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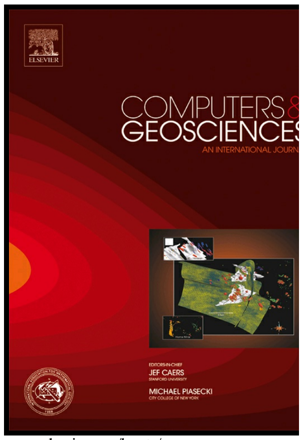

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Predicting uncertainty in sediment transport and landscape evolution – the influence of initial surface conditions

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Abstract

Numerical landscape evolution models were initially developed to examine natural catchment hydrology and geomorphology and have become a common tool to examine geomorphic behaviour over a range of time and space scales. These models all use a digital elevation model (DEM) as a representation of the landscape surface and a significant issue is the quality and resolution of this surface. Here we focus on how subtle perturbations or roughness on the DEM surface can produce alternative model results. This study is carried out by randomly varying the elevations of the DEM surface and examining the effect on sediment transport rates and geomorphology for a proposed rehabilitation design for a post-mining landscape using multiple landscape realisations with increasing magnitudes of random changes. We show that an increasing magnitude of random surface variability does not appear to have any significant effect on sediment transport over millennial time scales. However, the random surface variability greatly changes the temporal pattern or delivery of sediment output. A significant finding is that all simulations at the end of the 10000 year modelled period are geomorphologically similar and present a geomorphological equifinality. However, the individual patterns of erosion and deposition were different for repeat simulations with a different sequence of random perturbations. The alternative positions of random perturbations strongly influence local patterns of hillslope erosion and evolution together with the pattern and behaviour of deposition. The findings demonstrate the complex feedbacks that occur even within a simple modelled system.

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Keywords: sediment transport, equifinality, soil erosion modelling, SIBERIA, statistical uncertainty, mine rehabilitation

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1 Introduction

How landscapes evolve in response to the range of natural forcings is a basic scientific question that has long been examined by both qualitative and quantitative methods. Initially developed to examine natural catchment hydrology and geomorphology, numerical Landscape Evolution Models (LEMs) have become a common tool with which to examine geomorphic behaviour as well as geology, climate and the resultant soil and vegetation feedbacks. They can operate over time scales ranging from years to millennia and spatial scales from sub-hectare to entire regions (Dietrich et al., 2003; Tucker and Hancock, 2010).

A significant issue for both the short and long-term modelling of landscapes are model inputs, such as the initial landscape that is usually represented by a digital elevation model (DEM) (Perron and Fagherazzi, 2011). With the initial DEM there are two main causes for uncertainty. Firstly, a scenario uncertainty of what surface to represent: For example, if modelling a landscape several million years old how do you reconstruct this past surface? Secondly, a numerical uncertainty in how differences, errors or misrepresentations within the DEM surface can propagate during simulations to give alternative model results. For example, in landscape evolution there are a series of positive feedbacks that can lead to small surface perturbations generating significant changes as simulations progress (Ijjasz-Vasquez et al., 1992; Haff, 1996; Willgoose et al., 2003; Jerolmack and Paola, 2010).

The focus of this paper is on this second numerical uncertainty. A simple but often impracticable solution to this sensitivity is to use a very high spatial resolution for the DEM to capture surface heterogeneity. However, gaining accurate surface elevation data at a high spatial resolution can be difficult especially if we are dealing with highly variable surfaces. Additionally, modelling at a high resolution increases the number of data points or pixels in a modelled domain, increasing computational load and thus often leading to long run times (Tucker and Hancock, 2010). Therefore, LEMs use a compromise DEM resolution that is of

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sufficient detailed resolution to capture catchment and hillslope form, whilst retaining a low number of grid cells. For example, Hancock (2005) showed that a 10m DEM is a good compromise for most catchment scale assessment where the hillslope is the feature of interest. If other features such as creeks, contour banks, roads or constructed benches on mine sites are present then the DEM must be at sufficient resolution that these features are captured.

These issues have come to the fore with the increased use of LEMs to assess rehabilitation designs for post-mining landforms. These landforms can be simply defined as man-made hills usually burying mine sites, spoil tips and other industrial architecture blended into the surrounding landscape. They are often built from materials different to that of the surrounding landscape. In the example studied here, low grade uranium ore, tailings, brines and other mine wastes will be buried at depth in the areas of the former pits.

Ideally, a rehabilitated landform is intended to (i) minimise the area of disturbance; (ii) visually and geomorphologically blend in with the surrounding landscape; and (iii) be erosionally stable over the long-term. How these landscapes evolve is of the utmost importance for the surrounding environment as any erosion in excess of that of the surrounding environment may cause pollution and sedimentation of the surrounding waterways as well as the exposure and release of harmful contaminants. Mining companies design these landscapes with these concepts in mind but with surprisingly little assessment as to how changes in the landscape design or errors in construction influence landscape behaviour in either the short or long term. Similarly, relatively little consideration appears to be placed as to whether the erosion from the landscape is tolerable for the surrounding receiving environment.

These are important issues as post mining landscapes are required to be functional geomorphological and ecological entities that re-engage sites with the surrounding non-mined

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landscape. It is vital therefore that the short and long-term behaviour of these landscapes be assessed and qualitatively and quantitatively understood.

This study will examine the effect of initial surface roughness and resultant differing initial conditions on sediment transport rates and geomorphology on a proposed rehabilitated landform. This initial roughness is in keeping with the surface perturbations that could be expected when a new landform is constructed including features such as ‘rips’ (ploughed furrows added to reduce overland flow). We investigate how sensitive landscapes are to initial conditions by assessing the temporal patterns of sediment transport as well as geomorphic form at the end of a prescribed modelling period. These issues are significant from both a basic science perspective as well as for the long term management and stewardship of post-mining environments.

2 Site description

The Energy Resources of Australia (ERA) Ranger mine is surrounded by the World Heritage-listed Kakadu National Park in the Northern Territory of Australia. The mine is immediately adjacent to Magela Creek (Figure 1) and erosion products from the mine could potentially impact three tributaries of Magela Creek, - Corridor, Georgetown and Coonjimba Creeks, and the large catchment of Gulungul Creek to the west of the mine. Magela Creek connects to the East Alligator River through wetlands listed as “Wetlands of International Importance” under the Ramsar Convention (http://www.ramsar.org, 2003). The mine operates within some of the world’s most stringent environmental requirements (http://www.environment.gov.au/science/supervising-scientist).

Mine tailings are currently stored in the above grade tailings dam and in a mined-out pit (Pit 1) and are required to be contained for 10000 years. Mining at the site ceased in 2012, with milling and processing of ore due to cease in 2021. Consequently attention is

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increasingly focussing on the closure and the rehabilitation of the mine. The requirements for the closure and rehabilitation of the Ranger mine have been published as a series of Environmental Requirements. These state, with respect to erosion and landform stability, that the landform should possess *"erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas"* (Supervising Scientist Division, 1999). This will require the landscape to be rehabilitated in a way that restores environmental functions supporting local ecosystem diversity (Ludwig and Tongway 1995; 1996). The first stage in this process is to design and construct a landform which is erosionally stable.

2.1 Geology, climate and soils

The regional geology of the Kakadu region is dominated by the mineralised metasediments and igneous rocks of the Pine Creek geosyncline (one of the richest uranium provinces in the world) and the younger sandstones of the Mamadawerre Formation (East, 1996; Needham, 1988). Geomorphically, the Ranger lease is characterised as part of the deeply weathered Koolpinyah surface, which comprises plains, broad valleys and low gradient slopes, with isolated hills and ridges of resistant rock (East, 1996).

The Ranger lease lies in the wet-dry tropics of Northern Australia and receives high-intensity storms and tropical monsoons between October and April with little rain falling for the remainder of the year. The annual average rainfall is 1584 mm (Bureau of Meteorology, 2014). Vegetation on the lease consists of open Eucalypt forest dominated by *E. tetradonta, E. miniata, E. bleeseri* and *E. porrecta*. The understorey is characterised by *Acacia* spp., *Livistona humilis* and *Gardenia megasperma* with a variable grass cover of *Sorghum* spp., *Themada triandra* and *Eriachne triseta* (Chatres et al., 1991).

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2.2 Measured erosion rates

Understanding erosion rates of the natural surrounding area is needed to provide a baseline condition against which rates on the rehabilitated mine site can be compared and have been established using a variety of different methods. Regional denudation rates for the area (0.01 to 0.04 mm y^{-1}) were determined using stream sediment data from a range of catchments of different sizes in the general region (Cull et al., 1992; Erskine and Saynor, 2000). An assessment using the fallout environmental radioisotope caesium-137 (^{137}Cs) as an indicator of soil erosion status for two transects in the Tin Camp Creek catchment in the Alligator River Region produced net soil redistribution rates between 2 and 13 t $ha^{-1}y^{-1}$ (0.013 – 0.86 mm y^{-1}) (Hancock et al., 2008). Erosion rates at Tin Camp Creek are significant because the surface properties of that catchment are analogous to proposed rehabilitated landforms for the Ranger mine (Uren, 1992).

3 Landscape evolution models

Landscape evolution models were initially developed to examine landscape evolution and dynamics at geological time scales but they have been employed in more applied settings (i.e. mine sites) at much shorter time scales (years, decades, and centuries). Landform evolution modelling the stability of post-mining rehabilitated landform designs was first conducted by Willgoose and Riley (1993) using the SIBERIA landform evolution model (Willgoose et al., 1989). Since 1993, the model has been used principally to investigate surface stability of post-mining rehabilitated landforms or small catchment areas (i.e. Willgoose and Riley 1998; Evans et al., 1998; Hancock et al., 2000, 2002; Moliere et al., 2002). It has also been successfully employed at the nearby Nabarlek uranium mine following an assessment using the Revised Universal Soil Loss Equation (RUSLE) (Hancock et al., 2006; 2008). In more recent years the CAESAR and subsequent CAESAR-Lisflood model

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(Coulthard et al., 2013) have been used to assess rehabilitation designs on mine sites (Coulthard et al., 2012a, Lowry et al., 2009; 2011; Hancock et al., 2014).

3.1 The SIBERIA landscape evolution model

SIBERIA is a mathematical model that simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion and mass transport processes (Willgoose et al., 1991). The model links widely accepted hydrology and erosion models under the action of runoff and erosion over long time scales. The sediment transport equation of SIBERIA is

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

where q_s (m^3/s/m 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/m 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/m width), S (metre/metre) the slope in the steepest downslope direction and β_1, m_1 and n_1 are calibrated parameters.

The diffusive erosion or creep term, q_{sd}, is

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

where D (m^3/s/m width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface and combines the effects of creep and rain splash.

SIBERIA does not directly model runoff (Q, m^3 - for the area draining through a point) but uses a sub-grid effective parameterisation based on empirical observations and justified by theoretical analysis which conceptually relates discharge to area (A) draining

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through a point as

$$Q = \beta_3 A^{m_3} \qquad (4)$$

where β_3 is the runoff rate constant and m_3 is the exponent of area, both of which require calibration for the particular field site. SIBERIA uses the D8 routing algorithm.

For long-term elevation changes it is convenient to model the average effect of the above processes with time. Accordingly, individual events are not normally modelled but rather the average effect of many aggregated events over time. Consequently, SIBERIA describes how the catchment is expected to look, on average, at any given time. The sophistication of SIBERIA lies in its use of digital elevation models for the determination of drainage areas and geomorphology and also its ability to efficiently adjust the landform with time in response to the erosion that occurs on it.

The SIBERIA erosion model has been calibrated and applied for erosion assessment of proposed post-mining landforms (Evans and Willgoose 2000; Evans et al., 1999, 2000; Hancock et al., 2000, 2002; Lowry et al. 2006., Willgoose and Riley 1998).

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3.1.1 SIBERIA input parameters

Before SIBERIA can be used to simulate soil erosion, the sediment transport and area-discharge relationships require calibration. The model also requires a digital elevation model (DEM) of the landform of interest (described in Section 4). The fluvial sediment transport equation is parameterised using input from field sediment transport and hydrology data. For this study the SIBERIA model was calibrated using field data collected on the ERA Ranger mine (ERARM) site.

To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall and runoff for discrete rainfall events were collected allowing calibration from field plots (Table 1). The parameters were derived from plots on the batter slope of the waste rock

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dump (Evans et al., 2000; Moliere et al., 2002). This plot (38 m long by 16 m wide (608 m^2)) rose approximately 12 m above the surrounding land surface and had an average slope of 20.7%. The site was covered with an armour of coarse material and had negligible vegetation cover. Parameters for the vegetated surface condition were determined from a similar plot initially constructed of waste rock then covered in topsoil, ripped and vegetated with low shrubs and grasses which provided approximately 90% cover (Evans et al., 1998).

Using the above field data, parameter values were initially determined at unit scale value and would overestimate erosion if directly employed. These values were rescaled to be employed at the 10m DEM grid scale using the method described in Evans and Willgoose (2000) (Table 1), thus producing parameter sets for the different surfaces. The full derivation of these parameters are described elsewhere (Evans and Willgoose, 2000; Evans et al., 2000; Moliere et al., 2002).

4 Catchment digital elevation models

The DEM used here is a potential design for the rehabilitated landscape for the Corridor Creek catchment at the ERARM and does not necessarily reflect the design of the final landform (Figure 2). The landscape has been described elsewhere (Hancock et al., 2014) but in summary it is designed to rehabilitate an area that contained haul roads, waste rock dumps and drainage control structures as well as a mined out pit. This landscape is required to be reshaped so that it blends in with the surrounding landscape as well as ensuring that it is erosionally stable. The DEM of this potential rehabilitated landform supplied by ERA had a horizontal resolution of 10 metres. The DEM is also configured so that all runoff and sediment is designed to exit from the lowest edge of the catchment.

The supplied DEM assumes that the catchment can be constructed to the dimensions provided, yet there will be differences in the landform surface, due to construction errors.

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There have been few previous studies which have examined whether subtle perturbations (affecting the surface roughness) can influence the integrity of the structure. There is also the equally important issue as to how perturbations in the surface may influence erosion rates. Here, a maximum perturbation or random elevation increase of 0.25m is used as the traditional owners of the site, who have considerable influence on the final landform surface and function require a surface that can be easily traversed on foot. A roughness greater than 0.25m is unlikely to comply with this request.

0.25m also represents the roughness typical of that when a surface is ripped (here at this site by a bulldozer pulling a large tyne that is inserted into the ground) to induce surface roughness once the landscape is reshaped and ready for vegetation seeding (Figure 3). The height of the disturbance or surface roughness produced by the ripping process was measured from a ripped trial plot at the ERA Ranger site (Lowry et al. 2014; Coulthard et al. 2012a) (Figure 3). At this site the ripping process produced an average elevation change or roughness of 0.063m (σ = 0.06m), median of 0.05m and range of 0 to 0.19m.

Three sets of DEMs based on the original supplied DEM are created with increasing amounts of roughness added to each grid cell (Figure 2, bottom). Individual sets of 100 replicates of catchments each with a random error of up to +/- 0.05m (100 replicates), +/- 0.1m (100 replicates) and +/- 0.25m (100 replicates) were created (300 simulations in total). These DEMs were individually used as landscape input for the SIBERIA model.

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5 Simulation setup

The simulations were run for 10000 years as this is the period for which the structure is designed (Commonwealth of Australia, 1997). Two scenarios were simulated, representing a surface covered with waste rock (WRD parameters); and a vegetated (vegetation parameters) surface that was initially waste rock. Additionally, a limited number (5 randomly

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selected catchments with +/- 0.1m surface perturbations) of simulations were run for 100000 years to assess longer time scale behaviour.

The WRD parameters were run continuously for the entire period. However, for the vegetation parameters, the WRD parameter simulation results at 10 years were used as the starting condition. This is in keeping with past studies (Hancock et al., 2014) which have assumed that vegetation would be fully established at approximately 10 years.

The modelling domain was the DEM displayed in Figure 2 (bottom) which had dimensions of 235 by 244 pixels. All discharge was directed through a series of 24 outlet nodes located along the lowest edge of the DEM.

6 Results

6.1 Qualitative assessment

Visually, there has been considerable erosion and deposition over the 10000 year modelled period (Figure 4). All levels of surface roughness produce similar erosion and deposition patterns, however, subtle differences exist such as location of the channels and pattern of deposition. Channels have evolved on the hillslopes and extend up to the catchment divide. As found in previous work (Hancock et al., 2014), the channels are largely focused in similar locations as a result of small undulations or swales in the original DEM placed by the landform designers to direct runoff.

Eroded material has been deposited in the main channel with all levels of roughness (of +/- 0.05m, +/-0.1m and +/-0.25m), but producing subtly different and unique erosion patterns. Reworking of this deposition can be observed with new channels developing in this material. This same level of surface roughness also produces subtle variation in the pattern of erosion and deposition for both the WRD and Vegetation parameter sets (Figures 5 and 6) but with much less erosion when the Vegetation parameters are employed.

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Visually, the catchments are very similar. The initial imposed catchment shape exerts a first order control with all catchments being qualitatively similar. However, the subtle changes in surface topography as a result of the random perturbations affect drainage pattern position.

6.2 Quantitative assessment

Despite considerable channel and hillslope evolution, geomorphically, there are insignificant morphological differences when measures such as the area-slope relationship (Hack, 1957; Flint, 1974), hypsometric curve (Strahler, 1952; 1964) and cumulative area distribution (Rodriguez-Iturbe et al., 1992) are used. These measurements taken at 10000 years are little different from the original surface. Observable differences only occur at time scales approaching 50 000 years with little variability observed until this landscape age (Figure 7). This demonstrates the insensitivity of these measures to our shorter time scale simulations.This occurred for all levels of surface roughness.

Average erosion and deposition show that the channels have eroded the surface to depths of approximately 6-8m (Figure 8). In other areas, over 4 m of deposition has occurred (Table 2). Of importance here is the maximum depth of erosion (approximately 8m), which occurs over the former pit which contains tailings (Figure 8). This demonstrates that an inert cover over this area needs to be considerably greater than 8m to ensure long-term encapsulation. We do not have erosion parameters for tailings and have not modelled such a possibility here. However if exposed, it is reasonable to assume that given their fine and non-cohesive nature they would be highly mobile and rapidly move off-site.

For both the WRD and Vegetation parameters there is considerable variation in sediment output with results displayed as mean +/- one standard deviation (Figure 9). The results demonstrate that there are years when there is no sediment output together with years

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where there is considerable output. This variability is the result of differing patterns of erosion and deposition for each landscape realisation produced by the subtle changes in slope and drainage pattern from the random perturbations. The SIBERIA model determines erosion and deposition on a pixel by pixel basis and the variability in catchment sediment output reflects the net landscape change at each annual time step.

For the WRD parameters over the 10000 year simulation there is a steady decline in sediment output however there is considerable variation over the time period as found by others (Charru et al., 2014; Jerolmack and Paola, 2010; Zimmerman et al., 2010). For the majority of the 10000 year period sediment output is above that expected from the catchment as determined from background or natural erosion rates (30-120 m^3 y^{-1} is expected to exit the catchment annually based on the denudation rates described in Section 2.2). Of particular note is that for the first approximately 200 years sediment output is well above that expected if the catchment was undisturbed. After approximately 2000 years, mean sediment output settles to a range just above that of the maximum sediment output determined from the denudation rate.

The Vegetation parameter simulations produce much lower sediment outputs. However as for the WRD parameter simulations there is considerable variability. Interestingly the sediment output from the Vegetation simulations is largely within that of the background or natural erosion rates. Initially for the first approximately 100 years sediment output starts low and steadily increases. This is a result of the dynamic behaviour of the channel network reorganising in response to the change in erosion parameters from the initial 10 years of WRD parameters. At approximately 4000 years mean sediment output approximates the upper band of natural sediment output.

While temporally different, the simulations with +/- 0.05m, +/- 0.01m and +/-0.25m random roughness produced variability in sediment output similar to each other (Figure 10, top and middle). Cumulative sediment output was near identical for all three levels of

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roughness (Figure 10, bottom). This suggests that while initial surface roughness produces considerable variability in annual sediment output, over the 10000 year modelled period initial surface roughness has little influence on cumulative sediment load.

7 Discussion

This paper has focussed on the variability in landscape trajectory based on subtle surface differences. The findings highlight the diversity of the final landforms as well as the variability in sediment output at any point in time. Below we (1) discuss potential landscape outcomes, (2) the influence of parameter variability and sediment output and (3) propose a new way forward to assess the evolution of landscapes and engineered structures.

7.1 Potential landscape outcomes

A significant finding here is that erosion and deposition patterns are unique for each simulation. However all landscapes at the end of the 10000 years are qualitatively and quantitatively very similar in terms of surface morphology. Others have shown that when examining simple initial surfaces such as a sloping linear surface, resultant landscapes can produce considerable geomorphic divergence (Ijjasz-Vasquez et al. 1992). Here, given the imposed catchment shape and network, any divergence over the 10000 year period is minimised (Willgoose et al., 1991; Howard, 1994; Howard et al., 1994; Tucker, 1996).

While surface roughness changes the temporal pattern of sediment output, the overall cumulative sediment output is independent of initial roughness. We have not examined surface roughness above that employed here as it is considered that the error is within the range expected of modern construction equipment as well as the requirements of traditional owners. Introducing random roughness at levels greater than employed here (i.e. +/- 0.5m) is possible but not a realistic landscape management scenario.

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The similarity in final landscape form at 10000 years is an interesting outcome and not detectable between simulations using conventional geomorphic metrics. While it is evident that considerable erosion and deposition has occurred, the area-slope relationship, hypsometric curve and cumulative area distribution are not sufficiently sensitive to detect this change or between simulations with different surface roughness. Therefore at 10000 years the landscapes are geomorphologically similar to the initial landscape and can be said to be persistent at multi-millennia time scales. This suggests that any constructed landscape will be present at millennial time scales with little geomorphological change in this environment. Therefore correct landscape design using the best geomorphological understandings is imperative for sustainable landforms and resultant ecosystems.

To further evaluate long-term landscape trajectory the simulations were run out to 100000 years (Figure 11) (only two simulations with different initial surface roughness are displayed for brevity). Again, while there are differences in the position of hillslope and channel, the landscapes are very similar. Interestingly, while there has been considerable deposition in the main channel, Figure 11 (top) displays a new channel that has developed in the depositional material while Figure 11 (bottom) displays much less erosion in this area. This demonstrates that subtle random perturbations across a landscape can affect not just hillslope evolution but also affect the pattern and behaviour of depositional systems both at the short and longer time scales. The ability of landscape evolution models to predict deposition and the erosion and reworking of the sediment has not been demonstrated in the past and is an area of future investigation. However, this demonstrates the complex feedbacks that occur in this simple modelled system.

It should be recognised that we have only examined surface random perturbations. Given our findings, it is highly likely that other errors in a DEM such as steps in contours, incorrect drainage alignment and enforcement as well as excess or incorrect smoothing will

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all affect erosion patterns and ultimate landform evolution. It is therefore important to consider that for landform modelling, how a DEM is generated *can* make a difference to the final landscape shape and this difference will be greater over time.

In summary, these findings demonstrate that the initial surface has a strong and long-lasting control over landscape trajectory as a result of the initial imposition of a drainage network (Willgoose et al., 1991; Howard, 1994; Howard et al., 1994; Tucker, 1996). From a landscape rehabilitation perspective this is a good outcome as it

1. Allows landscape trajectory to be predicted with some certainty and
2. Subtle perturbations on an initial surface do not overrule catchment geomorphology.

7.2 Parameter variability and sediment transport

In Figure 9 the sediment discharge is displayed as the mean +/- one standard deviation and therefore the actual range of sediment output is much greater than that displayed here. An interesting result here is that even with all parameters constant (a constant hydrological forcing) with the only difference being the initial surface roughness, the SIBERIA model is generating a dynamic and highly variable sediment output. At any point in time sediment output at annual time scales can be predicted at best within an order of magnitude and only converge within a broad range (Nikora et al., 2002; Jerolmack and Paola, 2010; Zimmerman et al., 2010).

However, it should be recognised that there is the distinct likelihood of even greater variability (Haff, 1996). The WRD parameters have been derived from materials at the site that represent the first few years of hillslope evolution. How these parameters change past this initial period is open to debate. Similar to the WRD parameters, the vegetation parameters are derived from a waste rock material surface on which vegetation communities have established and been maintained for a relatively short time. The transition from bare waste rock to

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vegetation and how this vegetation cover evolves is also largely unknown for this surface (and in fact for all other post-mining surfaces) in response to weathering and pedogenesis. Further, the area is subject to fire with a return interval of every 2nd to 3rd year which complicates any long-term modelling assessment. Therefore the use of WRD and Vegetation parameters can be viewed as two possible end members of landform behaviour and outcome.

There is also the suggestion that waste materials at the site may evolve to that of soils at Tin Camp Creek (Uren, 1992). These soils have been shown to have high erosion rates and subject to gullying (Hancock et al., 2013). The process and rate of this evolution and likelihood of gullies is speculative at this stage. However, these are all possible pedogenic and landscape trajectories.

A further consideration is that of climate variability and how this

(1) Affects weathering, pedogenesis and overall landscape evolution and
(2) The impact of any extreme events

For northern Australia, climate models predict an increase in both intensity and frequency of extreme rainfall events (CSIRO, 2007). The model results here suggest that any contaminated material buried at depths greater than 8m will not be exposed under the imposed boundary conditions employed here. However, it is uncertain whether this will be the case if the catchment is subject to more intense and more frequent rainfall events. The development of a climate risk approach is needed.

Here we have used two parameter sets and recognised their limitations. When using such parameter sets it is assumed that the data set used to derive the parameters is representative and averages out the inherent natural variability. However a further question is, how reliable are the denudation rates derived for this area given recognised variability in sediment output (e.g. as per Van de Wiel and Coulthard, 2010; Jerolmack and Paola, 2010)? We have employed well recognised values (0.01 – 0.04 mm y^{-1}) as a guide to determine

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whether the landscapes are delivering excess sediment to the natural environment. The results here show that there are many years when sediment output is in excess of that of expected from a natural system, particularly in the first 10 to 20 years. Long-term reliable field data is needed to better validate model findings such as that discussed above.

7.3 A new way forward – LEM predictive uncertainty and sensitivity assessment

The modelling here demonstrates a quite interesting result. We find that despite imposed initial differences between simulations there is a statistical equifinality in both landscape form and sediment transport. This leads to a paradox as when there is a convergence or equifinality you expect that all landscapes behave similarly through time. However the journey to that final point may be very different. For example, at any point in time a landscape may be exporting little or no sediment while another may be exporting sediment at an order of magnitude greater than background levels. Similarly, at any point in the landscape there may be very different erosion and depositions patterns.

While we have shown that well defined catchment and hillslope shape largely controls broad scale landscape trajectory, specific differences in position of hillslope, channel and deposition do occur. Given the demonstrated variability, a way forward is to use composite landscapes where landscapes are the average of a number of simulations (i.e. the 100 simulations used here) (Figure 12). Landscapes will always be a product of multiple and often competing influences in terms of climate, vegetation, weathering pedogenesis and the synergies between all these. Such a *probabilistic* approach has been previously used in landscape modelling to look at the impacts of climate change on catchment sediment yield over shorter (30 year) time scales (Coulthard et al., 2012b). While this approach will mask individual features, gross landscape scale trends can be observed.

From an engineering point of view, plots of maximum depth of erosion (Figure 12) as

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well as erosion and deposition patterns can be developed (Figure 8). This is of particular relevance for encapsulated materials within the engineered landscape.

8 Conclusion and future issues

Humans have the power to dramatically alter the earth's surface both by the removal of material and also by its re-emplacement. It is both in the economic and environmental interests of the community to ensure that any re-emplacement, reconstruction and re-enabling of the disturbed system be performed using the best knowledge possible. Any reconstructed landscape will have millennial scale influences on its surrounds and behave in ways that may not be predictable given uncertainties regarding climate, soil and vegetation interactions.

The results of the modelled scenarios suggest that while the landscapes at 10000 years are similar, the initial roughness makes it impossible to predict exact topography or sediment discharge. However, there is an element of equifinality in the simulations largely because of the initial boundary conditions and imposed drainage network and fixed outlet location exert a strong control on landscape form and behaviour.

The results demonstrate that the landform will maintain its geomorphic properties for millennia. However, the conceptual landform design and resultant DEM is one of a range of possibilities for the ERA Ranger site. Other different landscape designs are possible as there is conjecture at present over the final life of the mine and different competing rehabilitation options. Therefore this study provides an assessment method for future landscape possibilities.

The focus here is on a 10000 year period that is a rehabilitation requirement for the mine site. The next step in this process is to fully evaluate landform trajectory using a Monte-Carlo type analysis where model parameter inputs are sampled from a possible range of values. However, while possible at present, this parameter range is derived from values

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defined largely from the here and now – not how the surface and consequent parameters transition from fresh unweathered material through to a fully integrated surface that is geomorphologically and ecologically linked to its undisturbed surrounds. How, and the rate at which this transition occurs is largely speculative. This evolutionary process requires qualitative and quantitative assessment so that reliable LEM input parameters can be developed.

This work presents a robust method for generating a range of possible landscapes for input to a LEM using field data (using calibrated parameters from short term field plots) as a guide over a 10000 year modelled period. The results show that a range of outcomes can be expected even with a small amount of error incorporated into the original DEM. From an engineering perspective this provides a method for evaluating risk and the type and depth of cover needed to cover high risk materials such as tailings.

In this study we have used the SIBERIA LEM as it has been extensively tested and used at this site and surrounding area. However, it is recognised that the results described here are from a single model with its unique numeric and computational procedures. Other LEMs may provide alternative and geomorphologically plausible alternative landforms.

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Acknowledgments

The traditional owners of the land where the study site is located, Parks Australia North, The Northern Land Council and Supervising Scientist Division staff, especially Wayne Erskine and Michael Saynor are thanked for their assistance. ERA staff provided the DEM used in this study and are thanked for their assistance. This paper was written while on SSP leave at Duke University. Conversations with Brian McGlynn, Christa Kelleher and team are acknowledged.

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Figure 12. Composite landform from an average of 100 simulations (top) and composite landform of maximum depths at 10000 years using Waste Rock Dump parameters (bottom).

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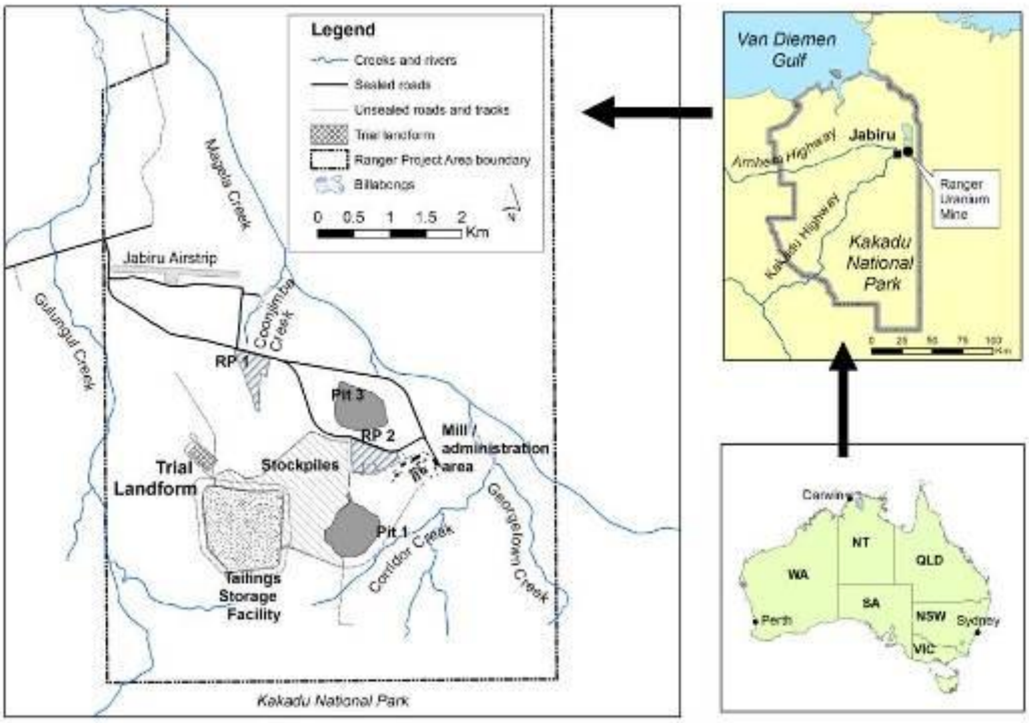

Figure 1. Location of the ERA Range mine.

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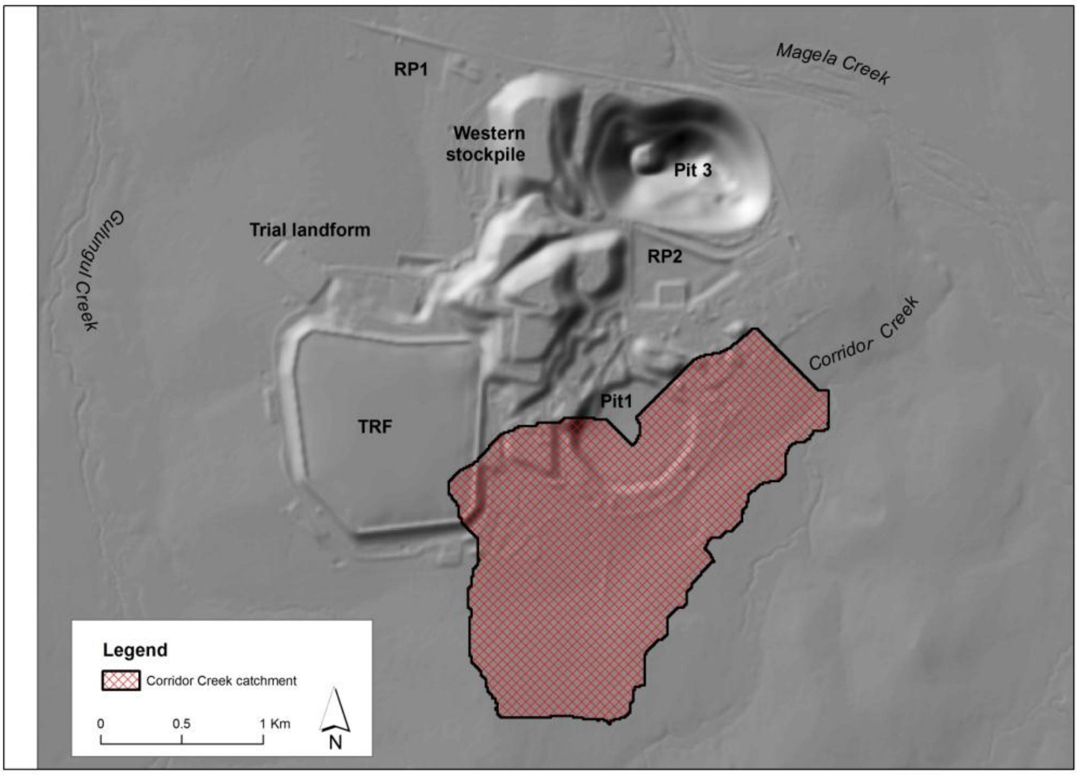

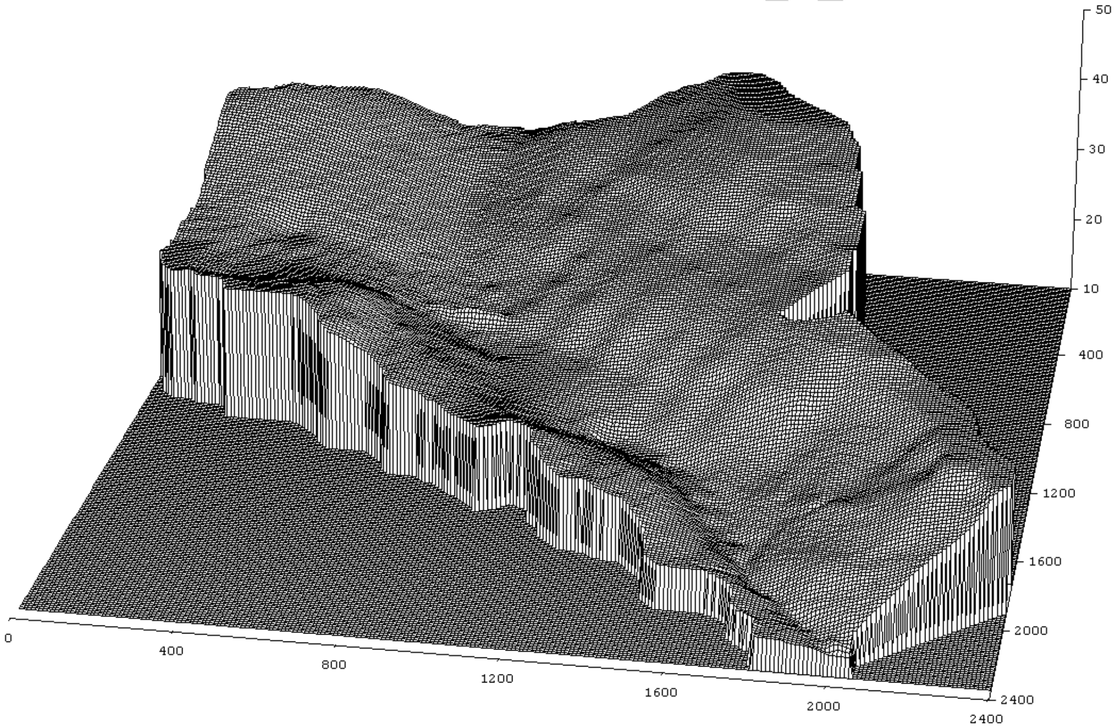

Figure 2. Planned rehabilitation (top) and proposed rehabilitation design (bottom). All dimensions are metres.

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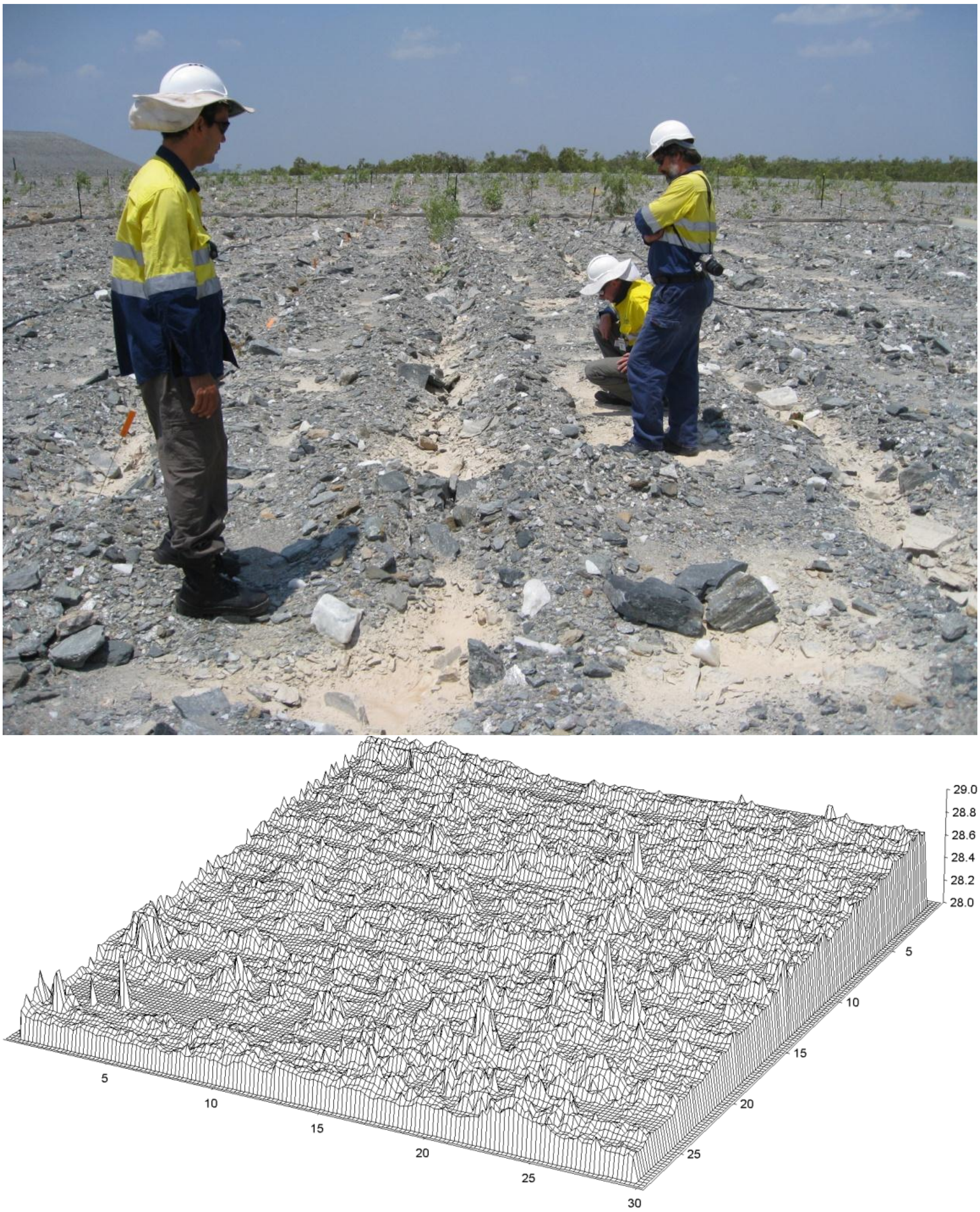

Figure 3. Surface roughness at the ERA Ranger trial landform (top) and DEM of the surface (0.2m by 0.2m grid) (bottom). All dimensions are metres.

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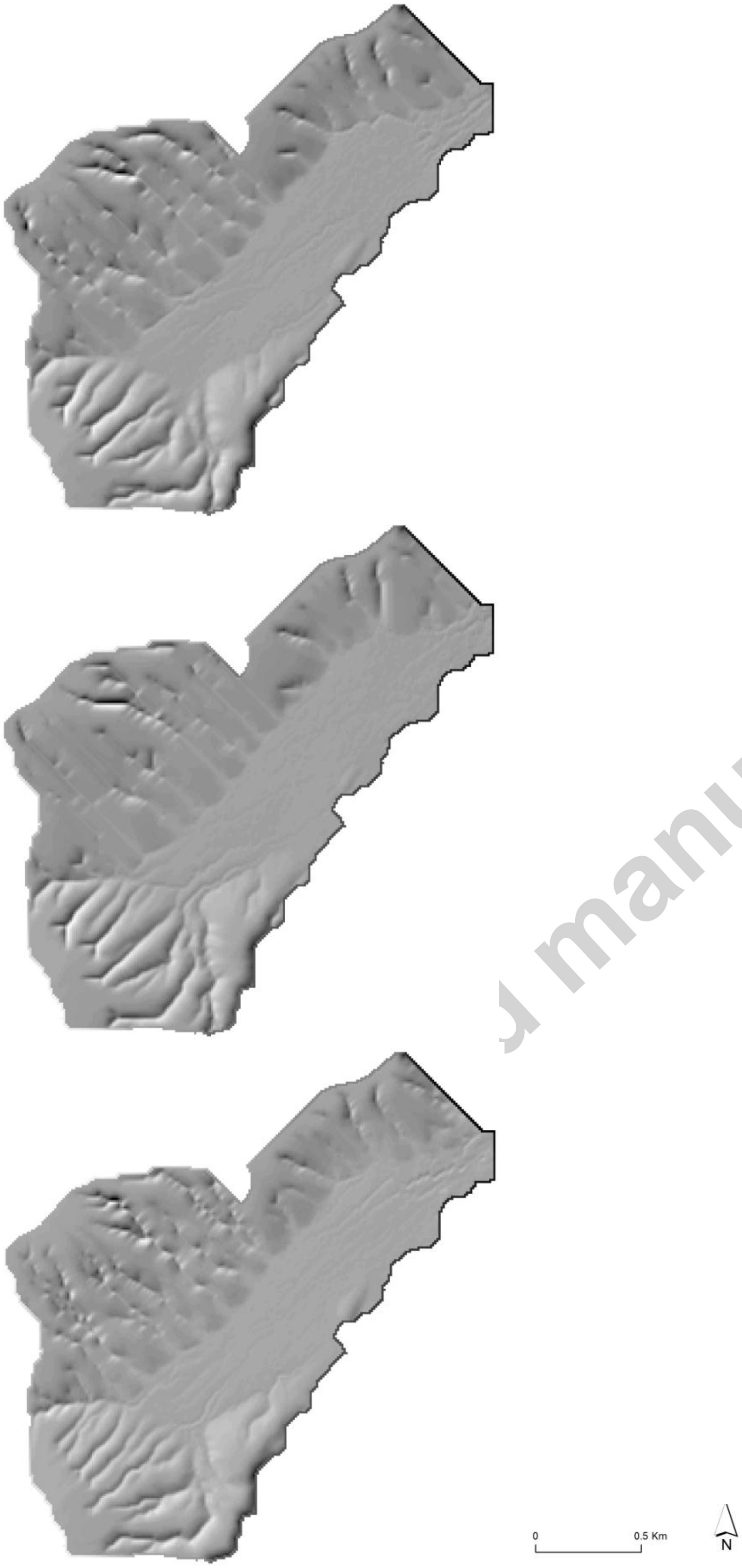

Figure 4. Corridor Creek landform after 10000 years (using Waste Rock Dump parameters) with +/-0.05m (top), +/-0.1m (middle) and +/-0.25m (bottom) initial surface roughness. While generally similar they all have different erosion patterns with gullies in particular having different location and morphology.

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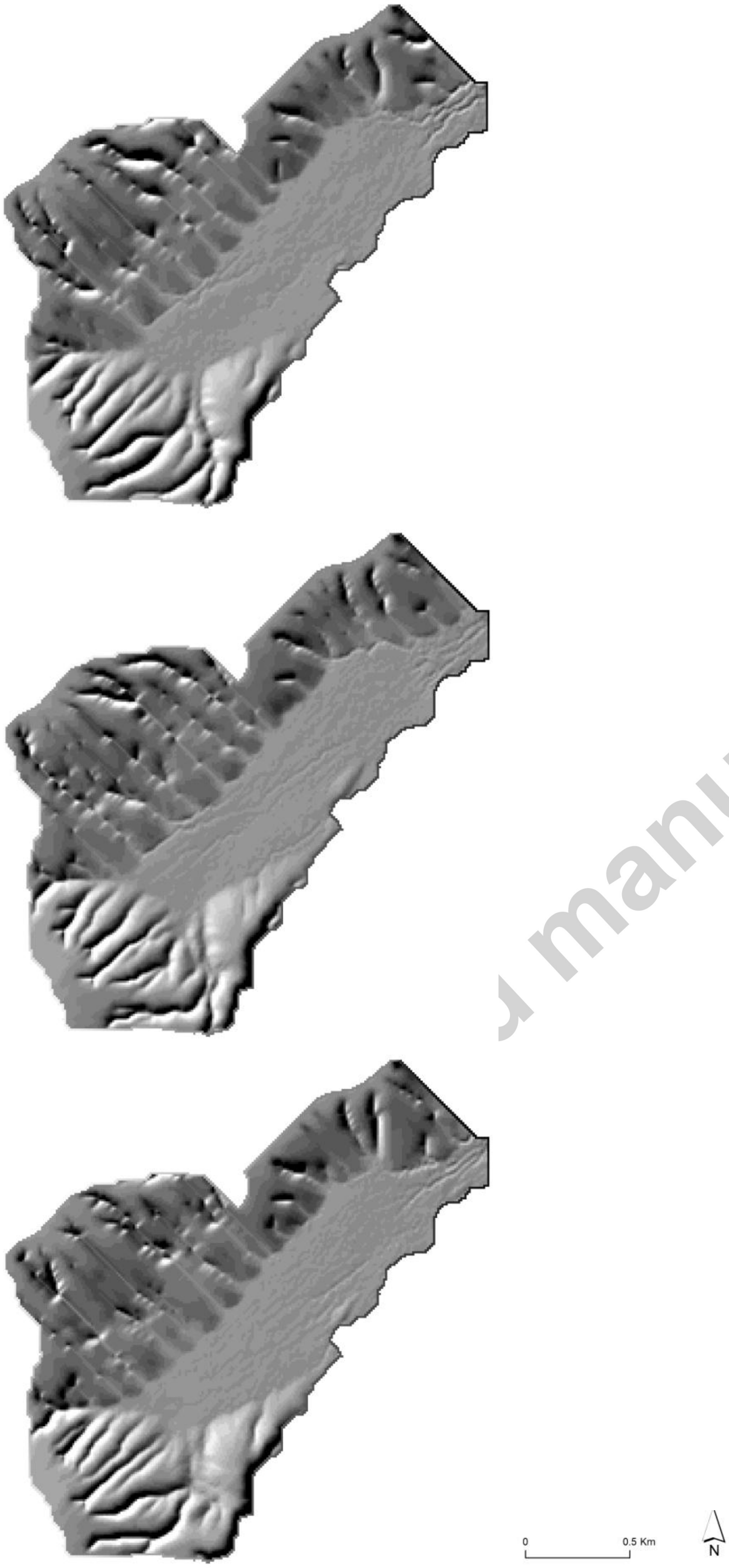

Figure 5. Three examples of the Corridor Creek landform (at 10000 years using Waste Rock Dump parameters) with three different random elevation patterns (+/-0.1 m) added to the initial surface. While generally similar they all have different erosion patterns with gullies in particular having different location and morphology.

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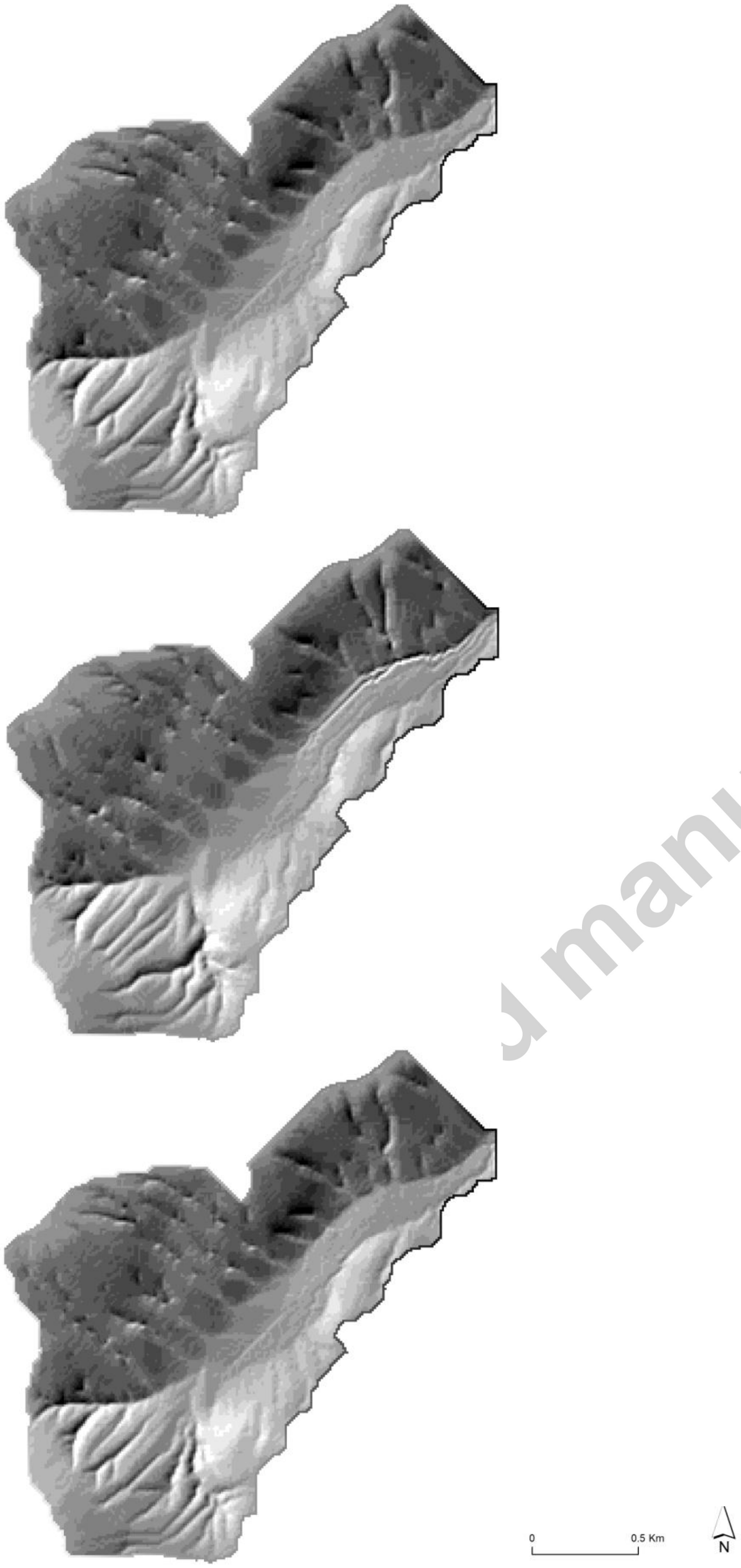

Figure 6. Three examples of the Corridor Creek landform (at 10000 years using Vegetation parameters) with three different random elevation patterns (+/-0.1 m) added to the initial surface. While generally similar they all have different erosion patterns with gullies in particular having different location and morphology.

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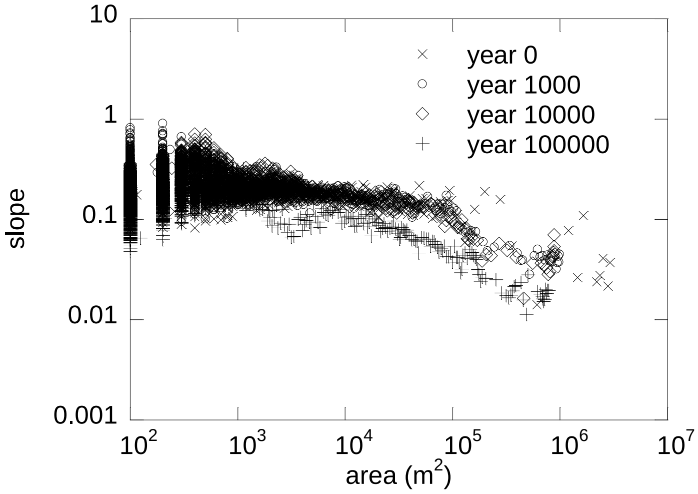

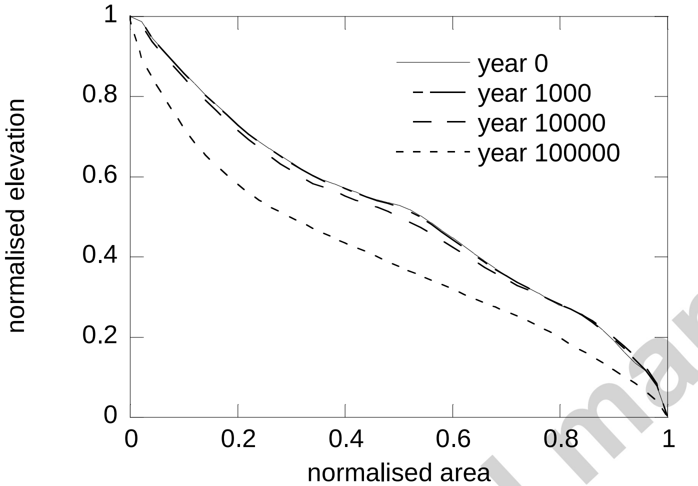

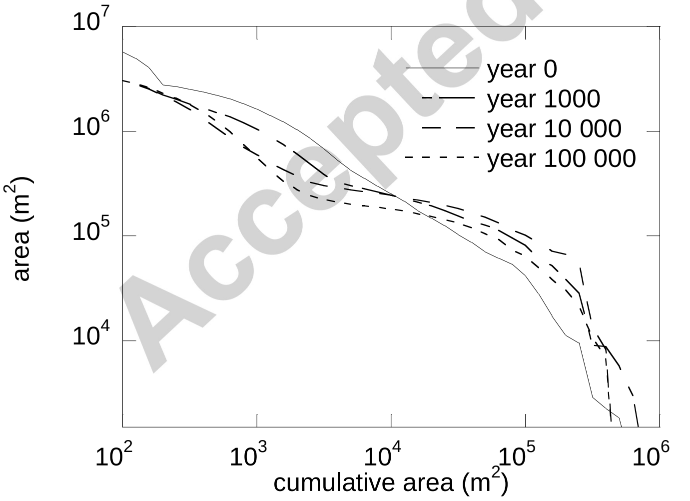

Figure 7. The area-slope relationship (top), hypsometric curve (middle) and cumulative area distribution (bottom) for the Corridor Ck catchment at year 0, 1000, 10000 and 100000 using roughness of +/-0.1 m for a single simulation.

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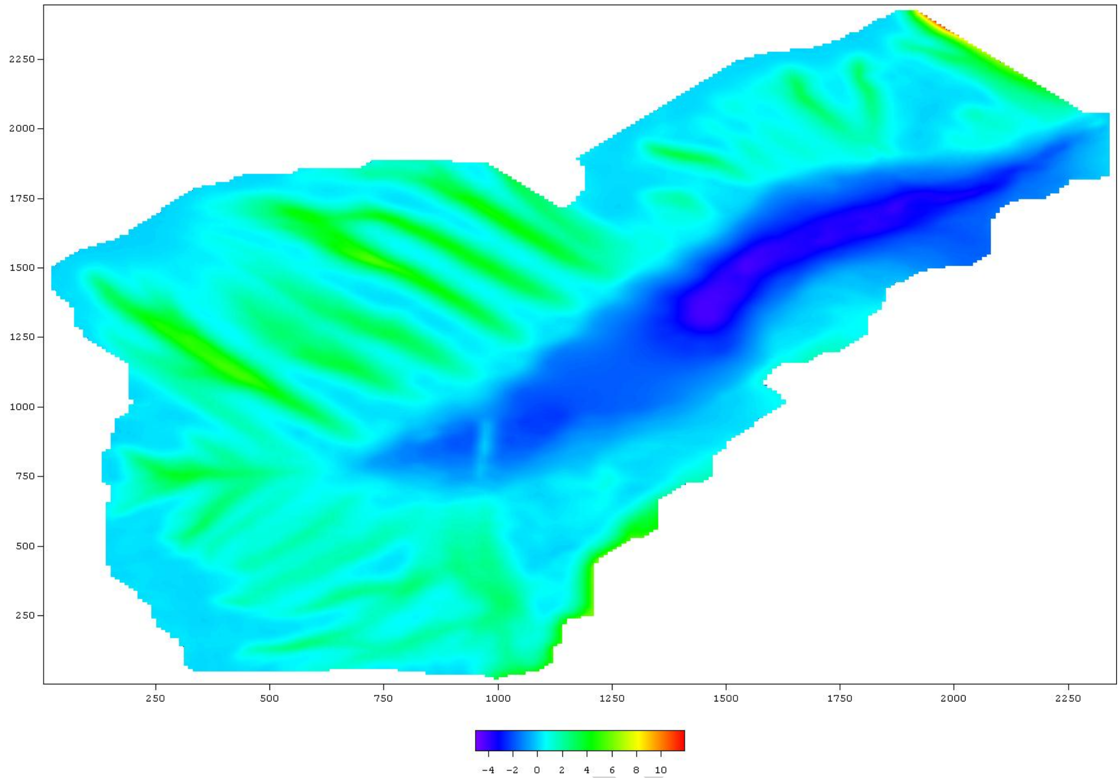

Figure 8. Average erosion and deposition depth for the Corridor Creek landform after 10000 years with +/-0.01m initial surface roughness. Results are an average of 100 simulations. Positive values represent erosion while negative values represent deposition. All dimensions are metres.

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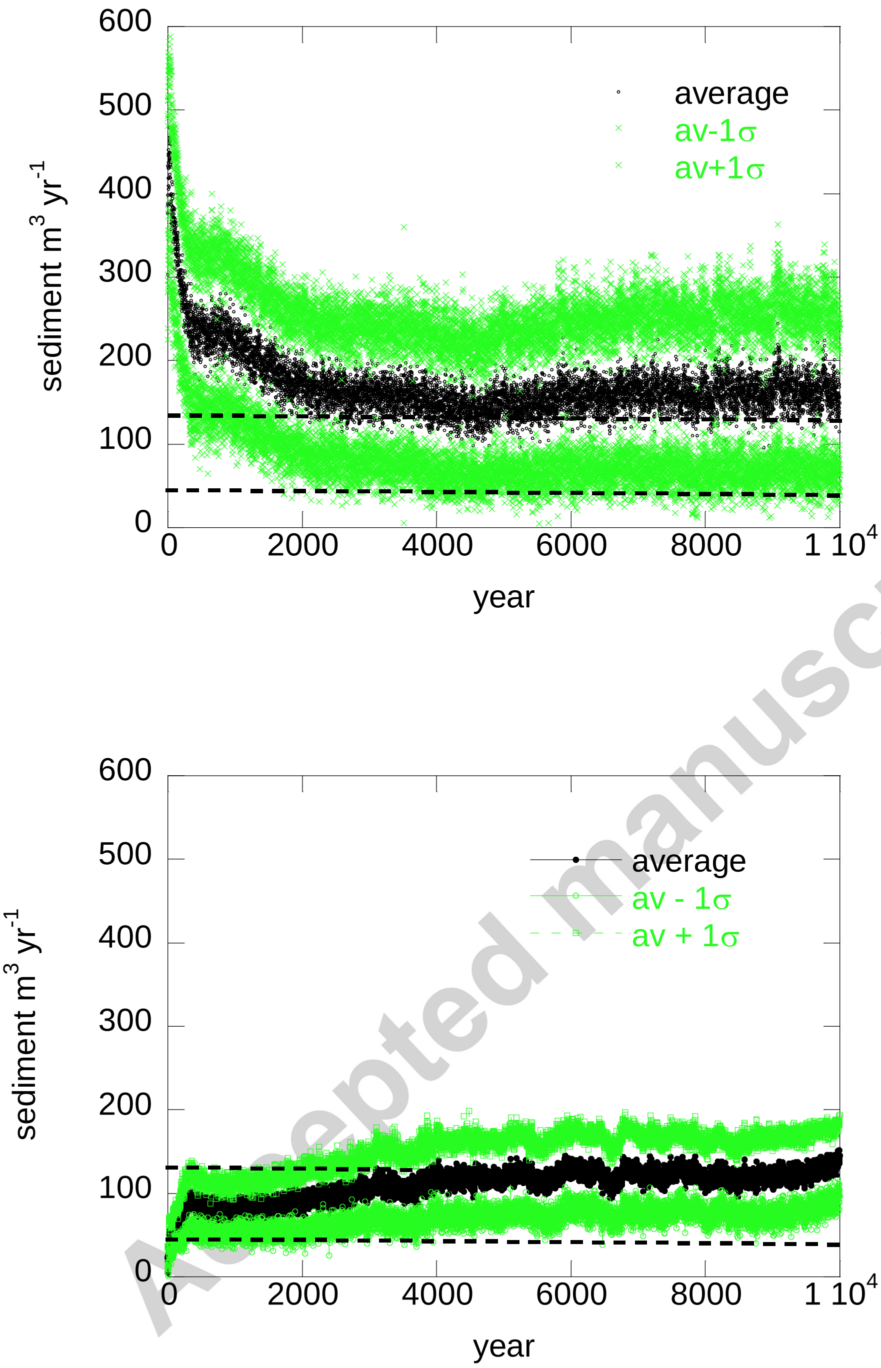

Figure 9. Sediment discharge from the Corridor Creek catchment using Waste Rock Dump (top) and Vegetation (bottom) parameters. The dotted lines indicate the range of sediment discharge expected from a natural or undisturbed system.

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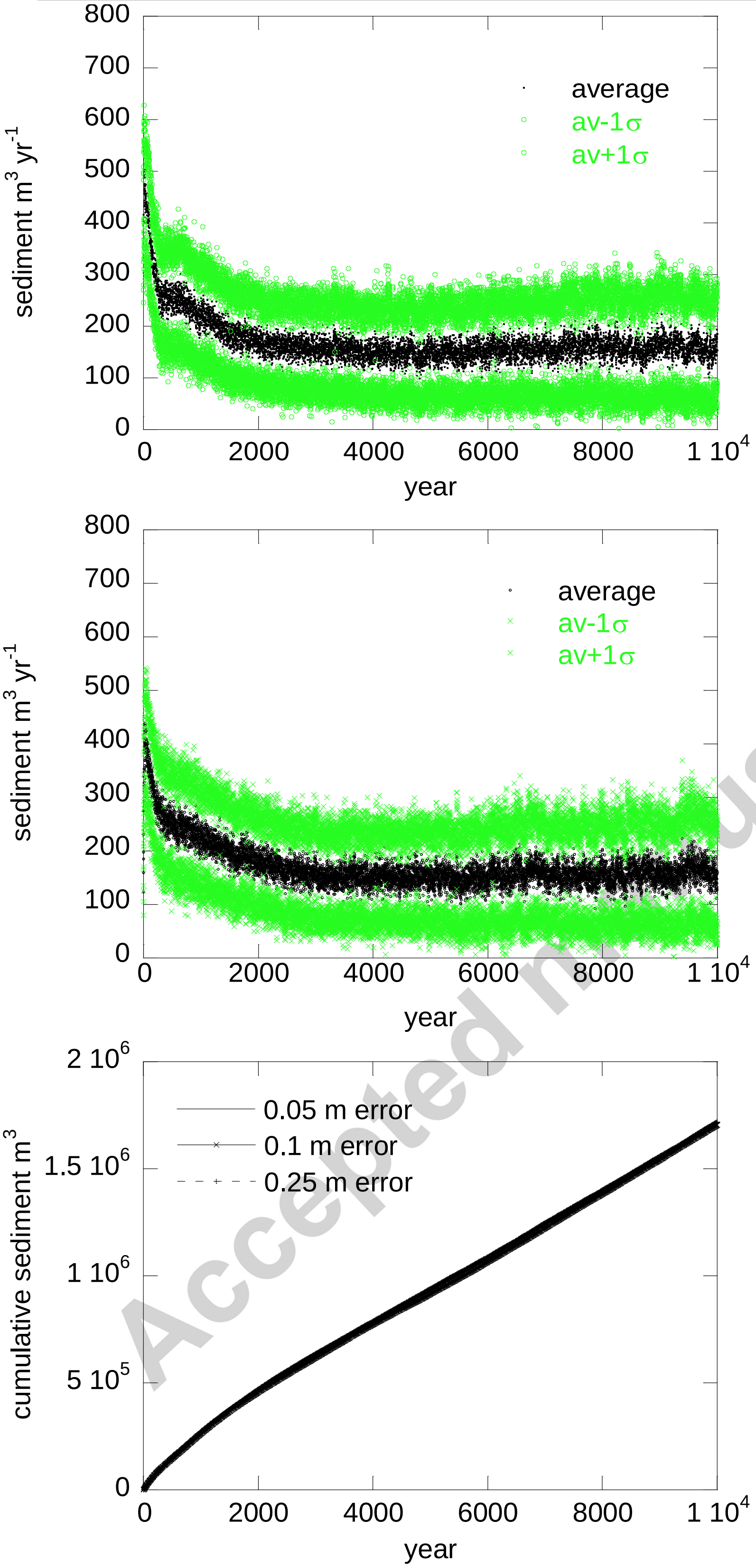

Figure 10. Sediment discharge from the Corridor Creek catchment using Waste Rock Dump parameters and +/-0.05m (top) and +/-0.25m (middle) initial surface roughness. The data from the simulation using +/-0.1m is displayed in Figure 9 (top). Cumulative sediment discharge for +/-0.05m, +/-0.1 and +/-0.25m initial roughness simulations (average of the 100 simulations) (bottom).

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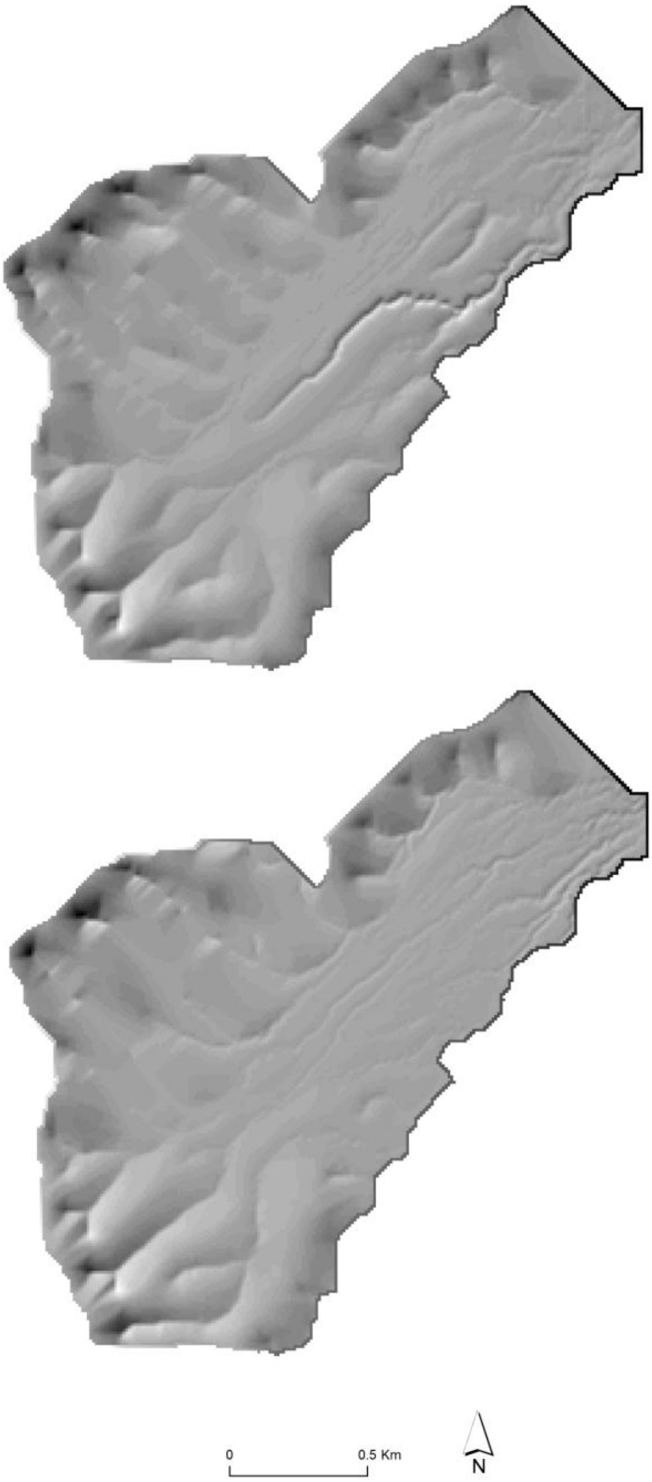

Figure 11. Two examples of the Corridor Creek landform at 100000 years with different sets of random initial roughness (+/- 0.1m) added to the surface (WRD parameters). These correspond to the top and middle landforms in Figure 5 which represent these same landforms at 10000 years.

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Figure 12. Composite landform from an average of 100 simulations (top) and composite landform of maximum depths at 10000 years using Waste Rock Dump parameters (bottom).

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Table 1. The SIBERIA parameter values for each region of the ERA Ranger mine

Surface type	Comparable site	SIBERIA parameter				
		m_1	n_1	β_3	m_3	β_1
Mine pit and waste rock dump	Ranger waste rock dump (Moliere et al 2002)	2.52	0.69	0.00016	0.81	27743
Vegetation	Vegetated, ripped surface (Evans et al 1998)	1.59	0.69	0.000006	0.90	2088

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Table 2. Results from the SIBERIA simulations after 10000 years with +/- 0.05m, +/- 0.1m and +/- 0.25m on initial surface roughness.

	average eros. (m^3/y)	st. dev. (m^3/y)	min. eros. (m^3/y)	max. eros. (m^3/y)	av. depth (m)	st. dev (m)	min. eros. (m)	max. eros. (m)
0.05 m	171.62	45.48	98.76	812.62	0.561	1.72	-4.76	12.29
0.10 m	170.44	41.71	80.84	479.97	0.562	1.69	-4.83	12.38
0.25 m	171.85	41.92	92.96	438.54	0.561	1.73	-4.78	12.29

The effect of different initial DEM surface roughness was examined using a numerical landscape evolution model

Different surface roughness in the DEM produced considerable variability in sediment output

However all simulated landscapes were very similar suggesting a geomorphic equifinality

The initial catchment shape exerts a first-order control over evolutionary landscape form

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