) for the 11 SIBERIA simulations of the Tin Camp Creek catchment using Catchment 1 erosion parameters.

	10 years	100 years	1000 years
Maximum depth of erosion (m)			
Mean	0.846	1.55	3.74
Standard deviation	0.132	0.31	0.398
Average catchment erosion (t ha^{-1} $year^{-1}$)			
Mean	9.50	5.52	3.57
Standard deviation	0.94	0.38	0.15

CONCLUSIONS

There is a need for a methodology to probabilistically assess environmental risk both in undisturbed and also in anthropogenically disturbed catchments. Methods are needed that can provide robust results using available and reliable models and input data. The incorporation of error into the DEM provides a method for the construction of multiple catchment realizations, each of which is unique, but equivalent to all the others. This provides an effective and statistically valid method of providing an error assessment of the variability of geomorphic simulations in catchments. These data can then be used reliably as input into models that utilize landscape information, providing considerably more data than a single model run.

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