

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

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

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32 **Abstract**

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34 A significant issue for the application of numerical Landscape Evolution Models (LEMs) is
35 their calibration/parameterisation and validation. LEMs are now at the stage of development
36 where if calibrated, they can provide meaningful and useful results. However, before use,
37 each LEM requires a set of data and parameter values for it to run reliably and most

38 importantly produce results with some measure of precision and accuracy. This
39 calibration/validation process is largely carried out using parameter values determined from
40 present day, or recent surface conditions which are themselves product of much longer-term
41 geology-soil-climate-vegetation interactions. Here we examine the reliability of an LEM to
42 predict catchment form over geological time (500, 000 years) for a potential rehabilitated
43 mine landform using defensible parameters derived from field plots. The findings demonstrate
44 that there is no equifinality in landscape form with different parameter sets producing
45 geomorphically and hydrologically unique landscapes throughout their entire evolution. This
46 shows that parameterisation does matter over geological time scales. However, for shorter
47 time scales (<10,000 years) the geomorphic differences in hillslope form are minimal as
48 described by the hypsometric curve, area–slope and cumulative area distribution, yet there are
49 large differences in sediment output. Therefore, obtaining reliable and defensible parameters
50 for input to LEMs is essential.

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

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58 **1 Introduction**

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

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

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

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

85 This and subsequent studies have demonstrated the potential for LEMs to give insights
86 into future geomorphic form and function and are now being applied to disturbed site
87 assessment and rehabilitation (Willgoose and Riley, 1998; Hancock et al., 2000, 2002; Evans

88 et al., 2000; Lowry et al., 2011; Coulthard et al., 2012). The focus of this paper and those
89 cited above is on post-mining landforms, which are designed to bury or encapsulate mine
90 sites, including tailings, drains, spoil tips and other industrial architecture. Post mining
91 landforms are intended to be constructed in such a way that they remain structurally intact
92 geomorphically stable, while being able to blend into the surrounding landscape. In the
93 example studied here, low-grade uranium ore, tailings, brines and other mine wastes will be
94 buried at depth in the areas of the former pits and tailings storage facilities of a de-
95 commissioned uranium mine.

96 The rehabilitation of uranium mines is a particular concern as radionuclides represent
97 a potential set of contaminants with long half-lives and persistence in the environment
98 (Schumm et al., 1984). Australian guidelines recommend a design life for a tailings cap of a
99 uranium mine of 200 years and a structural life of at least 10,000 years. This means the
100 structure used to encapsulate radioactive tailings must be built to maintain its integrity from a
101 1 in 10,000 year rainfall event. Understanding model parameter accuracy and reliability is
102 therefore particularly important when assessing landscapes at millennial time scales. This
103 generates a major research question, as we have the numerical methods to simulate landscape
104 stability over millennia, but not necessarily the correct parameter values and data sets with
105 which to drive these predictions.

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

111

112 **2 Site description**

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

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123 Mine tailings are currently stored in an above ground tailings dam and in the mined-
124 out Pit 3 (Figure 2). Pit 1 previously received tailings and is in the process of being capped.
125 Mining from Pit 3 ceased in 2012, and milling and processing of stockpiled ore is scheduled
126 to cease by 2021. Consequently, attention is increasingly focussing on the closure and the
127 rehabilitation of the mine.

128 The requirements for the closure and rehabilitation of the Ranger mine have been
129 published in a series of ~~e~~Environmental ~~r~~Requirements. These state, with respect to erosion
130 and landform stability, that the landform should possess "*erosion characteristics which, as
131 far as can reasonably be achieved, do not vary significantly from those of comparable
132 landforms in surrounding undisturbed areas*"(Supervising Scientist Division, 1999).
133 Consequently, ERA will be required to rehabilitate disturbed areas of the lease to satisfy the
134 above requirements. Implementing these ~~requirements~~-will require the landscape to be
135 rehabilitated in a way that restores environmental functions supporting local ecosystem
136 diversity (Ludwig and Tongway 1995; ~~1996~~). The first stage in this process is to design and
137 construct a landform which is erosionally stable.

Comment [A2]: I do not understand this capitalized expression. If this is something Australian, please add explanation so that people in other countries can understand.

Good point - Corrected

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138 The regional geology of the Alligators River Region is dominated by the mineralised
139 metasediments and igneous rocks of the Pine Creek geosyncline (one of the richest uranium
140 provinces in the world) and the younger sandstones of the Mamadawerre Formation
141 (Needham, 1988; East, 1996; ~~Needham, 1988~~). Geomorphically, the Ranger site is
142 characterised as part of the deeply weathered Koolpinyah surface. This consists of plains,
143 broad valleys and low gradient slopes, with isolated hills and ridges of resistant rock (East,
144 1996). -Regional denudation rates for the area (0.01 to 0.04 mm y⁻¹) have been determined
145 using stream sediment data from a range of catchments of different sizes in the general region
146 (Cull et al., 1992; Erskine and Saynor, 2000).

147 The study site is in the wet-dry tropics of northern Australia and is subject to high-
148 intensity storms and tropical monsoons between October and April. Minimal rain falls in the
149 remainder of the year; the annual average rainfall is 1583 mm (Bureau of Meteorology, 2015).
150 Vegetation on the mine lease and surrounds consists of open Eucalypt forest dominated by
151 *Eucalyptus. tetradonta*, *Eucalyptus. miniata*, *Eucalyptus. bleeseri* and *Eucalyptus. porrecta*.
152 The understorey is characterised by *Acacia* spp., *Livistona humilis* and *Gardenia megasperma*
153 with a variable grass cover of *Sorghum* spp., *Themada triandra* and *Eriachne triseta* (Chatres
154 et al., 1991).

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155

156 3 Landscape evolution models and their parameterisation

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

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Added to reference list

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apostrophe is a global standard.
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163 | diffusive erosion and mass transport processes (Willgoose et al., 1991). –SIBERIA describes
164 | how the catchment is expected to look, on average, at any given time. The sophistication of
165 | SIBERIA lies in its use of digital elevation models (DEMs) for the determination of drainage
166 | areas and geomorphology and its ability to efficiently adjust the landform with time in
167 | response to the erosion that could occur on it. –Since 1993, SIBERIA has been used
168 | principally to investigate surface stability of post-mining rehabilitated landforms or small
169 | catchment areas (i.e. Willgoose et al., 1991; Evans et al., 1998; Willgoose and Riley, 1998;
170 | Hancock et al., 2000, 2013 Moliere et al., 2002^a).

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171 | SIBERIA requires calibration of the sediment transport and area–discharge
172 | relationships, and a DEM of the landform of interest (described in Section 4). The fluvial
173 | sediment transport equation is parameterised using input from field sediment transport and
174 | hydrology data. Here SIBERIA was calibrated using field data collected from the Ranger
175 | mine site (the study site) and Tin Camp Creek ([the analogue site](#)). The Tin Camp Creek site,
176 | located approximately 50 km from Ranger, is on the same metamorphosed schist formation as
177 | found at the Ranger mine and the surface properties are seen as an analogue of proposed
178 | rehabilitated landforms for the Ranger Mine in the long-term (Uren, 1992; Riley and Rich,
179 | 1998).

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

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

189 For long-term landscape assessment SIBERIA requires both fluvial and diffusive
190 sediment transport data. The SIBERIA value for rainfall diffusivity (i.e. rainsplash) value of
191 $0.005 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ (width) was used as this has been found to be the most applicable for the
192 Alligator Rivers Region which includes the Ranger site (Hancock et al., 2002, 2014). The field
193 data parameter values determined for these surfaces are shown in Table 1. The methodology
194 employed in the derivation of the parameters for the different surfaces is described in Evans
195 and Willgoose (2000), Evans et al. (2000) and Moliere et al. (2002).

196

197 **4 Catchment digital elevation models, model setup and landscape assessment**

198 Several small catchments will drain from the proposed possible landform at Ranger
199 and here we focus on the Corridor Creek catchment that drains into Magela Creek. (Figure

200 2).

201 — The DEM was calculated from two datasets. Firstly, a ~~two-metre~~
202 dataset representing the current landform surface was produced from a LiDAR survey of the
203 mine in 2010. This was supplemented by an additional two-metre contour interval dataset that
204 represented the proposed rehabilitated landform design. The LiDAR contours outside of the
205 rehabilitated landform area were combined with the contours representing the proposed
206 rehabilitated landform area and used to produce a grid surface with a horizontal resolution of
207 ~~two metres~~. The DEM representing the rehabilitated surface was resampled to a horizontal
208 spatial resolution of 10 m. This was chosen as being the optimal resolution at which SIBERIA
209 could function within the spatial extent of the study catchment, and over the temporal periods
210 modelled yet still reliably capture the salient features of hillslope geomorphology (Hancock,
211 2005). The final DEM used in this study was understood to represent a fully consolidated

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

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

221 Short et al. (1989) estimated that the surrounding undisturbed landscape (termed the
222 Koolpinyah surface) is approximately 300,000 years old. Therefore, to allow an equivalent
223 landscape to develop and to examine long-term landscape trends and geomorphic change,
224 SIBERIA was run for 500,000 years. Outputs from the model included a DEM of the
225 catchment and sediment discharge at annual time steps (here we examine DEMs at 1,000,
226 10,000, 100,000, 500,000 years) as well as geomorphic descriptors of the catchments
227 (hypsometric curve, area–slope relationship, cumulative area distribution and width
228 function).

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

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

237
$$A^\alpha S = \text{constant} \quad (1)$$

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

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

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

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259 5 Results

260 5.1 *Qualitative visual assessment*

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

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

283 While not displayed here for brevity, the simulation using the Tin Camp Creek

284 parameters displays similar behaviour to that of the WRD and Vegetation parameter
285 simulations. Visually there are no striking differences between the simulated catchments.
286 However, all have qualitative differences in both hillslope form. They have different relief,
287 location of hills and valleys as well as the morphology of the depositional area in the main
288 channel. Therefore, the three different parameters sets produce qualitatively different
289 landscapes with unique hillslope length, shape and position. Importantly, each modelled
290 landscape output is not geomorphically impossible.

291

292 5.2 *Quantitative assessment – sediment output*

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293 In terms of erosion and landscape lowering, the maximum depth of erosion is 11.8 m,
294 2.5 m and 10.3 m for the WRD, Vegetation and Tin Camp Creek parameter simulations at
295 10,000 years, respectively (Table 2). This indicates a substantial difference that may be
296 especially relevant for areas where contaminants are buried

297 Simulated sediment yields from the catchment are highly variable but decline through
298 time for all simulations (Figure 5). For the WRD parameters, over the first 50,000 years the
299 sediment output is comparatively high and for much of this period well outside the upper
300 range for natural sediment output; (the expected sediment output from the catchment is 30–
301 120 m³/year based on a denudation rate of 0.01–0.04 mm y⁻¹ and corrected for catchment
302 area). However, after approximately 100,000 years, sediment output has declined and the
303 mean is within that of the expected sediment output range, though some peaks above this
304 range still exist.

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

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

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

316

317 *5.3 Quantitative assessment – catchment geomorphic descriptors*

318 In this study, we found little difference in the hypsometric properties for the WRD,
319 Vegetation and Tin Camp Creek parameter simulations up to 10,000 years (Figure 6). At this
320 time there has been insufficient erosion to change catchment area–elevation form. At
321 100,000 years, both catchments (WRD and Vegetation parameters) display hypsometric
322 curves which have mature landscape characteristics. At 500,000 years, the WRD and
323 Vegetation parameter simulations have mature landscape curves while the Tin Camp Creek
324 parameter curve has monadnock form. Overall, the hypsometric curve demonstrates that there
325 has been significant area–elevation change over the 500,000 year modelled period with the
326 three parameter sets producing different area-elevation form.

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

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333 | At the end of the modelled period the area-slope relationship for the WRD,
334 | Vegetation and Tin Camp Creek parameter simulations all display unique characteristics with
335 | both slope of the diffusive and fluvial regions being different (Figure 7, bottom). The area-
336 | slope relationship for the WRD, Vegetation and Tin Camp Creek parameters all have positive,
337 | yet different slopes for areas approximately less than 1000-2000 m² while at areas
338 | approximately greater than 1000-2000 m² both data sets (WRD and Vegetation) have a
339 | negative (yet different) log-log linear slope. Differences in all three area-slope plots result
340 | from the different model parameters. Interestingly, despite the same diffusivity parameters
341 | being applied for all simulations, the diffusive area of the curve is different and reflects the
342 | complex interaction between the evolving landform and the diffusive and fluvial parameters.
343 | For example, the WRD parameters are more erosive while the Vegetation parameters are
344 | considerably less erosive. The WRD parameters may produce incision (gullies) which have
345 | steeper slopes which will have higher diffusion (as the diffusion model is slope dependent).
346 | The reverse occurs for the Vegetation parameters.

347 | The CAD for the WRD parameter simulation (Figure 8) demonstrates a change in the
348 | diffusive and fluvial area of the hillslope at 10,000 years with the distribution remaining
349 | largely the same for the remaining duration of the simulation. The CAD for the WRD,
350 | Vegetation and Tin Camp Creek parameters all display different distributions at the
351 | termination of the simulation at 500,000 years in both the diffuse and fluvial regions of the
352 | curve. Interestingly, the Vegetation parameter simulation has a more rounded or convex
353 | distribution while the Tin Camp Creek parameter simulation is largely log-log linear with
354 | positive slope in the diffusive area of the curve. The extent of the diffusive region also varies
355 | for all three parameter sets. For the fluvial region, the slopes are all similar; however, the
356 | maximum area varies for all three simulations. This demonstrates that all three have different

357 area-aggregation patterns (also demonstrated below with the channel network and the width
358 function).

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

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

376

377 **6 Discussion**

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

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

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

389

390 *6.1 Long-term prediction and equifinality*

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

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

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

410

411 | *6.2 Landscape form and sediment output*

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

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

427 | A further issue is the direction and path that water and sediment flows over the
428 | landscape surface and how it is modelled (Garbrecht and Martz, 1997). To examine this issue
429 | a simulation was run using WRD parameters and the DInfinity (Tarboton, 1987) drainage
430 | direction algorithm (Figure 10). Similar to the WRD, Vegetation and Tin Camp Creek
431 | results, the landform at 500,000 years displays a unique distribution of hillslope shape and

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432 channel position and also has a unique sediment output. Therefore choice of drainage
433 direction model has an effect (Tarboton, 1987; Garbrecht and Martz, 1997). How other
434 models and drainage routing functions influence landscape evolution is an area for future
435 work ~~(and is discussed further in Section 7)~~.

Comment [A16]: This is a bit strange. Here is the Discussion section. So things discussed should be in this section, I think.
Good point! Deleted

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

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

456 Another significant issue is that these parameters were derived from a set of rainfall

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

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

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472 6.3 *The development of long-term understandings*

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

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

487 There are many mines around the world that will continue to operate for many
488 decades. Many of these sites lack specific long-term data for landscape planning. The issues
489 raised here could potentially be addressed through the establishment of a series of plots,
490 which are designed and setup so that long-term data to support rehabilitation can be provided
491 (Gerwin et al., 2009). An alternative approach is to examine sites that have been abandoned
492 and or rehabilitated. There has been little attempt to examine pedogenesis, surface armour and
493 vegetation development and how this influences erosion and landscape development on
494 former abandoned sites as we only now have developed the numerical models capable of
495 using this information (Cohen et al., 2009; Vanwalleghem et al., 2013; Minasny et al., 2015;
496 Temme et al., 2015). There are many rehabilitated and or abandoned sites that are several
497 decades old which could provide robust quantifiable data on the trajectory of these transient
498 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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500 7 Future issues and conclusions

501 While model input parameters are static, climate and the soil–vegetation interaction
502 clearly are not. Similarly, while a rehabilitated landscape will have different dimensions to
503 that of the pre-mine landscape and be constructed of essentially different materials, it is
504 unreasonable to assume that a new landscape will behave in a similar way to that of the past.
505 Yet the model parameterisation is based on the initial soil–vegetation interactions. Therefore,

506 | how valid is any prediction at times scales any longer than that of the period at which the
507 | parameters were derived?

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

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

530 This, therefore, leads to the question as to what LEM model is the most correct or
531 reliable. There are a number of models with different approaches available (see Tucker and
532 Hancock, 2010). A Monte Carlo type approach may be needed where all elements
533 contributing to landscape evolution are employed. This includes both models and parameters
534 sets. While the SIBERIA model is one of the most used and tested of the LEMs available, is
535 this model and its predictions correct? The authors in recent years have evaluated other
536 models such as CAESAR, CAESAR-Lisflood together with soil erosion models such as the
537 RUSLE (Renard et al., 1991) and found that for the landscapes and parameters sets examined
538 the models produce similar outcomes within broad error bands. Full evaluation may lead to an
539 approach where all available LEMs are employed using all available data for a series of initial
540 conditions and predictions made by providing a range of possible outcomes which utilise
541 models based on their individual capacity and focus. This approach would be similar to that
542 employed by the climate modelling community and programs such as the Coupled Model
543 Intercomparison Project (Covey et al., 2003). This approach would go some way to
544 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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546 **Acknowledgments**

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

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

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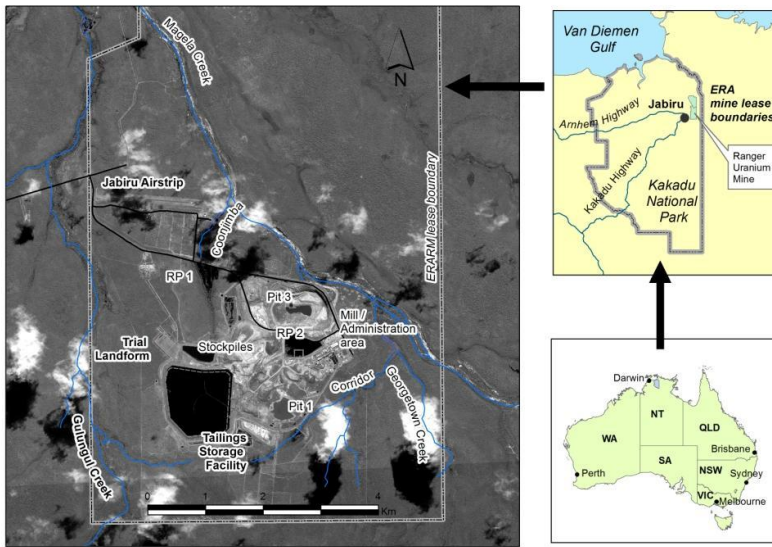
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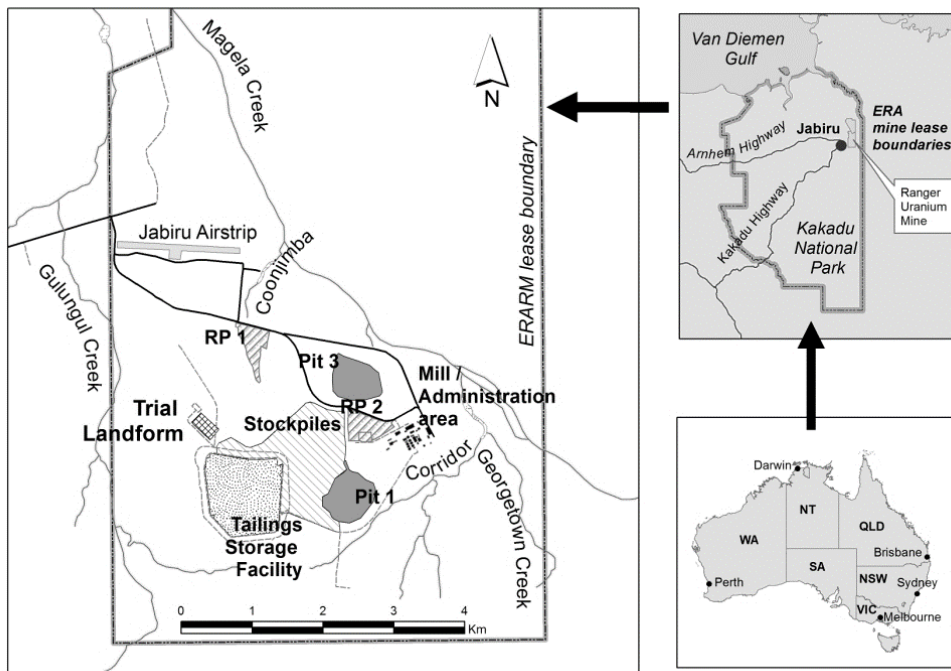


Comment [A25]: Please show in the lower right map where the upper right map is. The lower right map is currently a mere Australian map.

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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.

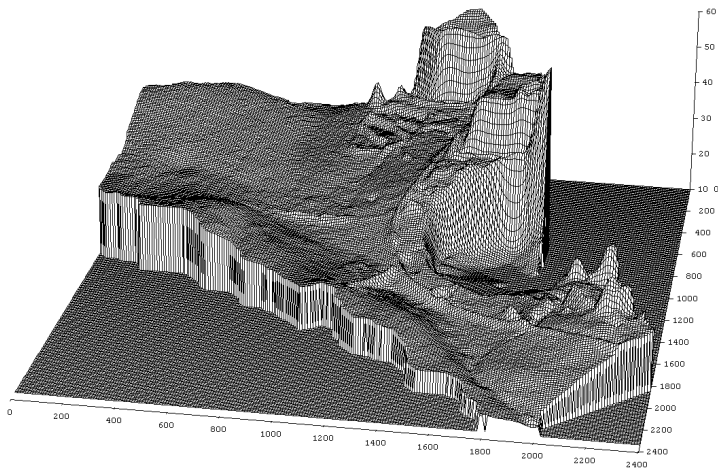


Comment [A26]: Please avoid overlapping of text labels with other symbols such as lines. About 10 cases are found in the map on the left; two cases in the upper right map.

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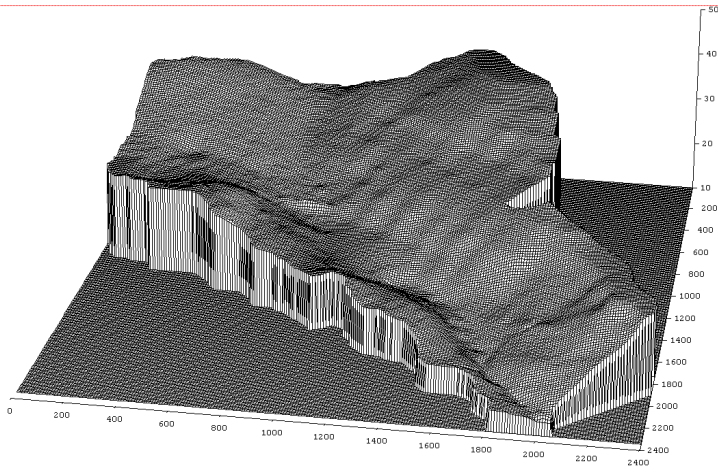
Figure 1.
Location of the study site. For brevity, the letters RP represent Retention Pond. The site is located approximately 300km west of Darwin.
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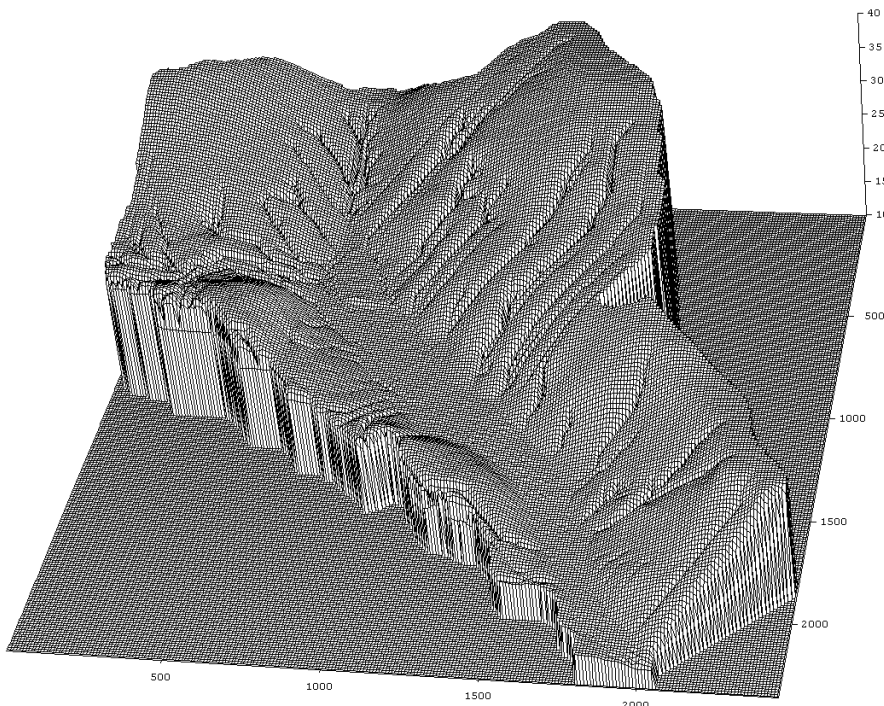
Figure 2. Digital elevation model (10_m grid) of the current mine site with mined out pit (**atop**) and potential rehabilitation design (**bottom**). All dimensions are metres.

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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918 | (a) 1000 years
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Comment [A28]: Please move this kind of labels to the upper left of each diagram, not lower left. Also Fig. 4.
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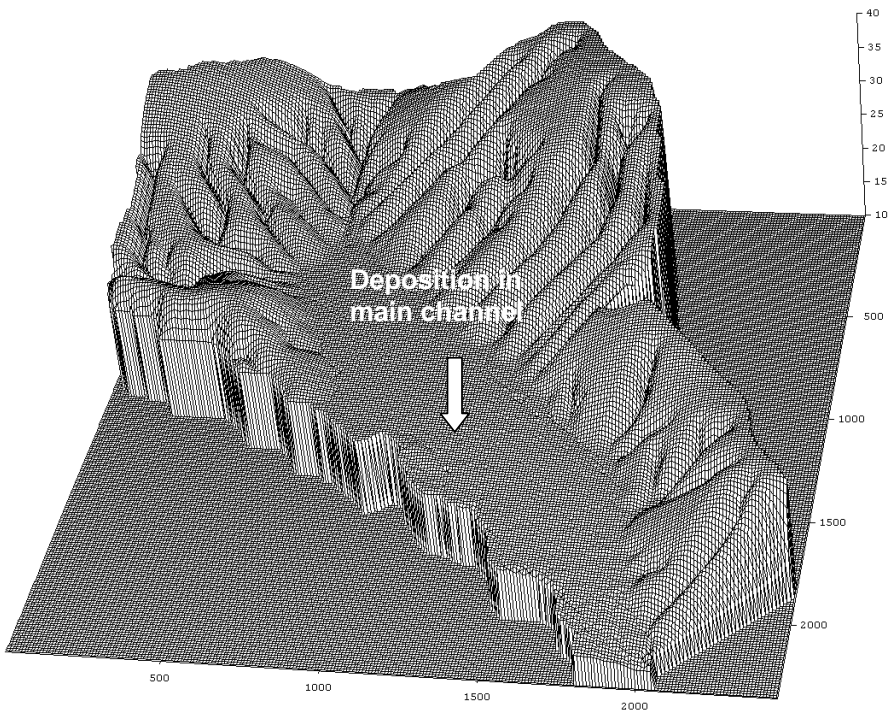


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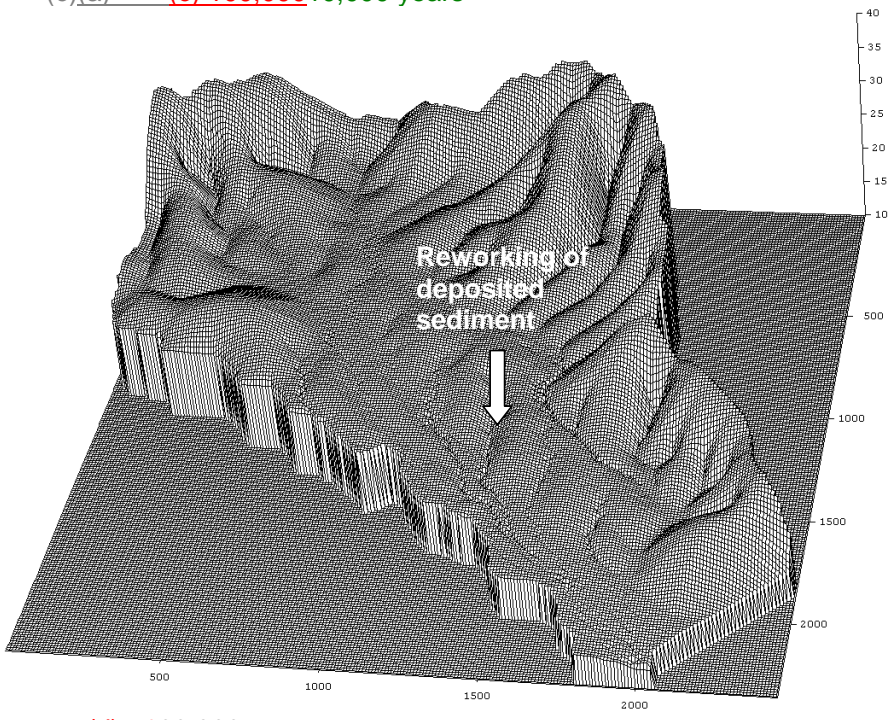
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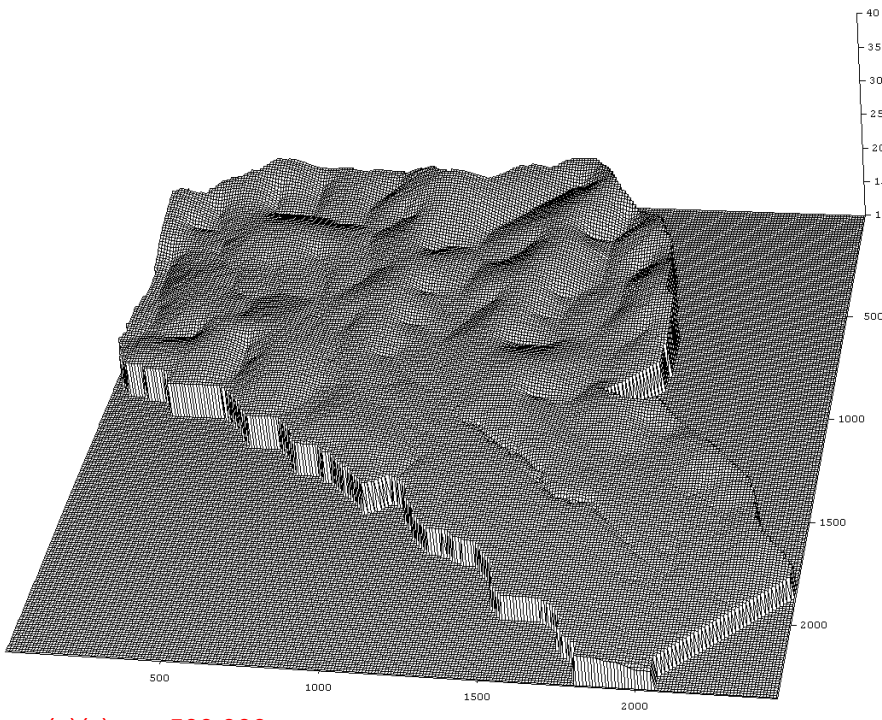
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(+) (d) 5400,000 years

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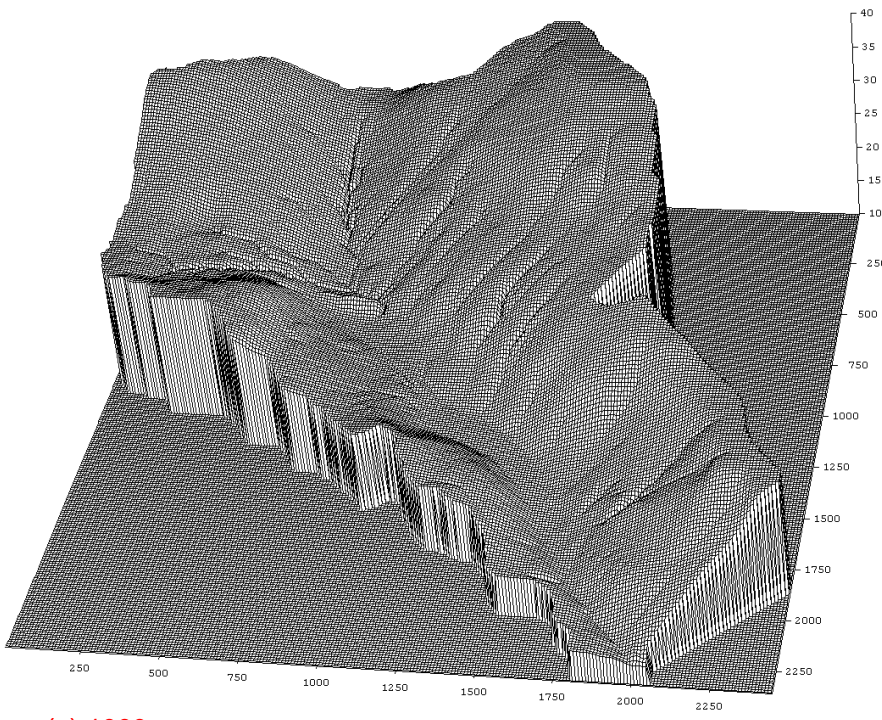
(e)(c) 500,000 years

Figure 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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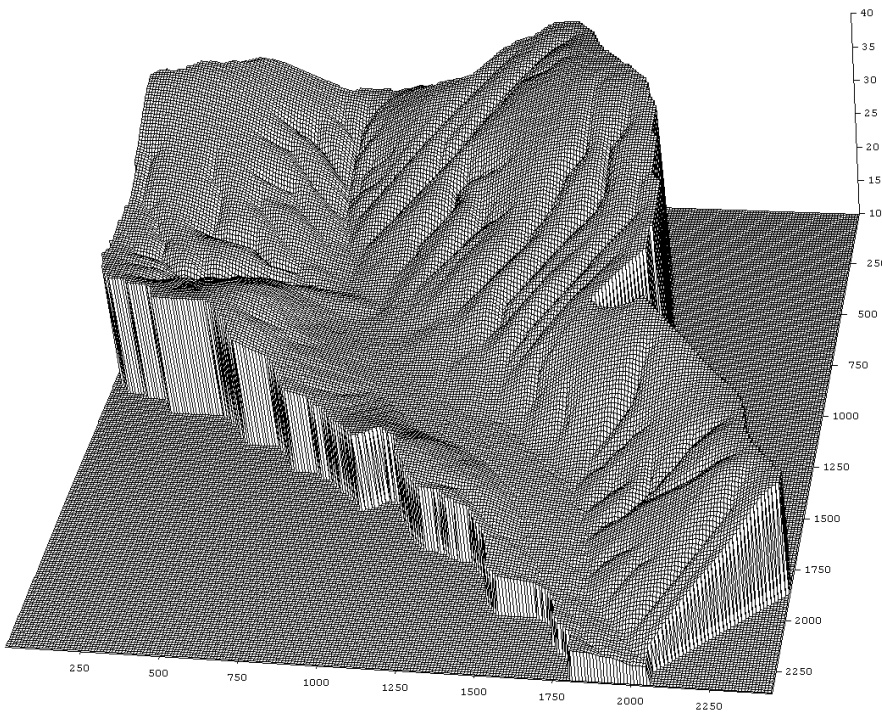
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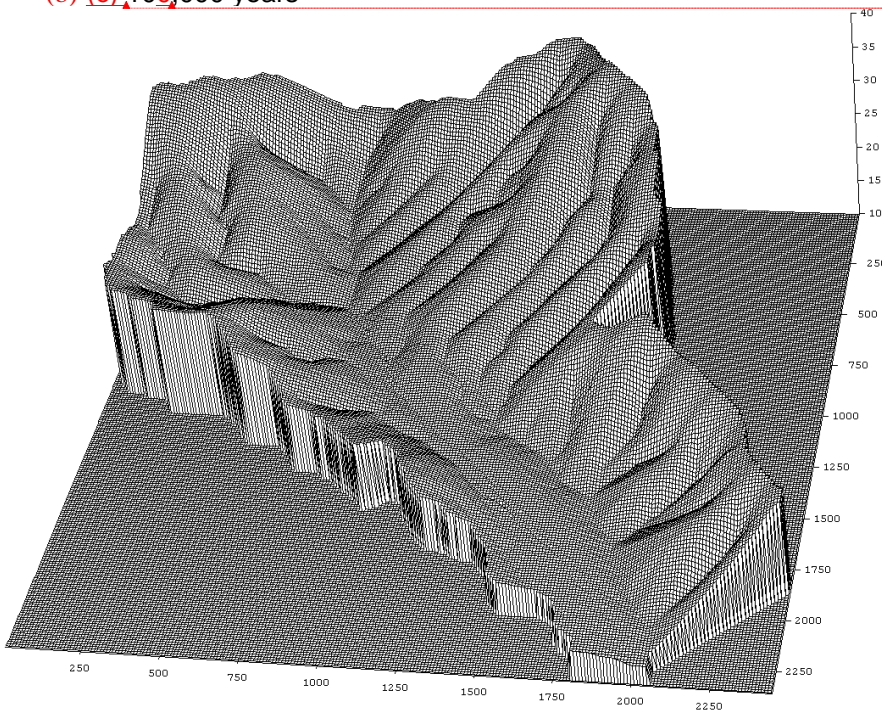
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(b) (c) 100,000 years



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(e) (d) 5400,000 years

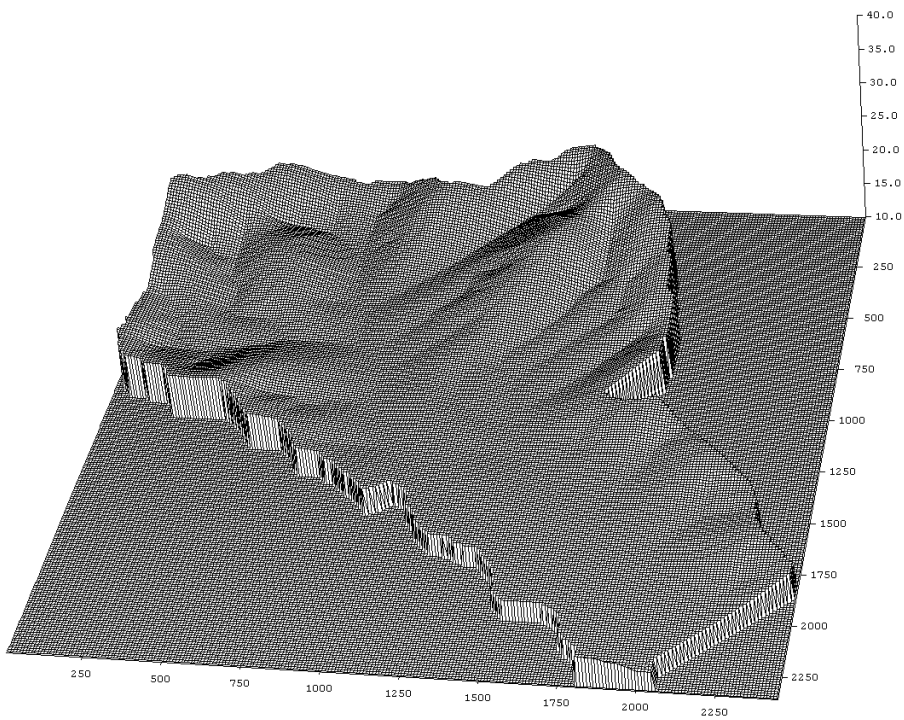
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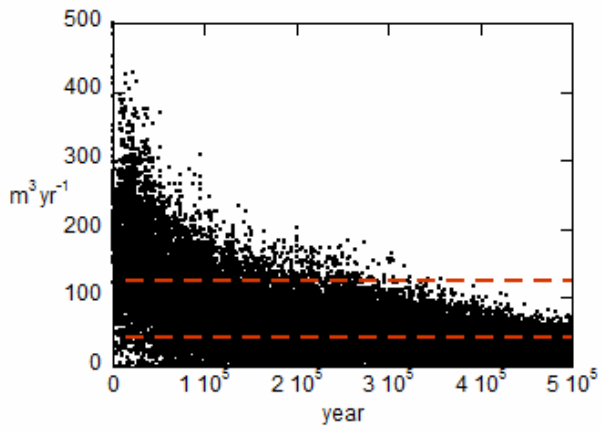
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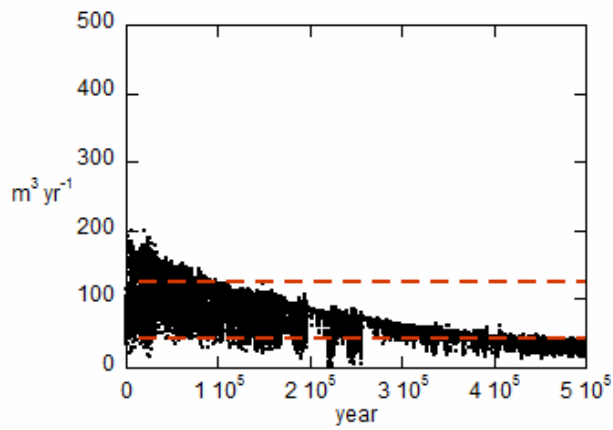


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 989 | (d) 500,000 years
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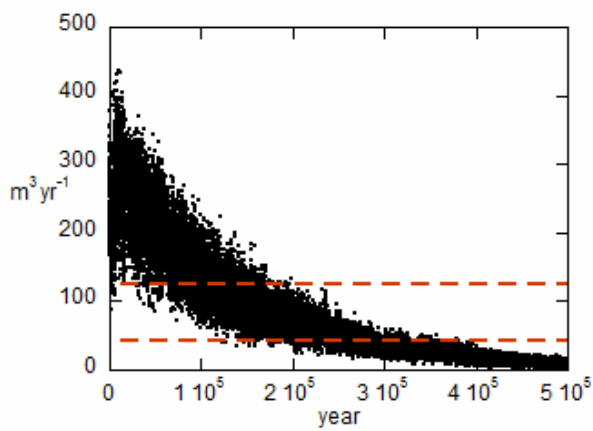
991 | **Figure 4.** Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years
 992 | using the SIBERIA model and Vegetation parameters. All dimensions are metres.



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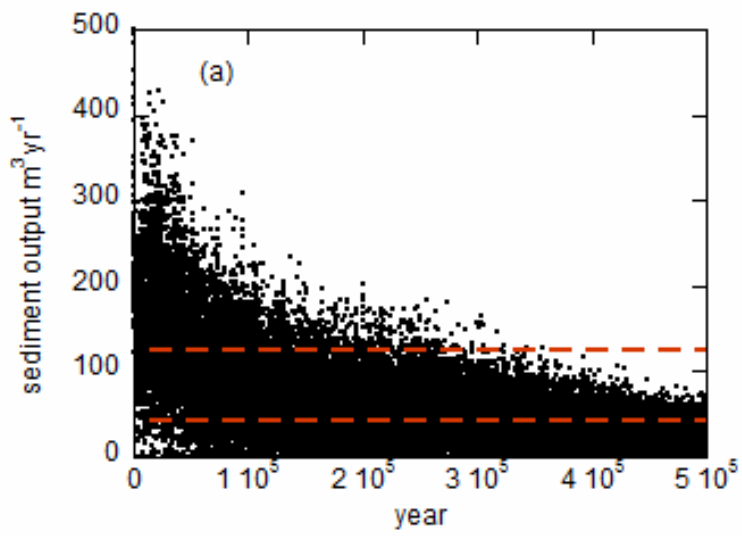


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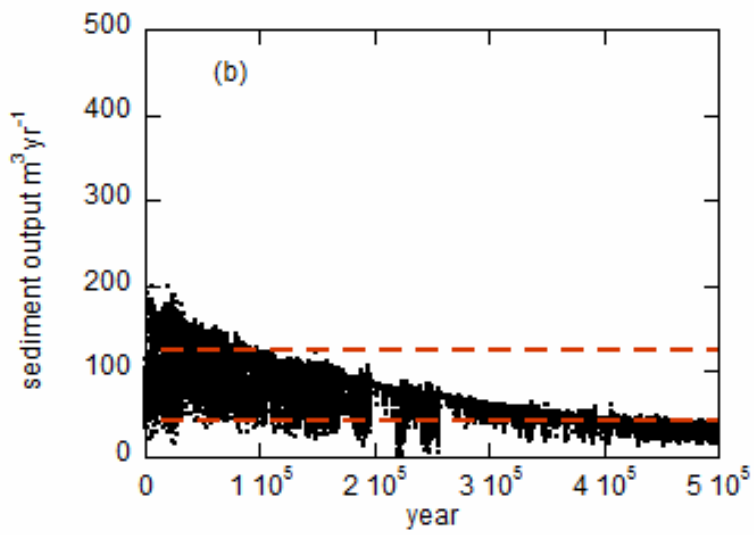
Figure 5. Simulated annual sediment discharge and average annual elevation from Corridor Creek landform using Waste Rock Dump (atop), Vegetation (middle) and Tin Camp Creek parameters (bottom). The red line represent the range of sediment discharge as predicted from the regional denudation rates of $0.01\text{--}0.04\text{ mm y}^{-1}$ ($30\text{--}120\text{ m}^3\text{ y}^{-1}$). 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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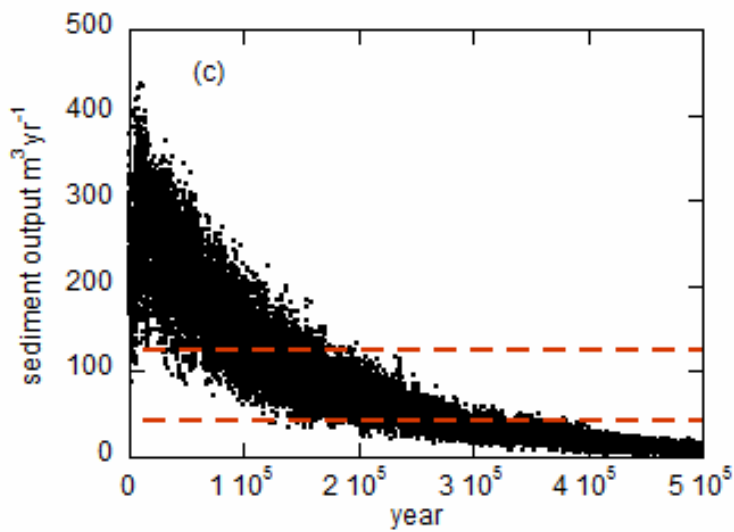
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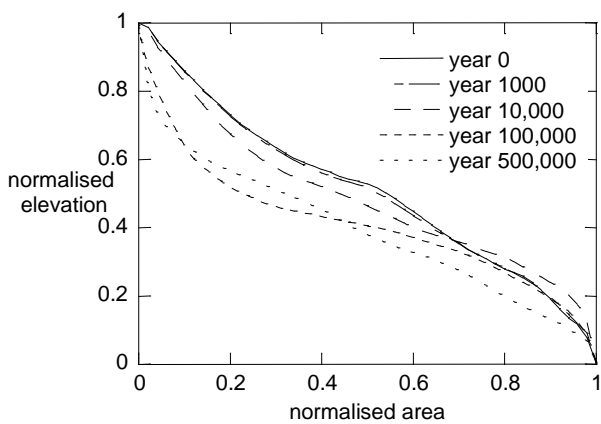


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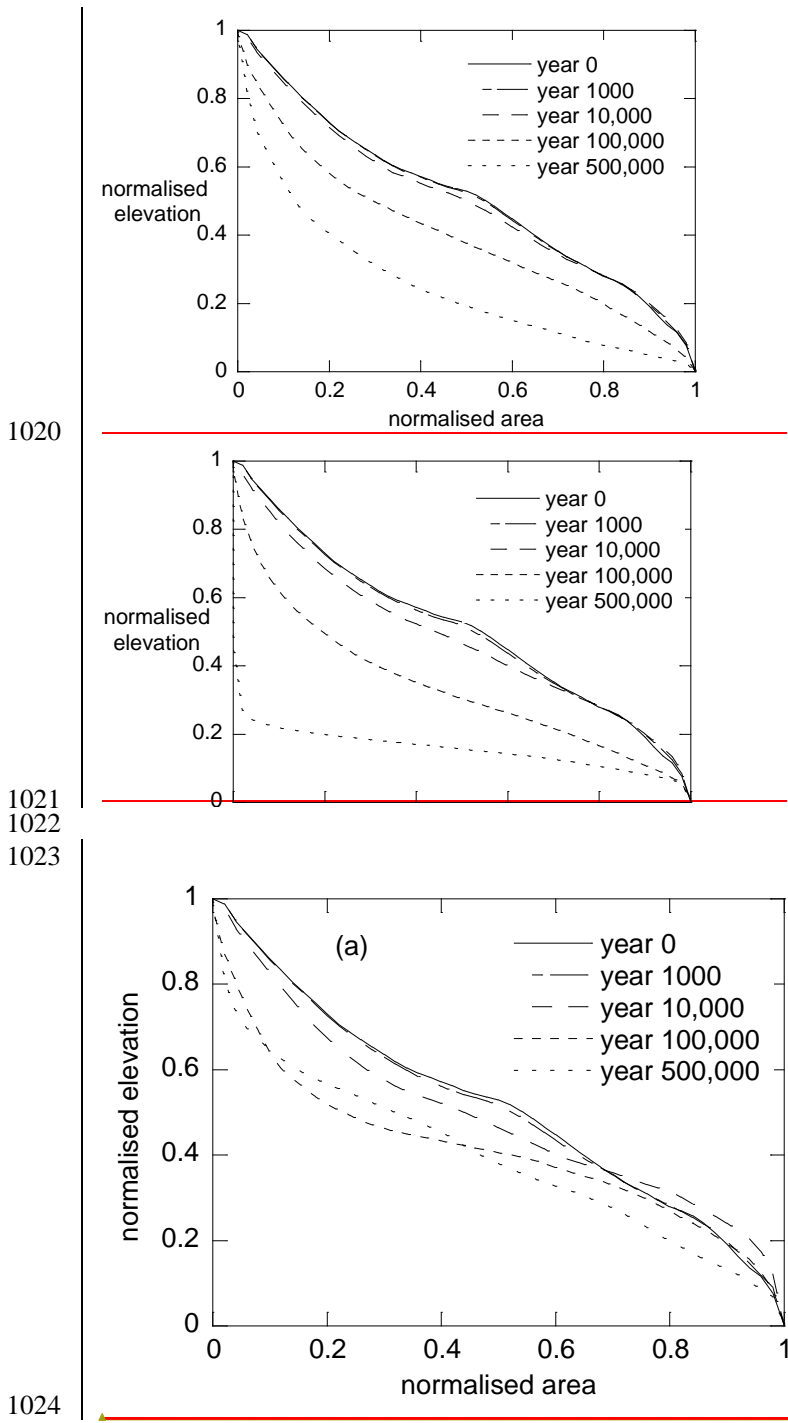
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Fig. 5. Simulated annual sediment discharge and average annual elevation from Corridor Creek landform using Waste Rock Dump (a), Vegetation (b) and Tin Camp Creek parameters (c). The red line represent the range of sediment discharge as predicted from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

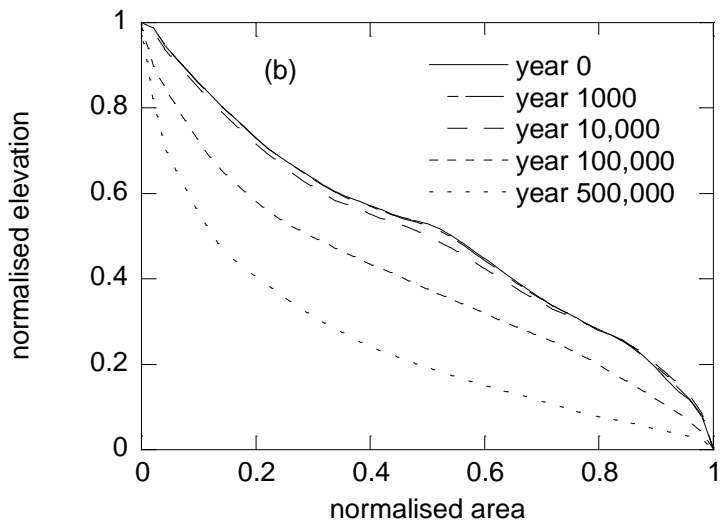
Comment [A31]: Y-axis labels only show the unit. This is strange. Please write what the values are. This also applies to the lower graph of Fig. 10. Also see the next comment.



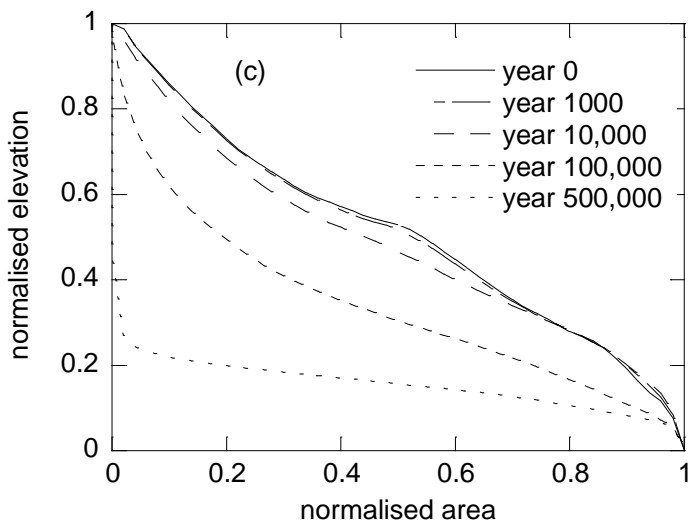
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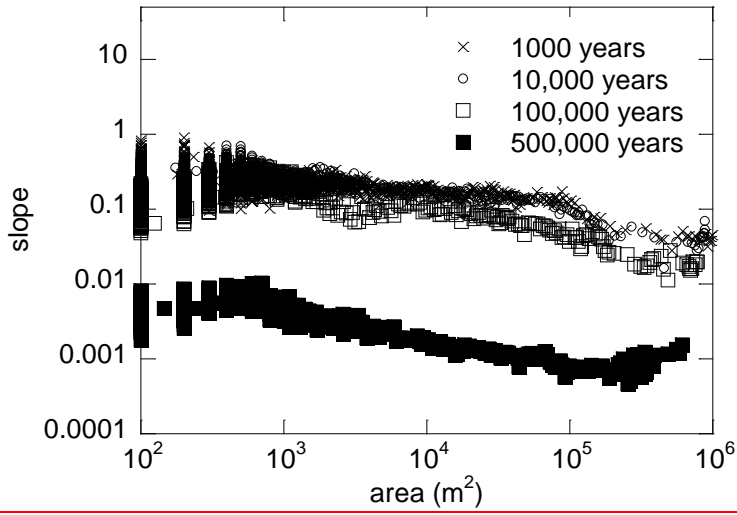
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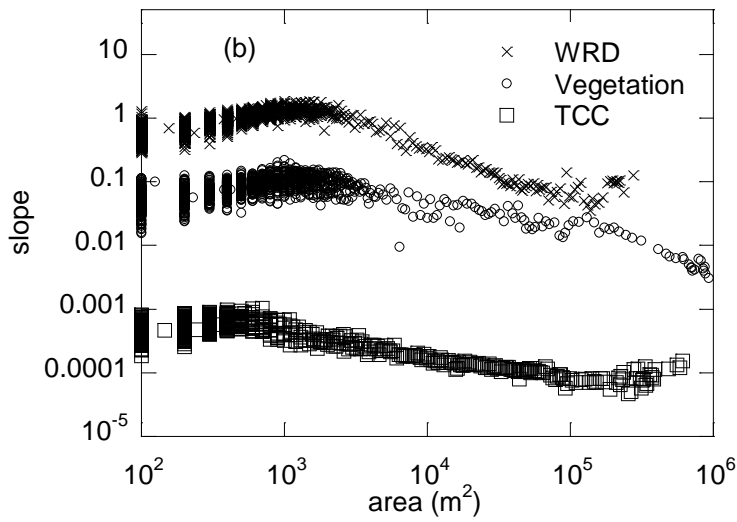
Figure 6. Hypsometric curves for the Corridor Creek catchment using Waste Rock Dump (atop), Vegetation (bmiddle) and Tin Camp Creek parameters (cbottom).

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.

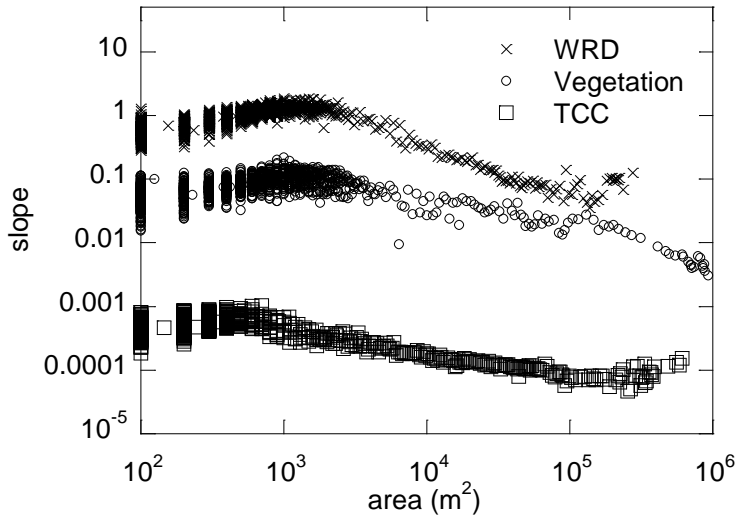
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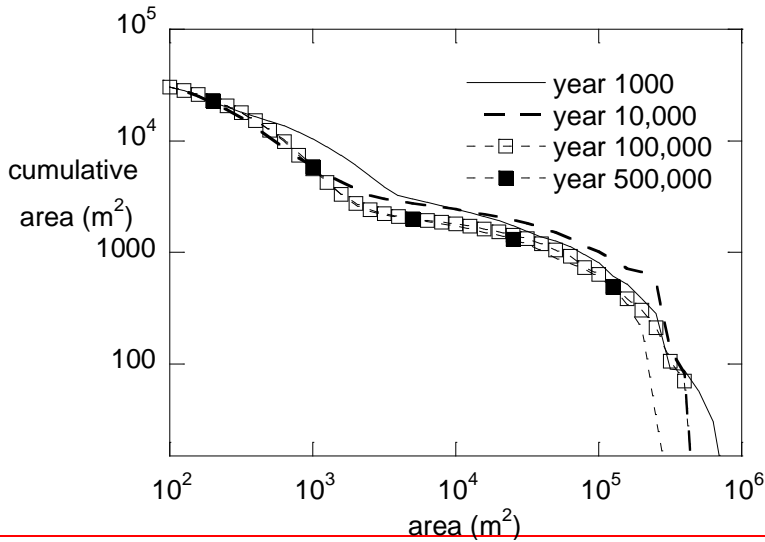
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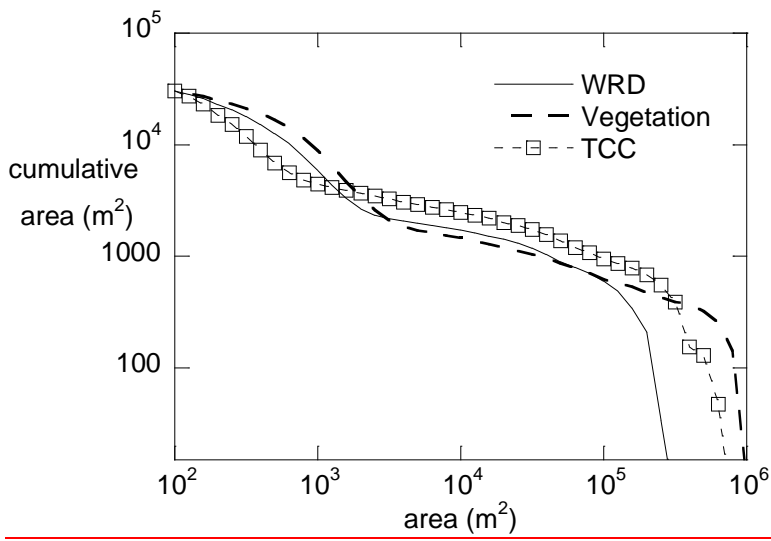
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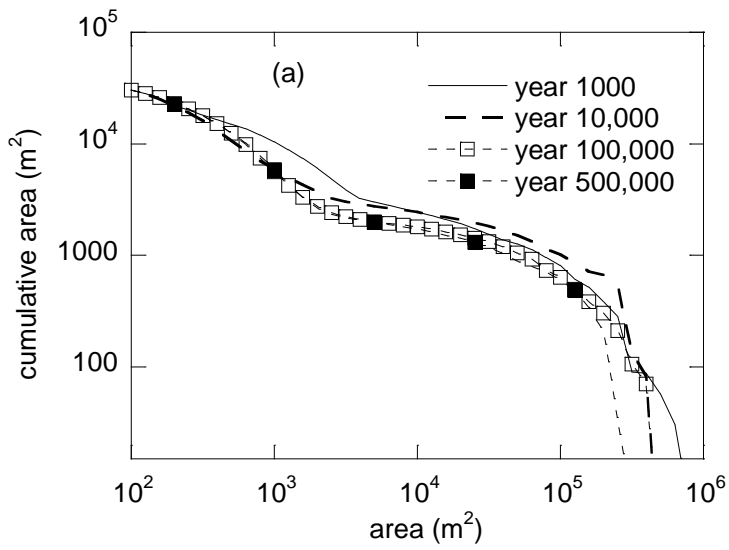
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 1036 **Figure 7.** Area-slope relationship for the Corridor Creek landform using Waste Rock Dump
 1037 parameters over the 500,000 year modelled period (atop) and comparison of the WRD,
 1038 Vegetation and Tin Camp Creek area-slope data at 500,000 years (bottom). In the (bottom)
 1039 figure the WRD parameter slope data have been multiplied by 10 while the Tin Camp Creek
 1040 parameter slope data has been divided by 10 for clarity.
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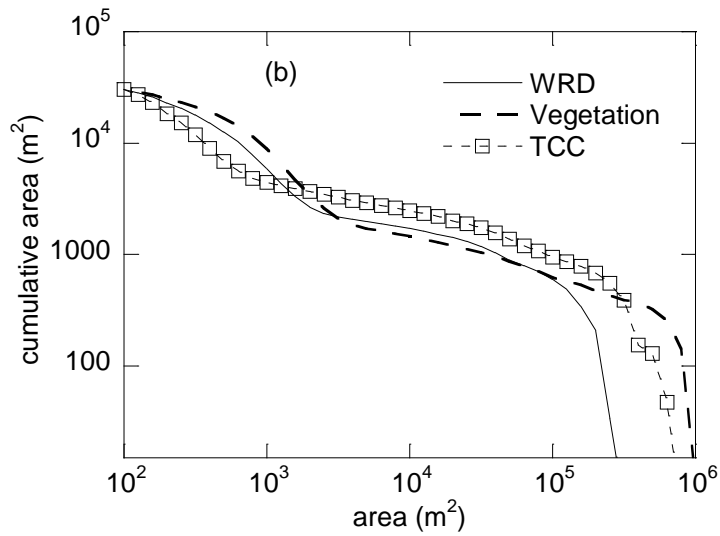
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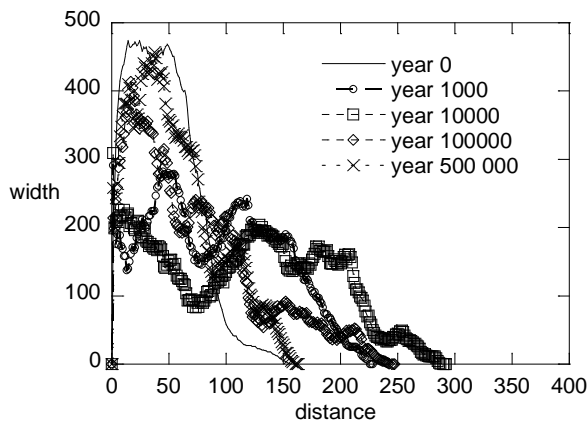


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Figure 8. Cumulative area distribution (atop) for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period (top) and comparison of the WRD, Vegetation and Tin Camp Creek cumulative area data at 500,000 years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

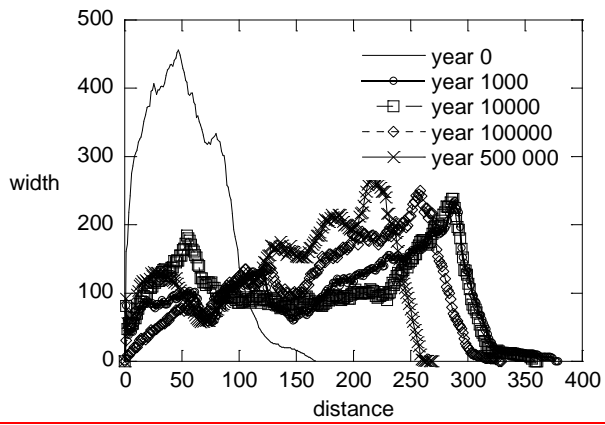
Comment [A33]: Please write (a) (formerly "top") only once.

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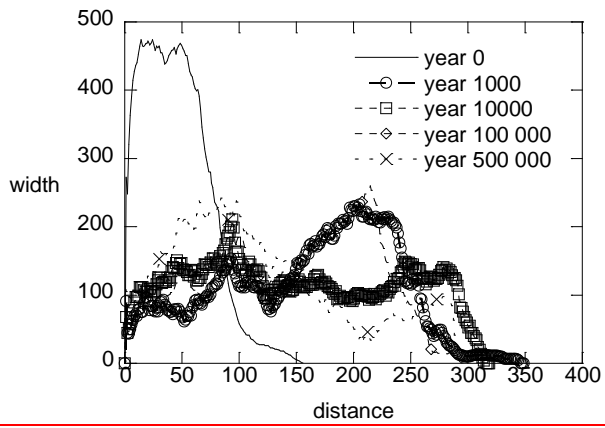
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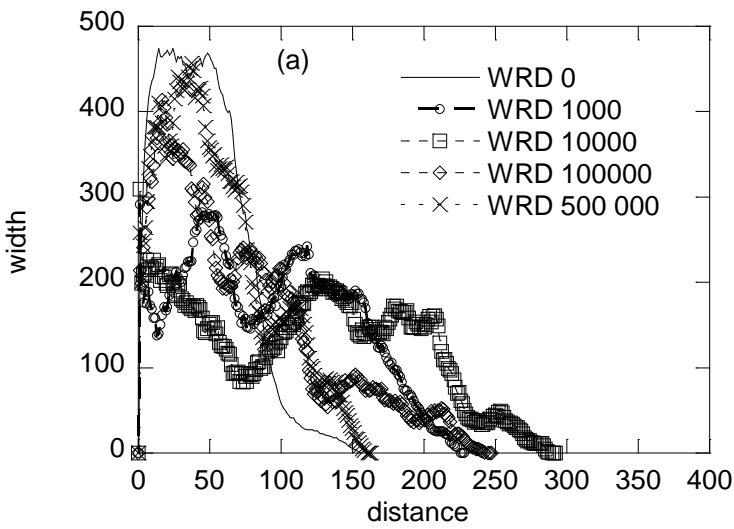
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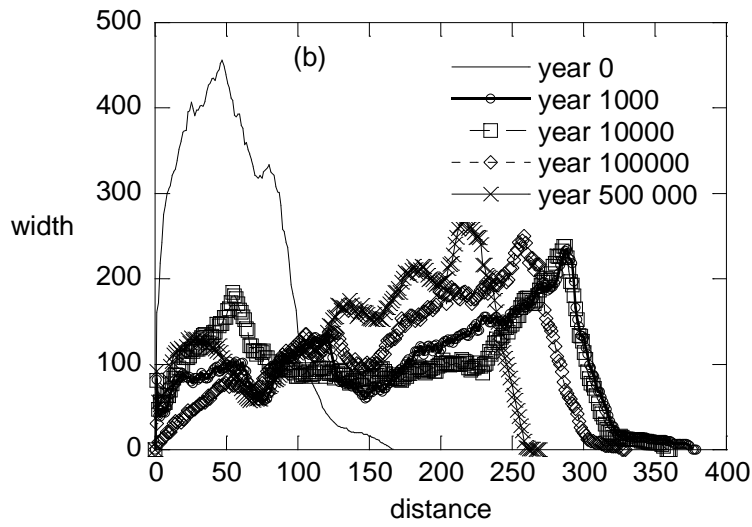
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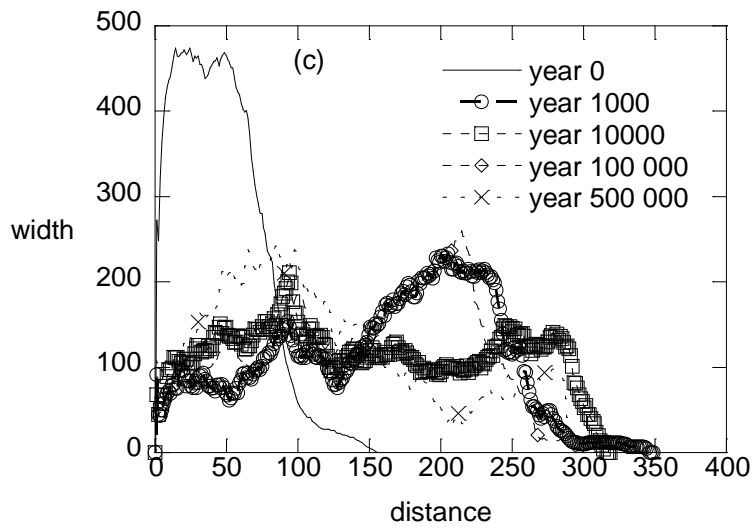


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1061 **Figure 9.** Width function for the Corridor Creek catchment using the WRD (a) and
 1062 Vegetation (b) and Tin Camp Creek parameters (c).

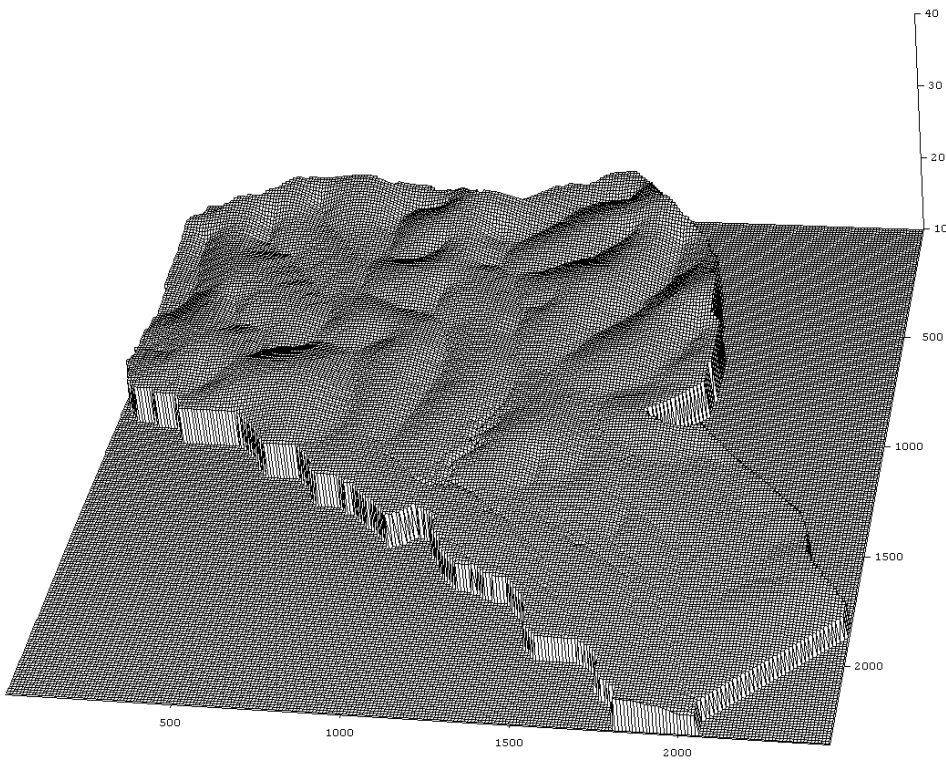
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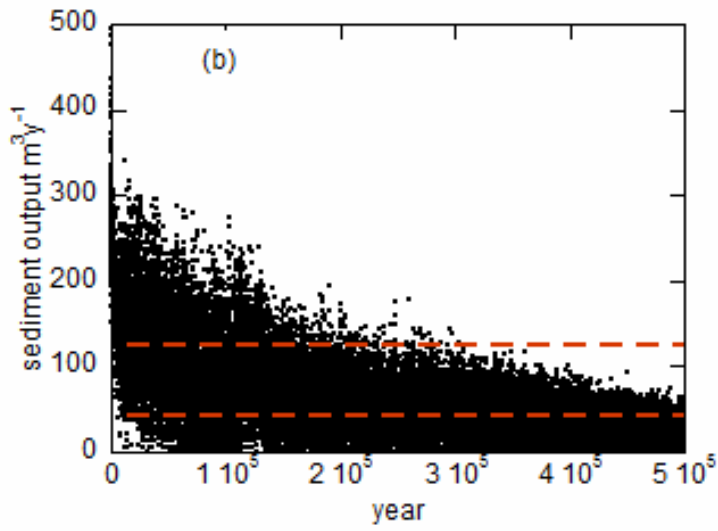
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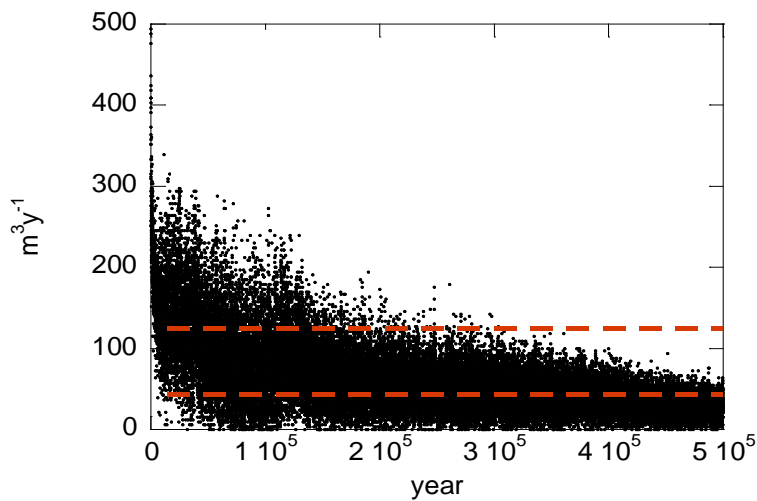


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1072 **Figure 10.** Corridor Creek landform at 500,000 years using WRD parameters and the
 1073 DInfinity drainage direction algorithm (atop) and sediment output from the simulation
 1074 (bottom). The red line represent the range of sediment discharge as predicted from the
 1075 regional denudation rates of 0.01–0.04 mm y⁻¹ (30–120 m³ y⁻¹). For clarity, each year
 1076 represents an average of 10 years sediment output.
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1084 **Table 1.** The SIBERIA parameter values for each region of the ERA Ranger mine for the
 1085 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

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.

WRD			
year	catchment relief (m)	average erosion rate (mm y ⁻¹)	max. erosion depth (m)
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?

1120	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
1121	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?**

Hancock, G.R.^{a,*}, Lowry, J.B.C.^b, Coulthard, T.J.^c

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Newcastle, Callaghan, New South Wales, 2308, Australia.

^b Hydrologic, Geomorphic and Chemical Processes Program, Environmental Research
Institute of the Supervising Scientist, Darwin, Northern Territory, Australia.

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7RX, UK.

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37 **Abstract**

38

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

56

57

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

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62

63 **1 Introduction**

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

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

84 LEMs were initially developed to examine landscape evolution and dynamics at
85 geological time scales but have since been employed in more applied settings such as mine
86 sites at much shorter time scales (years, decades, and centuries). For example, the first use of
87 landform evolution modelling to assess the stability of a post-mining rehabilitated landform

88 design at the study site was by Willgoose and Riley (1993) using the SIBERIA landform
89 evolution model (Willgoose et al., 1989).

90 This and subsequent studies have demonstrated the potential for LEMs to give insights
91 into future geomorphic form and function and are now being applied to disturbed site
92 assessment and rehabilitation (Willgoose and Riley, 1998; Hancock et al., 2000, 2002; Evans
93 et al., 2000; Lowry et al., 2011; Coulthard et al., 2012). The focus of this paper and those
94 cited above is on post-mining landforms, which are designed to bury or encapsulate mine
95 sites, including tailings, drains, spoil tips and other industrial architecture. Post mining
96 landforms are intended to be constructed in such a way that they remain structurally intact
97 geomorphically stable, while being able to blend into the surrounding landscape. In the
98 example studied here, low-grade uranium ore, tailings, brines and other mine wastes will be
99 buried at depth in the areas of the former pits and tailings storage facilities of a de-
100 commissioned uranium mine.

101 The rehabilitation of uranium mines is a particular concern as radionuclides represent
102 a potential set of contaminants with long half-lives and persistence in the environment
103 (Schumm et al., 1984). Australian guidelines recommend a design life for a tailings cap of a
104 uranium mine of 200 years and a structural life of at least 10,000 years. This means the
105 structure used to encapsulate radioactive tailings must be built to maintain its integrity from a
106 1 in 10,000 year rainfall event. Understanding model parameter accuracy and reliability is
107 therefore particularly important when assessing landscapes at millennial time scales. This
108 generates a major research question, as we have the numerical methods to simulate landscape
109 stability over millennia, but not necessarily the correct parameter values and data sets with
110 which to drive these predictions.

111 In this paper we examine three issues. Firstly, the reliability of an LEM to predict
112 catchment form over geological time is assessed. Secondly, the range of outcomes in

113 landscape form and function is examined based on estimated temporal parameter changes.
114 Finally, the need for more long-term understandings based on the need for more rigorous field
115 data for calibration and validation of these models is discussed.

116

117 **2 Site description**

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

128 Mine tailings are currently stored in an above ground tailings dam and in the mined-
129 out Pit 3 (Fig. 2). Pit 1 previously received tailings and is in the process of being capped.
130 Mining from Pit 3 ceased in 2012, and milling and processing of stockpiled ore is scheduled
131 to cease by 2021. Consequently, attention is increasingly focussing on the closure and the
132 rehabilitation of the mine.

133 The requirements for the closure and rehabilitation of the Ranger mine have been
134 published in a series of environmental requirements. These state, with respect to erosion and
135 landform stability, that the landform should possess "*erosion characteristics which, as far as*
136 *can reasonably be achieved, do not vary significantly from those of comparable landforms in*
137 *surrounding undisturbed areas*"(Supervising Scientist Division, 1999). Consequently, ERA

138 will be required to rehabilitate disturbed areas of the lease to satisfy the above requirements.
139 Implementing these will require the landscape to be rehabilitated in a way that restores
140 environmental functions supporting local ecosystem diversity (Ludwig and Tongway 1995.
141 The first stage in this process is to design and construct a landform which is erosionally
142 stable.

143 The regional geology of the Alligators River Region is dominated by the mineralised
144 metasediments and igneous rocks of the Pine Creek geosyncline (one of the richest uranium
145 provinces in the world) and the younger sandstones of the Mamadawerre Formation
146 (Needham, 1988; East, 1996). Geomorphically, the Ranger site is characterised as part of the
147 deeply weathered Koolpinyah surface. This consists of plains, broad valleys and low gradient
148 slopes, with isolated hills and ridges of resistant rock (East, 1996). Regional denudation rates
149 for the area (0.01 to 0.04 mm y⁻¹) have been determined using stream sediment data from a
150 range of catchments of different sizes in the general region (Cull et al., 1992; Erskine and
151 Saynor, 2000).

152 The study site is in the wet-dry tropics of northern Australia and is subject to high-
153 intensity storms and tropical monsoons between October and April. Minimal rain falls in the
154 remainder of the year; the annual average rainfall is 1583 mm (Bureau of Meteorology, 2015).
155 Vegetation on the mine lease and surrounds consists of open Eucalypt forest dominated by
156 *Eucalyptus. tetradonta*, *Eucalyptus. miniata*, *Eucalyptus. bleeseri* and *Eucalyptus. porrecta*.
157 The understorey is characterised by *Acacia* spp., *Livistona humilis* and *Gardenia megasperma*
158 with a variable grass cover of *Sorghum* spp., *Themada triandra* and *Eriachne trisetata* (Chatres
159 et al., 1991).

160

161 **3 Landscape evolution models and their parameterisation**

162 From the 1970s numerical models were developed to simulate processes ranging from

163 slope wash to chemical erosion and soil development over entire catchments (Carson and
164 Kirkby, 1972; Ahnert, 1976; Hirano, 1976; Armstrong, 1976). For further detail on the history
165 and background of LEM's see (Tucker and Hancock, 2010). The SIBERIA landform
166 evolution model (referred to hereafter as SIBERIA) builds on this early work and
167 mathematically simulates the geomorphic evolution of landforms subjected to fluvial and
168 diffusive erosion and mass transport processes (Willgoose et al., 1991). SIBERIA describes
169 how the catchment is expected to look, on average, at any given time. The sophistication of
170 SIBERIA lies in its use of digital elevation models (DEMs) for the determination of drainage
171 areas and geomorphology and its ability to efficiently adjust the landform with time in
172 response to the erosion that could occur on it. Since 1993, SIBERIA has been used principally
173 to investigate surface stability of post-mining rehabilitated landforms or small catchment
174 areas (i.e. Willgoose et al., 1991; Evans et al., 1998; Willgoose and Riley, 1998; Hancock et
175 al., 2000, 2013 Moliere et al., 2002).

176 SIBERIA requires calibration of the sediment transport and area-discharge
177 relationships, and a DEM of the landform of interest (described in Section 4). The fluvial
178 sediment transport equation is parameterised using input from field sediment transport and
179 hydrology data. Here SIBERIA was calibrated using field data collected from the Ranger
180 mine site (the study site) and Tin Camp Creek (the analogue site). The Tin Camp Creek site,
181 located approximately 50 km from Ranger, is on the same metamorphosed schist formation as
182 found at the Ranger mine and the surface properties are seen as an analogue of proposed
183 rehabilitated landforms for the Ranger Mine in the long-term (Uren, 1992; Riley and Rich,
184 1998).

185 Calibration of the erosion and hydrology models was conducted using data of
186 sediment loss, rainfall and runoff for discrete rainfall events that were collected from field
187 plots. Calibration data for the Ranger site were obtained from erosion plots on the batter slope

188 of the Ranger mine waste rock dump (Evans et al., 2000; Moliere et al., 2002). Data for a
189 vegetated surface were collected from a similar-sized plot on the waste rock dump covered in
190 topsoil, ripped and vegetated with low shrubs and grasses which provided approximately 90%
191 cover (Evans et al., 1998). SIBERIA was also calibrated from field data collected from the
192 Tin Camp Creek catchment during rainfall events in December 1992. This resulted in three
193 separate parameter sets which were employed in this study.

194 For long-term landscape assessment SIBERIA requires both fluvial and diffusive
195 sediment transport data. The SIBERIA value for rainfall diffusivity (i.e. rainsplash) value of
196 $0.005 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-1}$ (width) was used as this has been found to be the most applicable for the
197 Alligator Rivers Region which includes the Ranger site (Hancock et al., 2002). The field data
198 parameter values determined for these surfaces are shown in Table 1. The methodology
199 employed in the derivation of the parameters for the different surfaces is described in Evans
200 and Willgoose (2000), Evans et al. (2000) and Moliere et al. (2002).

201

202 **4 Catchment digital elevation models, model setup and landscape assessment**

203 Several small catchments will drain from the proposed possible landform at Ranger
204 and here we focus on the Corridor Creek catchment that drains into Magela Creek. (Fig. 2).
205 The DEM was calculated from two datasets. Firstly, a 2-m contour interval dataset
206 representing the current landform surface was produced from a LiDAR survey of the mine in
207 2010. This was supplemented by an additional two-metre contour interval dataset that
208 represented the proposed rehabilitated landform design. The LiDAR contours outside of the
209 rehabilitated landform area were combined with the contours representing the proposed
210 rehabilitated landform area and used to produce a grid surface with a horizontal resolution of
211 2 m. The DEM representing the rehabilitated surface was resampled to a horizontal spatial
212 resolution of 10 m. This was chosen as being the optimal resolution at which SIBERIA could

213 function within the spatial extent of the study catchment, and over the temporal periods
214 modelled yet still reliably capture the salient features of hillslope geomorphology (Hancock,
215 2005). The final DEM used in this study was understood to represent a fully consolidated
216 landform, from which there would be no subsidence or settlement. Other factors such as mass
217 failures were not considered.

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

225 Short et al. (1989) estimated that the surrounding undisturbed landscape (termed the
226 Koolpinyah surface) is approximately 300,000 years old. Therefore, to allow an equivalent
227 landscape to develop and to examine long-term landscape trends and geomorphic change,
228 SIBERIA was run for 500,000 years. Outputs from the model included a DEM of the
229 catchment and sediment discharge at annual time steps (here we examine DEMs at 1,000,
230 10,000, 100,000, 500,000 years) as well as geomorphic descriptors of the catchments
231 (hypsometric curve, area–slope relationship, cumulative area distribution and width function).

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

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

$$240 \quad A^\alpha \cdot S = \text{constant} \quad (1)$$

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

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

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

260

261 **5 Results**

262 5.1 *Qualitative visual assessment*

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

278 The simulation using the Vegetation parameters (Fig. 4) produces incised channels at
279 1000 years but these are not as deep or as well defined as the WRD simulation. At 10,000
280 years, the channels have become well-defined channels with deposition present in the main
281 channel bottom. At 100,000 years the catchment has developed well-rounded hillslopes with
282 the depositional material on the valley bottom being reworked. At 500,000 years, similar to
283 the WRD simulation, the landscape has evolved into a catchment of relatively low relief with
284 a series of low well rounded hills.

285 While not displayed here for brevity, the simulation using the Tin Camp Creek
286 parameters displays similar behaviour to that of the WRD and Vegetation parameter

287 simulations. Visually there are no striking differences between the simulated catchments.
288 However, all have qualitative differences in both hillslope form. They have different relief,
289 location of hills and valleys as well as the morphology of the depositional area in the main
290 channel. Therefore, the three different parameter sets produce qualitatively different
291 landscapes with unique hillslope length, shape and position. Importantly, each modelled
292 landscape output is not geomorphically impossible.

293 5.2 *Quantitative assessment – sediment output*

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

298 Simulated sediment yields from the catchment are highly variable but decline through
299 time for all simulations (Fig. 5). For the WRD parameters, over the first 50,000 years the
300 sediment output is comparatively high and for much of this period well outside the upper
301 range for natural sediment output; the expected sediment output from the catchment is 30–120
302 $\text{m}^3 \text{ year}^{-1}$ based on a denudation rate of 0.01–0.04 mm y^{-1} and corrected for catchment area).
303 However, after approximately 100,000 years, sediment output has declined and the mean is
304 within that of the expected sediment output range, though some peaks above this range still
305 exist.

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

310 A similar pattern occurs for the Tin Camp Creek simulation which has high sediment
311 yields for the first (approximately) 125,000 years and then reduces to within or less than that

312 of the expected output range from the denudation rates. However, the sediment yield from this
313 parameter set has considerably less variability than that of the WRD parameter simulation.

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

317

318 5.3 *Quantitative assessment – catchment geomorphic descriptors*

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

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

334 At the end of the modelled period the area–slope relationship for the WRD,
335 Vegetation and Tin Camp Creek parameter simulations all display unique characteristics with
336 both slope of the diffusive and fluvial regions being different (Fig. 7b). The area–slope

337 relationship for the WRD, Vegetation and Tin Camp Creek parameters all have positive, yet
338 different slopes for areas approximately less than 1000–2000 m² while at areas approximately
339 greater than 1000–2000 m² both data sets (WRD and Vegetation) have a negative (yet
340 different) log–log linear slope. Differences in all three area–slope plots result from the
341 different model parameters. Interestingly, despite the same diffusivity parameters being
342 applied for all simulations, the diffusive area of the curve is different and reflects the complex
343 interaction between the evolving landform and the diffusive and fluvial parameters. For
344 example, the WRD parameters are more erosive while the Vegetation parameters are
345 considerably less erosive. The WRD parameters may produce incision (gullies) which have
346 steeper slopes which will have higher diffusion (as the diffusion model is slope dependent).
347 The reverse occurs for the Vegetation parameters.

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

360 All three landscapes generate unique width functions (Fig. 9). Interestingly the width
361 function initially displays a high value but this peak reduces and distance increases with a

362 maximum distance at 10,000 years for the WRD and Vegetation simulations (Fig. 9). Post
363 10,000 years the distance begins to reduce and peak increases. However the Tin Camp Creek
364 width function rapidly reduces in width and increases distance and stays relatively fixed for
365 the duration of the simulation. This demonstrates that even though the catchment boundary is
366 fixed, the drainage network continually evolves producing unique drainage networks (Rigon
367 et al., 1993). The results also suggest that the movement and delivery of sediment routed
368 through the network will be different for the modelled landscapes. This corresponds well with
369 the different sediment output described in Section 5.2. This demonstrates that the hydrological
370 behaviour of the catchments will be spatially and temporally unique.

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

376

377 **6 Discussion**

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

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

388

389 *6.1 Long-term prediction and equifinality*

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

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

409

410 *6.2 Landscape form and sediment output*

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

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

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

434 However, for all simulations examined here, over the shorter runs (i.e. 0–10,000
435 years) there is little difference in qualitative and quantitative landscape form largely because

436 the landscape has not sufficiently eroded for any change to be detectable by these measures.
437 These geomorphic measures (hypsometric curve, area–slope relationship, CAD and width
438 function) are not sensitive to small changes in landscape form at 10,000 years. However,
439 where large changes have occurred they are quite useful. Interestingly, the width function
440 provides some insight into network hydrological change.

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

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

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

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

469

470

471 6.3 *Development of long-term understandings*

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

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

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

498

499 **7 Future issues and conclusions**

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

507 The important question for mine planners and regulators is which simulated landscape
508 is the correct one. Firstly, given the limited parameter data sets available and our
509 understanding of climate, all predictions are equally valid. However, the actual result is likely
510 to be a mix of all parameter data sets together with other complex unknown influences

511 relating to vegetation-climate interactions that influence pedogenesis. Secondly, while the
512 surface is unlikely to maintain its waste rock characteristics over the modelled period, it is
513 equally unlikely that vegetation will remain constant. The likelihood that the material will
514 evolve to a Tin Camp Creek type landscape is unknown. Both vegetation change as well as
515 the regular occurrence of fire is likely to influence erosion and therefore landscape evolution
516 in this (and any) environment. Finally, in terms of the worst case scenario, the WRD
517 parameter simulation is likely to provide the most conservative outcome of the three scenarios
518 examined here.

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

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

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

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547 **Acknowledgments**

548 We thank the traditional owners of the land where the study site is located, Parks Australia
549 North, Northern Land Council and current and former Supervising Scientist staff, especially
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551 this study. Conversations with Brian McGlynn and team at Duke University are
552 acknowledged.

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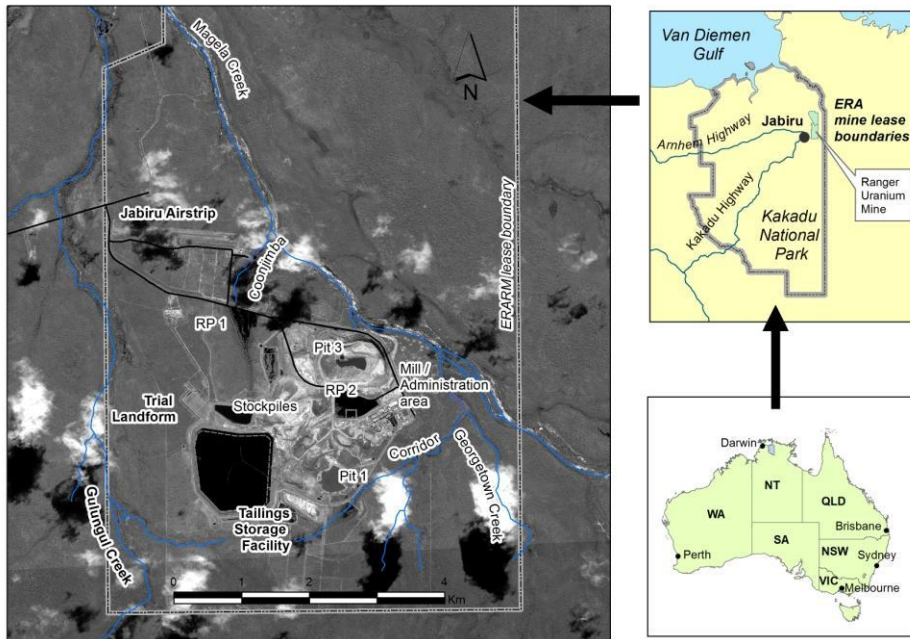
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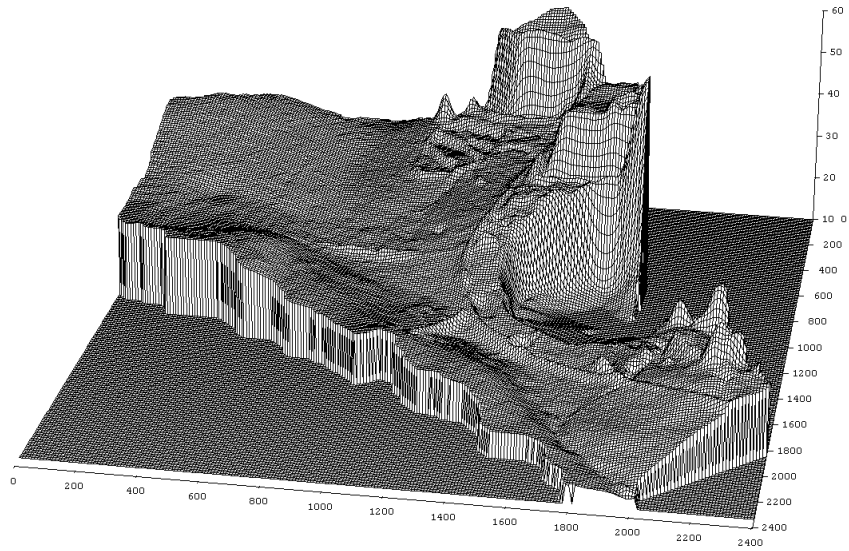
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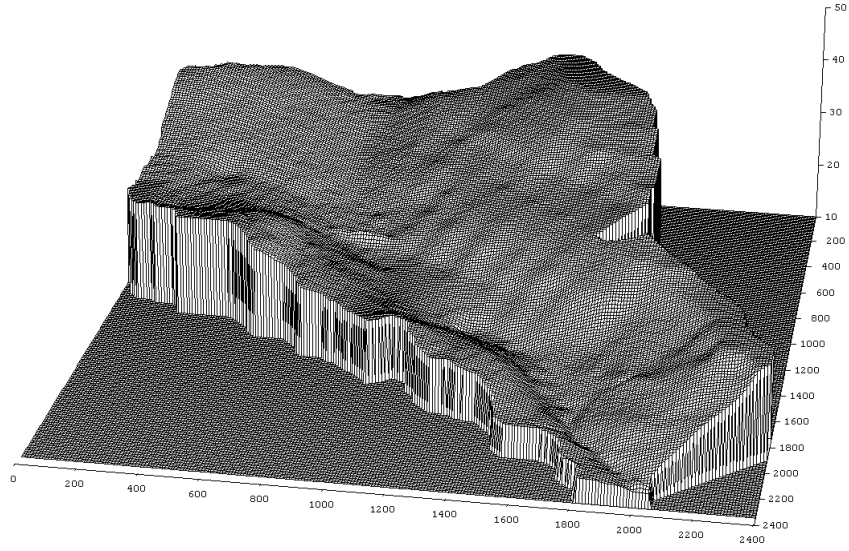
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Fig. 1. Location of the study site. For brevity, the letters RP represent Retention Pond. The site is located approximately 300km west of Darwin.

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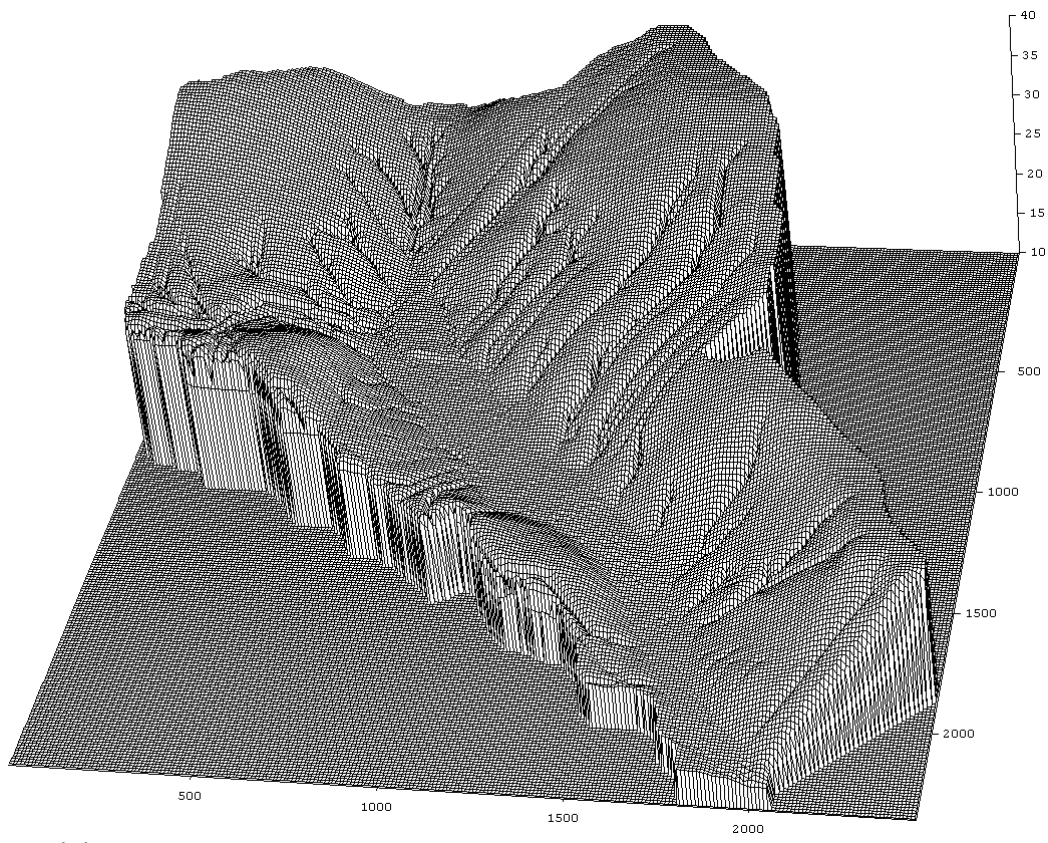


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Fig. 2. Digital elevation model (10 m grid) of the current mine site with mined out pit (a) and potential rehabilitation design (b). All dimensions are metres.

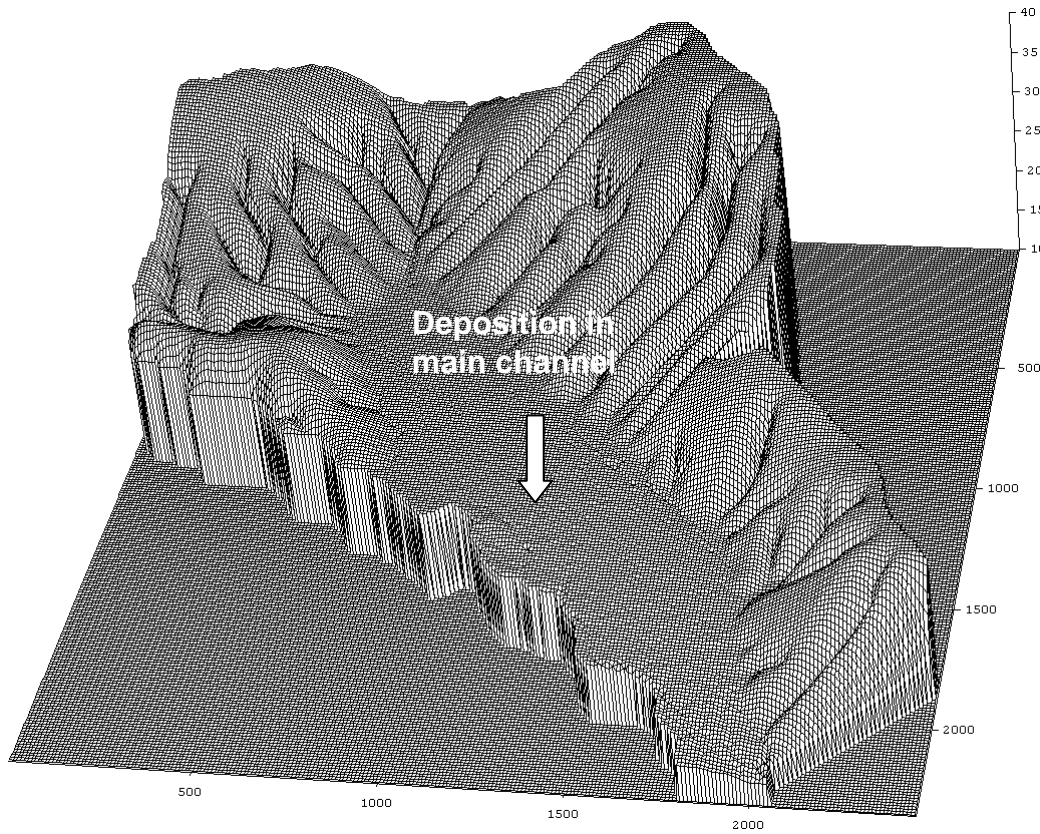
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(a) 1000 years



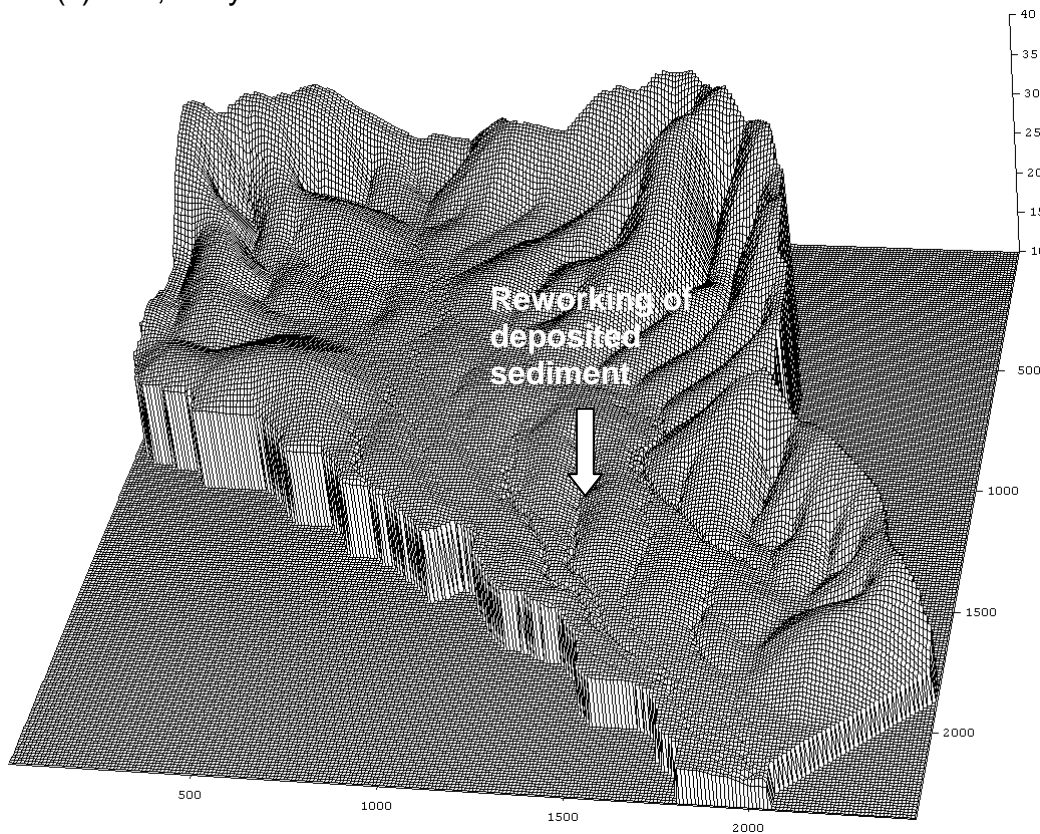
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(b) 10,000 years



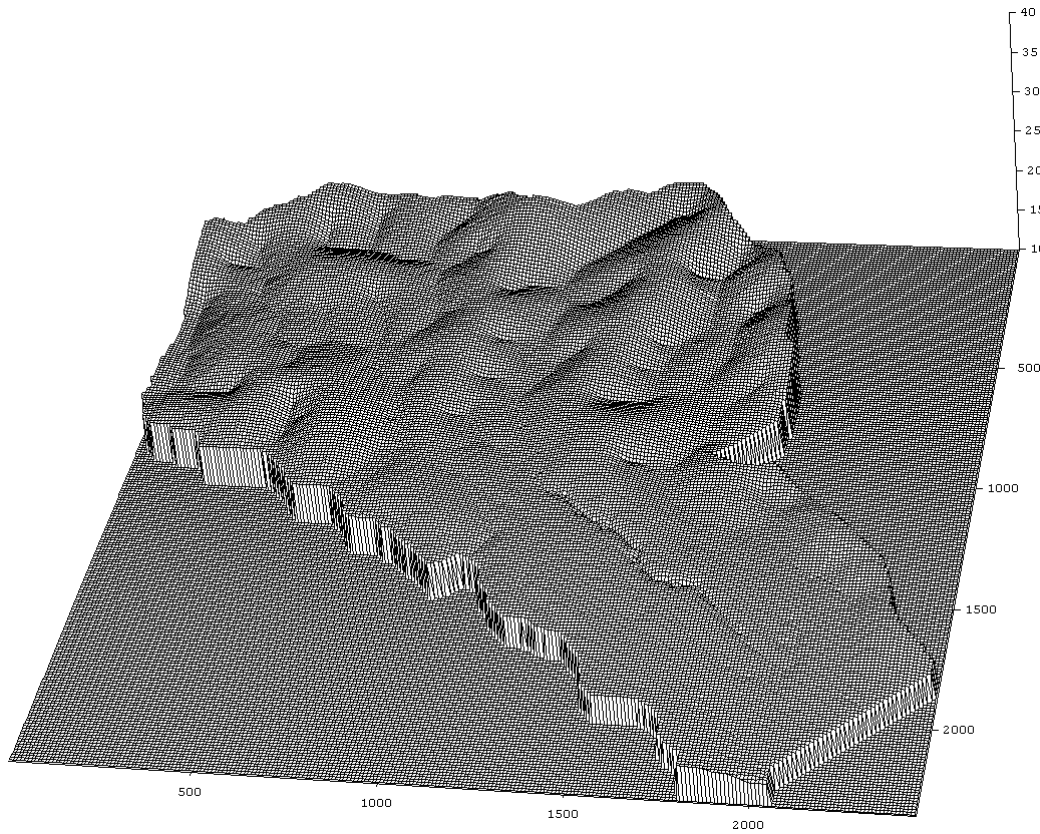
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(c) 100,000 years



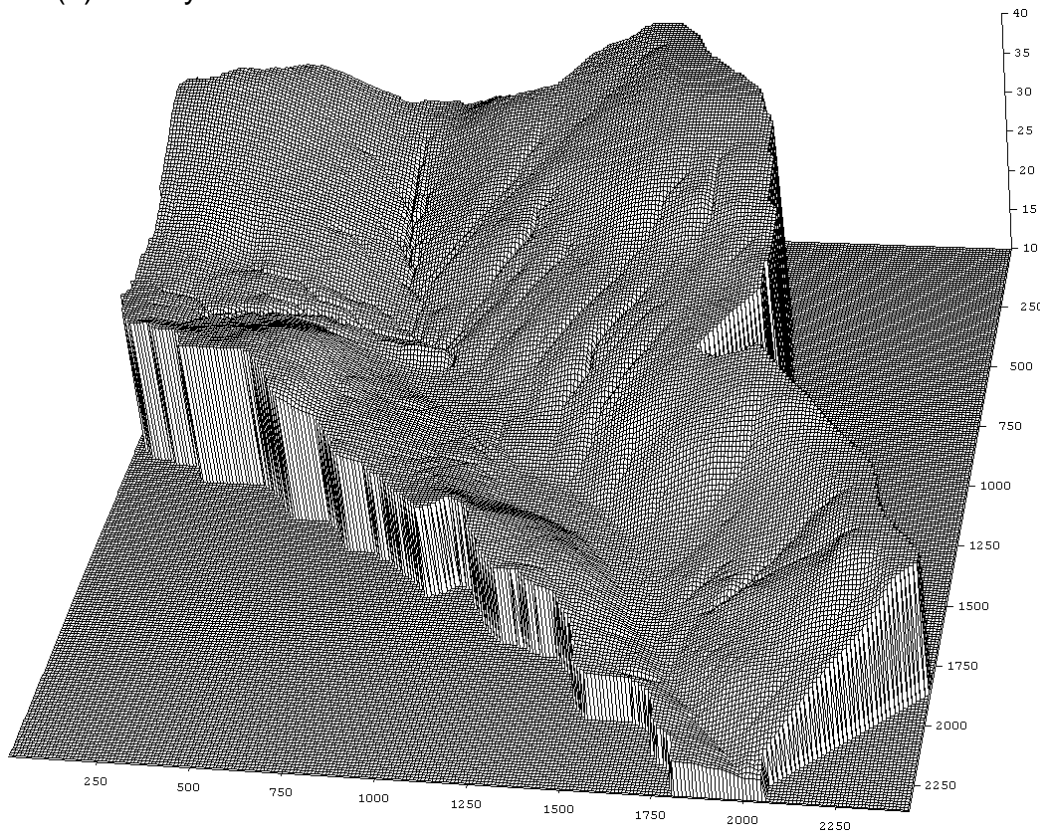
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(d) 500,000 years



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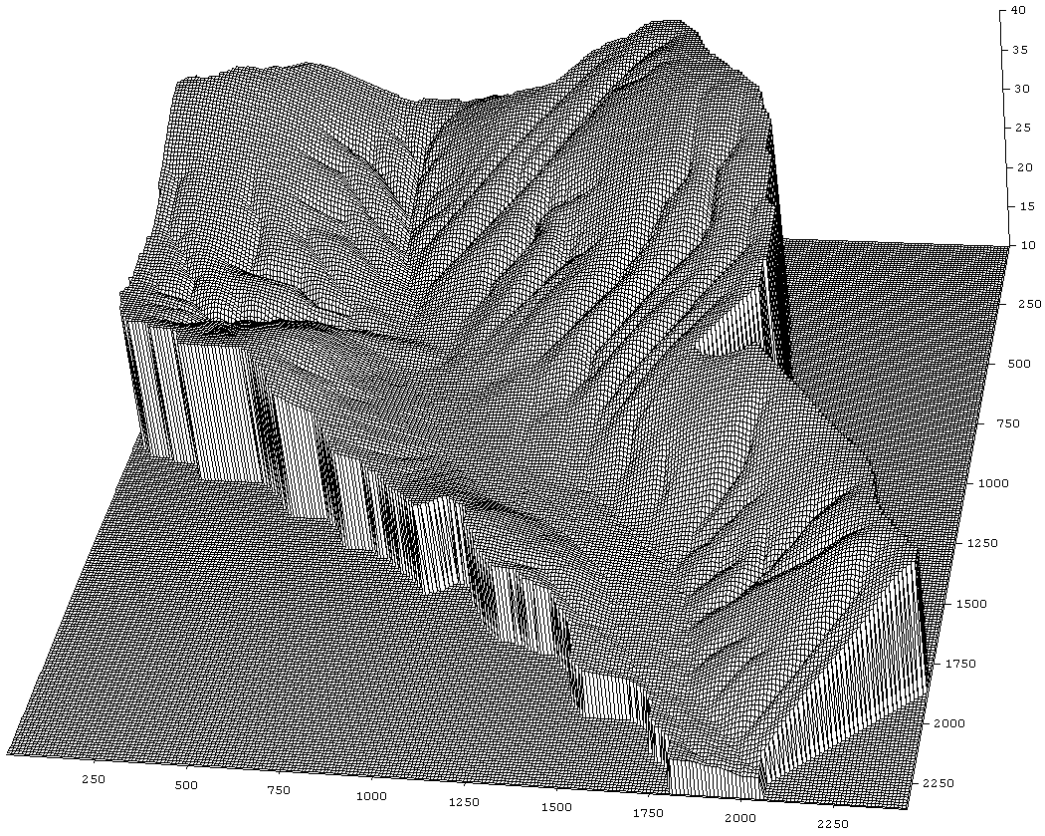
Fig. 3. Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years using the SIBERIA model and Waste Rock Dump parameters. All dimensions are metres.
(a) 1000 years



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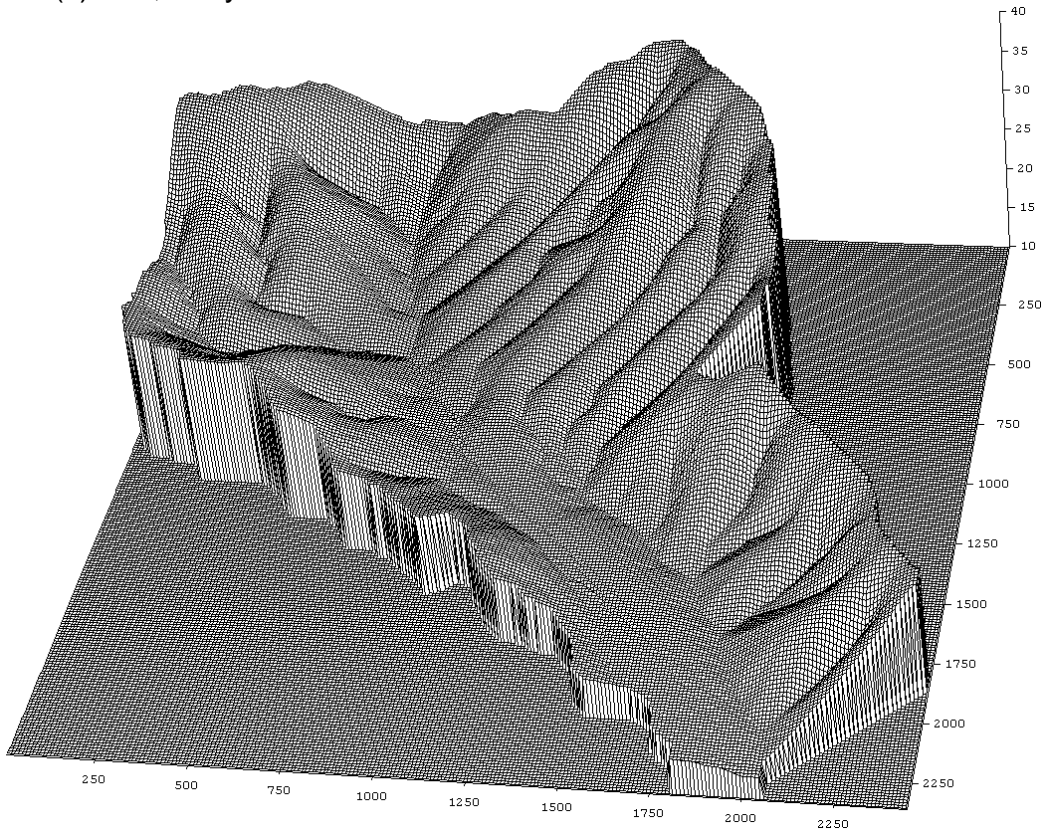
(b) 10,000 years

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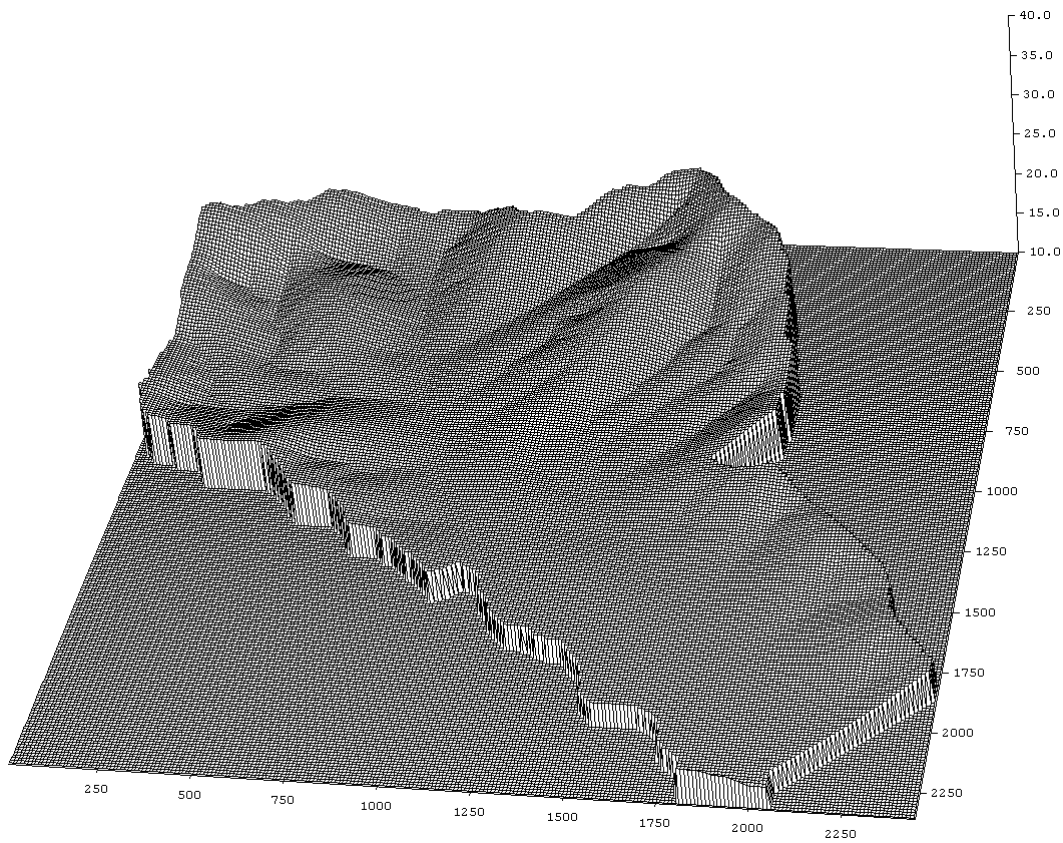
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(c) 100,000 years



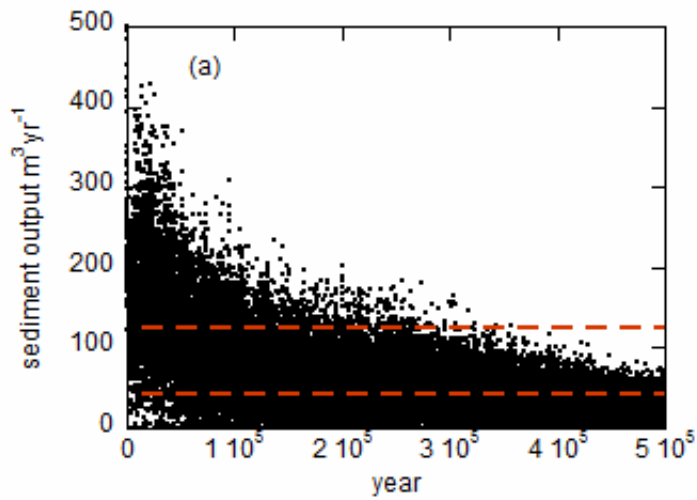
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(d) 500,000 years

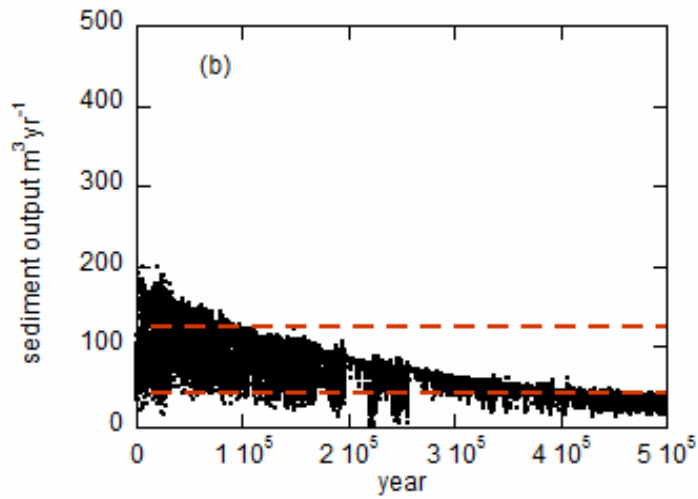


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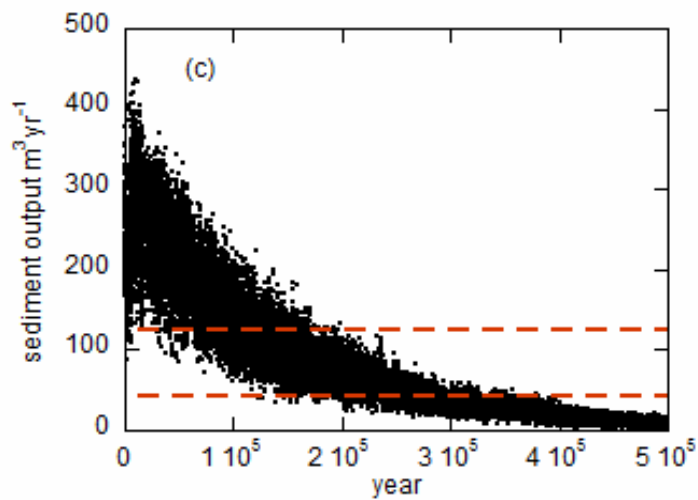
Fig. 4. Corridor Creek landform at (a) 1000, (b) 10,000, (c) 100,000 and (d) 500,000 years using the SIBERIA model and Vegetation parameters. All dimensions are metres.



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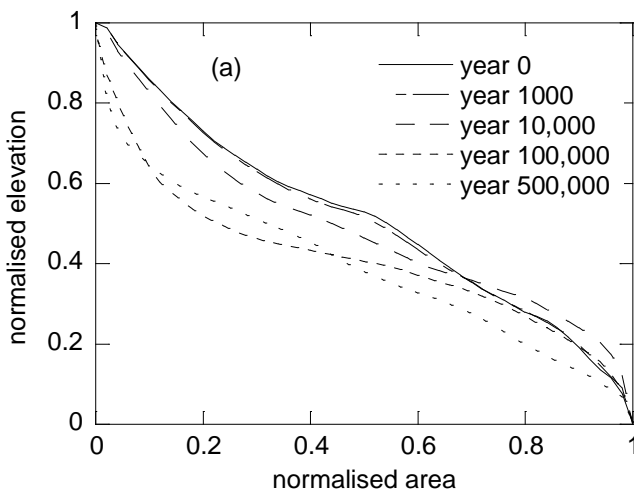


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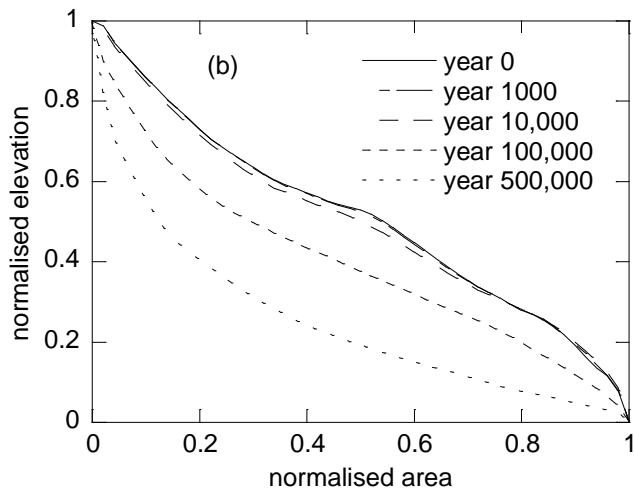


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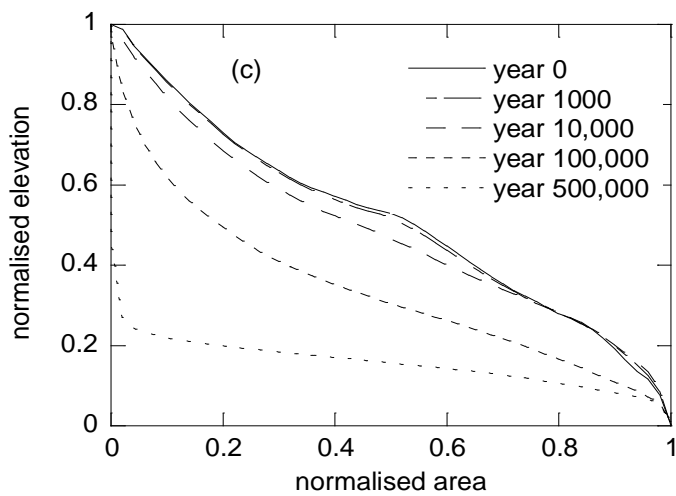
Fig. 5. Simulated annual sediment discharge and average annual elevation from Corridor Creek landform using Waste Rock Dump (a), Vegetation (b) and Tin Camp Creek parameters (c). The red line represent the range of sediment discharge as predicted from the regional denudation rates of $0.01\text{--}0.04\text{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



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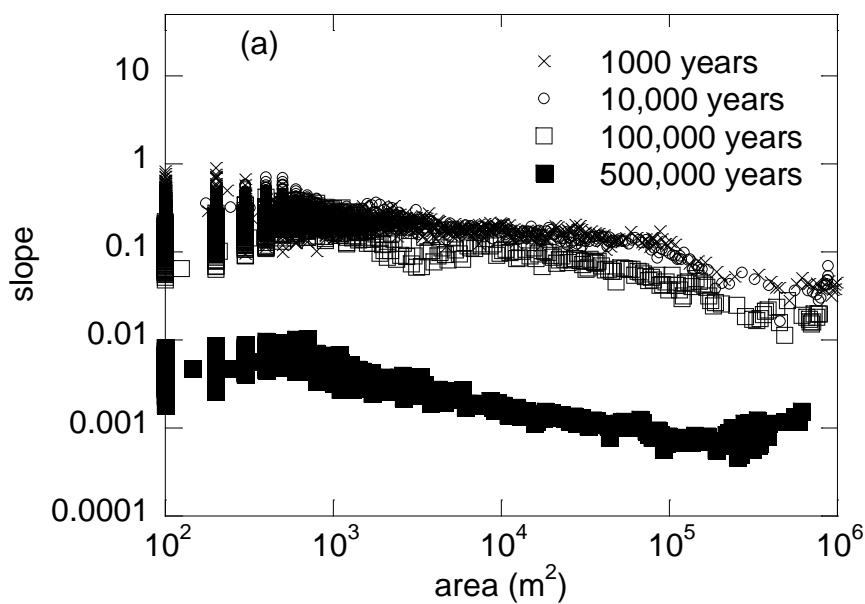
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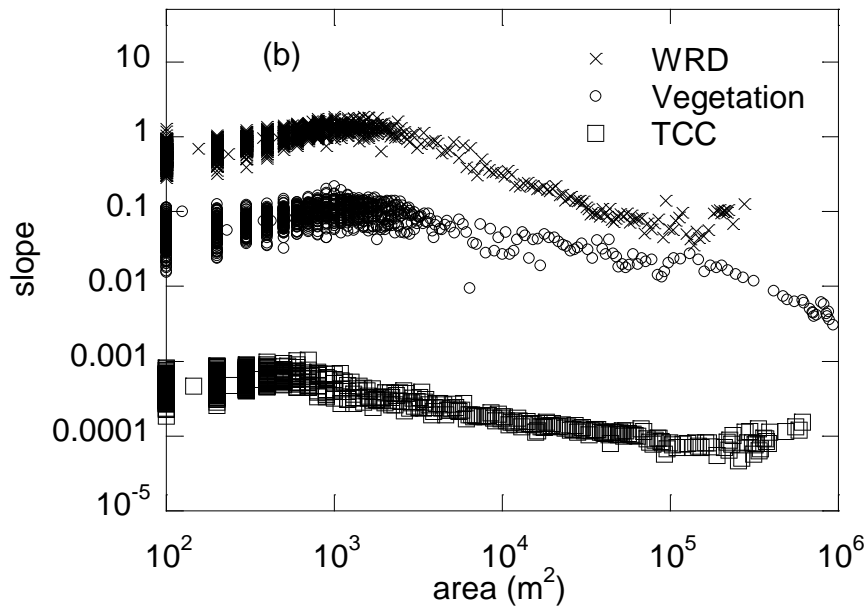
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Fig. 6. Hypsometric curves for the Corridor Creek catchment using Waste Rock Dump (a), Vegetation (b) and Tin Camp Creek parameters (c).



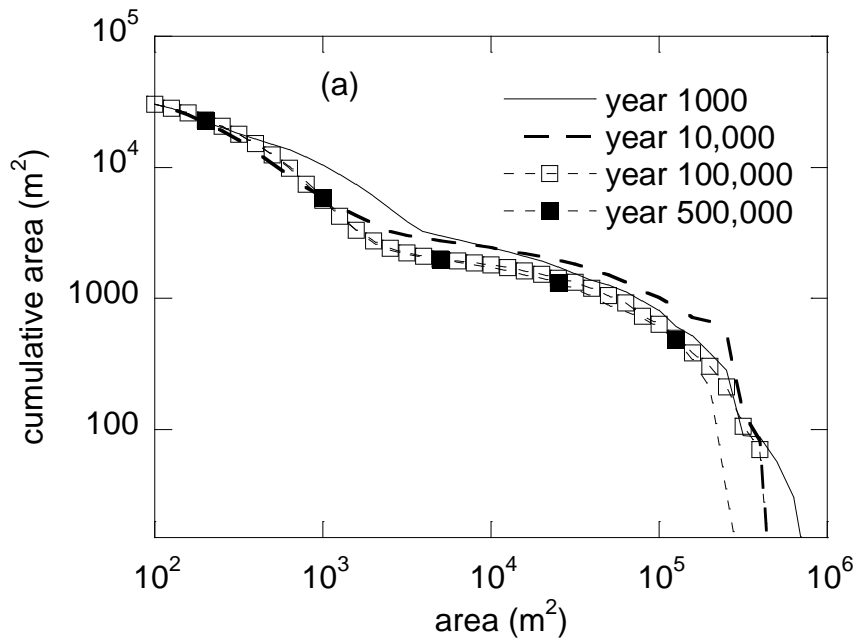
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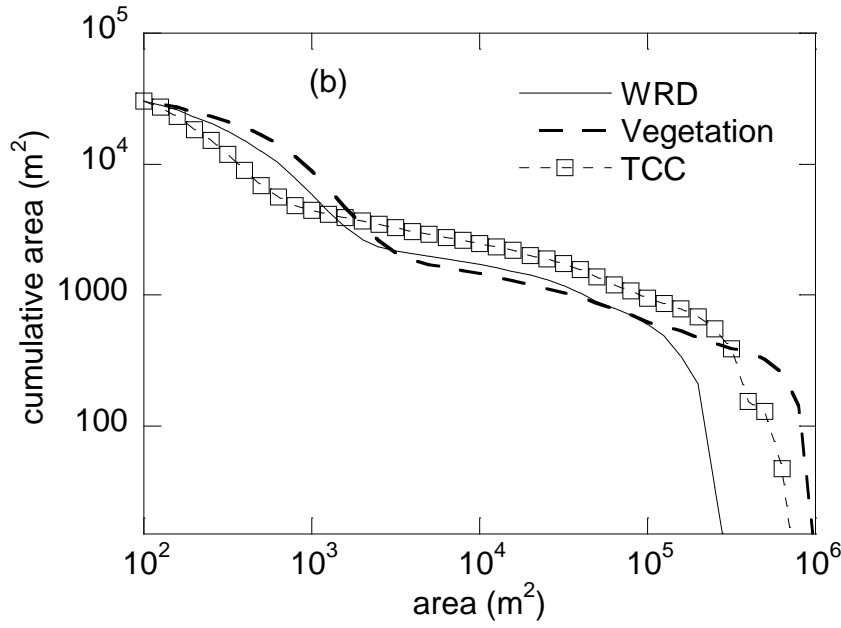


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Fig. 7. Area–slope relationship for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period (a) and comparison of the WRD, Vegetation and Tin Camp Creek area-slope data at 500,000 years (b). In (b) the WRD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

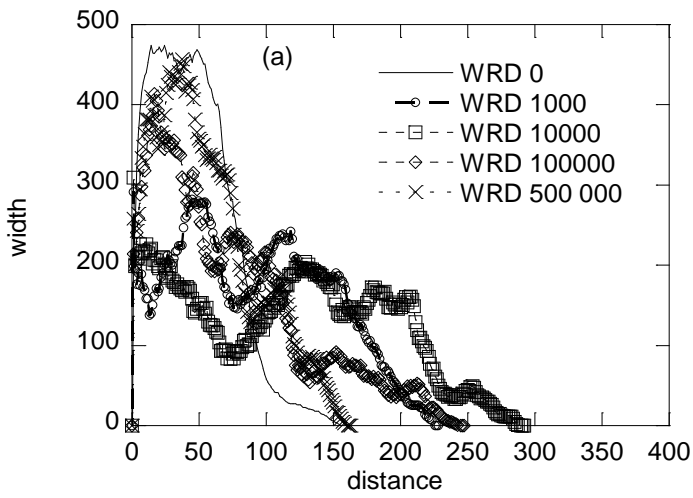


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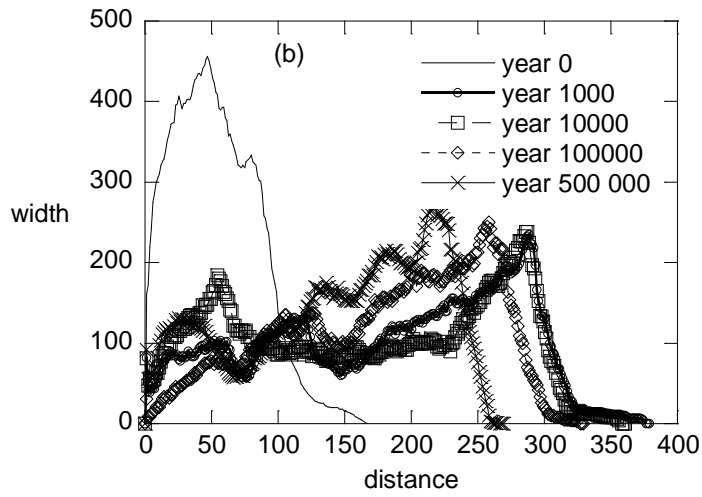


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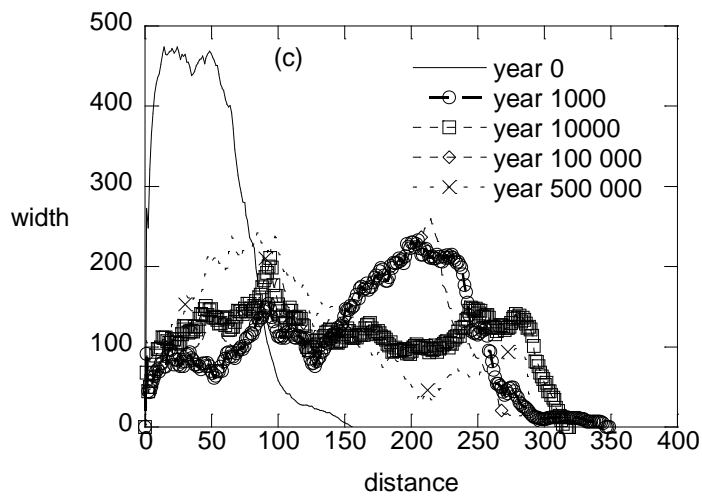
Fig. 8. Cumulative area distribution (a) for the Corridor Creek landform using Waste Rock Dump parameters over the 500,000 year modelled period and comparison of the WRD, Vegetation and Tin Camp Creek cumulative area data at 500,000 years (b).



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

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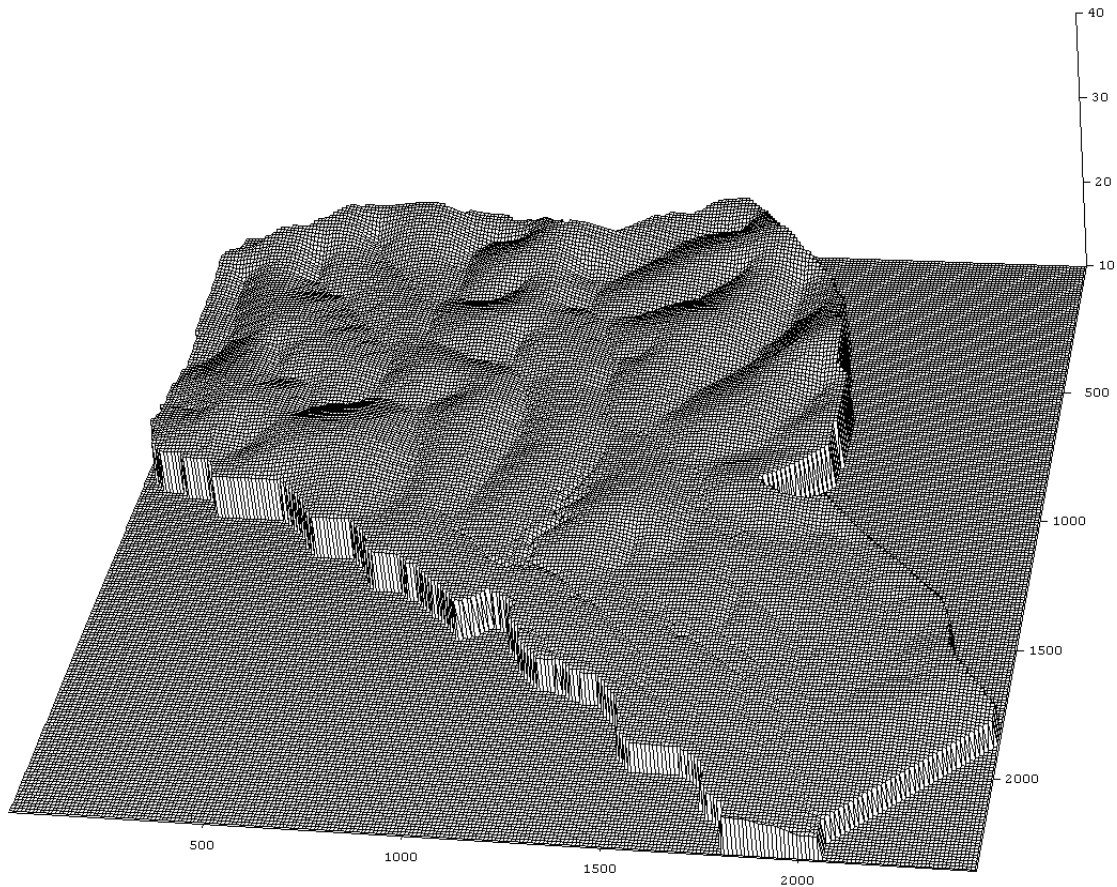
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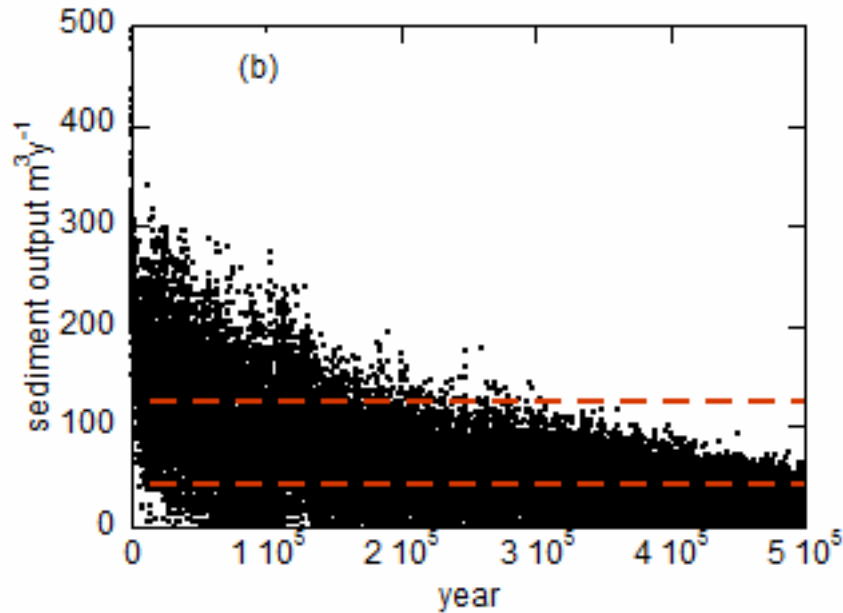
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(a)



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950 **Fig. 10.** Corridor Creek landform at 500,000 years using WRD parameters and the DInfinity
951 drainage direction algorithm (a) and sediment output from the simulation (b). The red line
952 represent the range of sediment discharge as predicted from the regional denudation rates of
953 $0.01\text{--}0.04 \text{ mm y}^{-1}$ ($30\text{--}120 \text{ m}^3 \text{ y}^{-1}$). For clarity, each year represents an average of 10 years
954 sediment output.
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956 **Table 1.** The SIBERIA parameter values for each region of the ERA Ranger mine for the
 957 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

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

WRD			
year	catchment relief (m)	average erosion rate (mm y⁻¹)	max. erosion depth (m)
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

992
 993
 994