Highlights (for review)

Can computer based landscape evolution models (LEMs) produce meaningful results?

Here we show that using calibrated parameters different possible landscapes result

Choice of parameter results in plausible landscapes over geological time

The finding demonstrates that parameter choice is major issue when using LEMs

Greater quantitative understanding of soil, vegetation, climate interactions are needed

This is a significant issue if these models are to be used for landscape assessment

Long-term landscape trajectory – can we make predictions about landscape form and function for post-mining landforms?

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Abstract

A significant issue for the application of numerical Landscape Evolution Models (LEMs) is their calibration/parameterisation and validation. LEMs are now at the stage of development where if calibrated, they can provide meaningful and useful results. However, before use, each LEM requires a set of data and parameter values for it to run reliably and most importantly produce results with some measure of precision and accuracy. This calibration/validation process is largely carried out using parameter values determined from present day, or recent surface conditions which are themselves product of much longer-term geology-soil-climate-vegetation interactions. Here we examine the reliability of an LEM to predict catchment form over geological time (500, 000 years) for a potential rehabilitated mine landform using defensible parameters derived from field plots. The findings demonstrate that there is no equifinality in landscape form with different parameter sets producing geomorphically and hydrologically unique landscapes throughout their entire evolution. This shows that parameterisation does matter over geological time scales. However, for shorter time scales (<10,000 years) the geomorphic differences in hillslope form are minimal as described by the hypsometric curve, area–slope and cumulative area distribution, yet there are large differences in sediment output. Therefore, obtaining reliable and defensible parameters for input to LEMs is essential.

Keywords: Landscape evolution, Mine rehabilitation, Soil erosion modelling, SIBERIA

1 Introduction

While conceptual models have helped further earth science understanding, more recently, numerically based Landscape Evolution Models (LEMs) have been developed, which have the capability to capture a range of surface erosion and deposition, tectonic processes and near surface or critical zone processes such as pedogenesis. Tucker and

Hancock (2010) have reviewed a range of LEMs which have been used in applications ranging from understanding theoretical landscape dynamics through to more applied situations, such as degraded site rehabilitation. .

LEMs have now reached the stage of development where they can provide meaningful and useful results for both theoretical studies as well as applied settings such as post-mining landscapes. However, two significant issues for all LEMs are their (1) calibration/parameterisation and (2) validation. Before use, each model requires a set of data and parameter values which are used to define the scenarios that are being modelled. The accuracy and reliability with which these values are collected and recorded could directly impact on the precision and accuracy of the model outputs and results. Crucially, LEMs are largely calibrated with parameter values determined from present, or comparatively recent surface conditions, which may only represent recent environmental conditions yet are also the product of much longer-term geology–soil–climate–vegetation interactions. Therefore, how these parameters spatially and temporally vary as a result of climate variability, weathering and pedogenesis and the resultant soil–climate–vegetation interaction is largely speculative and a source of model uncertainty.

LEMs were initially developed to examine landscape evolution and dynamics at geological time scales but have since been employed in more applied settings such as mine sites at much shorter time scales (years, decades, and centuries). For example, the first use of landform evolution modelling to assess the stability of a post-mining rehabilitated landform design at the study site was by Willgoose and Riley (1993) using the SIBERIA landform evolution model (Willgoose et al., 1989).

This and subsequent studies have demonstrated the potential for LEMs to give insights into future geomorphic form and function and are now being applied to disturbed site assessment and rehabilitation (Willgoose and Riley, 1998; Hancock et al., 2000, 2002; Evans et al., 2000; Lowry et al., 2011; Coulthard et al., 2012). The focus of this paper and those cited above is on post-mining landforms, which are designed to bury or encapsulate mine sites, including tailings, drains, spoil tips and other industrial architecture. Post mining landforms are intended to be constructed in such a way that they remain structurally intact geomorphically stable, while being able to blend into 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 and tailings storage facilities of a de-commissioned uranium mine.

The rehabilitation of uranium mines is a particular concern as radionuclides represent a potential set of contaminants with long half-lives and persistence in the environment (Schumm et al., 1984). Australian guidelines recommend a design life for a tailings cap of a uranium mine of 200 years and a structural life of at least 10,000 years. This means the structure used to encapsulate radioactive tailings must be built to maintain its integrity from a 1 in 10,000 year rainfall event. Understanding model parameter accuracy and reliability is therefore particularly important when assessing landscapes at millennial time scales. This generates a major research question, as we have the numerical methods to simulate landscape stability over millennia, but not necessarily the correct parameter values and data sets with which to drive these predictions.

In this paper we examine three issues. Firstly, the reliability of an LEM to predict catchment form over geological time is assessed. Secondly, the range of outcomes in landscape form and function is examined based on estimated temporal parameter changes. Finally, the need for more long-term understandings based on the need for more rigorous field data for calibration and validation of these models is discussed.

2 Site description

Disturbed landscape systems offer the opportunity to examine landscape change over relatively short time scales. In particular, restoration practices allow new landscapes to be studied, something that is sometimes difficult with natural systems. The mineral lease of the Energy Resources of Australia Ltd.'s (ERA) Ranger mine is located in the Alligator Rivers Region of the Northern Territory, Australia. Erosion from the mine could potentially impact on Magela Creek and its tributaries, Corridor, Georgetown, Coonjimba, and Gulungul Creeks (Fig.~~ure~~ 1). Magela Creek debouches into the East Alligator River through a broad expanse of floodplain and wetlands listed as "Wetlands of International Importance" under the Ramsar Convention~~.~~ (Ramsar sites information services, 2014~~http://www.ramsar.org, 2003~~). The mine lease is surrounded by the World Heritage-listed Kakadu National Park.

Mine tailings are currently stored in an above ground tailings dam and in the mined-out Pit 3 (Fig.~~ure~~ 2). Pit 1 previously received tailings and is in the process of being capped. Mining from Pit 3 ceased in 2012, and milling and processing of stockpiled ore is scheduled to cease by 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 in a series of e~~E~~nvironmental r~~R~~equirements. 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). Consequently, ERA will be required to rehabilitate disturbed areas of the lease to satisfy the above requirements. Implementing these ~~requirements~~ 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.

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The regional geology of the Alligators River 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 (Needham, 1988; East, 1996~~; Needham, 1988~~). Geomorphically, the Ranger site is characterised as part of the deeply weathered Koolpinyah surface. This consists of plains, broad valleys and low gradient slopes, with isolated hills and ridges of resistant rock (East, 1996). ~~-~~Regional denudation rates for the area (0.01 to 0.04 mm y^{-1}) have been 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).

The study site is in the wet-dry tropics of northern Australia and is subject to high-intensity storms and tropical monsoons between October and April. Minimal rain falls in the remainder of the year; the annual average rainfall is 1583 mm (Bureau of Meteorology, 2015). Vegetation on the mine lease and surrounds consists of open Eucalypt forest dominated by *Eucalyptus. tetradonta*, *Eucalyptus. miniata*, *Eucalyptus. bleeseri* and *Eucalyptus. 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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3 Landscape evolution models and their parameterisation

From the 1970~~'~~s numerical models were developed to simulate processes ranging from slope wash to chemical erosion and soil development over entire catchments (Carson and Kirkby, 1972; Ahnert, 1976; Hirano, 1976; Armstrong, 1976). For further detail on the history and background of LEM's see (Tucker and Hancock, 2010). The SIBERIA landform evolution model (referred to hereafter as SIBERIA) builds on this early work and mathematically simulates the geomorphic evolution of landforms subjected to fluvial and

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diffusive erosion and mass transport processes (Willgoose et al., 1991). 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 (DEMs) for the determination of drainage areas and geomorphology and its ability to efficiently adjust the landform with time in response to the erosion that could occur on it. Since 1993, SIBERIA has been used principally to investigate surface stability of post-mining rehabilitated landforms or small catchment areas (i.e. Willgoose et al., 1991; Evans et al., 1998; Willgoose and Riley, 1998; Hancock et al., 2000, 2013 Moliere et al., 2002~~a~~).

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SIBERIA requires calibration of the sediment transport and area ~~-~~discharge relationships, and a 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. Here SIBERIA was calibrated using field data collected from the Ranger mine site (the study site) and Tin Camp Creek (the analogue site). The Tin Camp Creek site, located approximately 50 km from Ranger, is on the same metamorphosed schist formation as found at the Ranger mine and the surface properties are seen as an analogue of proposed rehabilitated landforms for the Ranger Mine in the long-term (Uren, 1992; Riley and Rich, 1998).

Calibration of the erosion and hydrology models was conducted using data of sediment loss, rainfall and runoff for discrete rainfall events that were collected from field plots. Calibration data for the Ranger site were obtained from erosion plots on the batter slope of the Ranger mine waste rock dump (Evans et al., 2000; Moliere et al., 2002). Data for a vegetated surface were collected from a similar-sized plot on the waste rock dump covered in topsoil, ripped and vegetated with low shrubs and grasses which provided approximately 90% cover (Evans et al., 1998). SIBERIA was also calibrated from field data collected from the

Tin Camp Creek~~ (analogue site)~~ catchment during rainfall events in December 1992. This resulted in three separate parameter sets which were employed in this study.

For long-term landscape assessment SIBERIA requires both fluvial and diffusive sediment transport data. The SIBERIA value for rainfall diffusivity (i.e. rainsplash) value of 0.005 m^{3}~~/~~ s^{-1} ~~/~~m^{-1} (width) was used as this has been found to be the most applicable for the Alligator Rivers Region which includes the Ranger site (Hancock et al., 2002~~14~~). The field data parameter values determined for these surfaces are shown in Table 1. The methodology employed in the derivation of the parameters for the different surfaces is described in Evans and Willgoose (2000), Evans et al. (2000) and Moliere et al. (2002).

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4 Catchment digital elevation models, model setup and landscape assessment

Several small catchments will drain from the proposed possible landform at Ranger and here we focus on the Corridor Creek catchment that drains into Magela Creek. (Fig.~~ure~~ 2). The DEM was calculated from two datasets. Firstly, a 2~~two~~-m~~etre~~ contour interval dataset representing the current landform surface was produced from a LiDAR survey of the mine in 2010. This was supplemented by an additional two-metre contour interval dataset that represented the proposed rehabilitated landform design. The LiDAR contours outside of the rehabilitated landform area were combined with the contours representing the proposed rehabilitated landform area and used to produce a grid surface with a horizontal resolution of 2~~two~~ m~~etres~~. The DEM representing the rehabilitated surface was resampled to a horizontal spatial resolution of 10 m. This was chosen as being the optimal resolution at which SIBERIA could function within the spatial extent of the study catchment, and over the temporal periods modelled yet still reliably capture the salient features of hillslope geomorphology (Hancock, 2005). The final DEM used in this study was understood to represent a fully consolidated

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landform, from which there would be no subsidence or settlement. Other factors such as mass failures were not considered.

Simulations were run using Waste Rock Dump (WRD), Vegetation and Tin Camp Creek parameters described earlier in Section 3. For the WRD and Tin Camp Creek data the same parameters are used unchanged for the entire simulation length. However, for the Vegetation parameter simulations, the landscape output from the WRD simulation at 10 years was used as the starting point of the simulation. This 10-year period represents the time required for a stable vegetation cover to develop. The Vegetation parameters then remain unchanged for the duration of the simulation.

Short et al. (1989) estimated that the surrounding undisturbed landscape (termed the Koolpinyah surface) is approximately 300,000 years old. Therefore, to allow an equivalent landscape to develop and to examine long-term landscape trends and geomorphic change, SIBERIA was run for 500,000 years. Outputs from the model included a DEM of the catchment and sediment discharge at annual time steps (here we examine DEMs at 1,000, 10,000, 100,000, 500,000 years) as well as geomorphic descriptors of the catchments (hypsometric curve, area–~~-~~slope relationship, cumulative area distribution and width function).

The hypsometric curve (Langbein, 1947) is a non-dimensional area–~~-~~elevation curve, which allows a ready comparison of catchments with different area and steepness. The hypsometric curve has been used as an indicator of the geomorphic maturity of catchments and landforms. For example, Strahler (1952,~~;~~ 1964) divided landforms into youth, mature and monadnock characteristic shapes, reflecting increasing catchment age.

The area–~~-~~slope relationship is the relationship between the areas draining through a point versus the slope at the point for fluvial landscapes. It quantifies the local topographic gradient as a function of drainage area such that

$$A^{\alpha} S = \text{constant} \qquad (1)$$

where A is the contributing area to the point of interest, S is the slope of the point of interest and α is a constant (Hack, 1957; Flint, 1974; Willgoose, 1994). It is generally recognised that the log–~~-~~log positive slope region at small catchment areas describes the diffusive dominated (i.e. rainsplash) areas of the catchment, while the log–~~-~~log negative region represents fluvial areas of the catchment.

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The cumulative area distribution (CAD) has been used as a means of characterising the flow aggregation structure of channel networks (Rodriguez et al., 1992; LaBarbera and Roth, 1994; Pereira and Willgoose, 1998). The CAD, similar to the area–~~-~~slope relationship, provides the ability to examine the relationship between diffusive and fluvial processes. Small catchment areas generally have a convex profile (representing the diffusive dominated region of the catchment) which then becomes log–~~-~~log linear as area increases and represents the fluvial dominated area of the catchment.

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Originally developed by Surkan (1968), the width function describes the number of drainage paths (whether they be channel or hillslope) at a given distance from the basin outlet, measured along the network (Naden, 1992)~~ (Figure 9)~~. This approach is taken as that SIBERIA does not differentiate between channel and hillslope cells here. The width function is a measure of hydrologic response since it can be strongly correlated with the instantaneous unit hydrograph. If it is assumed that rainfall excess is routed with a constant velocity, then the width function can be linearly transformed into the instantaneous unit hydrograph.

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5 Results

5.1 Qualitative visual assessment

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Using the WRD parameters for the entire simulation produces a landscape that visually (or qualitatively) looks geomorphically feasible for all time periods (Fig.~~ure~~ 3). That is, the model produces a catchment which has realistic hillslope length and curvature together with a drainage network that realistically fills the domain (i.e. there are no sharp breaks in slope or illogical or unrealistic landscape features). While considerable erosion has occurred at 1000 years in the form of gullies, at 10,000 years these gullies have evolved into rounded hills and channels. The eroded hillslope material has been deposited in the main channel bottom with flat expanses of deposition clearly evident. Over time the landscape continues to erode and after a simulated period of 100,000 years has considerably lowered with the incised channels being replaced by rounded low hills. The depositional material in the main channel has been reworked and has a system of low hills and channels. While no incision is evident on the hillslope, there is incision in the depositional material on the valley floor demonstrating that the system is still dynamic and evolving. At 500,000 years the catchment consists of a series of low hills with relatively consistent relief and uniform hillslope shape. A small poorly incised channel is evident in the valley bottom.

The simulation using the Vegetation parameters (Fig.~~ure~~ 4) produces incised channels at 1000 years but these are not as deep or as well defined as the WRD simulation. At 10,000 years, the channels have become well-defined channels with deposition present in the main channel bottom. At 100,000 years the catchment has developed well-rounded hillslopes with the depositional material on the valley bottom being reworked. At 500,000 years, similar to the WRD simulation, the landscape has evolved into a catchment of relatively low relief with a series of low well rounded hills.

While not displayed here for brevity, the simulation using the Tin Camp Creek parameters displays similar behaviour to that of the WRD and Vegetation parameter simulations. Visually there are no striking differences between the simulated catchments. However, all have qualitative differences in both hillslope form. They have different relief, location of hills and valleys as well as the morphology of the depositional area in the main channel. Therefore, the three different parameter~~s~~ sets produce qualitatively different landscapes with unique hillslope length, shape and position. Importantly, each modelled landscape output is not geomorphically impossible.

5.2 Quantitative assessment – sediment output

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In terms of erosion and landscape lowering, the maximum depth of erosion is 11.8~~ m~~, 2.5~~ m~~ and 10.3 m for the WRD, Vegetation and Tin Camp Creek parameter simulations at 10,000 years, respectively (Table 2). This indicates a substantial difference that may be especially relevant for areas where contaminants are buried

Simulated sediment yields from the catchment are highly variable but decline through time for all simulations (Fig.~~ure~~ 5). For the WRD parameters, over the first 50,000 years the sediment output is comparatively high and for much of this period well outside the upper range for natural sediment output; ~~(~~the expected sediment output from the catchment is 30–~~-~~120 m^3~~/~~ year^{-1} based on a denudation rate of 0.01–~~-~~0.04 mm y^{-1} and corrected for catchment area). However, after approximately 100,000 years, sediment output has declined and the mean is within that of the expected sediment output range, though some peaks above this range still exist.

The Vegetation parameter simulations display considerable variability particularly over the first 50,000 years where there are sustained periods where the sediment output is above that of the expected output. After this period, the sediment output is largely within that expected by the regional denudation rates.

A similar pattern occurs for the Tin Camp Creek simulation which has high sediment yields for the first (approximately) 125,000 years and then reduces to within or less than that of the expected output range from the denudation rates. However, the sediment yield from this parameter set has considerably less variability than that of the WRD parameter simulation.

The three different parameter sets therefore produce distinct sediment outputs. All three predicted sediment outputs are plausible results if the surface and materials characteristics remain unchanged and climate is constant for the duration of the simulation.

5.3 Quantitative assessment – catchment geomorphic descriptors

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In this study, we found little difference in the hypsometric properties for the WRD, Vegetation and Tin Camp Creek parameter simulations up to 10,000 years (Fig.~~ure~~ 6). At this time there has been insufficient erosion to change catchment area–~~-~~elevation form. At 100,000 years, both catchments (WRD and Vegetation parameters) display hypsometric curves which have mature landscape characteristics. ~~–~~At 500,000 years, the WRD and Vegetation parameter simulations have mature landscape curves while the Tin Camp Creek parameter curve has monadnock form. Overall, the hypsometric curve demonstrates that there has been significant area–~~-~~elevation change over the 500,000 year modelled period with the three parameter sets producing different area-elevation form.

The area–~~-~~slope relationship for the WRD parameter set is relatively constant for the first 10,000 years after which a reduction in slope can be observed particularly at the termination of the simulation at 500,000 years (Fig.~~ure~~ 7a~~, top~~). This, like the hypsometric curve suggests that it takes millennia for any real change to be observed in catchment area–~~-~~slope properties. Similar temporal patterns were observed for the Vegetation and WRD parameter simulations (not displayed here for brevity).

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At the end of the modelled period the area–~~-~~slope relationship for the WRD, Vegetation and Tin Camp Creek parameter simulations all display unique characteristics with both slope of the diffusive and fluvial regions being different (Fig.~~ure~~ 7~~, bottom~~). The area–~~-~~slope relationship for the WRD, Vegetation and Tin Camp Creek parameters all have positive, yet different slopes for areas approximately less than 1000–~~-~~2000 m^2 while at areas approximately greater than 1000–~~-~~2000 m^2 both data sets (WRD and Vegetation) ~~-~~have a negative (yet different) log–~~-~~log linear slope. Differences in all three area–~~-~~slope plots result from the different model parameters. Interestingly, despite the same diffusivity parameters being applied for all simulations, the diffusive area of the curve is different and reflects the complex interaction between the evolving landform and the diffusive and fluvial parameters. For example, the WRD parameters are more erosive while the Vegetation parameters are considerably less erosive. The WRD parameters may produce incision (gullies) which have steeper slopes which will have higher diffusion (as the diffusion model is slope dependent). The reverse occurs for the Vegetation parameters.

The CAD for the WRD parameter simulation (Fig.~~ure~~ 8) demonstrates a change in the diffusive and fluvial area of the hillslope at 10,000 years with the distribution remaining largely the same for the remaining duration of the simulation. The CAD for the WRD, Vegetation and Tin Camp Creek parameters all display different distributions at the termination of the simulation at 500,000 years in both the diffuse and fluvial regions of the curve. Interestingly, the Vegetation parameter simulation has a more rounded or convex distribution while the Tin Camp Creek parameter simulation is largely log–~~-~~log linear with positive slope in the diffusive area of the curve. The extent of the diffusive region also varies for all three parameter sets. For the fluvial region, the slopes are all similar;~~,~~ however, the maximum area varies for all three simulations. This demonstrates that all three have different area-aggregation patterns (also demonstrated below with the channel network and the width function).

All three landscapes generate unique width functions (Fig.~~ure~~ 9). Interestingly the width function initially displays a high value but this peak reduces and distance increases with a maximum distance at 10,000 years for the WRD and Vegetation simulations (Fig.~~ure~~ 9). Post 10,000 years the distance begins to reduce and peak increases. However the Tin Camp Creek width function rapidly reduces in width and increases distance and stays relatively fixed for the duration of the simulation. This demonstrates that even though the catchment boundary is fixed, the drainage network continually evolves producing unique drainage networks (Rigon et al., 1993). The results also suggest that the movement and delivery of sediment routed through the network will be different for the modelled landscapes. This corresponds well with the different sediment output described in Section 5.2. This demonstrates that the hydrological behaviour of the catchments will be spatially and temporally unique.

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The assessment using these geomorphic descriptors demonstrates that all three are distinct catchments with different geomorphological properties as well as individual sediment transport and runoff properties. However, they are all plausible entities in their own right if it is assumed that the surface and material properties remain constant and climate has limited variability.

6 Discussion

LEMs have been tested across a range of climates and landscapes. It is broadly agreed that they are qualitatively reliable at decadal to multi-decadal time scales. The results presented within this study support this assumption, as they demonstrate that the simulated landscapes produced using static parameter sets are geomorphologically realistic and possible.

Importantly, the modelling used the best available input parameter data determined from field plots, ~~(~~from a range of different surface options, ~~)~~ to evaluate long-term landscape trajectory. Therefore, we have examined the potential range of outcomes based on data from current surfaces which we believe may represent future outcomes.

In the sections below, long-term model predictions and equifinality, landscape form and sediment output together with the development of long-term understandings are discussed.

6.1 Long-term prediction and equifinality

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While LEMs have been used in the past to assess landform designs for mine closure, they have rarely been run and assessed at time scales greater than 1000 years for synthetic or anthropogenetically designed and constructed landscapes. The landform in this study was modelled for a simulated period of 500,000 years which represents a significant amount of time for geomorphic change to occur. Using three parameter sets that represent the surface characteristics of a potential rehabilitated surface, results in three unique landforms. While visually similar, the analysis of the results showed that the simulated catchments are geomorphically different at the end of simulation. Area–~~-~~elevation (hypsometry), area–~~-~~slope and distribution of areas (CAD) vary and, are unique both during and at the end of each simulation. Additionally, the channel network is highly variable, demonstrating that the location of the drainage network will vary as well as amount and timing of runoff.

The findings suggest that here there is no equifinality in landscape form. The employment of different parameter sets produce geomorphically and hydrologically unique landscapes throughout their entire evolution. Therefore, parameterisation is important for landscape evolution model predictions. While at relatively short (<10,000 years) time scales the differences in hillslope form are minimal (as described by the hypsometric curve, area–~~-~~

slope and cumulative area distribution) there are large differences in sediment output. Obtaining the correct parameter set is vital for reliable long-term prediction for applied situations.

6.2 Landscape form and sediment output

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The sediment output displays considerable temporal variability with unique patterns for each parameter set (Fig.~~ure~~ 5). The simulations demonstrate that all landforms will be delivering sediment to the surrounding natural system at rates higher than that of the natural system. Importantly, this work demonstrates how models can provide an estimate of the inherent variability observed in catchment systems (Coulthard et al., 2002,~~;~~ 2012,~~;~~ 2013). We show that there is considerable variability in sediment output from a numerical model where no random bias has been included (Hancock, 2012).

However, there are some caveats on the above statements. The findings suggest that a period may be required for the model to generate sediment output similar to the present day as the initial surface roughness in the DEM (potential error and random roughness) may initially produce increased levels of sediment output. Such error and its e~~a~~ffect is impossible to quantify. In this study, the initial DEM was not smoothed or pit filled before use and was used as supplied by ERA as this is the same level of accuracy/precision that would be supplied to the earth moving contractors to construct the landform. How surface roughness or subtle changes in topography influence landscape evolution is an area for future work.

A further issue is the direction and path that water and sediment flows over the landscape surface and how it is modelled (Garbrecht and Martz, 1997). To examine this issue a simulation was run using WRD parameters and the DInfinity (Tarboton, 1987) drainage direction algorithm (Fig.~~ure~~ 10). Similar to the WRD, Vegetation and Tin Camp Creek results, the landform at 500,000 years displays a unique distribution of hillslope shape and channel position and also has a unique sediment output. Therefore choice of drainage direction model has an effect (Tarboton, 1987; Garbrecht and Martz, 1997). How other models and drainage routing functions influence landscape evolution is an area for future work~~ (and is discussed further in Section 7)~~.

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Good point! Deleted

However, for all simulations examined here, over the shorter runs (i.e. 0–~~-~~10,000 years) there is little difference in qualitative and quantitative landscape form largely because the landscape has not sufficiently eroded for any change to be detectable by these measures. These geomorphic measures (hypsometric curve, area–~~-~~slope relationship, CAD and width function) are not sensitive to small changes in landscape form at 10,000 years. However, where large changes have occurred they are quite useful. Interestingly, the width function provides some insight into network hydrological change.

While not examined in detail in this study, a further complexity is the relationship between fluvial and diffusive erosion. The results suggest that the relationship between diffusive and fluvial processes is complex and that determining the correct parameter sets is very important particularly for long-term simulations (see Willgoose et al., 1991 for a description of the fluvial and diffusive transport equations and their relationship). We have used the same diffusivity parameters for all simulations but vary the fluvial erosion parameters based on defensible field based parameters. Changes in rainfall intensity and resultant diffusivity will have a large impact on landscape form (Hancock, 2012). Hancock et al. (2002) showed that an absence of diffusion will produce landscapes that have linear erosion features with sharp edges while a large value of diffusion produces a landscape with overly rounded hillslopes. The impact of changing diffusivity on erosion and landscape evolution in a region where there is a predicted increase in rainfall intensity is an area of further research (Tucker and Hancock, 2010).

Another significant issue is that these parameters were derived from a set of rainfall events that are believed to be average or representative seasons. Are these seasons representative for the determination of parameters for models that run at millennial time scales? Further, the use of WRD parameters in particular for the entire simulation assumes that any landscape erosion surface properties are static and do not evolve. In reality, this assumption is quite unrealistic as the freshly shaped surface will evolve into a soil in conjunction with influence of vegetation as it establishes and forms a new soil–~~-~~vegetation–~~-~~climate evolutionary path. However, this simulation using static WRD parameters provides an end member of possible landscape scenarios.

Models such as SIBERIA have the advantage that they dynamically adjust the hillslope in response to erosion and deposition, a process presented here with the erosion of the hillslope and channel becoming a depositional area and then over time this depositional material being reworked. Therefore, the model is not geomorphically static and attempts to capture hillslope behaviour. However, what these models lack is a further coupling to long-term climate and the resulting influence of long-term soil-vegetation interactions.

6.3 ~~The d~~Development of long-term understandings

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The single biggest issue for the employment of LEMs is that of parameterisation. These models are based on parameters derived largely from the present. At 100 year time scales and longer, with the cyclicity of climate, how realistic is it to run models with limited or no climatic cyclicity? In many aspects the models now have more functionality than we have field data with which to calibrate and validate their inputs and outputs. Field processes could be better incorporated into models if they were better understood and quantified. This requires more field and laboratory data input particularly if these models are to be used outside of their initial calibration period.

At present the best calibration available for the reliable employment of LEMs at this site comes from plot studies over a number of years (see Section 3). This has the advantage that it provides input data for the current surface material, climate as well as soil–climate–vegetation interaction. However, this type of data clearly provides little insight into the longer term soil–vegetation–landscape trajectory, especially where climate is expected to change (CSIRO, 2007). Natural analogues also provide opportunity (Tucker, 2009).

There are many mines around the world that will continue to operate for many decades. Many of these sites lack specific long-term data for landscape planning. The issues raised here could potentially be addressed through the establishment of a series of plots, which are designed and setup so that long-term data to support rehabilitation can be provided (Gerwin et al., 2009). An alternative approach is to examine sites that have been abandoned and or rehabilitated. There has been little attempt to examine pedogenesis, surface armour and vegetation development and how this influences erosion and landscape development on former abandoned sites as we only now have developed the numerical models capable of using this information (Cohen et al., 2009; Vanwalleghem et al., 2013; Minasny et al., 2015; Temme et al., 2015). There are many rehabilitated and or abandoned sites that are several decades old which could provide robust quantifiable data on the trajectory of these transient landforms (Gerwin et al., 2009; Hancock et al., 2000, 2006).

Comment [A17]: There are two “Hancock et al. 2006” in the reference list. Which one?

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7 Future issues and conclusions

While model input parameters are static, climate and the soil–vegetation interaction clearly are not. Similarly, while a rehabilitated landscape will have different dimensions to that of the pre-mine landscape and be constructed of essentially different materials, it is unreasonable to assume that a new landscape will behave in a similar way to that of the past. Yet the model parameterisation is based on the initial soil–vegetation interactions. Therefore, how valid is any prediction at time~~s~~ scales any longer than that of the period at which the parameters were derived?

The important question for mine planners and regulators is which simulated landscape is the correct one. Firstly, given the limited parameter data sets available and our understanding of climate, all predictions are equally valid. However, the actual result is likely to be a mix of all parameter data sets together with other complex unknown influences relating to vegetation-climate interactions that influence pedogenesis. Secondly, while the surface is unlikely to maintain its waste rock characteristics over the modelled period, it is equally unlikely that vegetation will remain constant. The likelihood that the material will evolve to a Tin Camp Creek type landscape is unknown. Both vegetation change as well as the regular occurrence of fire is likely to influence erosion and therefore landscape evolution in this (and any) environment. Finally, in terms of the worst case scenario, the WRD parameter simulation is likely to provide the most conservative outcome of the three scenarios examined here.

A significant advance is that pedogenesis models (Cohen et al., 2009; Vanwalleghem et al., 2013; Minasny et al., 2015; Temme et al., 2015) can now be incorporated into LEMs. However, field data with which to reliably parameterise or validate them is not currently available. Future long-term landform evolution simulations and predictions will need to address questions such as (1) how and at what rate does a surface armour form? (2) At what rate and by how much does surface armour reduce erosion? (3) What is the weathering process and rate down the soil profile and will layers form? (4) How does vegetation interact with this armouring-weathering and soil formation process? We now have the models (or the capability of developing the models if we understood the process) but not the field understandings or data with which to calibrate and validate any output.

This, therefore, leads to the question as to what LEM model is the most correct or reliable. There are a number of models with different approaches available (see Tucker and Hancock, 2010). A Monte Carlo type approach may be needed where all elements contributing to landscape evolution are employed. This includes both models and parameters sets. While the SIBERIA model is one of the most used and tested of the LEMs available, is this model and its predictions correct? The authors in recent years have evaluated other models such as CAESAR, CAESAR-Lisflood together with soil erosion models such as the RUSLE (Renard et al., 1991) and found that for the landscapes and parameters sets examined the models produce similar outcomes within broad error bands. Full evaluation may lead to an approach where all available LEMs are employed using all available data for a series of initial conditions and predictions made by providing a range of possible outcomes which utilise models based on their individual capacity and focus. This approach would be similar to that employed by the climate modelling community and programs such as the Coupled Model Intercomparison Project (Covey et al., 2003). This approach would go some way to addressing the issue of reliability of long term predictions.

Comment [A18]: Please cite an article so that interested readers can understand this. I suppose most readers do not know this.

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Acknowledgments

We thank the traditional owners of the land where the study site is located, Parks Australia North, Northern Land Council and current and former Supervising Scientist staff, especially Wayne Erskine, Michael Saynor and Alana Mackay. ERA staff provided the DEM used in this study. Conversations with Brian McGlynn and team at Duke University are acknowledged.

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Comment [A19]: This is probably not cited (NC hereafter). Note: 2015 is cited.

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Comment [A21]: The order of et al. papers does not depend on the 2nd author name but year.

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Comment [A23]: See my previous comment. Two papers of Hancock et al. (2006) here.

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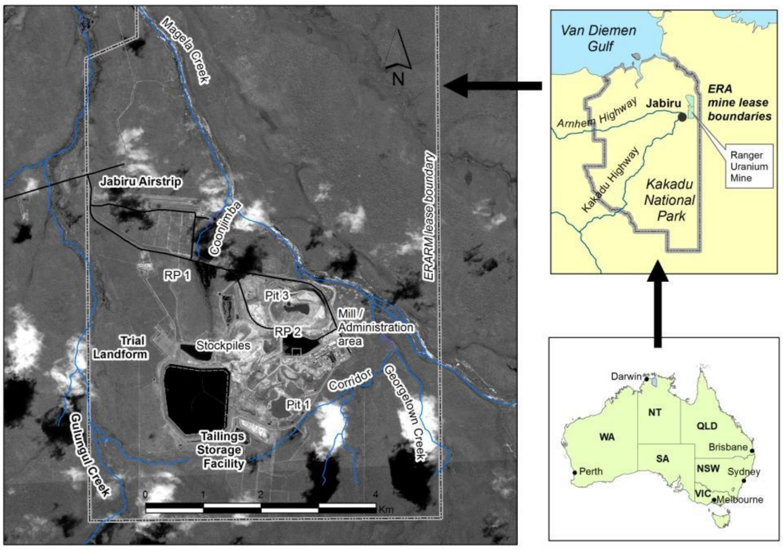

Figure 1. Location of the study site. For brevity, the letters RP represent Retention Pond. The site is located approximately 300km west of Darwin.

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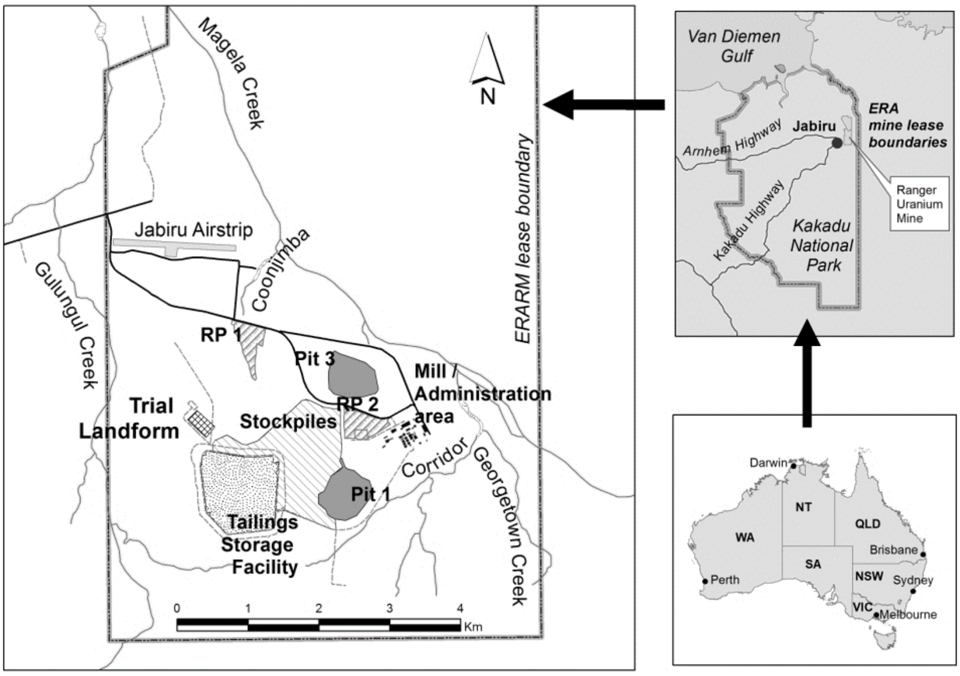

Comment [A26]: Please avoid overlapping of text labels with other symbols such as lines. About 10 cases are found in the map on the left; two cases in the upper right map.

Fig.~~ure~~ 1.

Location of the study site. For brevity, the letters RP represent Retention Pond. The site is located approximately 300km west of Darwin.

~~Location of the study site.~~

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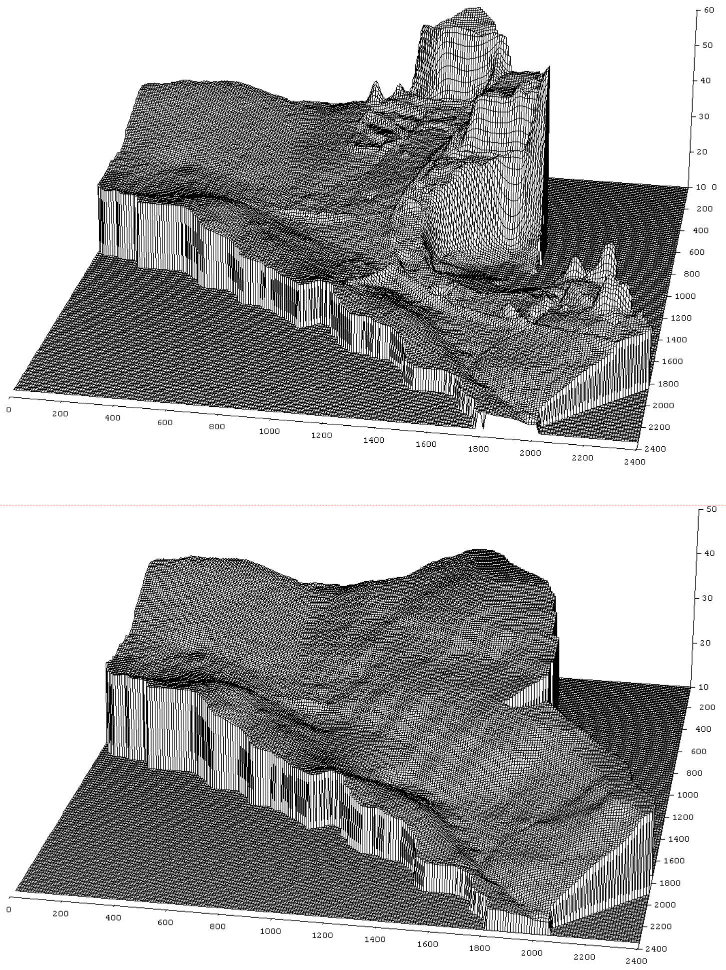

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Fig.~~ure~~ 2. Digital elevation model (10 m grid) of the current mine site with mined out pit (a~~top~~) and potential rehabilitation design (b~~ottom~~). All dimensions are metres.

Comment [A27]: Please add labels "a" and "b" at the upper left of each subfigure. The same applies to Figs. 5 to 10.

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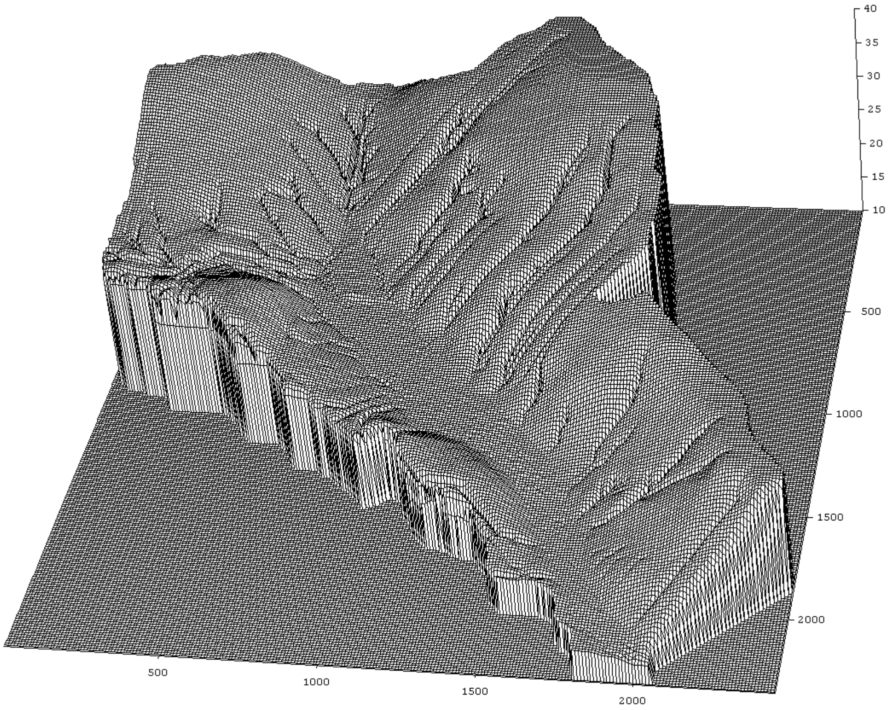
(a) 1000 years



~~(a)~~(b) 10,000 years

~~(b) 1000 years~~

(c) 100,000

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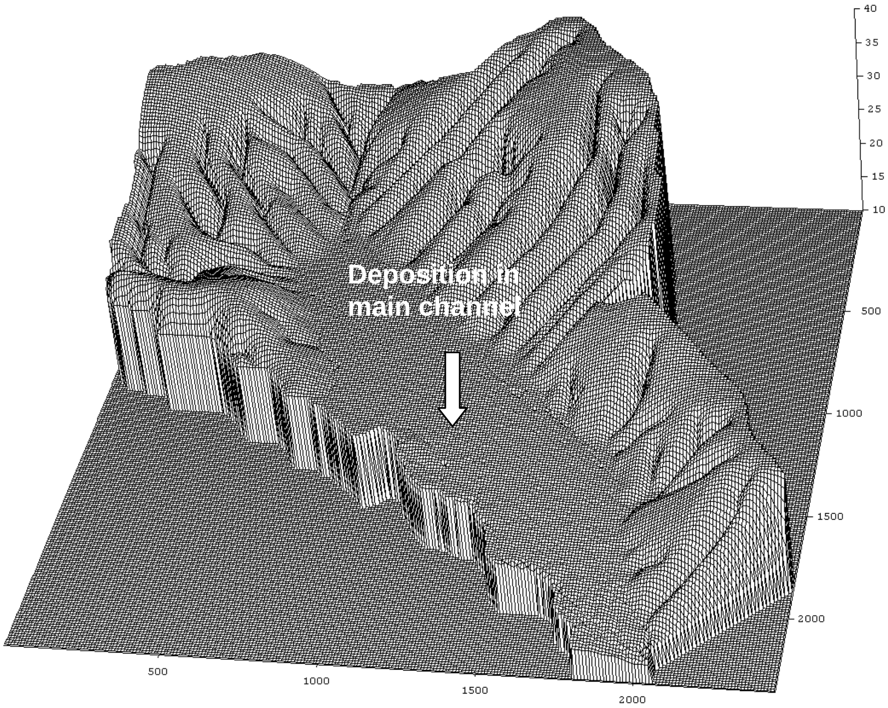

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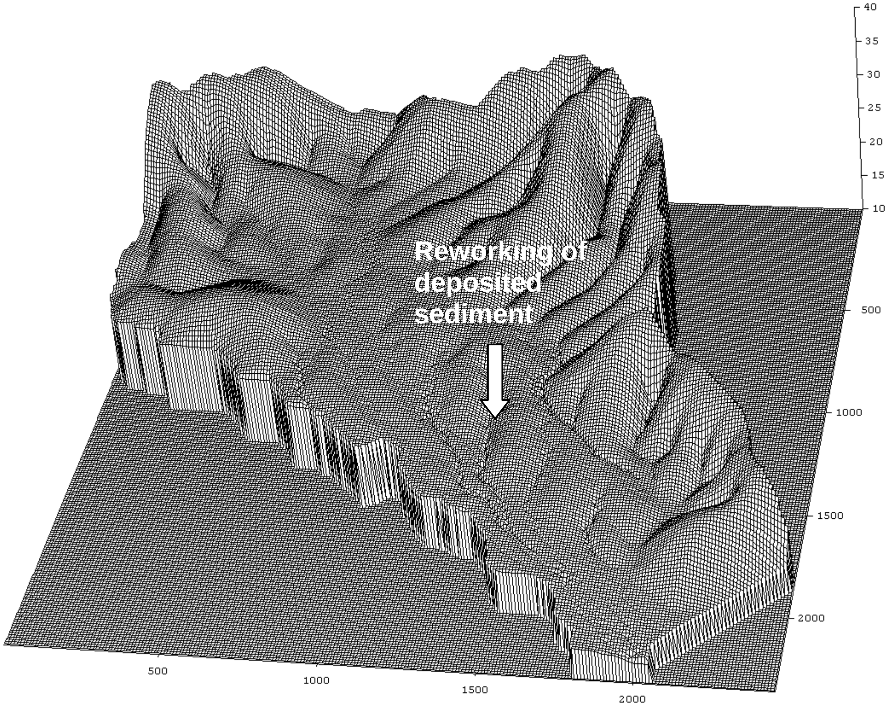

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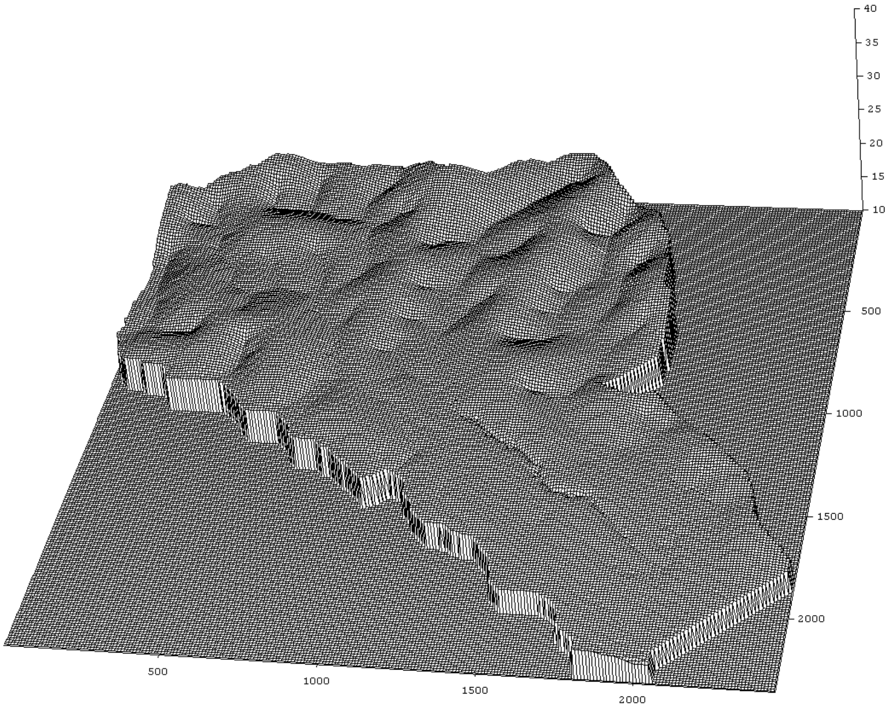

~~(e)~~(c) ~~500,000 years~~

Fig.~~ure~~ 3. Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years using the SIBERIA model and Waste Rock Dump parameters. All dimensions are metres.

(a) 1000 years

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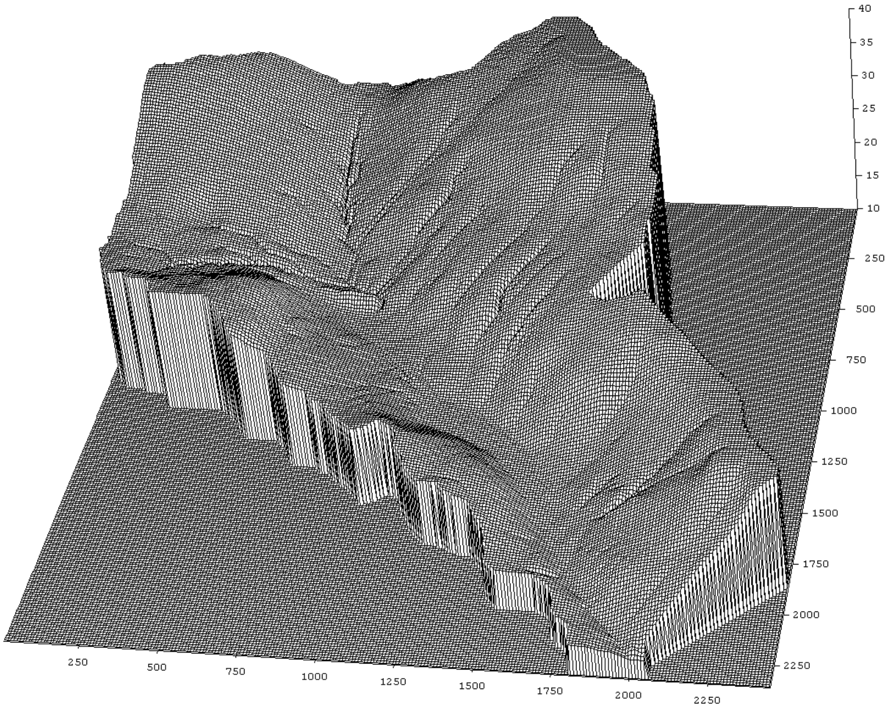

~~(a) 1000 years~~

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(b) 10,000 years

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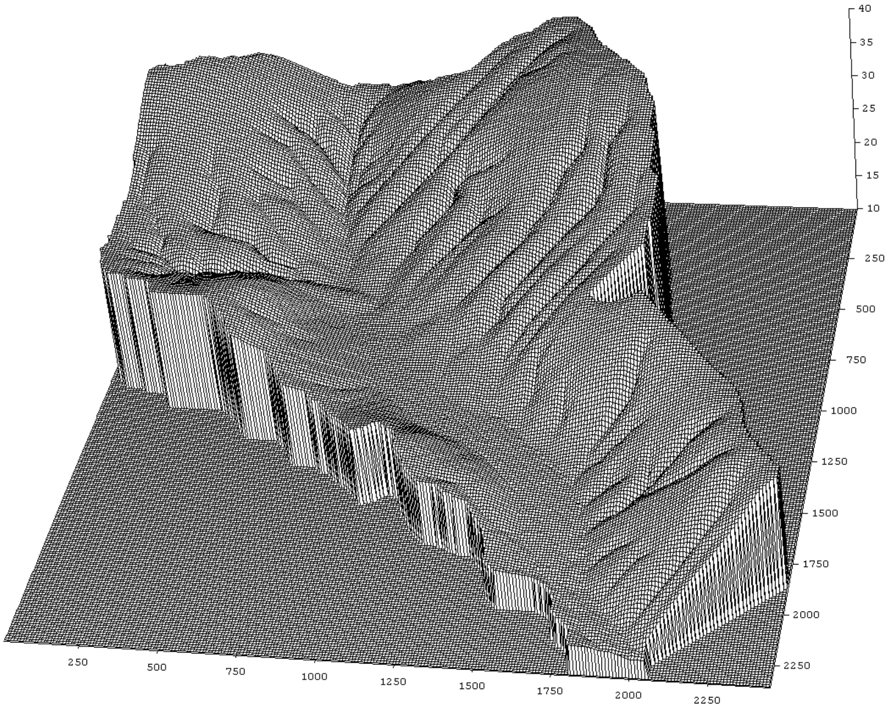

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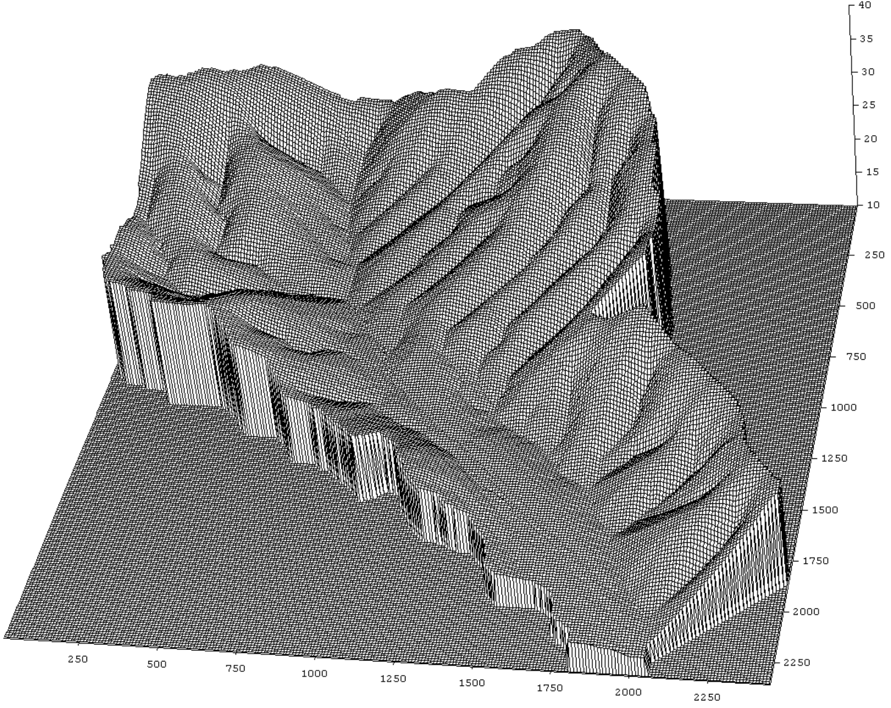

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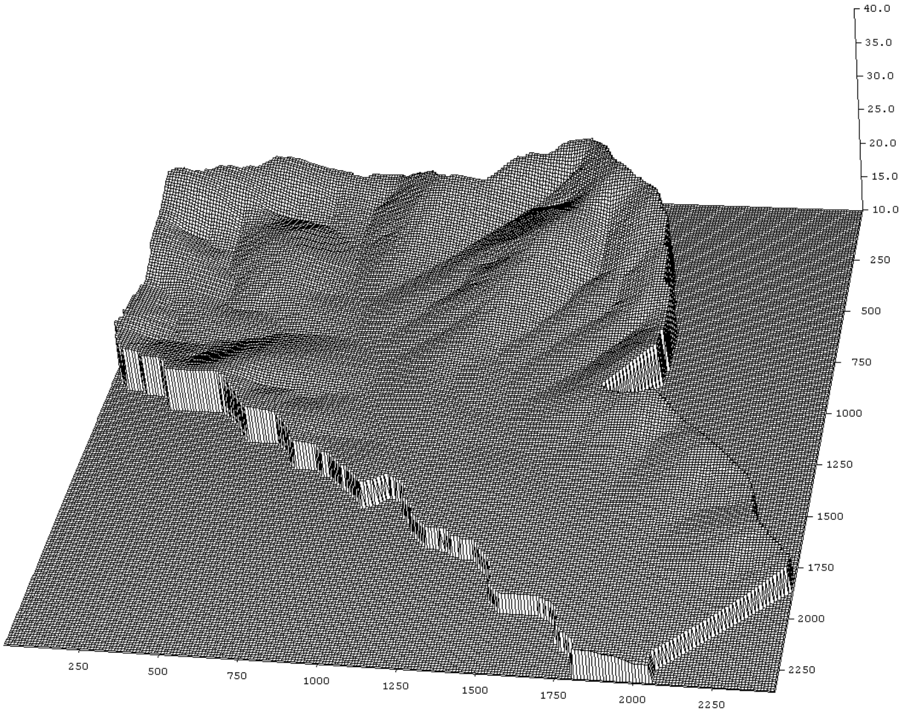
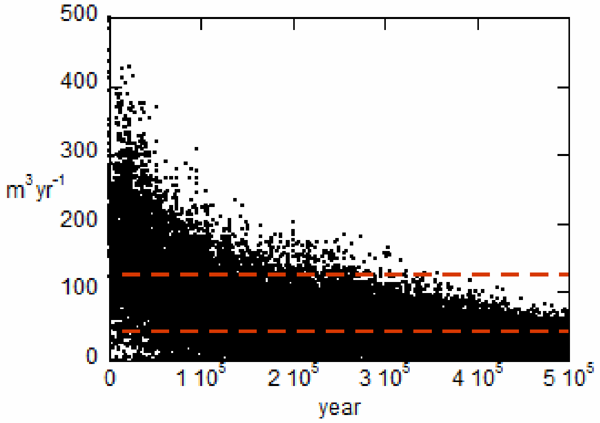


~~(d) 500,000 years~~

Fig.~~ure~~ 4. Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years using the SIBERIA model and Vegetation parameters. All dimensions are metres.



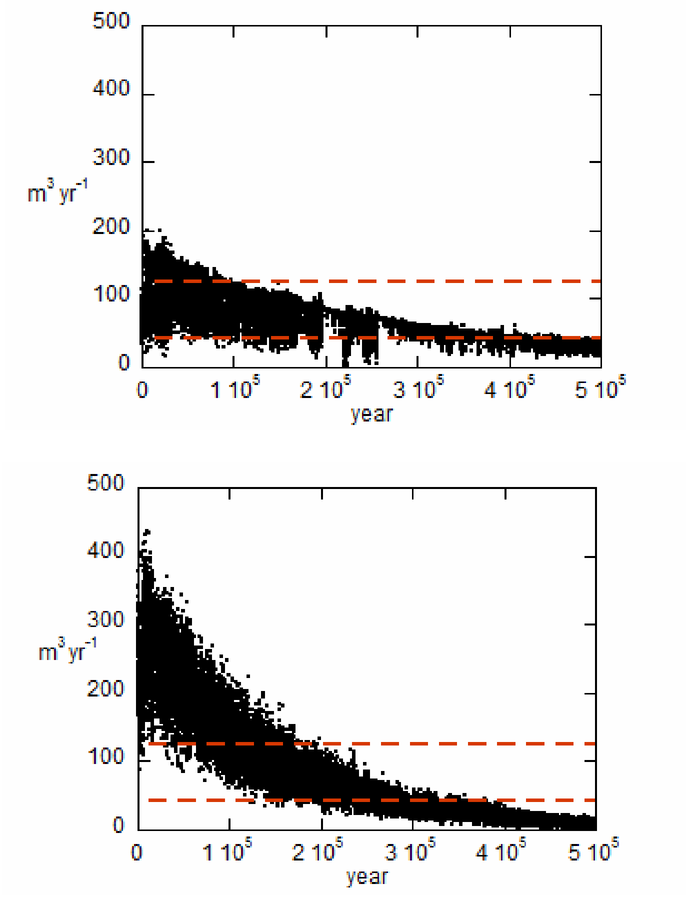


Fig.~~ure~~ 5. Simulated annual sediment discharge and average annual elevation from Corridor Creek landform using Waste Rock Dump (a~~top~~), Vegetation (b~~middle~~) and Tin Camp Creek parameters (c~~bottom~~). The red line represent the range of sediment discharge as predicted from the regional denudation rates of 0.01—0.04 mm y^{-1} (30–~~-~~120 $m^3\ y^{-1}$). For clarity, each year represents an average of 10 years sediment output.

Comment [A30]: Y-axis labels only show the unit. This is strange. Please write what the values are. This also applies to the lower graph of Fig. 10. Also see the next comment.

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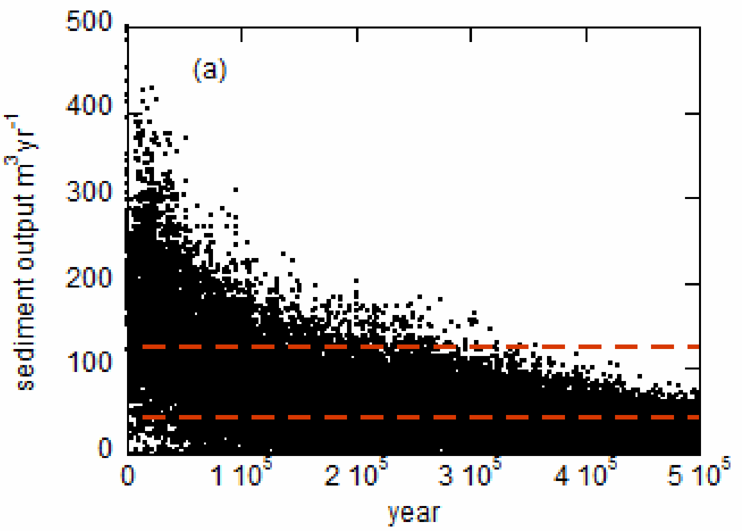

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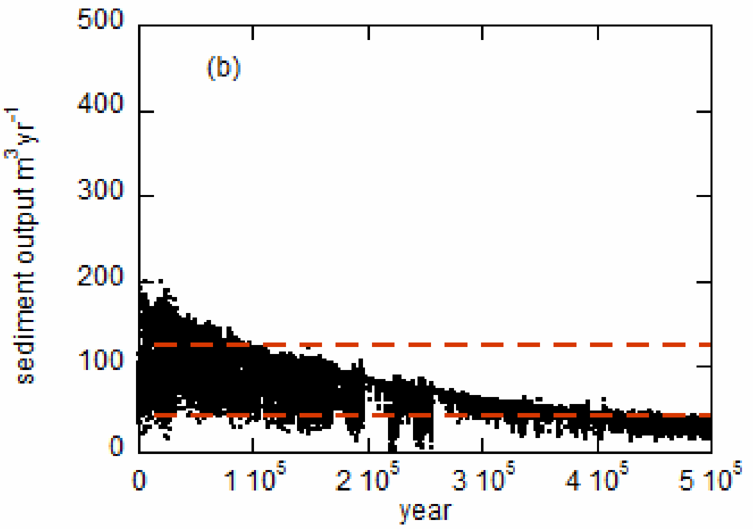

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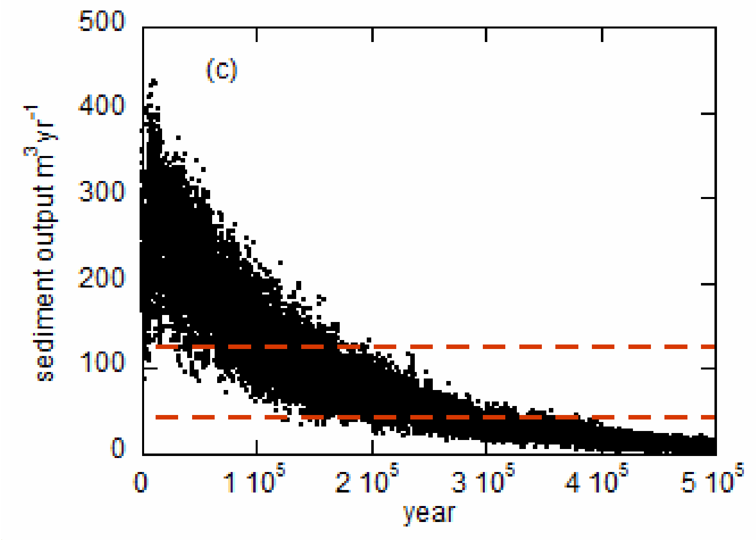

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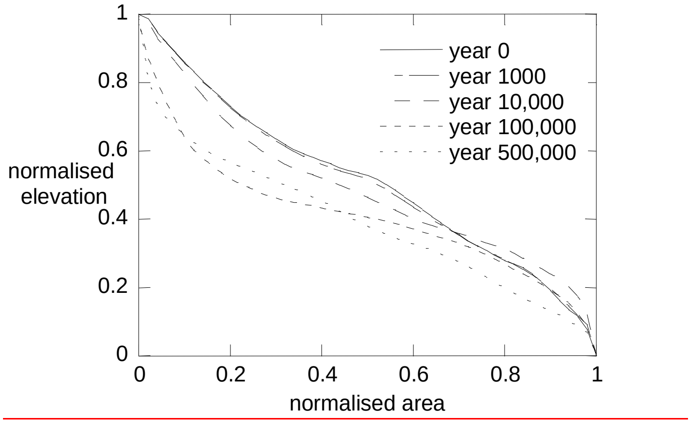
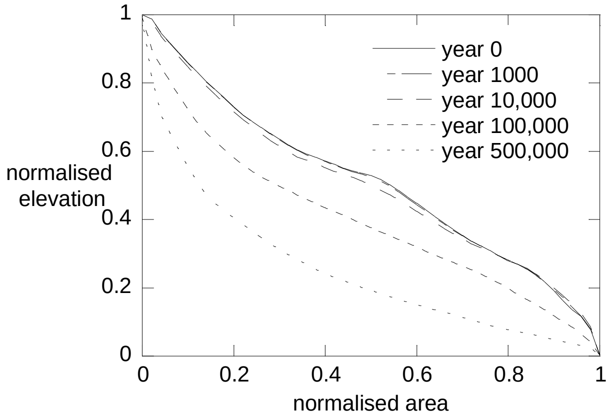
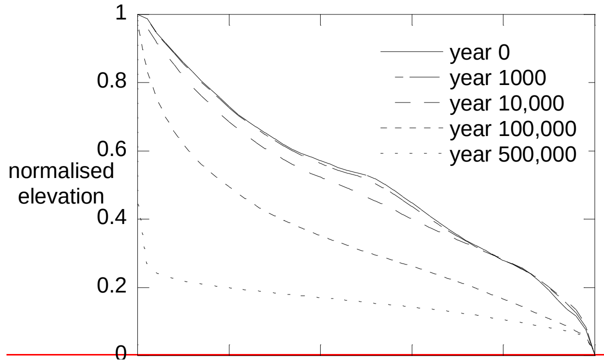
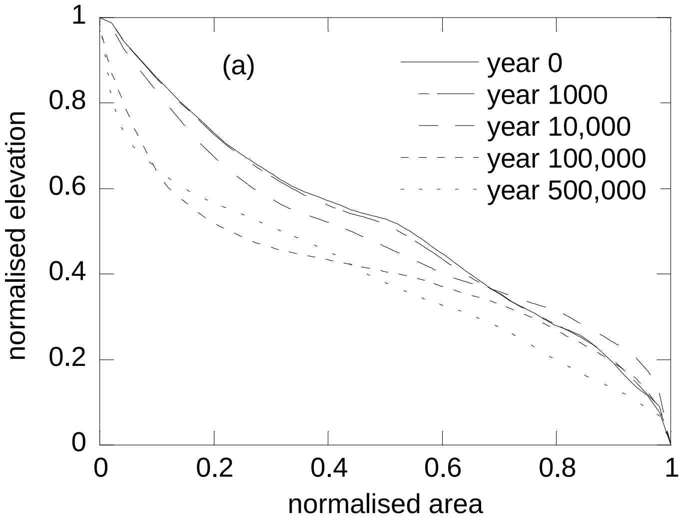
Fig. 5. Simulated annual sediment discharge and average annual elevation from Corridor Creek landform using Waste Rock Dump (a), Vegetation (b) and Tin Camp Creek parameters (c). The red line represent the range of sediment discharge as predicted from the regional denudation rates of 0.01–0.04 mm y^{-1} (30–120 m^3 y^{-1}). For clarity, each year represents an average of 10 years sediment output.

Comment [A31]: Y-axis labels only show the unit. This is strange. Please write what the values are. This also applies to the lower graph of Fig. 10. Also see the next comment.









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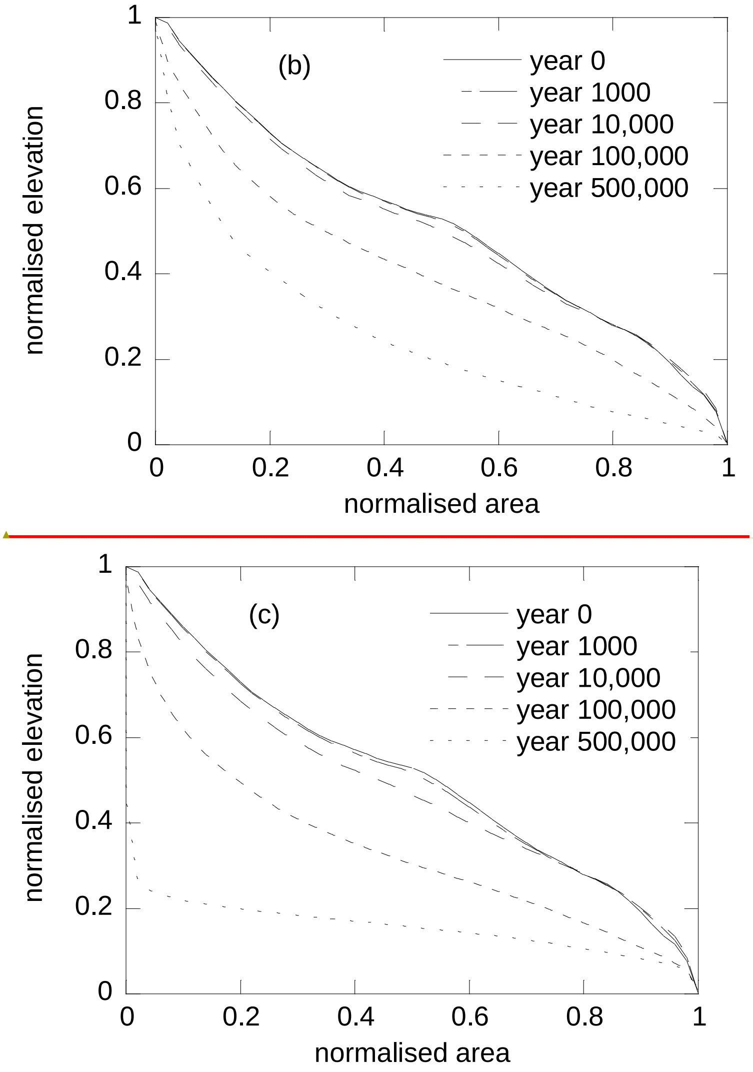

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Fig.~~ure~~ 6. Hypsometric curves for the Corridor Creek catchment using Waste Rock Dump (a~~top~~), Vegetation (b~~middle~~) and Tin Camp Creek parameters (c~~bottom~~).

Comment [A32]: The Y-axis labels are put horizontally but it is strange. Please put them vertically, as you did in Fig. 7. This also applies to Figs. 5, 8 and 9.

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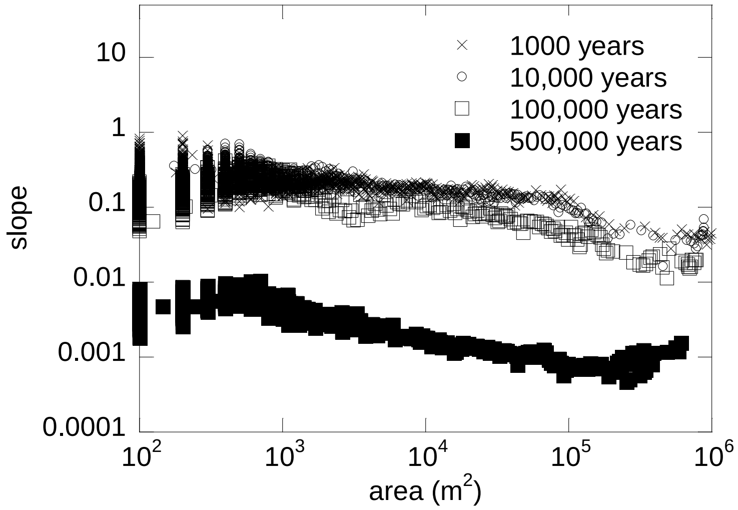
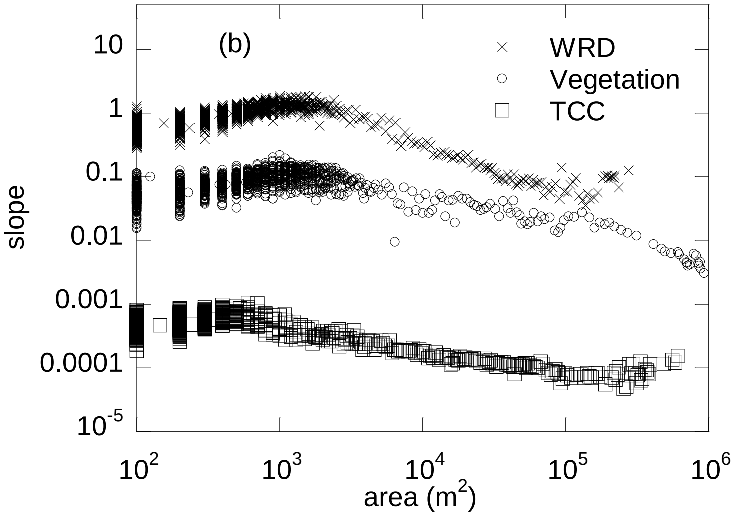

1000 years
10,000 years
100,000 years
500,000 years
slope
10
1
0.1
0.01
0.001
0.0001
10^2
10^3
10^4
10^5
10^6
area (m^2)


(b)
WRD
Vegetation
TCC
slope
10
1
0.1
0.01
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0.0001
10^{-5}
10^2
10^3
10^4
10^5
10^6
area (m^2)

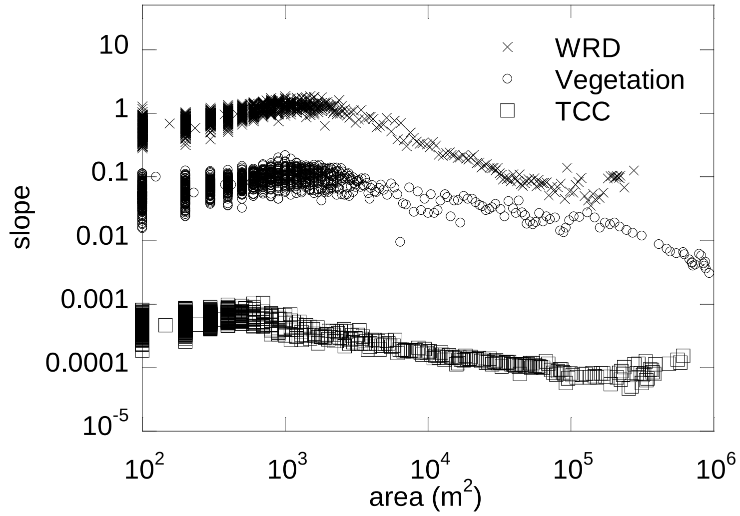
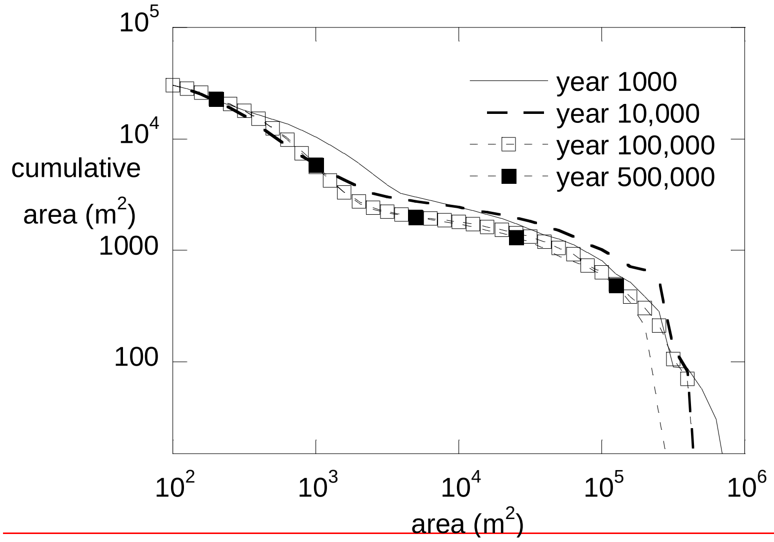
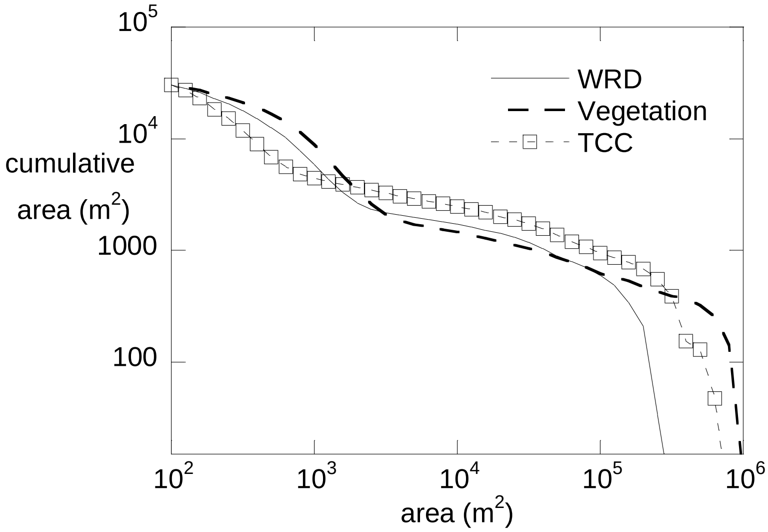
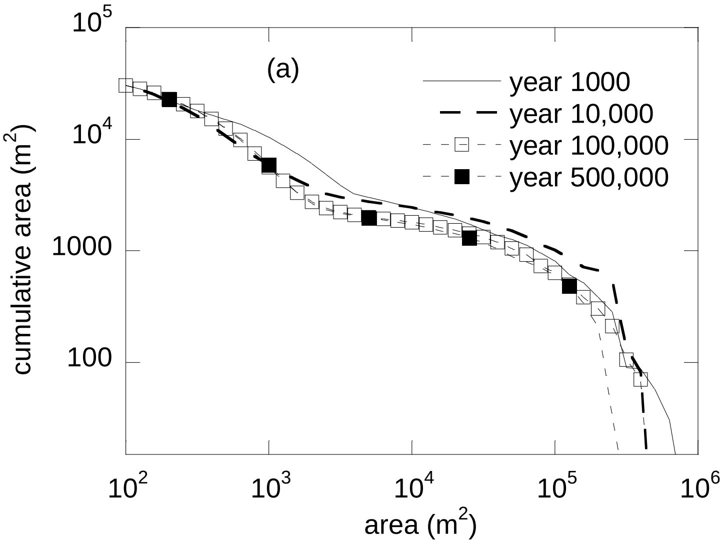


Fig.~~ure~~ 7. Area–~~-~~slope relationship for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period (a~~top~~) and comparison of the WRD, Vegetation and Tin Camp Creek area-slope data at 500,000 years (b~~ottom~~). In ~~the (~~b)~~ottom figure~~ the WRD parameter slope data have been~~s~~ multiplied by 10 while the Tin Camp Creek parameter slope data has been divided by 10 for clarity~~)~~.





10^5
10^4
1000
100
cumulative area (m^2)
10^2
10^3
10^4
10^5
10^6
area (m^2)
WRD
Vegetation
TCC



(a)
10^5
10^4
1000
100
cumulative area (m^2)
10^2
10^3
10^4
10^5
10^6
area (m^2)
year 1000
year 10,000
year 100,000
year 500,000

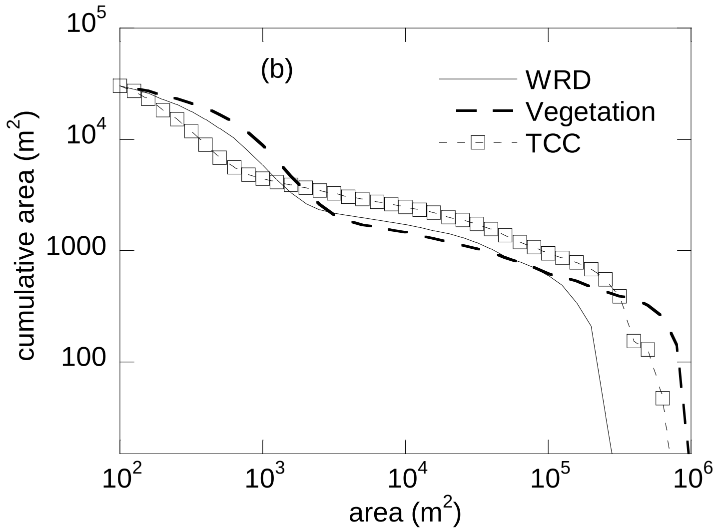


Fig.~~ure~~ 8. Cumulative area distribution (a~~top~~) for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period~~ (top)~~ and comparison of the WRD, Vegetation and Tin Camp Creek cumulative area data at 500,000 years (b~~ottom~~).

Comment [A33]: Please write (a) (formerly "top") only once.

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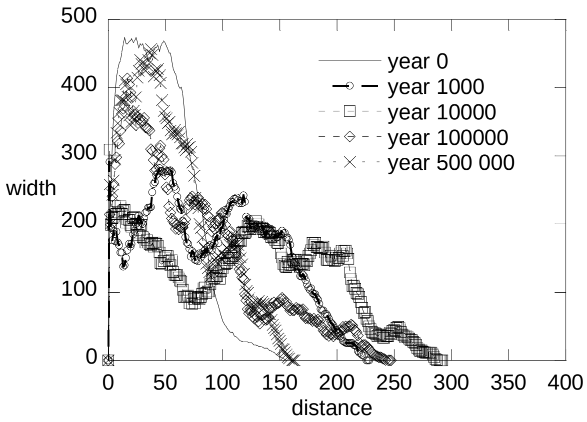

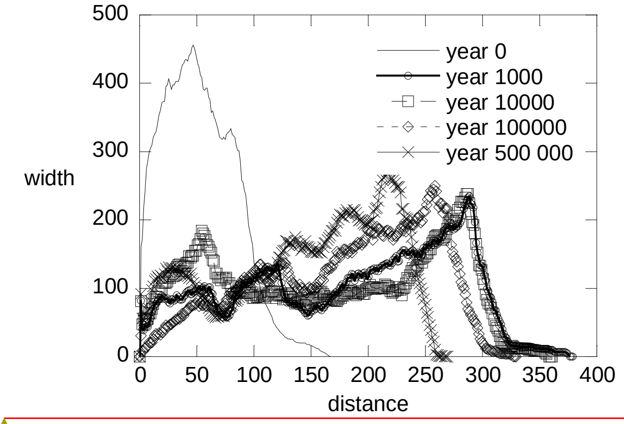

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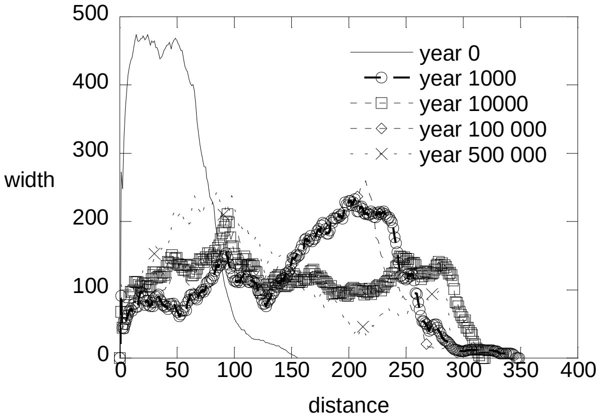

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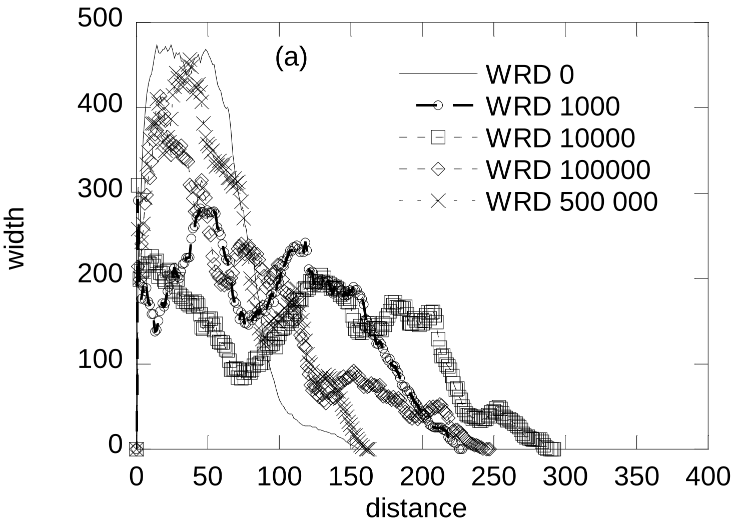

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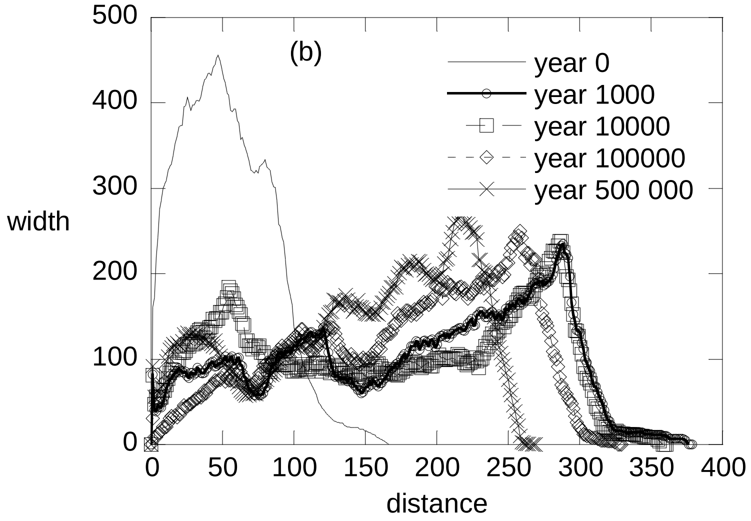

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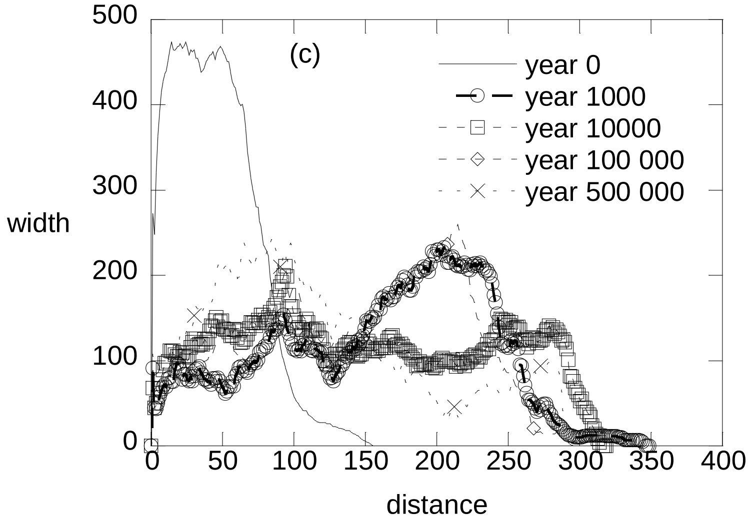

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Fig.~~ure~~ 9. Width function for the Corridor Creek catchment using the WRD (a~~top~~), ~~and~~ Vegetation (b~~middle~~) and Tin Camp Creek parameters (c~~bottom~~).

(a)

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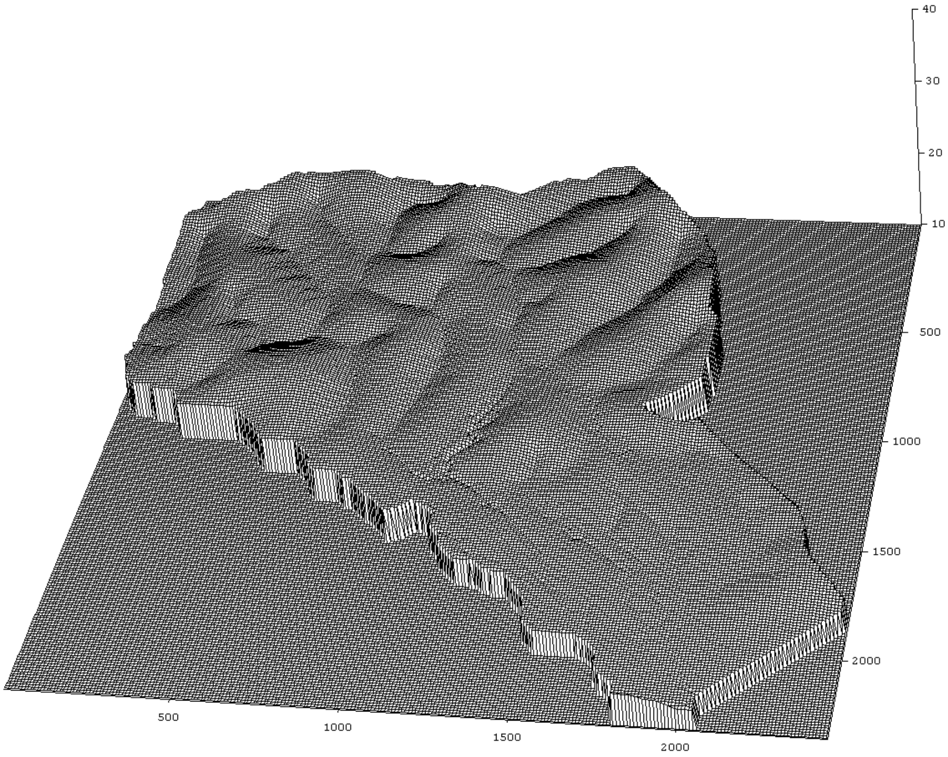

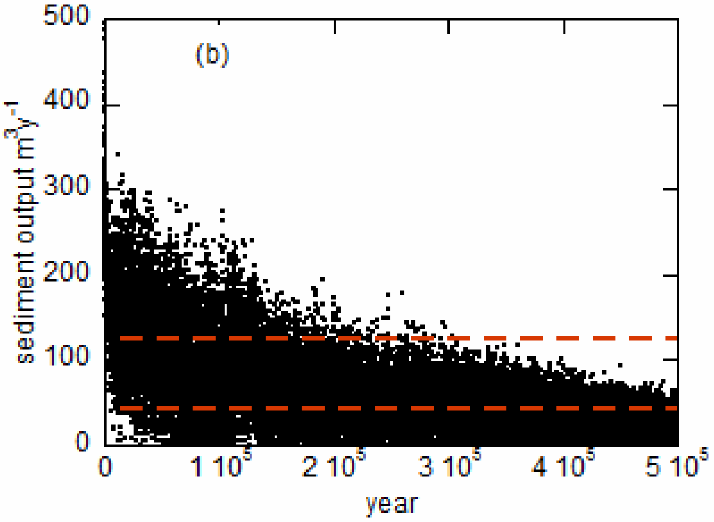

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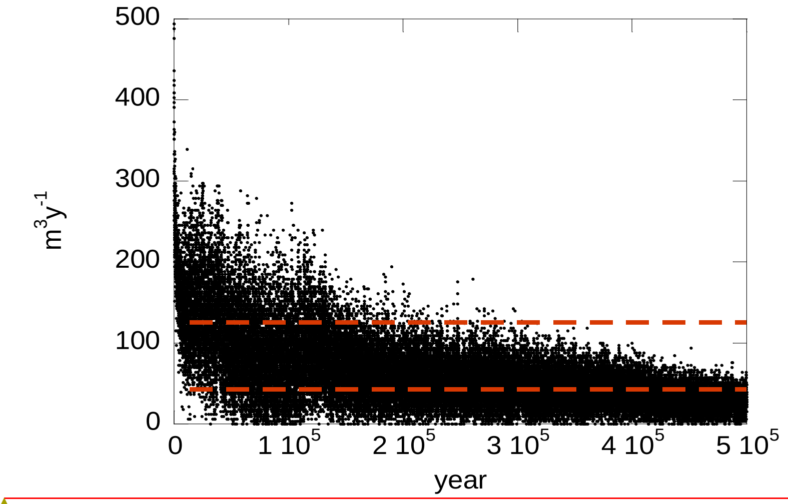

Fig.~~ure~~ 10. Corridor Creek landform at 500,000 years using WRD parameters and the DInfinity drainage direction algorithm (a~~top~~) and sediment output from the simulation (b~~ottom~~). The red line represent the range of sediment discharge as predicted from the regional denudation rates of 0.01~~—~~0.04 mm y^{-1} (30–~~-~~120 m^3 y^{-1}). For clarity, each year represents an average of 10 years sediment output.

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Table 1. The SIBERIA parameter values for each region of the ERA Ranger mine for the Einstein-Brown sediment transport equation.

Surface type	**Comparable site**	**SIBERIA parameter**				
		m_1	n_1	β_3	m_3~~m3~~	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
Analogue soil	Natural soil at Tin Camp Creek (Moliere, et al. 2002)	1.7	0.69	0.186	0.79	1067

Comment [A34]: Why only is this large? Also please explain the parameter names in the caption.

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Table 2. Results from the SIBERIA simulations using Waste Rock Dump (WRD), Vegetation and Tin Camp Creek analogue soil parameters.

year	catchment relief (m)	average erosion rate (mm y^{-1})	max. erosion depth (m)
	WRD		
0	25.874	-	-
1000	25.872	0.053	7.035
10,000	25.860	0.053	11.842
100,000	22.528	0.040	16.097
500,000	7.589	0.021	23.314
	Vegetation		
0	25.874	-	-
1000	25.873	0.024	1.212
10,000	25.855	0.031	2.526
100,000	24.422	0.035	9.339
500,000	8.849	0.022	21.084

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Comment [A35]: Please define this. Relief of what unit area?

Comment [A36]: Average erosion rate?

Comment [A37]: Vague. Depth of what? Depth from what?

	Tin Camp Creek		
0	25.874	-	-
1000	25.611	0.082	6.719
10,000	24.904	0.078	10.345
100,000	18.826	0.067	13.598
500,000	12.674	0.026	25.511

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Long-term landscape trajectory – can we make predictions about landscape form and function for post-mining landforms?

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Abstract

A significant issue for the application of numerical Landscape Evolution Models (LEMs) is their calibration/parameterisation and validation. LEMs are now at the stage of development where if calibrated, they can provide meaningful and useful results. However, before use, each LEM requires a set of data and parameter values for it to run reliably and most importantly produce results with some measure of precision and accuracy. This calibration/validation process is largely carried out using parameter values determined from present day, or recent surface conditions which are themselves product of much longer-term geology-soil-climate-vegetation interactions. Here we examine the reliability of an LEM to predict catchment form over geological time (500, 000 years) for a potential rehabilitated mine landform using defensible parameters derived from field plots. The findings demonstrate that there is no equifinality in landscape form with different parameter sets producing geomorphically and hydrologically unique landscapes throughout their entire evolution. This shows that parameterisation does matter over geological time scales. However, for shorter time scales (<10,000 years) the geomorphic differences in hillslope form are minimal as described by the hypsometric curve, area–slope and cumulative area distribution, yet there are large differences in sediment output. Therefore, obtaining reliable and defensible parameters for input to LEMs is essential.

Keywords: Landscape evolution, Mine rehabilitation, Soil erosion modelling, SIBERIA

1 Introduction

While conceptual models have helped further earth science understanding, more recently, numerically based Landscape Evolution Models (LEMs) have been developed, which have the capability to capture a range of surface erosion and deposition, tectonic processes and near surface or critical zone processes such as pedogenesis. Tucker and Hancock (2010) have reviewed a range of LEMs which have been used in applications ranging from understanding theoretical landscape dynamics through to more applied situations, such as degraded site rehabilitation. .

LEMs have now reached the stage of development where they can provide meaningful and useful results for both theoretical studies as well as applied settings such as post-mining landscapes. However, two significant issues for all LEMs are their (1) calibration/parameterisation and (2) validation. Before use, each model requires a set of data and parameter values which are used to define the scenarios that are being modelled. The accuracy and reliability with which these values are collected and recorded could directly impact on the precision and accuracy of the model outputs and results. Crucially, LEMs are largely calibrated with parameter values determined from present, or comparatively recent surface conditions, which may only represent recent environmental conditions yet are also the product of much longer-term geology–soil–climate–vegetation interactions. Therefore, how these parameters spatially and temporally vary as a result of climate variability, weathering and pedogenesis and the resultant soil–climate–vegetation interaction is largely speculative and a source of model uncertainty.

LEMs were initially developed to examine landscape evolution and dynamics at geological time scales but have since been employed in more applied settings such as mine sites at much shorter time scales (years, decades, and centuries). For example, the first use of landform evolution modelling to assess the stability of a post-mining rehabilitated landform design at the study site was by Willgoose and Riley (1993) using the SIBERIA landform evolution model (Willgoose et al., 1989).

This and subsequent studies have demonstrated the potential for LEMs to give insights into future geomorphic form and function and are now being applied to disturbed site assessment and rehabilitation (Willgoose and Riley, 1998; Hancock et al., 2000, 2002; Evans et al., 2000; Lowry et al., 2011; Coulthard et al., 2012). The focus of this paper and those cited above is on post-mining landforms, which are designed to bury or encapsulate mine sites, including tailings, drains, spoil tips and other industrial architecture. Post mining landforms are intended to be constructed in such a way that they remain structurally intact geomorphically stable, while being able to blend into 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 and tailings storage facilities of a de-commissioned uranium mine.

The rehabilitation of uranium mines is a particular concern as radionuclides represent a potential set of contaminants with long half-lives and persistence in the environment (Schumm et al., 1984). Australian guidelines recommend a design life for a tailings cap of a uranium mine of 200 years and a structural life of at least 10,000 years. This means the structure used to encapsulate radioactive tailings must be built to maintain its integrity from a 1 in 10,000 year rainfall event. Understanding model parameter accuracy and reliability is therefore particularly important when assessing landscapes at millennial time scales. This generates a major research question, as we have the numerical methods to simulate landscape stability over millennia, but not necessarily the correct parameter values and data sets with which to drive these predictions.

In this paper we examine three issues. Firstly, the reliability of an LEM to predict catchment form over geological time is assessed. Secondly, the range of outcomes in landscape form and function is examined based on estimated temporal parameter changes. Finally, the need for more long-term understandings based on the need for more rigorous field data for calibration and validation of these models is discussed.

2 Site description

Disturbed landscape systems offer the opportunity to examine landscape change over relatively short time scales. In particular, restoration practices allow new landscapes to be studied, something that is sometimes difficult with natural systems. The mineral lease of the Energy Resources of Australia Ltd.'s (ERA) Ranger mine is located in the Alligator Rivers Region of the Northern Territory, Australia. Erosion from the mine could potentially impact on Magela Creek and its tributaries, Corridor, Georgetown, Coonjimba, and Gulungul Creeks (Fig. 1). Magela Creek debouches into the East Alligator River through a broad expanse of floodplain and wetlands listed as "Wetlands of International Importance" under the Ramsar Convention (Ramsar sites information services, 2014). The mine lease is surrounded by the World Heritage-listed Kakadu National Park.

Mine tailings are currently stored in an above ground tailings dam and in the mined-out Pit 3 (Fig. 2). Pit 1 previously received tailings and is in the process of being capped. Mining from Pit 3 ceased in 2012, and milling and processing of stockpiled ore is scheduled to cease by 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 in 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). Consequently, ERA will be required to rehabilitate disturbed areas of the lease to satisfy the above requirements. Implementing these will require the landscape to be rehabilitated in a way that restores environmental functions supporting local ecosystem diversity (Ludwig and Tongway 1995. The first stage in this process is to design and construct a landform which is erosionally stable.

The regional geology of the Alligators River 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 (Needham, 1988; East, 1996). Geomorphically, the Ranger site is characterised as part of the deeply weathered Koolpinyah surface. This consists of plains, broad valleys and low gradient slopes, with isolated hills and ridges of resistant rock (East, 1996). Regional denudation rates for the area (0.01 to 0.04 mm y^{-1}) have been 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).

The study site is in the wet-dry tropics of northern Australia and is subject to high-intensity storms and tropical monsoons between October and April. Minimal rain falls in the remainder of the year; the annual average rainfall is 1583 mm (Bureau of Meteorology, 2015). Vegetation on the mine lease and surrounds consists of open Eucalypt forest dominated by *Eucalyptus. tetradonta, Eucalyptus. miniata, Eucalyptus. bleeseri* and *Eucalyptus. 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).

3 Landscape evolution models and their parameterisation

From the 1970s numerical models were developed to simulate processes ranging from slope wash to chemical erosion and soil development over entire catchments (Carson and Kirkby, 1972; Ahnert, 1976; Hirano, 1976; Armstrong, 1976). For further detail on the history and background of LEM's see (Tucker and Hancock, 2010). The SIBERIA landform evolution model (referred to hereafter as SIBERIA) builds on this early work and mathematically simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion and mass transport processes (Willgoose et al., 1991). 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 (DEMs) for the determination of drainage areas and geomorphology and its ability to efficiently adjust the landform with time in response to the erosion that could occur on it. Since 1993, SIBERIA has been used principally to investigate surface stability of post-mining rehabilitated landforms or small catchment areas (i.e. Willgoose et al., 1991; Evans et al., 1998; Willgoose and Riley, 1998; Hancock et al., 2000, 2013 Moliere et al., 2002).

SIBERIA requires calibration of the sediment transport and area–discharge relationships, and a 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. Here SIBERIA was calibrated using field data collected from the Ranger mine site (the study site) and Tin Camp Creek (the analogue site). The Tin Camp Creek site, located approximately 50 km from Ranger, is on the same metamorphosed schist formation as found at the Ranger mine and the surface properties are seen as an analogue of proposed rehabilitated landforms for the Ranger Mine in the long-term (Uren, 1992; Riley and Rich, 1998).

Calibration of the erosion and hydrology models was conducted using data of sediment loss, rainfall and runoff for discrete rainfall events that were collected from field plots. Calibration data for the Ranger site were obtained from erosion plots on the batter slope of the Ranger mine waste rock dump (Evans et al., 2000; Moliere et al., 2002). Data for a vegetated surface were collected from a similar-sized plot on the waste rock dump covered in topsoil, ripped and vegetated with low shrubs and grasses which provided approximately 90% cover (Evans et al., 1998). SIBERIA was also calibrated from field data collected from the Tin Camp Creek catchment during rainfall events in December 1992. This resulted in three separate parameter sets which were employed in this study.

For long-term landscape assessment SIBERIA requires both fluvial and diffusive sediment transport data. The SIBERIA value for rainfall diffusivity (i.e. rainsplash) value of 0.005 m^3 s^{-1} m^{-1} (width) was used as this has been found to be the most applicable for the Alligator Rivers Region which includes the Ranger site (Hancock et al., 2002. The field data parameter values determined for these surfaces are shown in Table 1. The methodology employed in the derivation of the parameters for the different surfaces is described in Evans and Willgoose (2000), Evans et al. (2000) and Moliere et al. (2002).

4 Catchment digital elevation models, model setup and landscape assessment

Several small catchments will drain from the proposed possible landform at Ranger and here we focus on the Corridor Creek catchment that drains into Magela Creek. (Fig. 2). The DEM was calculated from two datasets. Firstly, a 2-m contour interval dataset representing the current landform surface was produced from a LiDAR survey of the mine in 2010. This was supplemented by an additional two-metre contour interval dataset that represented the proposed rehabilitated landform design. The LiDAR contours outside of the rehabilitated landform area were combined with the contours representing the proposed rehabilitated landform area and used to produce a grid surface with a horizontal resolution of 2 m. The DEM representing the rehabilitated surface was resampled to a horizontal spatial resolution of 10 m. This was chosen as being the optimal resolution at which SIBERIA could function within the spatial extent of the study catchment, and over the temporal periods modelled yet still reliably capture the salient features of hillslope geomorphology (Hancock, 2005). The final DEM used in this study was understood to represent a fully consolidated landform, from which there would be no subsidence or settlement. Other factors such as mass failures were not considered.

Simulations were run using Waste Rock Dump (WRD), Vegetation and Tin Camp Creek parameters described earlier in Section 3. For the WRD and Tin Camp Creek data the same parameters are used unchanged for the entire simulation length. However, for the Vegetation parameter simulations, the landscape output from the WRD simulation at 10 years was used as the starting point of the simulation. This 10-year period represents the time required for a stable vegetation cover to develop. The Vegetation parameters then remain unchanged for the duration of the simulation.

Short et al. (1989) estimated that the surrounding undisturbed landscape (termed the Koolpinyah surface) is approximately 300,000 years old. Therefore, to allow an equivalent landscape to develop and to examine long-term landscape trends and geomorphic change, SIBERIA was run for 500,000 years. Outputs from the model included a DEM of the catchment and sediment discharge at annual time steps (here we examine DEMs at 1,000, 10,000, 100,000, 500,000 years) as well as geomorphic descriptors of the catchments (hypsometric curve, area–slope relationship, cumulative area distribution and width function).

The hypsometric curve (Langbein, 1947) is a non-dimensional area–elevation curve, which allows a ready comparison of catchments with different area and steepness. The hypsometric curve has been used as an indicator of the geomorphic maturity of catchments and landforms. For example, Strahler (1952, 1964) divided landforms into youth, mature and monadnock characteristic shapes, reflecting increasing catchment age.

The area–slope relationship is the relationship between the areas draining through a point versus the slope at the point for fluvial landscapes. It quantifies the local topographic gradient as a function of drainage area such that

$$A^{\alpha} \cdot S = \text{constant} \qquad (1)$$

where A is the contributing area to the point of interest, S is the slope of the point of interest and α is a constant (Hack, 1957; Flint, 1974; Willgoose, 1994). It is generally recognised that the log–log positive slope region at small catchment areas describes the diffusive dominated (i.e. rainsplash) areas of the catchment, while the log–log negative region represents fluvial areas of the catchment.

The cumulative area distribution (CAD) has been used as a means of characterising the flow aggregation structure of channel networks (Rodriguez et al., 1992; LaBarbera and Roth, 1994; Pereira and Willgoose, 1998). The CAD, similar to the area–slope relationship, provides the ability to examine the relationship between diffusive and fluvial processes. Small catchment areas generally have a convex profile (representing the diffusive dominated region of the catchment) which then becomes log–log linear as area increases and represents the fluvial dominated area of the catchment.

Originally developed by Surkan (1968), the width function describes the number of drainage paths (whether they be channel or hillslope) at a given distance from the basin outlet, measured along the network (Naden, 1992). This approach is taken as that SIBERIA does not differentiate between channel and hillslope cells here. The width function is a measure of hydrologic response since it can be strongly correlated with the instantaneous unit hydrograph. If it is assumed that rainfall excess is routed with a constant velocity, then the width function can be linearly transformed into the instantaneous unit hydrograph.

5 Results

5.1 Qualitative visual assessment

Using the WRD parameters for the entire simulation produces a landscape that visually (or qualitatively) looks geomorphically feasible for all time periods (Fig. 3). That is, the model produces a catchment which has realistic hillslope length and curvature together with a drainage network that realistically fills the domain (i.e. there are no sharp breaks in slope or illogical or unrealistic landscape features). While considerable erosion has occurred at 1000 years in the form of gullies, at 10,000 years these gullies have evolved into rounded hills and channels. The eroded hillslope material has been deposited in the main channel bottom with flat expanses of deposition clearly evident. Over time the landscape continues to erode and after a simulated period of 100,000 years has considerably lowered with the incised channels being replaced by rounded low hills. The depositional material in the main channel has been reworked and has a system of low hills and channels. While no incision is evident on the hillslope, there is incision in the depositional material on the valley floor demonstrating that the system is still dynamic and evolving. At 500,000 years the catchment consists of a series of low hills with relatively consistent relief and uniform hillslope shape. A small poorly incised channel is evident in the valley bottom.

The simulation using the Vegetation parameters (Fig. 4) produces incised channels at 1000 years but these are not as deep or as well defined as the WRD simulation. At 10,000 years, the channels have become well-defined channels with deposition present in the main channel bottom. At 100,000 years the catchment has developed well-rounded hillslopes with the depositional material on the valley bottom being reworked. At 500,000 years, similar to the WRD simulation, the landscape has evolved into a catchment of relatively low relief with a series of low well rounded hills.

While not displayed here for brevity, the simulation using the Tin Camp Creek parameters displays similar behaviour to that of the WRD and Vegetation parameter simulations. Visually there are no striking differences between the simulated catchments. However, all have qualitative differences in both hillslope form. They have different relief, location of hills and valleys as well as the morphology of the depositional area in the main channel. Therefore, the three different parameter sets produce qualitatively different landscapes with unique hillslope length, shape and position. Importantly, each modelled landscape output is not geomorphically impossible.

5.2 *Quantitative assessment – sediment output*

In terms of erosion and landscape lowering, the maximum depth of erosion is 11.8, 2.5 and 10.3 m for the WRD, Vegetation and Tin Camp Creek parameter simulations at 10,000 years, respectively (Table 2). This indicates a substantial difference that may be especially relevant for areas where contaminants are buried

Simulated sediment yields from the catchment are highly variable but decline through time for all simulations (Fig. 5). For the WRD parameters, over the first 50,000 years the sediment output is comparatively high and for much of this period well outside the upper range for natural sediment output; the expected sediment output from the catchment is 30–120 m^3 $year^{-1}$ based on a denudation rate of 0.01–0.04 mm y^{-1} and corrected for catchment area). However, after approximately 100,000 years, sediment output has declined and the mean is within that of the expected sediment output range, though some peaks above this range still exist.

The Vegetation parameter simulations display considerable variability particularly over the first 50,000 years where there are sustained periods where the sediment output is above that of the expected output. After this period, the sediment output is largely within that expected by the regional denudation rates.

A similar pattern occurs for the Tin Camp Creek simulation which has high sediment yields for the first (approximately) 125,000 years and then reduces to within or less than that of the expected output range from the denudation rates. However, the sediment yield from this parameter set has considerably less variability than that of the WRD parameter simulation.

The three different parameter sets therefore produce distinct sediment outputs. All three predicted sediment outputs are plausible results if the surface and materials characteristics remain unchanged and climate is constant for the duration of the simulation.

5.3 Quantitative assessment – catchment geomorphic descriptors

In this study, we found little difference in the hypsometric properties for the WRD, Vegetation and Tin Camp Creek parameter simulations up to 10,000 years (Fig. 6). At this time there has been insufficient erosion to change catchment area–elevation form. At 100,000 years, both catchments (WRD and Vegetation parameters) display hypsometric curves which have mature landscape characteristics. At 500,000 years, the WRD and Vegetation parameter simulations have mature landscape curves while the Tin Camp Creek parameter curve has monadnock form. Overall, the hypsometric curve demonstrates that there has been significant area–elevation change over the 500,000 year modelled period with the three parameter sets producing different area-elevation form.

The area–slope relationship for the WRD parameter set is relatively constant for the first 10,000 years after which a reduction in slope can be observed particularly at the termination of the simulation at 500,000 years (Fig. 7a). This, like the hypsometric curve suggests that it takes millennia for any real change to be observed in catchment area–slope properties. Similar temporal patterns were observed for the Vegetation and WRD parameter simulations (not displayed here for brevity).

At the end of the modelled period the area–slope relationship for the WRD, Vegetation and Tin Camp Creek parameter simulations all display unique characteristics with both slope of the diffusive and fluvial regions being different (Fig. 7b). The area–slope relationship for the WRD, Vegetation and Tin Camp Creek parameters all have positive, yet different slopes for areas approximately less than 1000–2000 m^2 while at areas approximately greater than 1000–2000 m^2 both data sets (WRD and Vegetation) have a negative (yet different) log–log linear slope. Differences in all three area–slope plots result from the different model parameters. Interestingly, despite the same diffusivity parameters being applied for all simulations, the diffusive area of the curve is different and reflects the complex interaction between the evolving landform and the diffusive and fluvial parameters. For example, the WRD parameters are more erosive while the Vegetation parameters are considerably less erosive. The WRD parameters may produce incision (gullies) which have steeper slopes which will have higher diffusion (as the diffusion model is slope dependent). The reverse occurs for the Vegetation parameters.

The CAD for the WRD parameter simulation (Fig. 8) demonstrates a change in the diffusive and fluvial area of the hillslope at 10,000 years with the distribution remaining largely the same for the remaining duration of the simulation. The CAD for the WRD, Vegetation and Tin Camp Creek parameters all display different distributions at the termination of the simulation at 500,000 years in both the diffuse and fluvial regions of the curve. Interestingly, the Vegetation parameter simulation has a more rounded or convex distribution while the Tin Camp Creek parameter simulation is largely log–log linear with positive slope in the diffusive area of the curve. The extent of the diffusive region also varies for all three parameter sets. For the fluvial region, the slopes are all similar; however, the maximum area varies for all three simulations. This demonstrates that all three have different area-aggregation patterns (also demonstrated below with the channel network and the width function).

All three landscapes generate unique width functions (Fig. 9). Interestingly the width function initially displays a high value but this peak reduces and distance increases with a maximum distance at 10,000 years for the WRD and Vegetation simulations (Fig. 9). Post 10,000 years the distance begins to reduce and peak increases. However the Tin Camp Creek width function rapidly reduces in width and increases distance and stays relatively fixed for the duration of the simulation. This demonstrates that even though the catchment boundary is fixed, the drainage network continually evolves producing unique drainage networks (Rigon et al., 1993). The results also suggest that the movement and delivery of sediment routed through the network will be different for the modelled landscapes. This corresponds well with the different sediment output described in Section 5.2. This demonstrates that the hydrological behaviour of the catchments will be spatially and temporally unique.

The assessment using these geomorphic descriptors demonstrates that all three are distinct catchments with different geomorphological properties as well as individual sediment transport and runoff properties. However, they are all plausible entities in their own right if it is assumed that the surface and material properties remain constant and climate has limited variability.

6 Discussion

LEMs have been tested across a range of climates and landscapes. It is broadly agreed that they are qualitatively reliable at decadal to multi-decadal time scales. The results presented within this study support this assumption, as they demonstrate that the simulated landscapes produced using static parameter sets are geomorphologically realistic and possible. Importantly, the modelling used the best available input parameter data determined from field plots, from a range of different surface options, to evaluate long-term landscape trajectory. Therefore, we have examined the potential range of outcomes based on data from current surfaces which we believe may represent future outcomes. In the sections below, long-term model predictions and equifinality, landscape form and sediment output together with the development of long-term understandings are discussed.

6.1 Long-term prediction and equifinality

While LEMs have been used in the past to assess landform designs for mine closure, they have rarely been run and assessed at time scales greater than 1000 years for synthetic or anthropogenetically designed and constructed landscapes. The landform in this study was modelled for a simulated period of 500,000 years which represents a significant amount of time for geomorphic change to occur. Using three parameter sets that represent the surface characteristics of a potential rehabilitated surface, results in three unique landforms. While visually similar, the analysis of the results showed that the simulated catchments are geomorphically different at the end of simulation. Area–elevation (hypsometry), area–slope and distribution of areas (CAD) vary and, are unique both during and at the end of each simulation. Additionally, the channel network is highly variable, demonstrating that the location of the drainage network will vary as well as amount and timing of runoff.

The findings suggest that here there is no equifinality in landscape form. The employment of different parameter sets produce geomorphically and hydrologically unique landscapes throughout their entire evolution. Therefore, parameterisation is important for landscape evolution model predictions. While at relatively short (<10,000 years) time scales the differences in hillslope form are minimal (as described by the hypsometric curve, area–slope and cumulative area distribution) there are large differences in sediment output. Obtaining the correct parameter set is vital for reliable long-term prediction for applied situations.

6.2 Landscape form and sediment output

The sediment output displays considerable temporal variability with unique patterns for each parameter set (Fig. 5). The simulations demonstrate that all landforms will be delivering sediment to the surrounding natural system at rates higher than that of the natural system. Importantly, this work demonstrates how models can provide an estimate of the inherent variability observed in catchment systems (Coulthard et al., 2002, 2012, 2013). We show that there is considerable variability in sediment output from a numerical model where no random bias has been included (Hancock, 2012).

However, there are some caveats on the above statements. The findings suggest that a period may be required for the model to generate sediment output similar to the present day as the initial surface roughness in the DEM (potential error and random roughness) may initially produce increased levels of sediment output. Such error and its effect is impossible to quantify. In this study, the initial DEM was not smoothed or pit filled before use and was used as supplied by ERA as this is the same level of accuracy/precision that would be supplied to the earth moving contractors to construct the landform. How surface roughness or subtle changes in topography influence landscape evolution is an area for future work.

A further issue is the direction and path that water and sediment flows over the landscape surface and how it is modelled (Garbrecht and Martz, 1997). To examine this issue a simulation was run using WRD parameters and the DInfinity (Tarboton, 1987) drainage direction algorithm (Fig. 10). Similar to the WRD, Vegetation and Tin Camp Creek results, the landform at 500,000 years displays a unique distribution of hillslope shape and channel position and also has a unique sediment output. Therefore choice of drainage direction model has an effect (Tarboton, 1987; Garbrecht and Martz, 1997). How other models and drainage routing functions influence landscape evolution is an area for future work.

However, for all simulations examined here, over the shorter runs (i.e. 0–10,000 years) there is little difference in qualitative and quantitative landscape form largely because the landscape has not sufficiently eroded for any change to be detectable by these measures. These geomorphic measures (hypsometric curve, area–slope relationship, CAD and width function) are not sensitive to small changes in landscape form at 10,000 years. However, where large changes have occurred they are quite useful. Interestingly, the width function provides some insight into network hydrological change.

While not examined in detail in this study, a further complexity is the relationship between fluvial and diffusive erosion. The results suggest that the relationship between diffusive and fluvial processes is complex and that determining the correct parameter sets is very important particularly for long-term simulations (see Willgoose et al., 1991 for a description of the fluvial and diffusive transport equations and their relationship). We have used the same diffusivity parameters for all simulations but vary the fluvial erosion parameters based on defensible field based parameters. Changes in rainfall intensity and resultant diffusivity will have a large impact on landscape form (Hancock, 2012). Hancock et al. (2002) showed that an absence of diffusion will produce landscapes that have linear erosion features with sharp edges while a large value of diffusion produces a landscape with overly rounded hillslopes. The impact of changing diffusivity on erosion and landscape evolution in a region where there is a predicted increase in rainfall intensity is an area of further research (Tucker and Hancock, 2010).

Another significant issue is that these parameters were derived from a set of rainfall events that are believed to be average or representative seasons. Are these seasons representative for the determination of parameters for models that run at millennial time scales? Further, the use of WRD parameters in particular for the entire simulation assumes that any landscape erosion surface properties are static and do not evolve. In reality, this assumption is quite unrealistic as the freshly shaped surface will evolve into a soil in conjunction with influence of vegetation as it establishes and forms a new soil–vegetation–

climate evolutionary path. However, this simulation using static WRD parameters provides an end member of possible landscape scenarios.

Models such as SIBERIA have the advantage that they dynamically adjust the hillslope in response to erosion and deposition, a process presented here with the erosion of the hillslope and channel becoming a depositional area and then over time this depositional material being reworked. Therefore, the model is not geomorphically static and attempts to capture hillslope behaviour. However, what these models lack is a further coupling to long-term climate and the resulting influence of long-term soil-vegetation interactions.

6.3 Development of long-term understandings

The single biggest issue for the employment of LEMs is that of parameterisation. These models are based on parameters derived largely from the present. At 100 year time scales and longer, with the cyclicity of climate, how realistic is it to run models with limited or no climatic cyclicity? In many aspects the models now have more functionality than we have field data with which to calibrate and validate their inputs and outputs. Field processes could be better incorporated into models if they were better understood and quantified. This requires more field and laboratory data input particularly if these models are to be used outside of their initial calibration period.

At present the best calibration available for the reliable employment of LEMs at this site comes from plot studies over a number of years (see Section 3). This has the advantage that it provides input data for the current surface material, climate as well as soil–climate–vegetation interaction. However, this type of data clearly provides little insight into the longer term soil–vegetation–landscape trajectory, especially where climate is expected to change (CSIRO, 2007). Natural analogues also provide opportunity (Tucker, 2009).

There are many mines around the world that will continue to operate for many decades. Many of these sites lack specific long-term data for landscape planning. The issues raised here could potentially be addressed through the establishment of a series of plots, which are designed and setup so that long-term data to support rehabilitation can be provided (Gerwin et al., 2009). An alternative approach is to examine sites that have been abandoned and or rehabilitated. There has been little attempt to examine pedogenesis, surface armour and vegetation development and how this influences erosion and landscape development on former abandoned sites as we only now have developed the numerical models capable of using this information (Cohen et al., 2009; Vanwalleghem et al., 2013; Minasny et al., 2015; Temme et al., 2015). There are many rehabilitated and or abandoned sites that are several decades old which could provide robust quantifiable data on the trajectory of these transient landforms (Gerwin et al., 2009; Hancock et al., 2000, 2006).

7 Future issues and conclusions

While model input parameters are static, climate and the soil–vegetation interaction clearly are not. Similarly, while a rehabilitated landscape will have different dimensions to that of the pre-mine landscape and be constructed of essentially different materials, it is unreasonable to assume that a new landscape will behave in a similar way to that of the past. Yet the model parameterisation is based on the initial soil–vegetation interactions. Therefore, how valid is any prediction at time scales any longer than that of the period at which the parameters were derived?

The important question for mine planners and regulators is which simulated landscape is the correct one. Firstly, given the limited parameter data sets available and our understanding of climate, all predictions are equally valid. However, the actual result is likely to be a mix of all parameter data sets together with other complex unknown influences relating to vegetation-climate interactions that influence pedogenesis. Secondly, while the surface is unlikely to maintain its waste rock characteristics over the modelled period, it is equally unlikely that vegetation will remain constant. The likelihood that the material will evolve to a Tin Camp Creek type landscape is unknown. Both vegetation change as well as the regular occurrence of fire is likely to influence erosion and therefore landscape evolution in this (and any) environment. Finally, in terms of the worst case scenario, the WRD parameter simulation is likely to provide the most conservative outcome of the three scenarios examined here.

A significant advance is that pedogenesis models (Cohen et al., 2009; Vanwalleghem et al., 2013; Minasny et al., 2015; Temme et al., 2015) can now be incorporated into LEMs. However, field data with which to reliably parameterise or validate them is not currently available. Future long-term landform evolution simulations and predictions will need to address questions such as (1) how and at what rate does a surface armour form? (2) At what rate and by how much does surface armour reduce erosion? (3) What is the weathering process and rate down the soil profile and will layers form? (4) How does vegetation interact with this armouring-weathering and soil formation process? We now have the models (or the capability of developing the models if we understood the process) but not the field understandings or data with which to calibrate and validate any output.

This, therefore, leads to the question as to what LEM model is the most correct or reliable. There are a number of models with different approaches available (see Tucker and Hancock, 2010). A Monte Carlo type approach may be needed where all elements contributing to landscape evolution are employed. This includes both models and parameters sets. While the SIBERIA model is one of the most used and tested of the LEMs available, is this model and its predictions correct? The authors in recent years have evaluated other models such as CAESAR, CAESAR-Lisflood together with soil erosion models such as the

RUSLE (Renard et al., 1991) and found that for the landscapes and parameters sets examined the models produce similar outcomes within broad error bands. Full evaluation may lead to an approach where all available LEMs are employed using all available data for a series of initial conditions and predictions made by providing a range of possible outcomes which utilise models based on their individual capacity and focus. This approach would be similar to that employed by the climate modelling community and programs such as the Coupled Model Intercomparison Project (Covey et al., 2003). This approach would go some way to addressing the issue of reliability of long term predictions.

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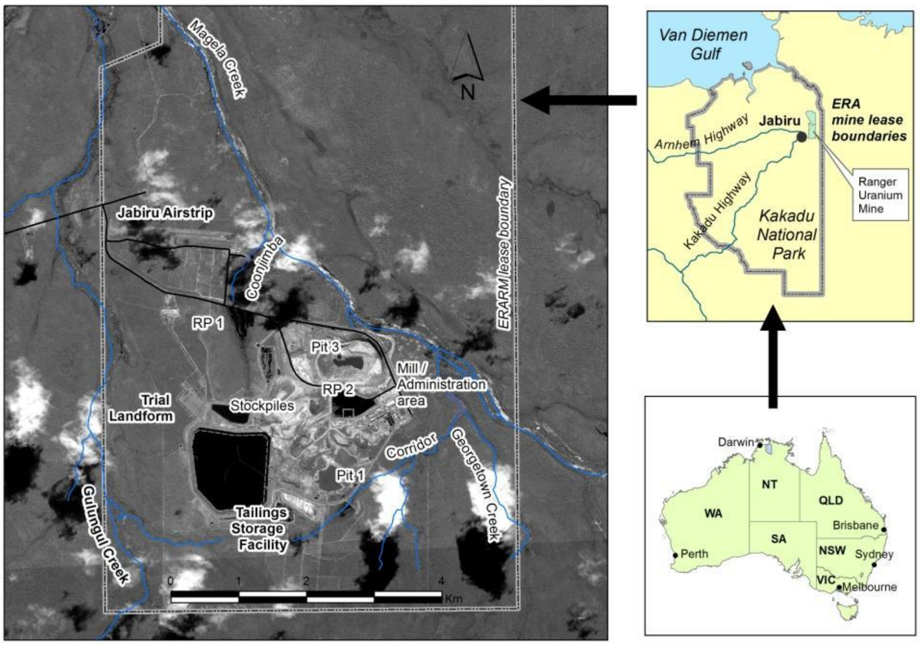


Fig. 1. Location of the study site. For brevity, the letters RP represent Retention Pond. The site is located approximately 300km west of Darwin.

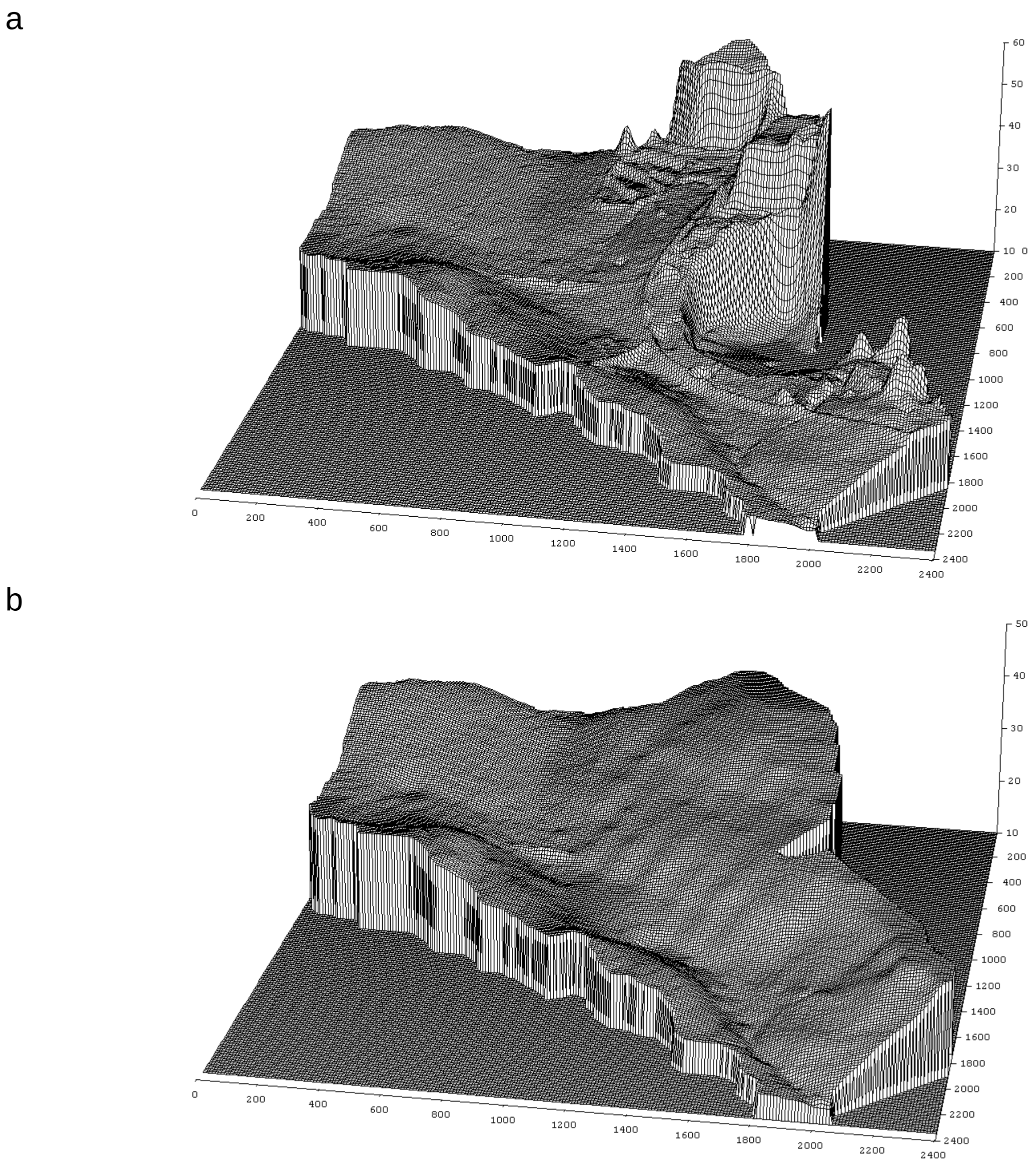
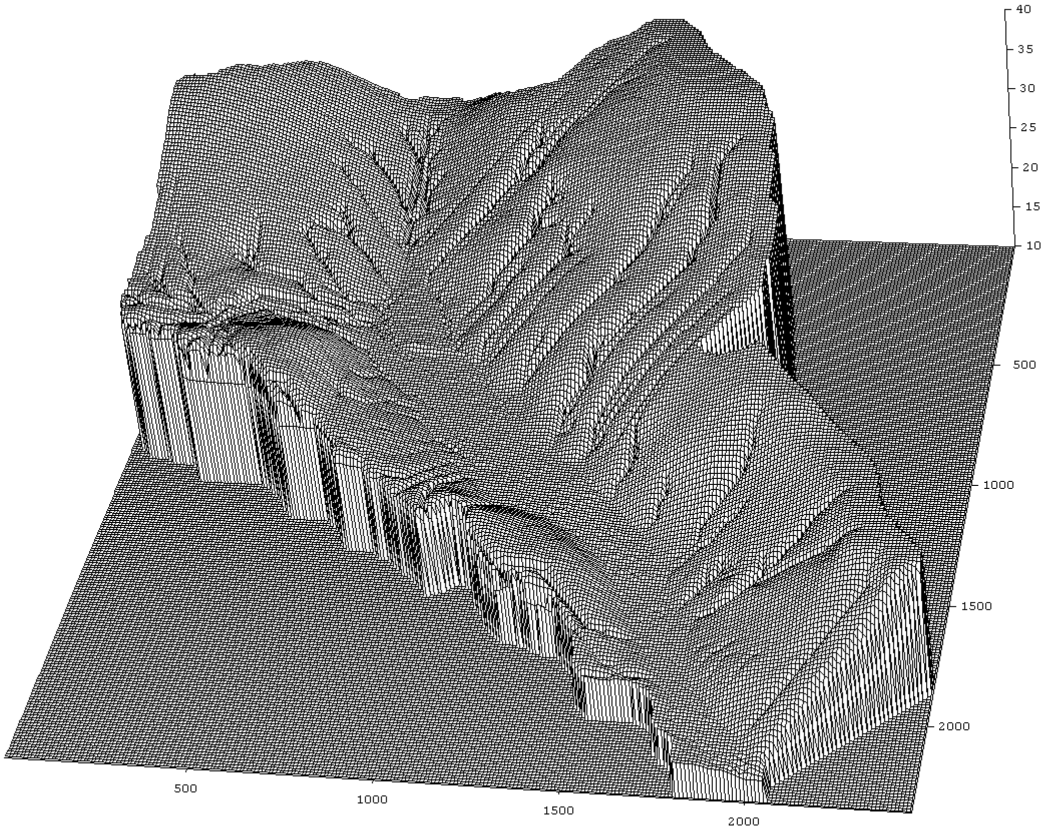
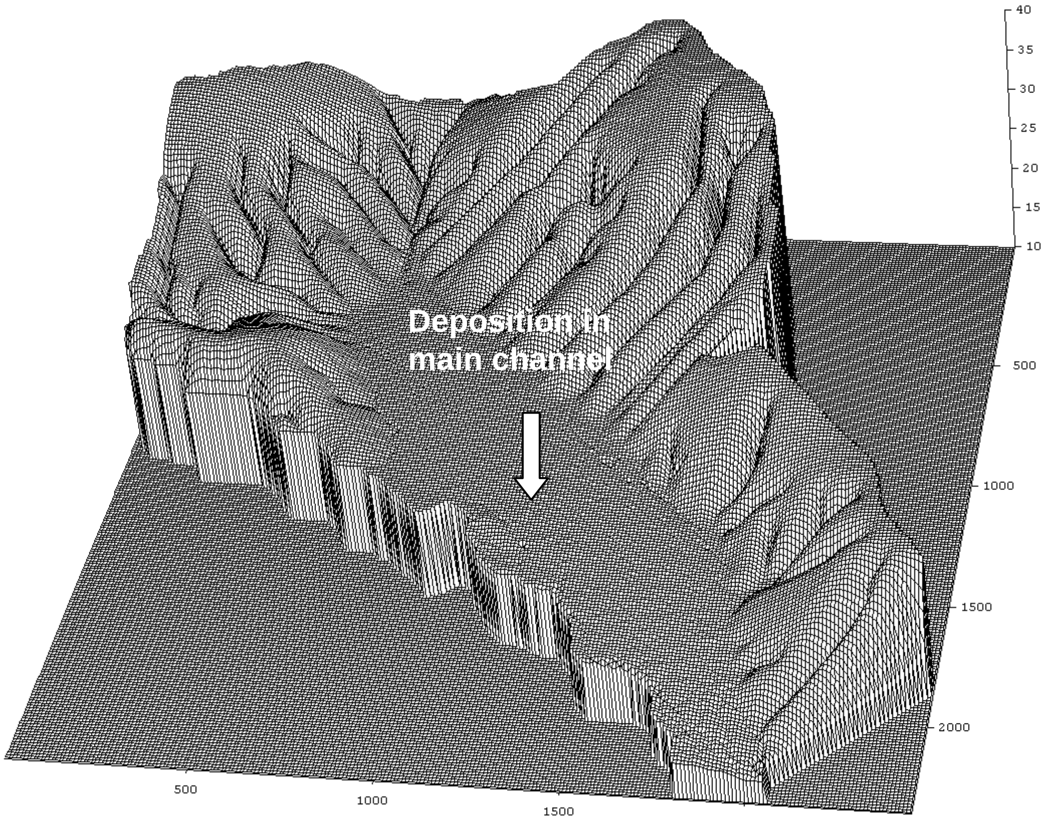


Fig. 2. Digital elevation model (10 m grid) of the current mine site with mined out pit (a) and potential rehabilitation design (b). All dimensions are metres.

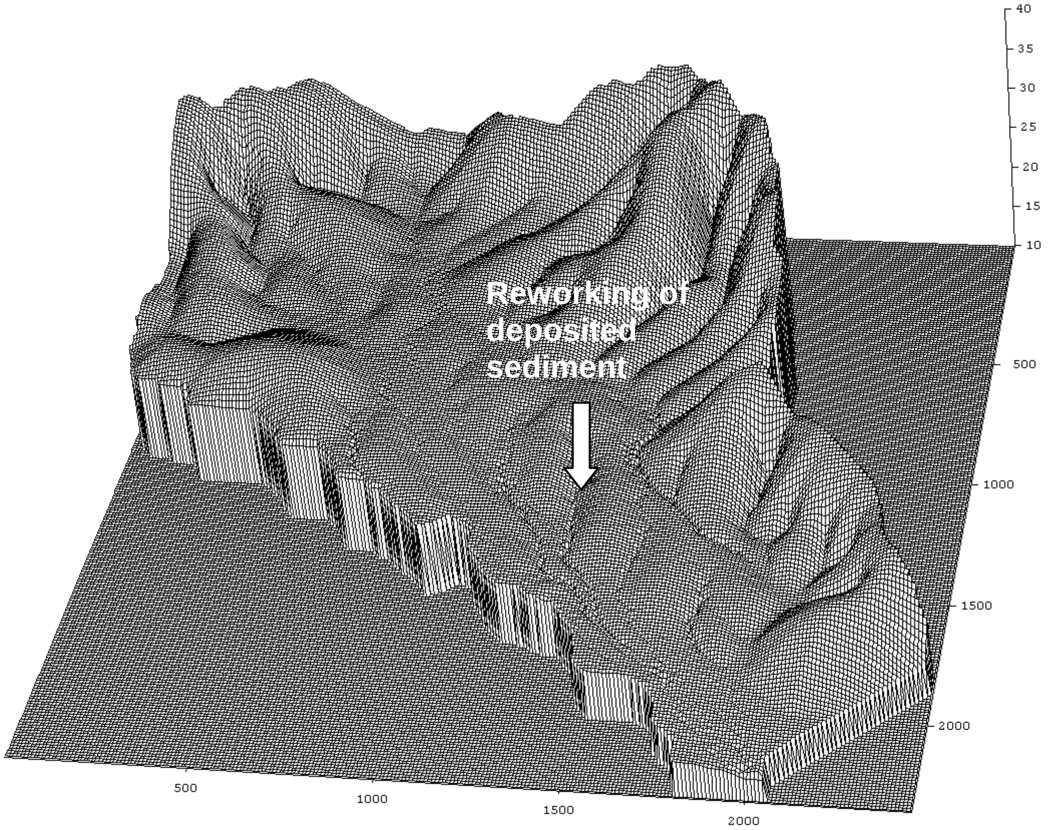
(a) 1000 years



(b) 10,000 years



(c) 100,000 years



(d) 500,000 years

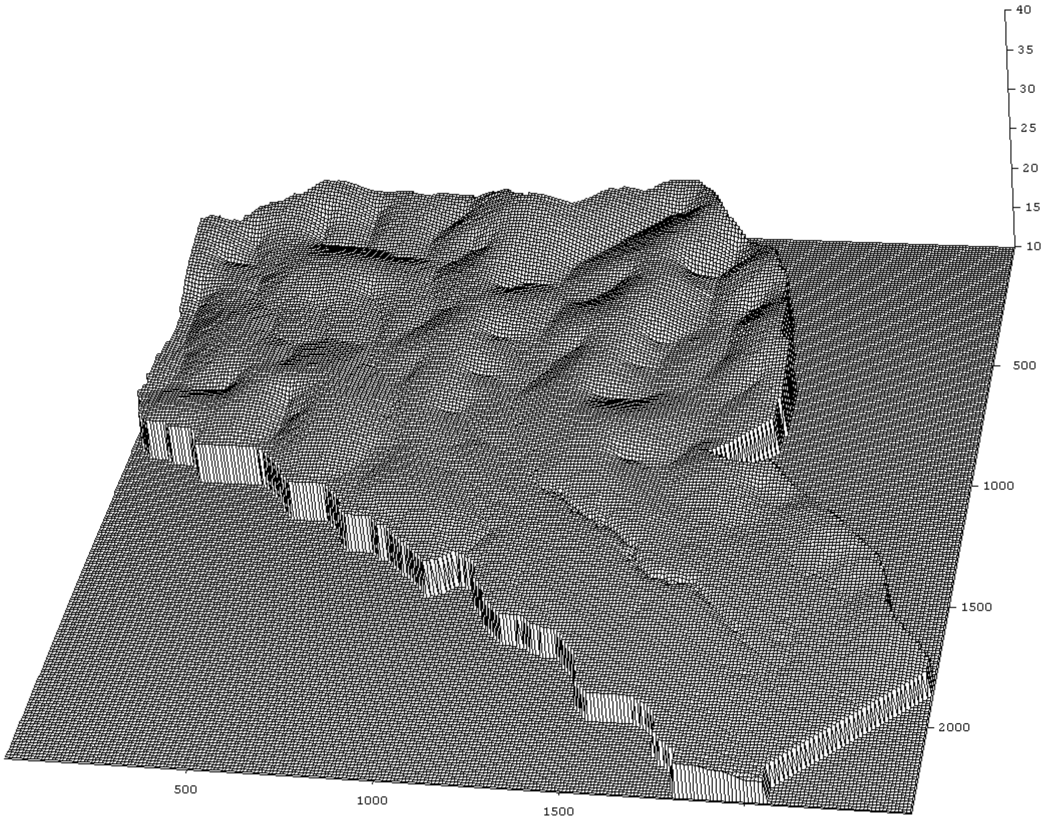
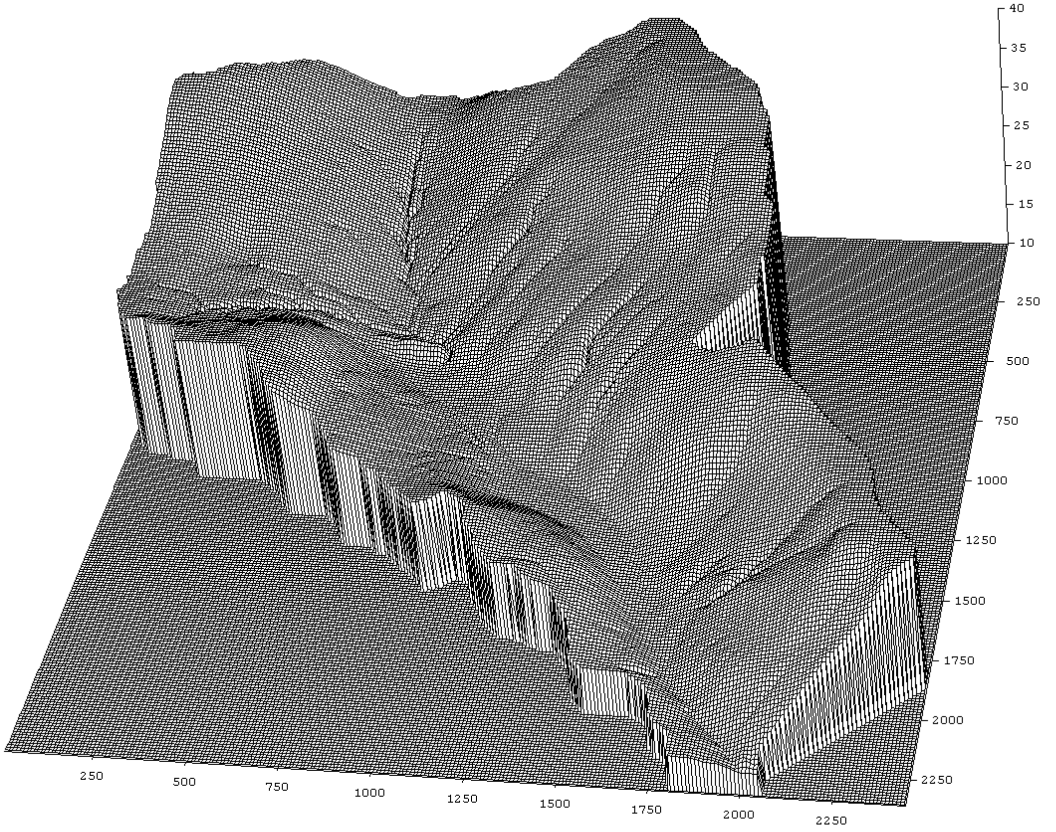
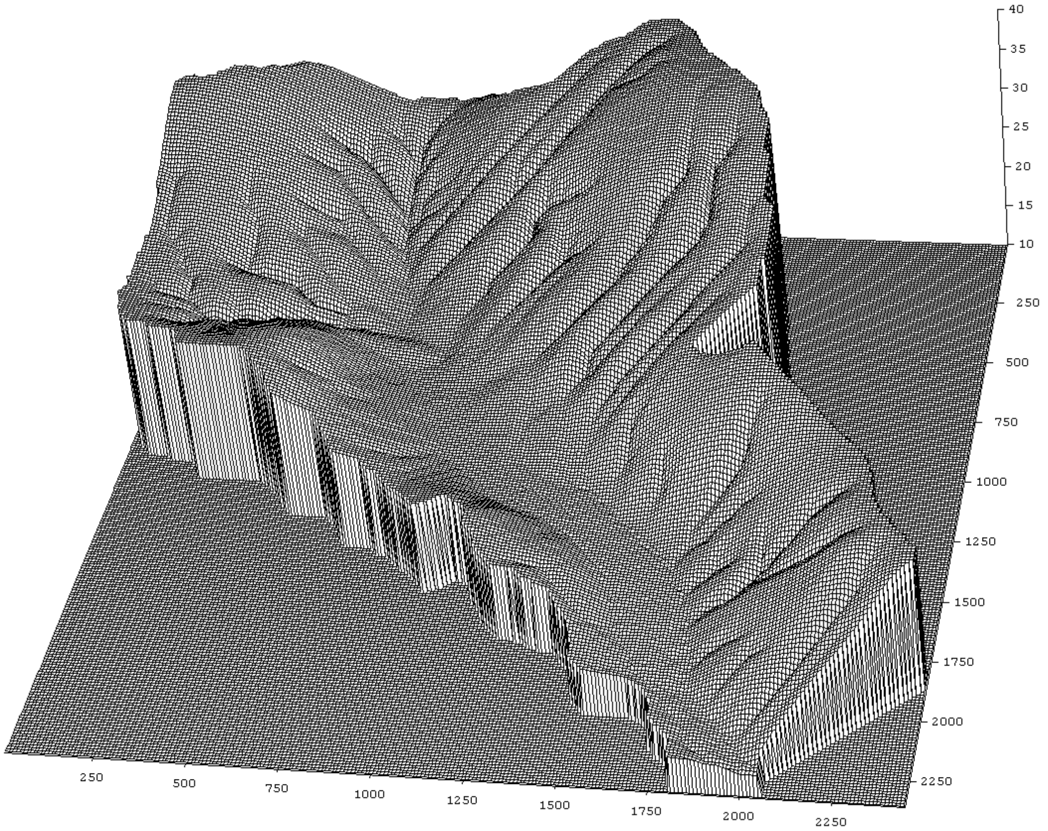


Fig. 3. Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years using the SIBERIA model and Waste Rock Dump parameters. All dimensions are metres.

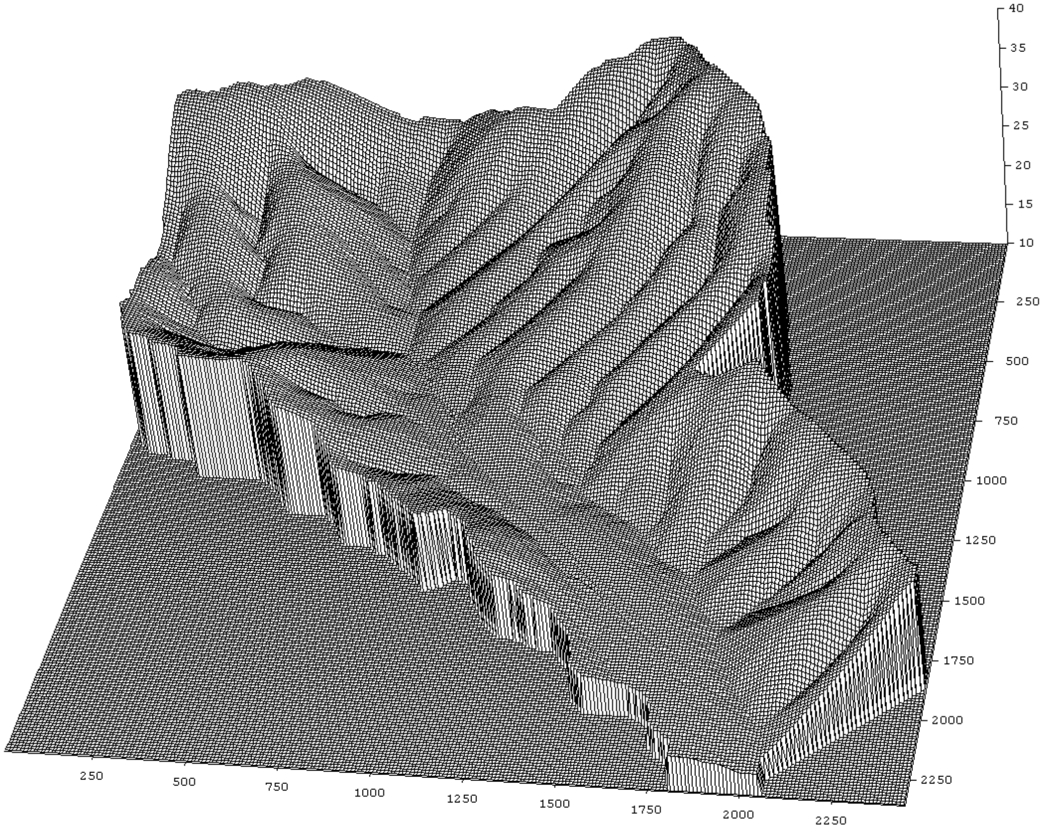
(a) 1000 years



(b) 10,000 years



(c) 100,000 years



(d) 500,000 years

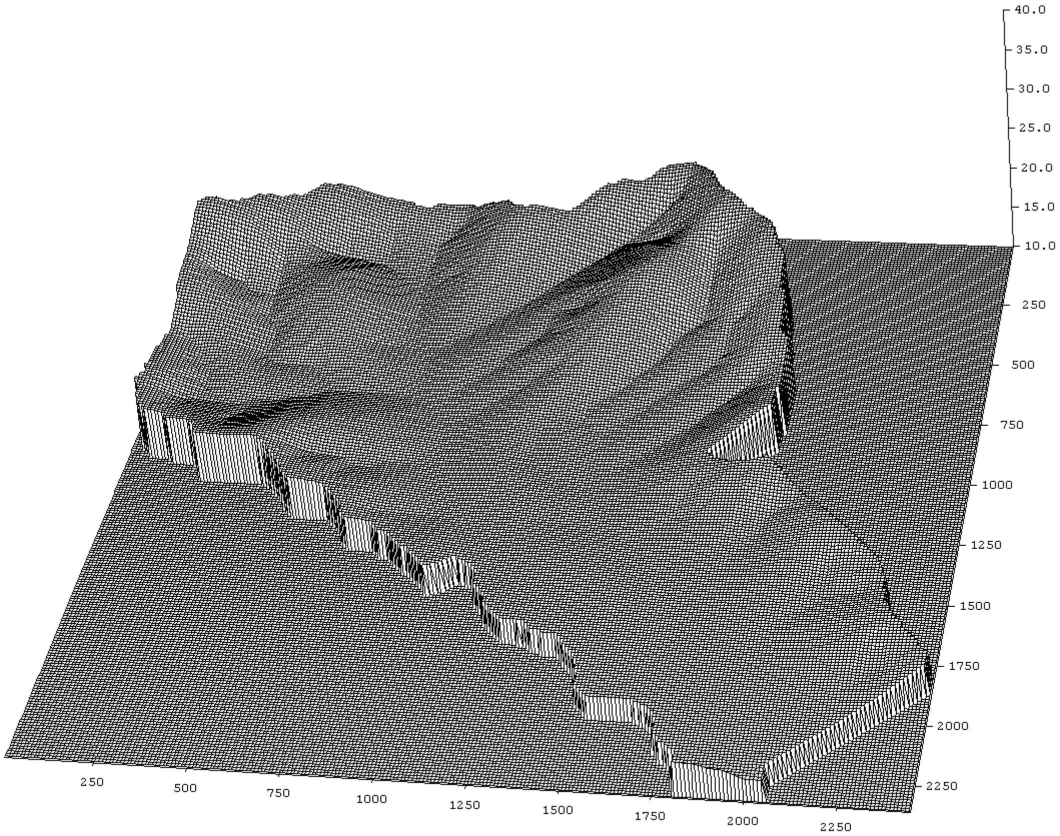
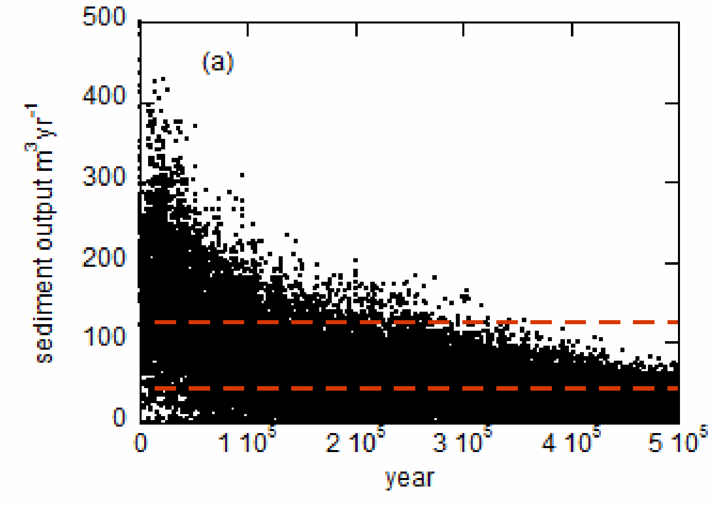


Fig. 4. Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years using the SIBERIA model and Vegetation parameters. All dimensions are metres.



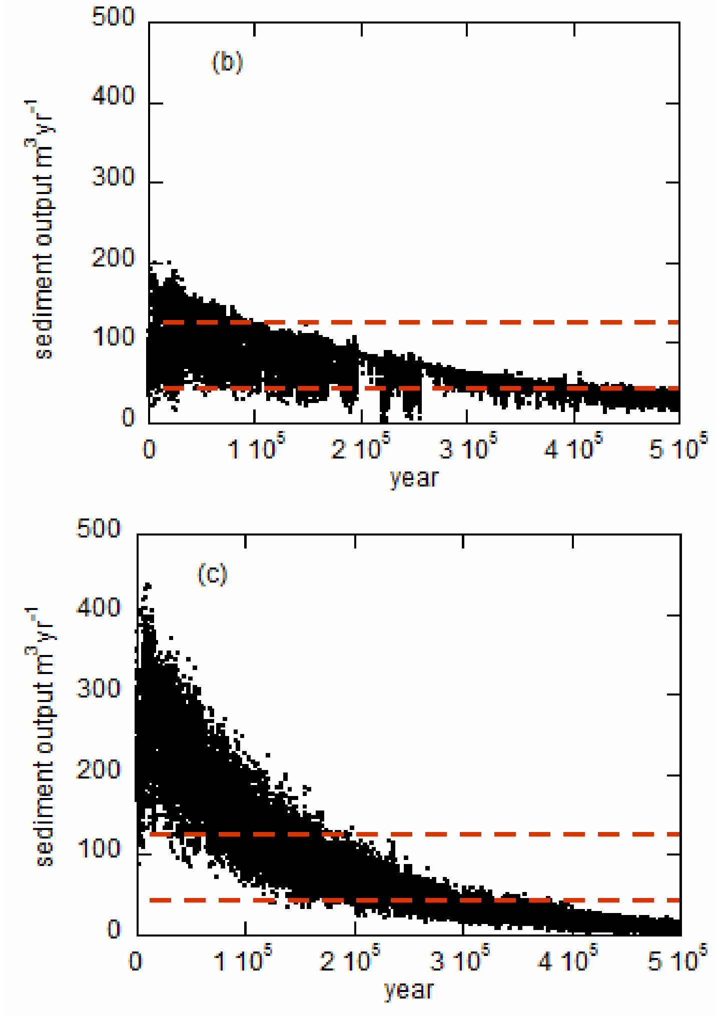
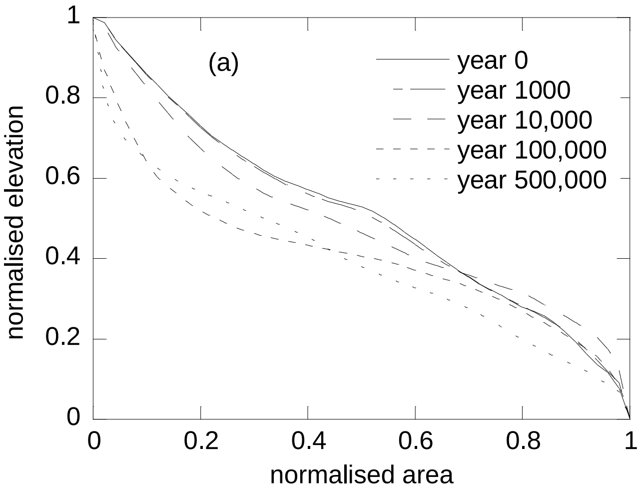
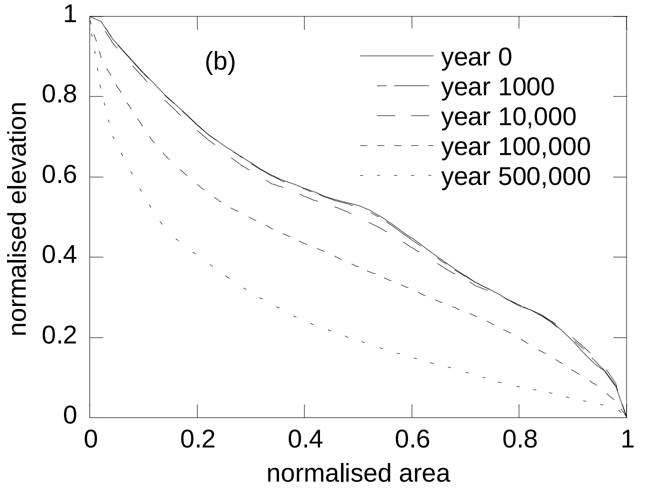


Fig. 5. Simulated annual sediment discharge and average annual elevation from Corridor Creek landform using Waste Rock Dump (a), Vegetation (b) and Tin Camp Creek parameters (c). The red line represent the range of sediment discharge as predicted from the regional denudation rates of 0.01–0.04 mm y^{-1} (30–120 m^3 y^{-1}). For clarity, each year represents an average of 10 years sediment output.





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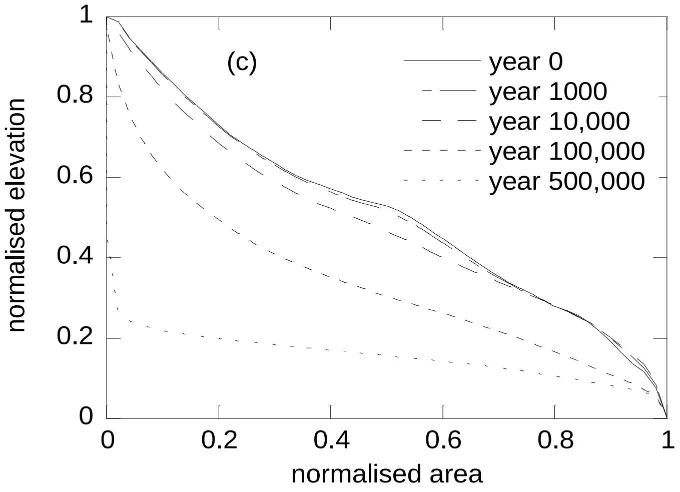

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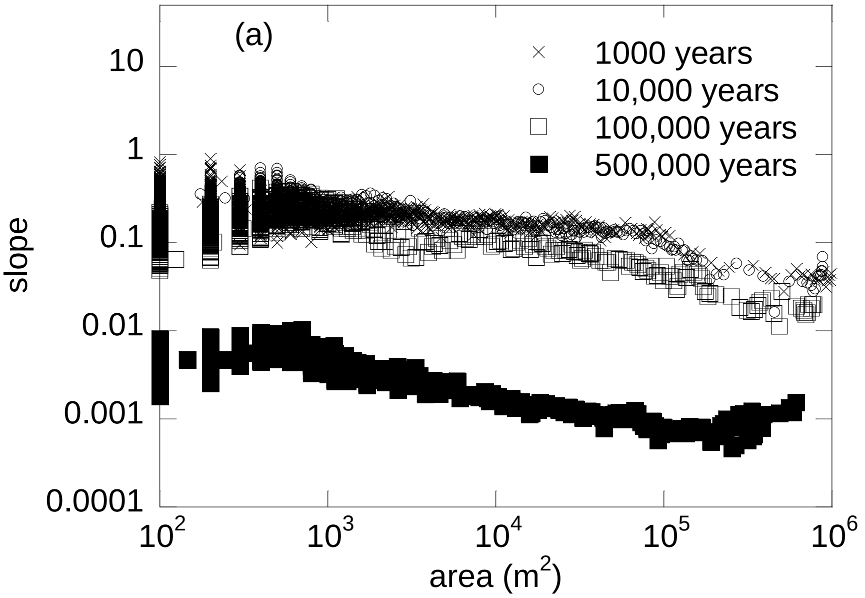
907 **Fig. 6**. Hypsometric curves for the Corridor Creek catchment using Waste Rock Dump (a),
908 Vegetation (b) and Tin Camp Creek parameters (c).



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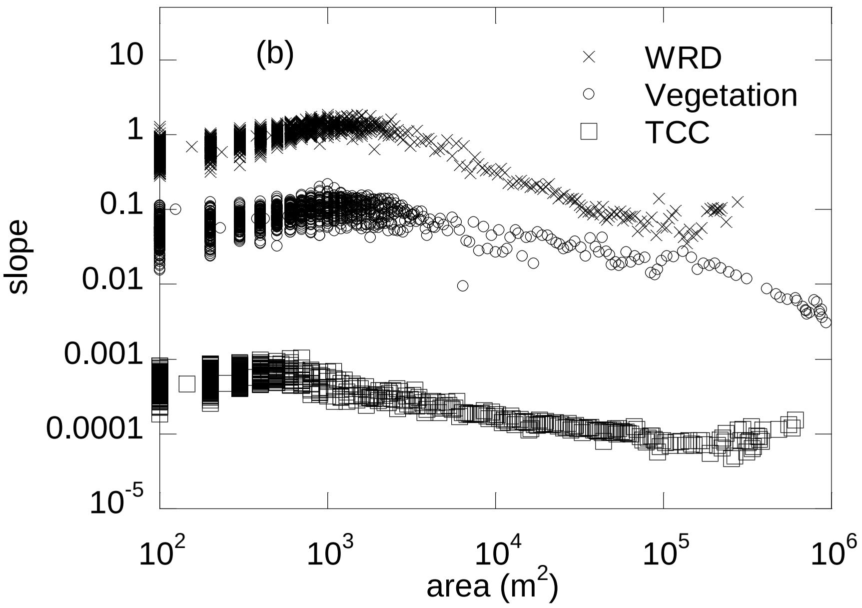
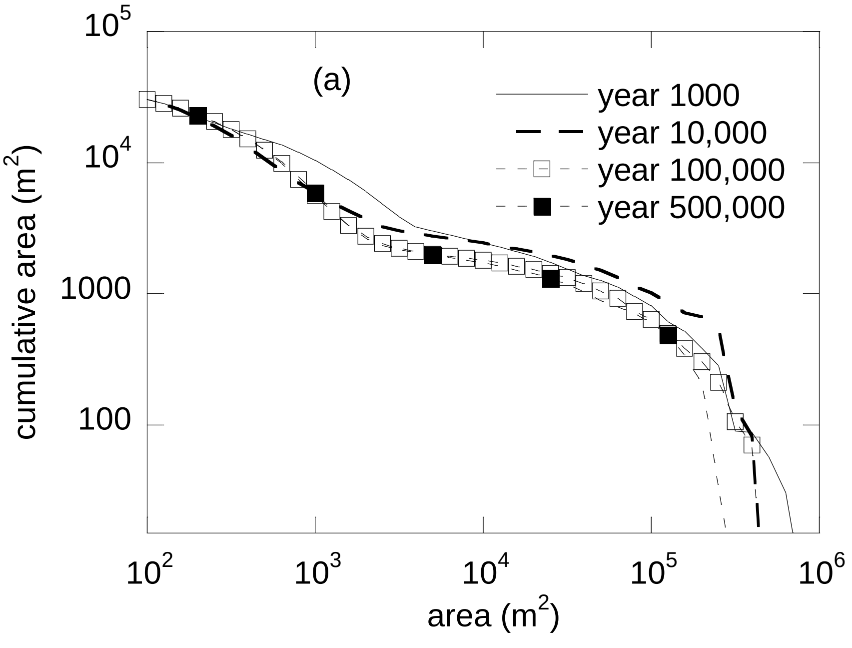


Fig. 7. Area–slope relationship for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period (a) and comparison of the WRD, Vegetation and Tin Camp Creek area-slope data at 500,000 years (b). In (b) the WRD parameter slope data have been multiplied by 10 while the Tin Camp Creek parameter slope data has been divided by 10 for clarity.



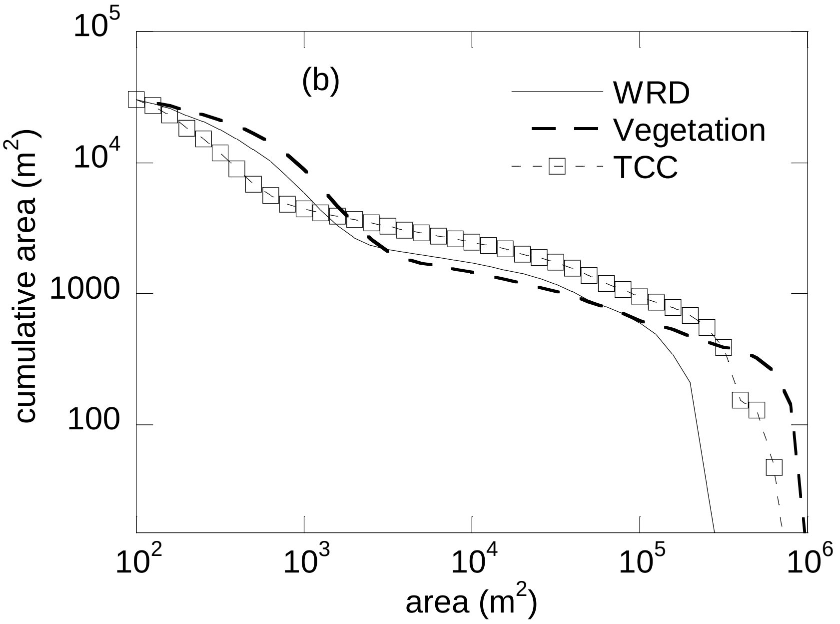
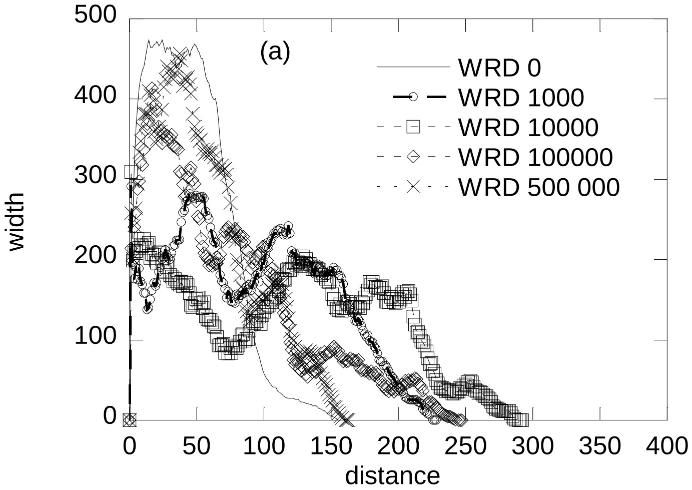


Fig. 8. Cumulative area distribution (a) for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period and comparison of the WRD, Vegetation and Tin Camp Creek cumulative area data at 500,000 years (b).



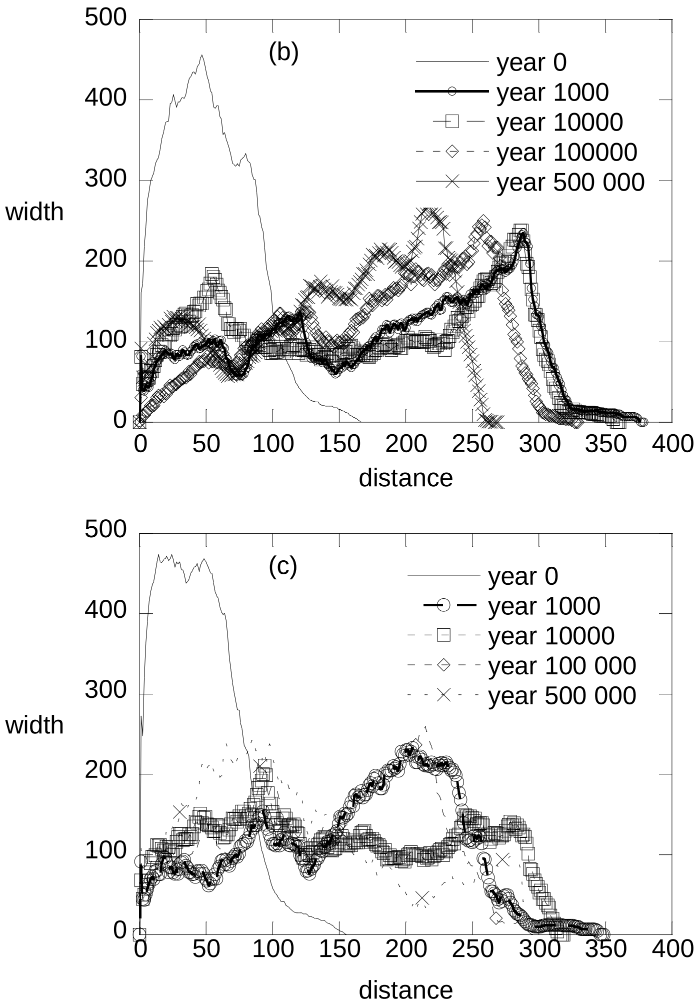


Fig. 9. Width function for the Corridor Creek catchment using the WRD (a), Vegetation (b) and Tin Camp Creek parameters (c).

(a)

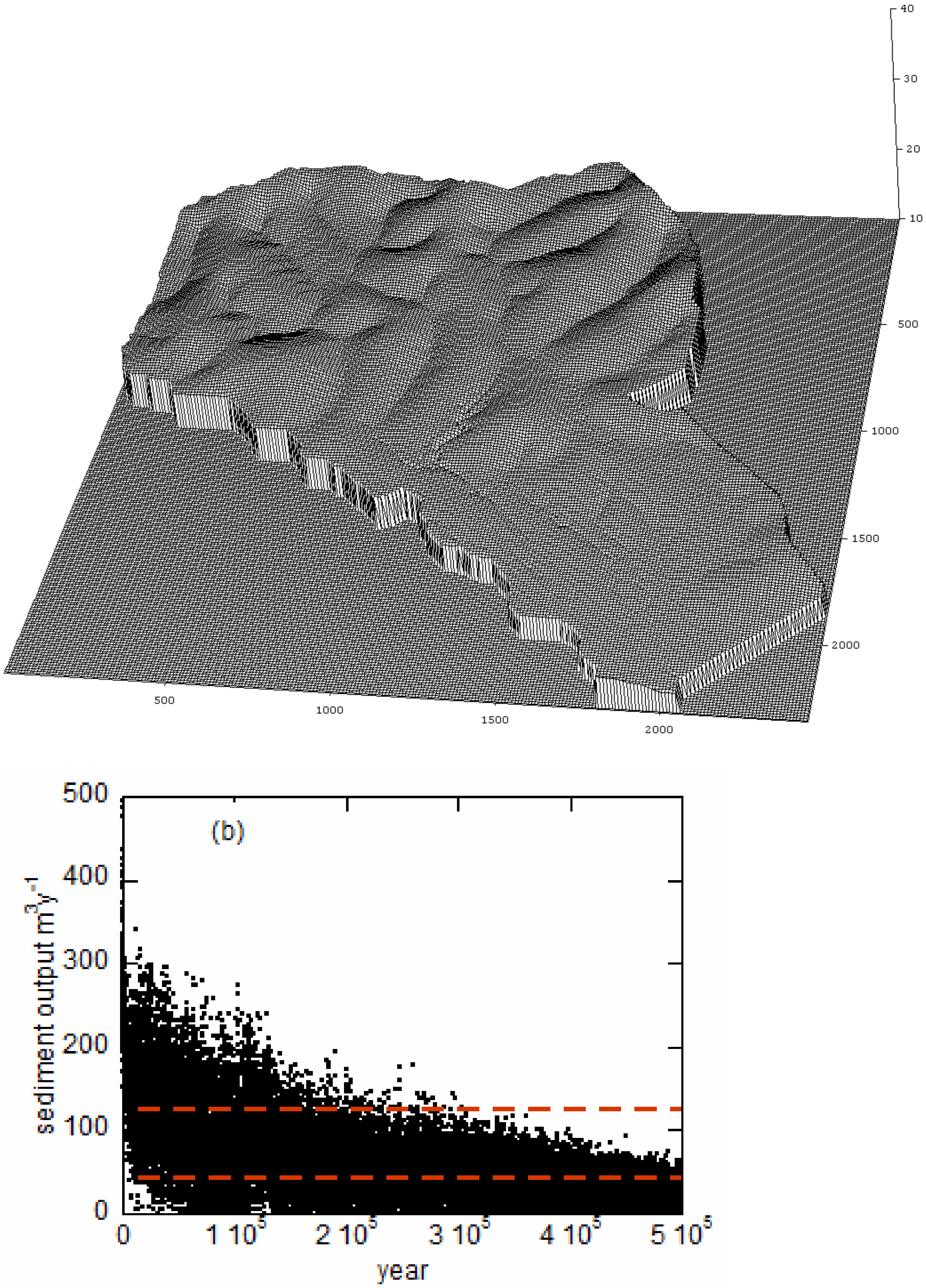


Fig. 10. Corridor Creek landform at 500,000 years using WRD parameters and the DInfinity drainage direction algorithm (a) and sediment output from the simulation (b). The red line represent the range of sediment discharge as predicted from the regional denudation rates of 0.01–0.04 mm y^{-1} (30–120 m^3 y^{-1}). For clarity, each year represents an average of 10 years sediment output.

Table 1. The SIBERIA parameter values for each region of the ERA Ranger mine for the Einstein-Brown sediment transport equation.

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
Analogue soil	Natural soil at Tin Camp Creek (Moliere, et al. 2002)	1.7	0.69	0.186	0.79	1067

Table 2. Results from the SIBERIA simulations using Waste Rock Dump (WRD), Vegetation and Tin Camp Creek analogue soil parameters.

year	catchment relief (m)	average erosion rate (mm y^{-1})	max. erosion depth (m)
	WRD		
0	25.874	-	-
1000	25.872	0.053	7.035
10,000	25.860	0.053	11.842
100,000	22.528	0.040	16.097
500,000	7.589	0.021	23.314
	Vegetation		
0	25.874	-	-
1000	25.873	0.024	1.212
10,000	25.855	0.031	2.526
100,000	24.422	0.035	9.339
500,000	8.849	0.022	21.084
	Tin Camp Creek		
0	25.874	-	-
1000	25.611	0.082	6.719
10,000	24.904	0.078	10.345
100,000	18.826	0.067	13.598
500,000	12.674	0.026	25.511