



ELSEVIER

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Case study

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

G.R. Hancock^{a,*}, T.J. Coulthard^b, J.B.C. Lowry^c^a School of Environmental and Life Sciences, Geology Building, The University of Newcastle, Callaghan, New South Wales 2308, Australia^b Department of Geography, University of Hull, Hull HU6 7RX, UK^c Hydrologic, Geomorphic and Chemical Processes Program, Environmental Research Institute of the Supervising Scientist, Darwin, Northern Territory, Australia

ARTICLE INFO

Article history:

Received 7 January 2015

Received in revised form

26 August 2015

Accepted 31 August 2015

Available online 16 September 2015

Keywords:

Sediment transport

Equifinality

Soil erosion modelling

SIBERIA

Statistical uncertainty

Mine rehabilitation

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 10,000 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.

© 2016 Published by Elsevier Ltd.

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; Wilgoose 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 sufficient

* Corresponding author.

E-mail address: Greg.Hancock@newcastle.edu.au (G.R. Hancock).

detailed resolution to capture catchment and hillslope form, whilst retaining a low number of grid cells. For example, Hancock (2005) showed that a 10 m 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 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 (Fig. 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 10,000 years. Mining at the site ceased in 2012, with milling and processing of ore due to cease in 2021. Consequently attention is 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

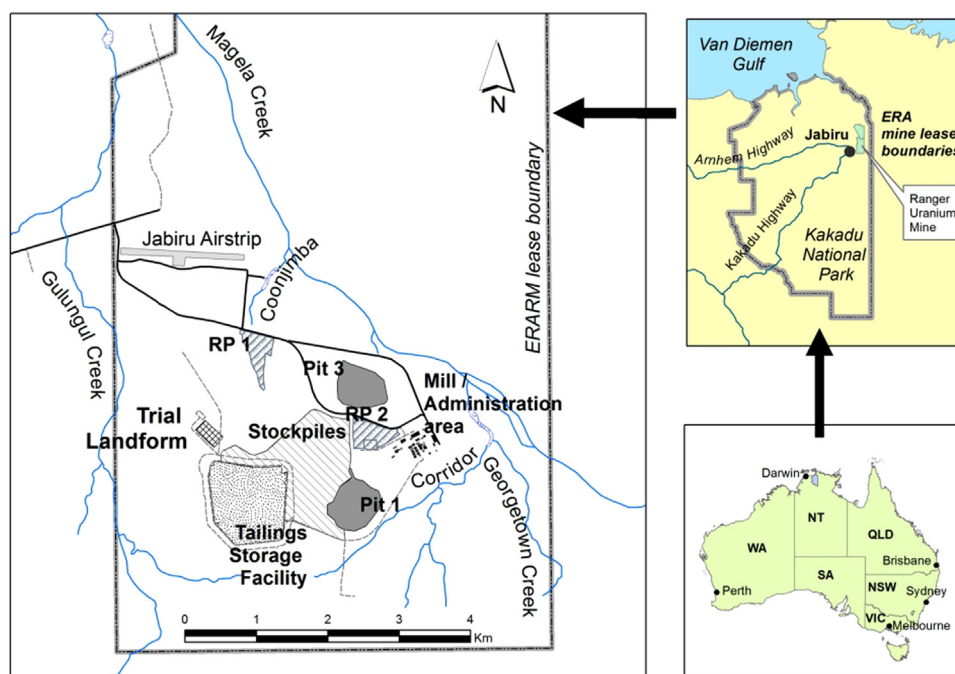


Fig. 1. Location of the ERA Range mine.

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 trisetata* (Chartres et al., 1991).

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 ($0.01\text{--}0.04\text{ mm y}^{-1}$) 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 $13\text{ t ha}^{-1}\text{ y}^{-1}$ ($0.013\text{--}0.86\text{ mm y}^{-1}$) (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 (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., in press).

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., 1991a, 1991b). 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

$$q_s = q_{sf} + q_{sd} \quad (1)$$

where q_s ($\text{m}^3/\text{s}/\text{m}$ 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 $\text{m}^3/\text{s}/\text{m}$ 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:

$$q_{sf} = \beta_1 Q^{m_1} S^{n_1} \quad (2)$$

where Q is the discharge per unit width ($\text{m}^3/\text{s}/\text{m}$ 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

$$q_{sd} = DS \quad (3)$$

where D ($\text{m}^3/\text{s}/\text{m}$ 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 through a point as

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

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).

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 dump (Evans et al., 2000; Moliere et al., 2002). This

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

plot (38 m long by 16 m wide (608 m²)) 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 10 m 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 (Fig. 2). The landscape has been described elsewhere (Hancock et al., in press) 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 m. 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. 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 0.25 m 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 0.25 m is unlikely to comply with this request.

0.25 m also represents the roughness typical of that when a surface is ripped (here at this site by a bulldozer pulling a large tyre that is inserted into the ground) to induce surface roughness once the landscape is reshaped and ready for vegetation seeding (Fig. 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) (Fig. 3). At this site the ripping process produced an

average elevation change or roughness of 0.063 m ($\sigma=0.06$ m), median of 0.05 m and range of 0–0.19 m.

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

5. Simulation setup

The simulations were run for 10,000 years as this is the period for which the structure is designed (Commonwealth of Australia, 1987). 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 selected catchments with ± 0.1 m surface perturbations) of simulations were run for 100,000 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., in press) which have assumed that vegetation would be fully established at approximately 10 years.

The modelling domain was the DEM displayed in Fig. 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 10,000 year modelled period (Fig. 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., in press), 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 ± 0.05 m, ± 0.1 m and ± 0.25 m), 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 (Figs. 5 and 6) but with much less erosion when the Vegetation parameters are employed.

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

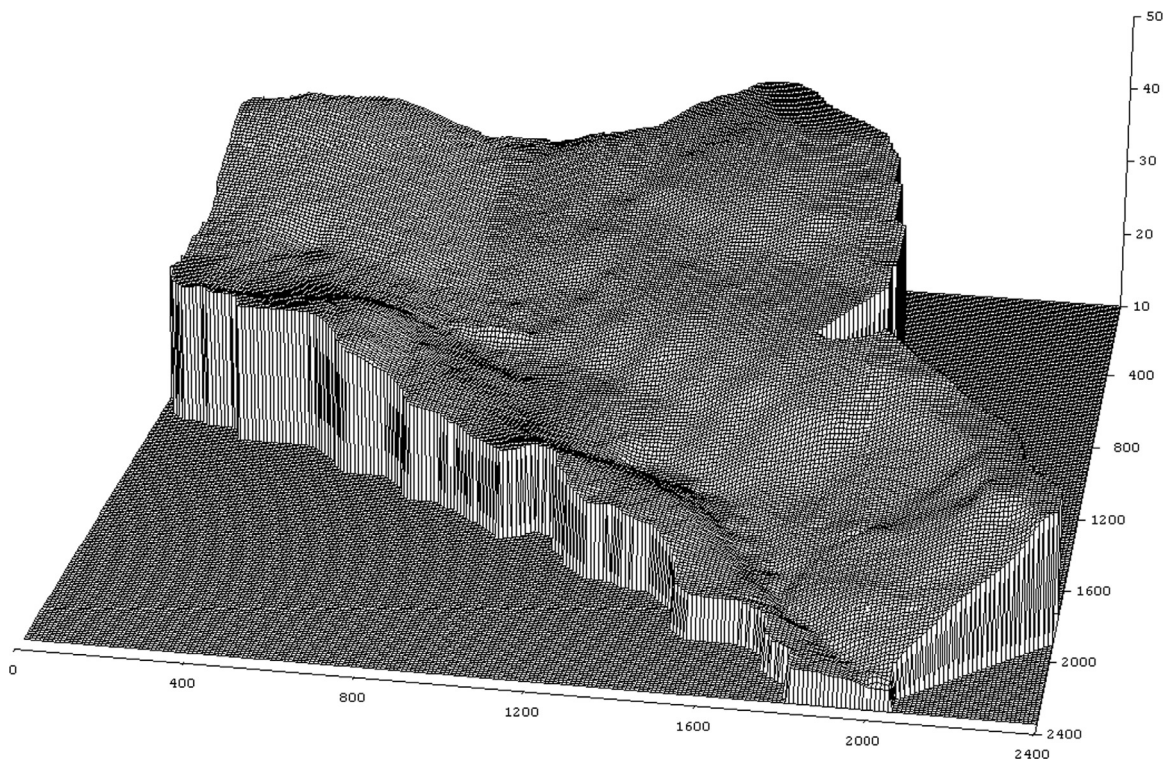
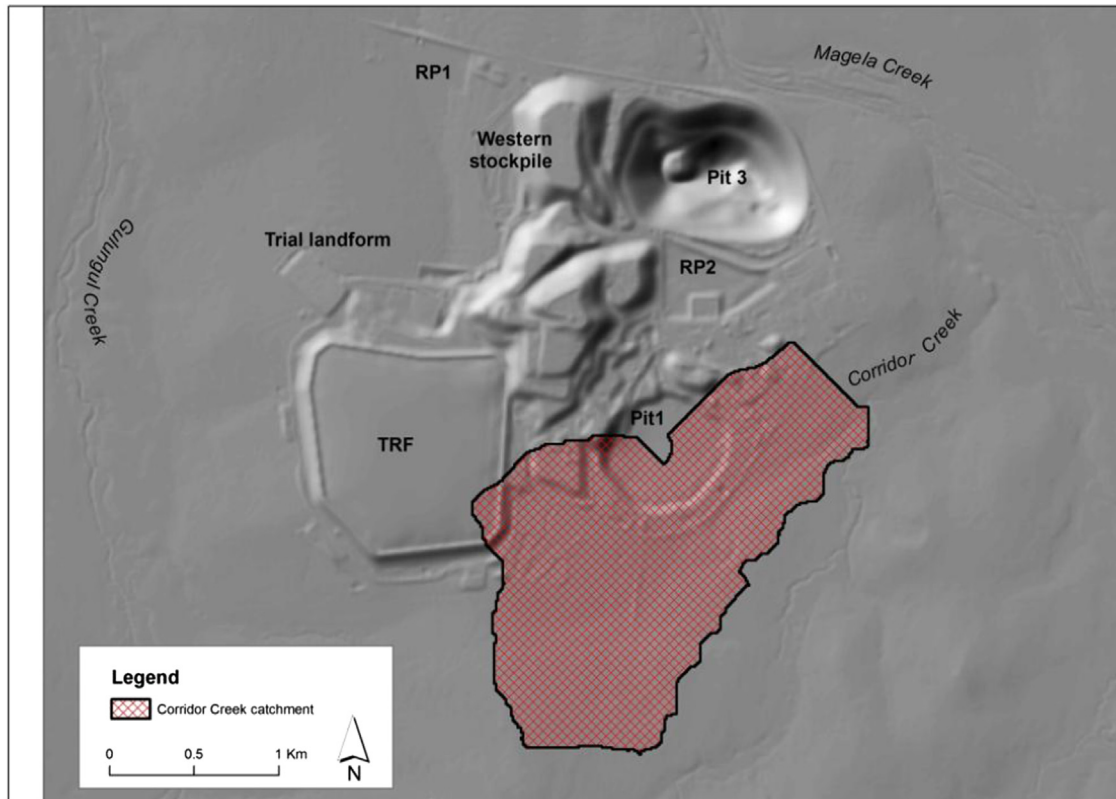


Fig. 2. Planned rehabilitation (top) and proposed rehabilitation design (bottom). All dimensions are metres.

area distribution (Rodríguez-Iturbe et al., 1992) are used. These measurements taken at 10,000 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 (Fig. 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 6–8 m (Fig. 8). In other areas, over 4 m of deposition has occurred (Table 2). Of importance here is the maximum depth of erosion (approximately 8 m), which occurs over the former pit which contains tailings

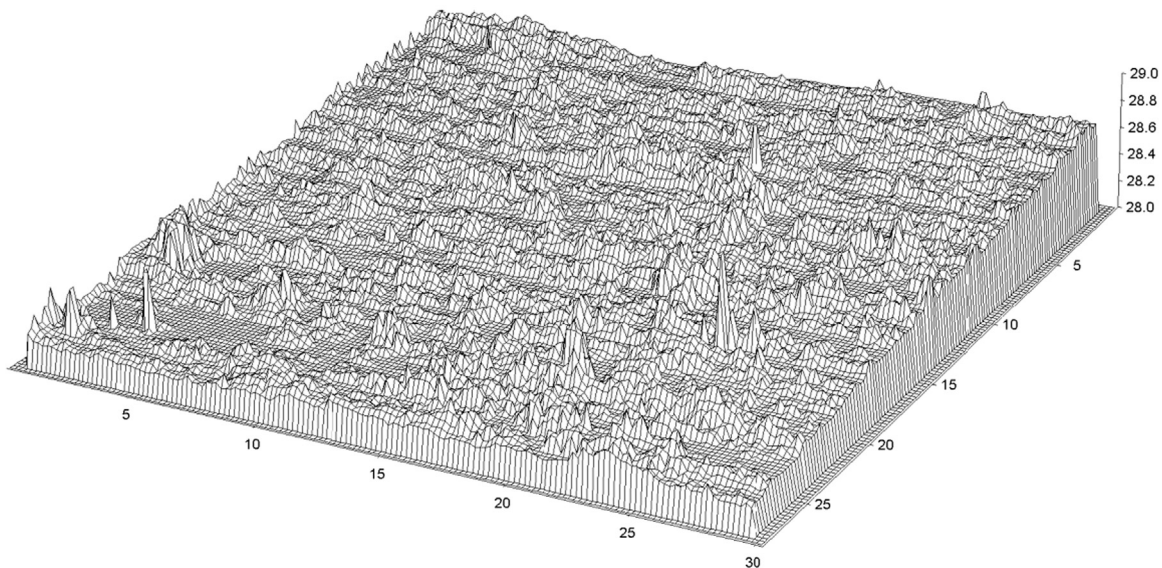


Fig. 3. Surface roughness at the ERA Ranger trial landform (top) and DEM of the surface (0.2 m by 0.2 m grid) (bottom). All dimensions are metres.

(Fig. 8). This demonstrates that an inert cover over this area needs to be considerably greater than 8 m 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 \pm one standard deviation (Fig. 9). The results demonstrate that there are years when there is no sediment output together with years 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 10,000 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., 2004; Jerolmack and Paola, 2010; Zimmerman et al., 2010). For the majority of the 10,000 year period sediment output is

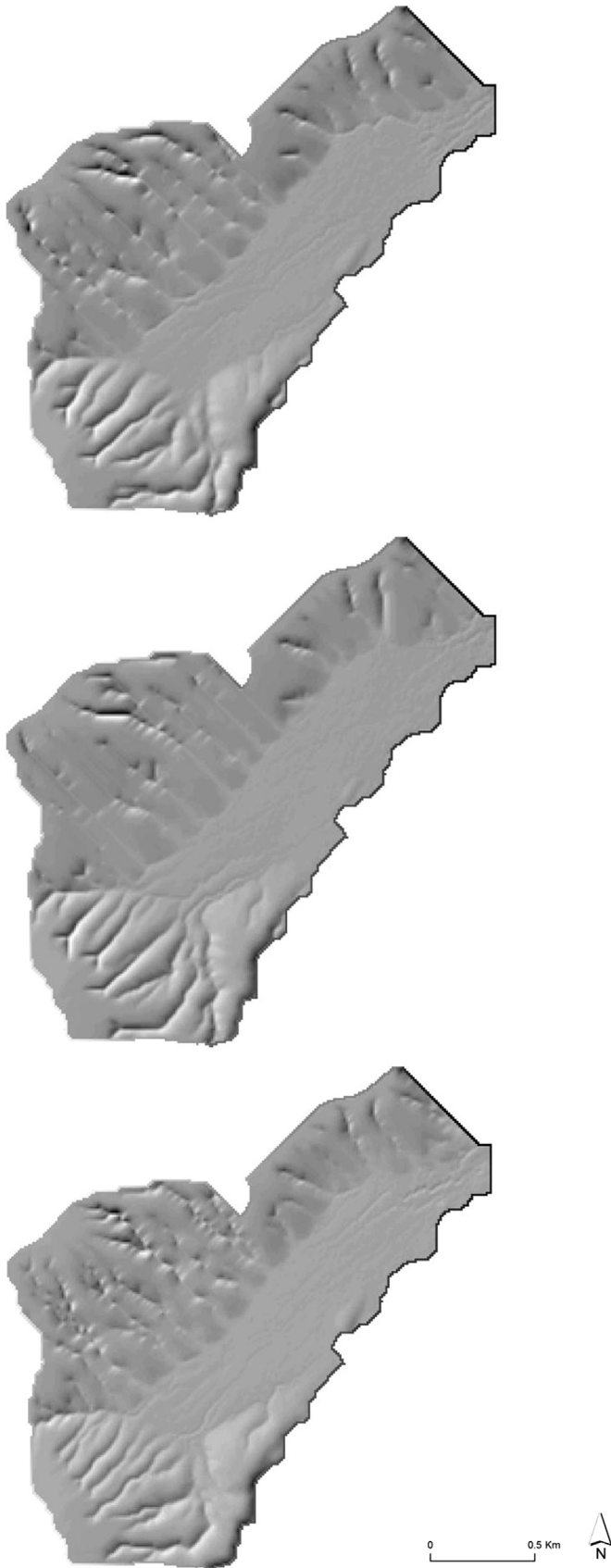


Fig. 4. Corridor Creek landform after 10,000 years (using Waste Rock Dump parameters) with ± 0.05 m (top), ± 0.1 m (middle) and ± 0.25 m (bottom) initial surface roughness. While generally similar they all have different erosion patterns with gullies in particular having different location and morphology.

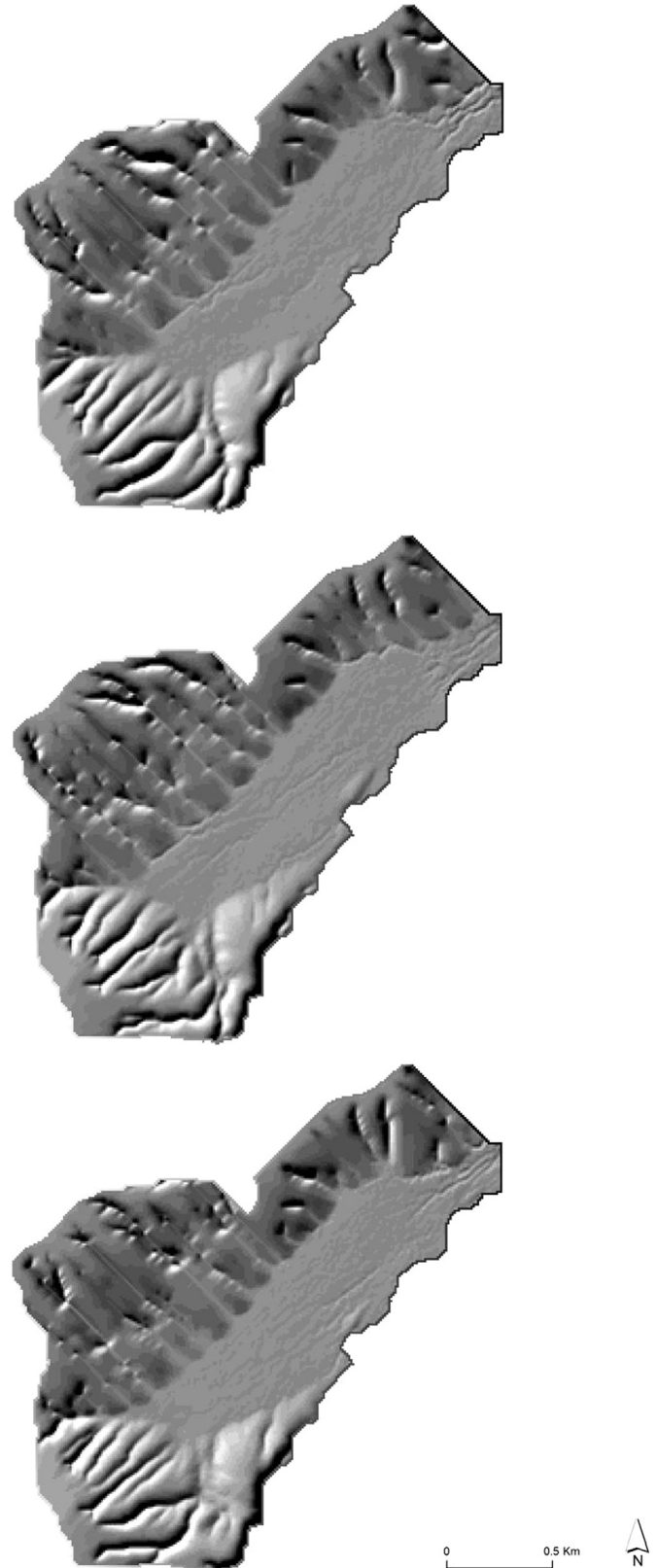


Fig. 5. Three examples of the Corridor Creek landform (at 10,000 years using Waste Rock Dump parameters) with three different random elevation patterns (± 0.1 m) added to the initial surface. While generally similar they all have different erosion patterns with gullies in particular having different location and morphology.

above that expected from the catchment as determined from background or natural erosion rates ($30\text{--}120\text{ m}^3\text{ y}^{-1}$ is expected to exit the catchment annually based on the denudation rates

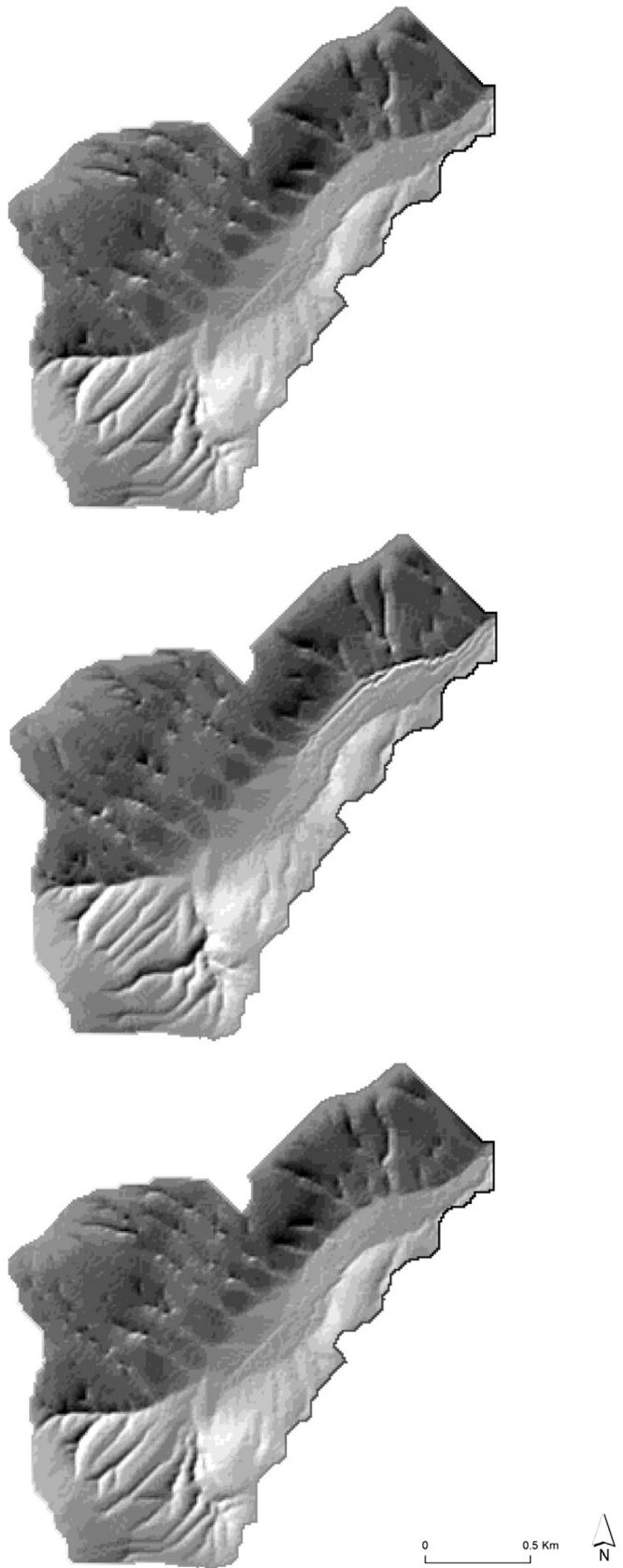


Fig. 6. Three examples of the Corridor Creek landform (at 10,000 years using Vegetation parameters) with three different random elevation patterns (± 0.1 m) added to the initial surface. While generally similar they all have different erosion patterns with gullies in particular having different location and morphology.

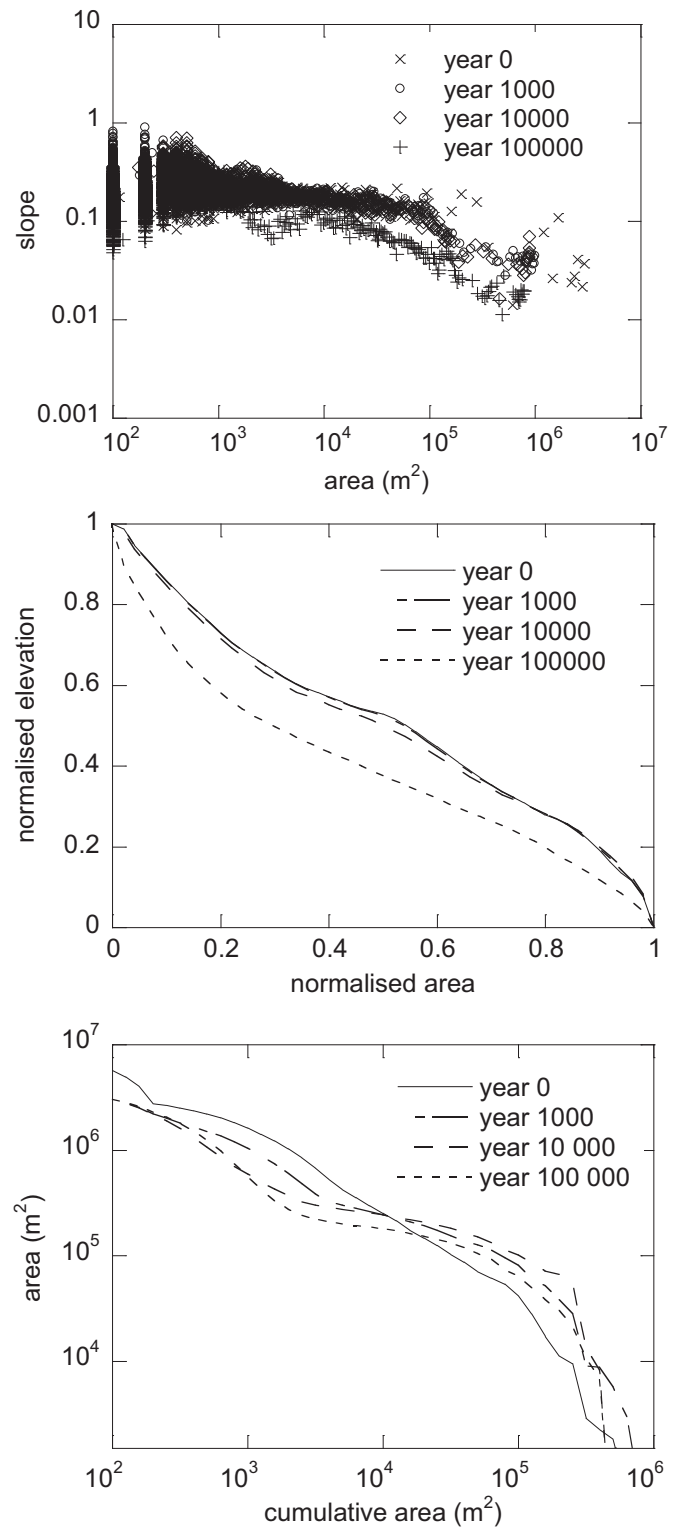


Fig. 7. The area-slope relationship (top), hypsometric curve (middle) and cumulative area distribution (bottom) for the Corridor Ck catchment at year 0, 1000, 10,000 and 100,000 using roughness of ± 0.1 m for a single simulation.

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

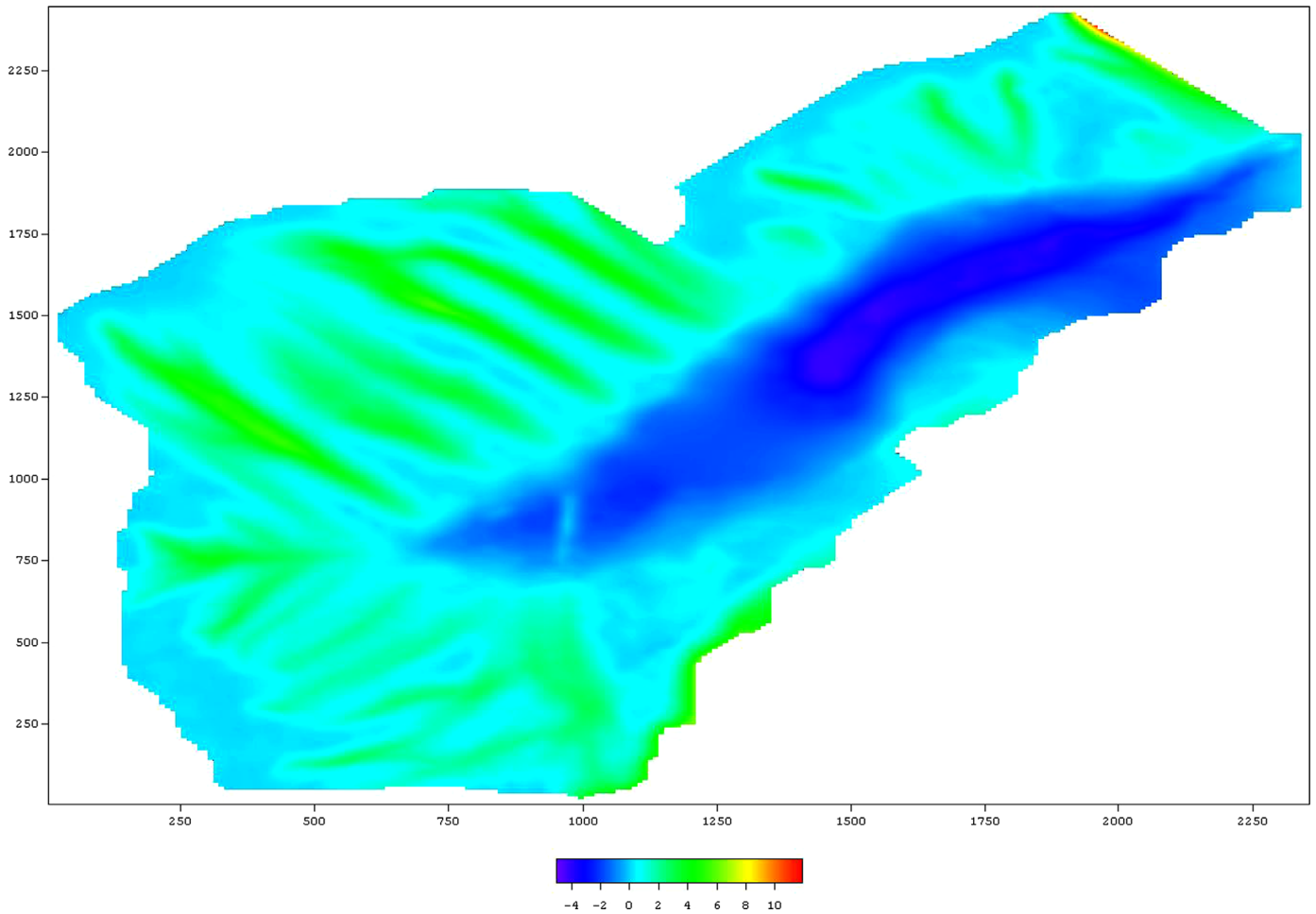


Fig. 8. Average erosion and deposition depth for the Corridor Creek landform after 10,000 years with ± 0.01 m initial surface roughness. Results are an average of 100 simulations. Positive values represent erosion while negative values represent deposition. All dimensions are metres.

Table 2
Results from the SIBERIA simulations after 10,000 years with ± 0.05 m, ± 0.1 m and ± 0.25 m 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

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 ± 0.05 m, ± 0.01 m and ± 0.25 m random roughness produced variability in sediment output similar to each other (Fig. 10, top and middle). Cumulative sediment output was near identical for all three levels of roughness (Fig. 10, bottom). This suggests that while initial surface roughness produces considerable variability in annual

sediment output, over the 10,000 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 10,000 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 10,000 year period is minimised (Willgoose et al., 1991a, 1991b; Howard, 1994; Howard et al., 1994; Tucker, 1996).

While surface roughness changes the temporal pattern of

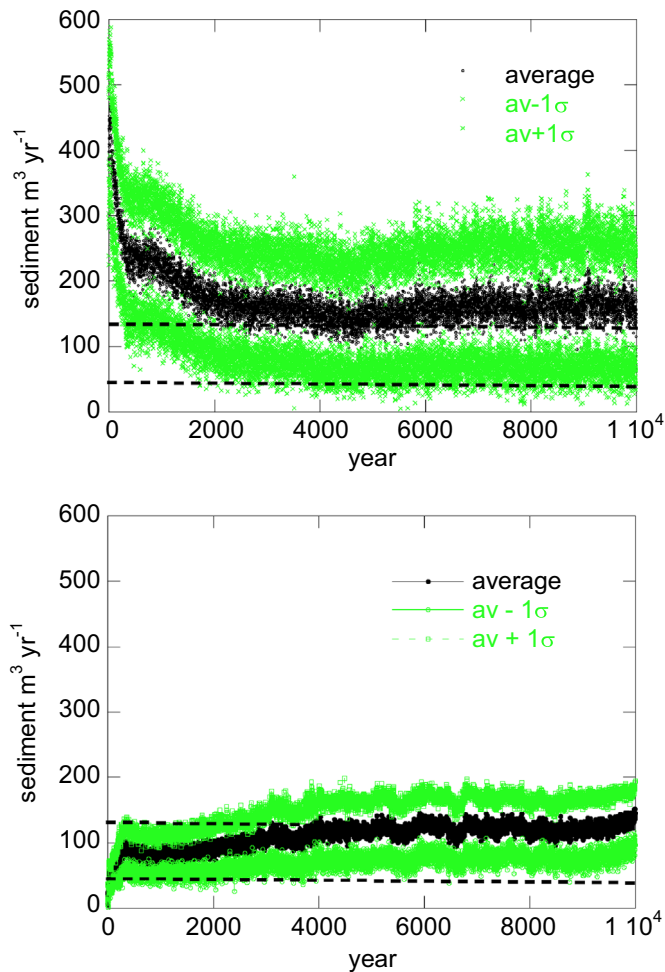


Fig. 9. Sediment discharge from the Corridor Creek catchment using Waste Rock Dump (top) and Vegetation (bottom) parameters. The dotted lines indicate the range of sediment discharge expected from a natural or undisturbed system.

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. ± 0.5 m) is possible but not a realistic landscape management scenario.

The similarity in final landscape form at 10,000 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 10,000 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 100,000 years (Fig. 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,

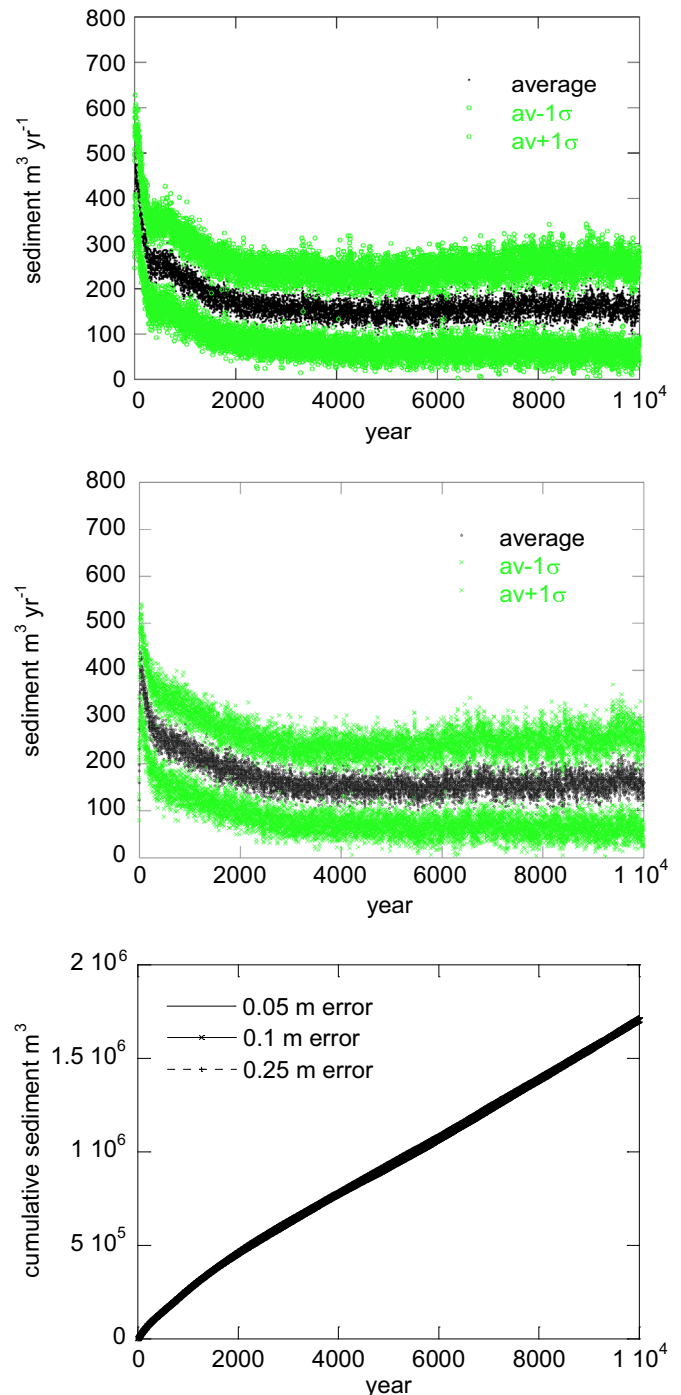


Fig. 10. Sediment discharge from the Corridor Creek catchment using Waste Rock Dump parameters and ± 0.05 m (top) and ± 0.25 m (middle) initial surface roughness. The data from the simulation using ± 0.1 m is displayed in Fig. 9 (top). Cumulative sediment discharge for ± 0.05 m, ± 0.1 and ± 0.25 m initial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

while there has been considerable deposition in the main channel, Fig. 11 (top) displays a new channel that has developed in the depositional material while Fig. 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

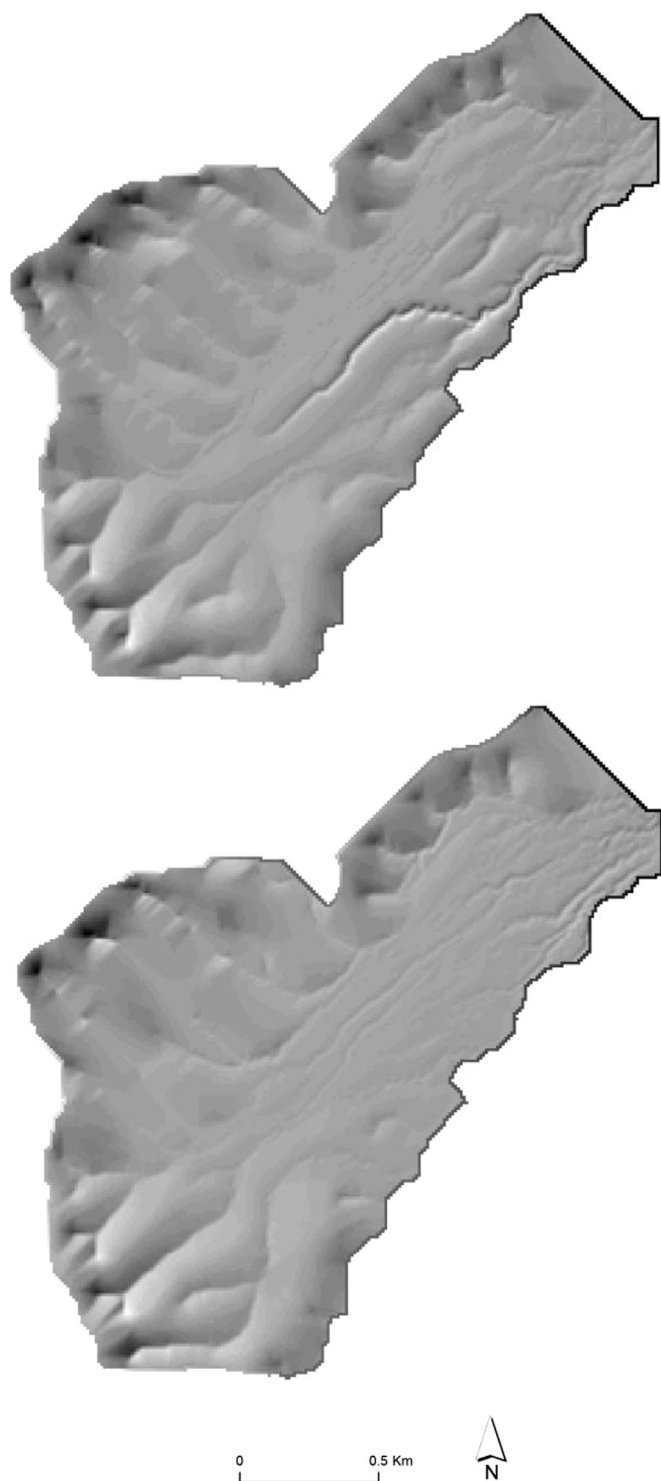


Fig. 11. Two examples of the Corridor Creek landform at 100,000 years with different sets of random initial roughness (± 0.1 m) added to the surface (WRD parameters). These correspond to the top and middle landforms in Fig. 5 which represent these same landforms at 10,000 years.

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 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., 1991a, 1991b; 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 Fig. 9 the sediment discharge is displayed as the mean \pm 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 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 8 m 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 ($0.01\text{--}0.04\text{ mm y}^{-1}$) as a guide to determine 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 10–20 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 deposition 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) (Fig. 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 (Fig. 12) as well as erosion and deposition patterns can be developed (Fig. 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-emplacment. It is both in the economic and environmental interests of the community to ensure that any re-emplacment, 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 10,000 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



Fig. 12. Composite landform from an average of 100 simulations (top) and composite landform of maximum depths at 10,000 years using Waste Rock Dump parameters (bottom).

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 10,000 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 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 10,000 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.

Acknowledgements

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.

References

- Bureau of Meteorology, 2014. Climate statistics for Australian locations – Jabiru Airport. Available at: (http://www.bom.gov.au/climate/averages/tables/cw_014198.shtml).
- Charru, F.U., Moulleron, H., Eiff, O., 2004. Erosion and deposition of particles on a bed sheared by viscous flow. *J. Fluid Mech.* 519, 55–80. <http://dx.doi.org/10.1017/S0022112004001028>.
- Chartres, C.J., Walker, P.H., Willett, I.R., East, T.J., Cull, R.F., Talsma, T., Bond, W.J., 1991. Soils and hydrology of Ranger uranium mine sites in relation to application of retention pond water. Technical memorandum 34, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra.
- Commonwealth of Australia, 1987. Department of Arts, Sports, the Environment, Tourism and Territories Code of Practice on the Management of Radioactive Wastes from Mining of Radioactive Ores 1982. Guidelines, AGPS Canberra.
- Coulthard, T., Hancock, G.R., Lowry, J., 2012a. Modelling soil erosion with a down-scaled landscape evolution model. *Earth Surf. Process. Landf.* 37, 1046–1055.
- Coulthard, T.J., Ramirez, J., Fowler, H.J., Glenis, V., 2012b. Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield. *Hydrol. Earth Syst. Sci.* 16, 4401–4416. <http://dx.doi.org/10.5194/hess-16-4401-2012>.
- Coulthard, T.J., Neal, J.C., Bates, P.D., Ramirez, J., de Almeida, G.A.M., Hancock, G.R., 2013. Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. *Earth Surf. Process. Landf.* 38, 1897–1906. <http://dx.doi.org/10.1002/esp.3478>.
- CSIRO, 2007. Climate Change in Australia – Technical Report 2007. CSIRO, Australia.
- Cull, R., Hancock, G., Johnston, A., Martin, P., Marten, R., Murray, A.S., Pfitzner, J., Warner, R.F., Wasson, R.J., 1992. Past, present and future sedimentation on the Magela plain and its catchment. In: Wasson, R.J. (Ed.), *Modern Sedimentation and Late Quaternary Evolution of the Magela Plain*. AGPS, Canberra, pp. 226–268 (Supervising scientist for the alligator rivers region research report 6).
- Dietrich, W.E., Bellugi, D.G., Sklar, L.S., Stock, J.D., Heimsath, A.M., Roering, J.J., 2003. Geomorphic transport laws for predicting landscape form and dynamics. In: Wilcock, P.R., Iverson, R.M. (Eds.), *Prediction in Geomorphology*. American Geophysical Union, Washington, DC, pp. 103–132 (Geophysical monograph 135).
- East, T.J., 1996. Landform evolution. In: Finlayson, C.M., von Oertzen, I. (Eds.), *Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 37–55.
- Erskine, W.D., Saynor, M.J., 2000. Assessment of the off-site geomorphic impacts of Uranium mining on Magela Creek, Northern Territory, Australia, Supervising Scientist Report 156. Supervising Scientist, Darwin.
- Evans, K.G., Willgoose, G.R., Saynor, M.J., House, T., 1998. Effect of vegetation and surface amelioration on simulated landform evolution of the post-mining landscape at ERA Ranger Mine, Northern Territory, Supervising Scientist Report 134. Supervising Scientist, Canberra.
- Evans, K.G., Saynor, M.J., Willgoose, G.R., 1999. Changes in hydrology, sediment loss and microtopography of a vegetated mine waste rock dump impacted by fire. *Land Degrad. Dev.* 10, 507–522.
- Evans, K.G., Willgoose, G.R., 2000. Post-mining landform evolution modelling: 2. Effects of vegetation and surface ripping. *Earth Surf. Process. Landf.* 25 (8), 803–823.
- Evans, K.G., Willgoose, G.R., Saynor, M.J., Riley, S.J., 2000. Post-mining landform evolution modelling. I. Derivation of sediment transport model and rainfall-runoff model parameters. *Earth Surf. Process. Landf.* 25 (7), 743–763.
- Flint, J.J., 1974. Stream gradient as a function of order, magnitude and discharge. *Water Resour. Res.* 10 (5), 969–973.
- Hack, J.T., 1957. Studies of longitudinal stream profiles in Virginia and Maryland. *United States Geol. Surv. Prof. Pap.* 292B, 45–97.
- Haff, P.K., 1996. Limitation on predictive modelling in geomorphology. In: Rhoads, B.L., Thorn, C.E. (Eds.), *The Scientific Nature of Geomorphology*. John Wiley and Sons, New York, pp. 337–358.
- Hancock, G.R., 2005. The use of digital elevation models in the identification and characterisation of catchments. *Hydrol. Process.* 19, 1727–1749.
- Hancock, G.R., Willgoose, G.R., Evans, K.G., Moliere, D.R., Saynor, M.J., 2000. Medium term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model. *Aust. J. Soil Res.* 38, 249–263.
- Hancock, G.R., Willgoose, G.R., Evans, K.G., 2002. Testing of the SIBERIA landscape evolution model using the Tin Camp Creek, Northern Territory, Australia, field catchment. *Earth Surf. Process. Landf.* 27 (2), 125–143.
- Hancock, G.R., Grabham, M.K., Martin, P., Evans, K.G., Bollhöfer, A., 2006. A methodology for the assessment of rehabilitation success of post mining landscapes – sediment and radionuclide transport at the former Nabarlek uranium mine, Northern Territory, Australia. *Sci. Total Environ.* 354, 103–119.
- Hancock, G.R., Lowry, J.B.C., Moliere, D.R., Evans, K.G., 2008. An evaluation of an enhanced soil erosion and landscape evolution model: a case study assessment of the former Nabarlek uranium mine, Northern Territory, Australia. *Earth Surf. Process. Landf.* 33, 2045–2063. <http://dx.doi.org/10.1002/esp.1653>.
- Hancock, G.R., Lowry, J.B.C., Coulthard, T.J., 2015. Catchment reconstruction – erosional stability at millennial time scales using landscape evolution models. *Geomorphology* 231, 15–27.
- Hancock, G.R., Willgoose, G.R., Lowry, J., 2013. Transient landscapes: gully development and evolution using a landscape evolution model. *Stochastic Environmental Research and Risk Assessment* <http://dx.doi.org/10.1007/s00477-013-0741-y>. pp. 83–98.
- Howard, A.D., 1994. A detachment-limited model of drainage basin evolution. *Water Resour. Res.* 30 (7), 2261–2286.
- Howard, A.D., Dietrich, W.E., Seidl, M.A., 1994. Modelling fluvial erosion on regional to continental scales. *J. Geophys. Res.* 99, 13971–13986.
- Ijjasz-Vasquez, E.J., Bras, R.L., Moglen, G.E., 1992. Sensitivity of a basin evolution model to the nature of runoff production an initial conditions. *Water Resour. Res.* 28, 2733–2742.
- Jerolmack, D.J., Paola, C., 2010. Shredding on environmental signals by sediment transport. *Geophys. Res. Lett.* 37, L19401. <http://dx.doi.org/10.1029/2010GL044638>.
- Lowry, J.B.C., Evans, K.G., Moliere, D.R., Hollingsworth, I., 2006. Assessing landscape reconstruction at the Ranger Mine using landform evolution modelling. In: *Proceedings of the First International Seminar on Mine Closure*. 13–15 September 2006. Australian Centre for Geomechanics, Perth, Australia. pp. 577–586.
- Lowry, J.B.C., Evans, K.G., Coulthard, T.J., Hancock, G.R., Moliere, D.R., 2009. Assessing the impact of extreme rainfall events on the geomorphic stability of a conceptual rehabilitated landform in the Northern Territory of Australia. In: Fourie, A., Tibbett, M. (Eds.), *Mine Closure 2009*. Proceedings of the Fourth International Conference on Mine Closure 9–11 September 2009. Australian Centre for Geomechanics, Perth. pp. 203–212.
- Lowry, J., Saynor, M., Erskine, W., Coulthard, T., Hancock, G., 2014. A multi-year assessment of landform evolution predictions for a trial rehabilitated landform. In: *Proceedings of the Life-of-Mine 2014 Conference*. 16–18 July 2014. Australasian Institute of Mining and Metallurgy, Brisbane, Australia. pp. 67–80.
- Lowry, J.B.C., Coulthard, T.J., Hancock, G.R., Jones, D.R., 2011. Assessing soil erosion on a rehabilitated landform using the CAESAR landscape evolution model, in *Proceedings of the 6th International Conference on Mine Closure*, A.B. Fourie, M. Tibbett and A. Beersing (Eds.) 18–21 September 2011, Australian Centre for Geomechanics, Perth, pp. 613–21.
- Ludwig, J.A., Tongway, D.J., 1995. Spatial organisation of landscapes and its function in semi-arid woodlands, Australia. *Landsc. Ecol.* 10, 51–63.
- Moliere, D.R., Evans, K.G., Willgoose, G.R., Saynor, M.J., 2002. Temporal trends in erosion and hydrology for a post-mining landform at Ranger Mine. Northern

- Territory, Supervising Scientist Report 165. Supervising Scientist, Darwin NT.
- Needham, R.S., 1988. Geology of the Alligator Rivers uranium Field, Northern Territory, Bulletin 224, Bureau of Mineral Resources. Australian Government Publishing Service, Canberra.
- Nikora, V., Habersack, H., Huber, T., McEwan, I. 2002. On bed particle diffusion in gravel bed flows under weak bed load transport. *Water Resour. Res.* 38: 10.1029/2001WR000513. ISSN: 0043-1397.
- Perron, J.T., Fagherazzi, S. 2011. The legacy of initial conditions in landscape evolution, *Earth Surface and Processes*, <http://dx.doi.org/10.1002/esp.2205>:52-63.
- Rodriguez-Iturbe, I., Ijjasz-Vasquez, E.J., Bras, R.L., Tarboton, D.G., 1992. Distributions of discharge, mass and energy in river basins. *Water Resour. Res.* 28 (4), 1089–1093.
- Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. *Geol. Soc. Am. Bull.* 63, 1117–1142.
- Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: Chow, V.T. (Ed.), *Handbook of Applied Hydrology*. McGraw-Hill, New York, pp. 4.40–4.74.
- Supervising Scientist Division, 1999. Environmental Requirements for the Ranger Uranium Mine, Department of Sustainability, Environment, Water, Populations and Communities (accessed 03.04.13). (<http://www.environment.gov.au/ssd/about/legislation/pubs/ranger-ers.pdf>).
- Tongway, D.J., Ludwig, J.A., 1996. Rehabilitation of semiarid landscapes in Australia, 1. Restoring productive soil patches. *Restor. Ecol.* 4 (4), 388–397.
- Tucker, G.E., 1996. Modelling the Large-scale Interaction of Climate, Tectonics and Topography (Ph.D. thesis). Pennsylvania State University, State College, PA, p. 267.
- Tucker, G., Hancock, G.R., 2010. Modelling landscape evolution. *Earth Surf. Process. Landf.* 35, 28–50.
- Uren, C., 1992. An investigation of surface geology in the Alligator Rivers Region for possible analogues of uranium mine rehabilitation structures. Internal report 56, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.
- Van De Wiel, M.J., Coulthard, T.J., 2010. Self-organized criticality in river basins: challenging sedimentary records of environmental change. *Geology* 38, 87–90. <http://dx.doi.org/10.1130/G30490.1>.
- Willgoose, G.R., Bras, R.L., Rodríguez-Iturbe, I., 1991a. Results from a new model of river basin evolution. *Earth Surf. Process. Landf.* 16, 237–254.
- Willgoose, G.R., Bras, R.L., Rodríguez-Iturbe, I., 1989. A Physically Based Channel Network and Catchment Evolution Model. Ralph M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge (TR 322).
- Willgoose, G.R., Bras, R.L., Rodríguez-Iturbe, I., 1991b. A physically based coupled network growth and hillslope evolution model: 1 theory. *Water Resour. Res.* 27 (7), 1671–1684.
- Willgoose, G.R., Hancock, G.R., Kuczera, G., 2003. A framework for the quantitative testing of landform evolution models. In: Wilcock, P.R., Iverson, R.M. (Eds.), *Prediction in Geomorphology*. American Geophysical Union, Washington, DC, pp. 195–216 (Geophysical monograph 135).
- Willgoose, G. R., Riley, S. 1993. Application of a catchment evolution model to the prediction of long-term erosion on the spoil heap at Ranger Uranium Mine. Open File Report 107. The Office of the Supervising Scientist, Jabiru.
- Willgoose, G.R., Riley, S., 1998. The long-term stability of engineered landforms of the Ranger Uranium Mine Northern Territory, Australia: Application of a catchment evolution model. *Earth Surf. Process. Land.* 23, 237–259.
- Zimmerman, A., Church, M., Hassan, M.A., 2010. Step-pool stability: Testing the jammed state hypothesis. *J. Geophys. Res.* 115, F02008. <http://dx.doi.org/10.1029/2009JF001365>.