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# A catchment scale evaluation of the SIBERIA and CAESAR landscape evolution models

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ABSTRACT: Landscape evolution models provide a way to determine erosion rates and landscape stability over times scales from tens to thousands of years. The SIBERIA and CAESAR landscape evolution models both have the capability to simulate catchment–wide erosion and deposition over these time scales. They are both cellular, operate over a digital elevation model of the landscape, and represent fluvial and slope processes. However, they were initially developed to solve research questions at different time and space scales and subsequently the perspective, detail and process representation vary considerably between the models. Notably, CAESAR simulates individual events with a greater emphasis on fluvial processes whereas SIBERIA averages erosion rates across annual time scales. This paper describes how both models are applied to Tin Camp Creek, Northern Territory, Australia, where soil erosion rates have been closely monitored over the last 10 years. Results simulating 10 000 years of erosion are similar, yet also pick up subtle differences that indicate the relative strengths and weaknesses of the two models. The results from both the SIBERIA and CAESAR models compare well with independent field data determined for the site over different time scales. Representative hillslope cross-sections are very similar between the models. Geomorphologically there was little difference between the modelled catchments after 1000 years but significant differences were revealed at longer simulation times. Importantly, both models show that they are sensitive to input parameters and that hydrology and erosion parameter derivation has long-term implications for sediment transport prediction. Therefore selection of input parameters is critical. This study also provides a good example of how different models may be better suited to different applications or research questions. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: sediment transport; catchment; hydrology; geomorphology; soil erosion modelling; SIBERIA; CAESAR

## Introduction

The ability to measure and model soil erosion and resultant land degradation is important because soil erosion has a range of environmental impacts, including loss of organic matter and nutrients, reduction of landscape productivity and reduction in downstream water quality. Numerous soil erosion models such as the Water Erosion Prediction Program (WEPP) (Laflen *et al.*, 1991; Flanagan and Livingston, 1995), Universal Soil Loss Equation (USLE), Modified Universal Soil Loss Equation (MUSLE) and the Revised Universal Soil Loss Equation (RUSLE) (Onstad and Foster, 1975; Wischmeier and Smith, 1978; Renard *et al.*, 1994) have been developed, each with their own individual strengths and weaknesses. The models have been applied across a broad range of landscape types with varying degrees of success.

More recently, and possibly coincident with ever increasing computer processing power, landscape evolution and soil erosion models that use digital elevation models to represent the landscape surface have been developed (Willgoose *et al.*, 1991a,b; Braun and Sambridge, 1997; Tucker *et al.*, 2001) with some models being applied to the assessment of degraded and mining landscapes (Willgoose and Riley, 1998; Coulthard and Macklin, 2003). These models have considerable advantages over traditional modelling approaches, such as the RUSLE and WEPP, as they remove the need to manually determine slope length and angle. These models can also determine both erosion and deposition, something not possible with the RUSLE. A further advantage of using digital elevation based models is that they dynamically adjust the landscape to erosion and deposition, producing a better representation of slope and angle over the duration of the simulation.

Soil erosion and landscape evolution models are especially pertinent for landform design and the rehabilitation of mine sites. When planning for the rehabilitation of current mines such as the Ranger Uranium Mine, in the Northern Territory, Australia, it is important for engineers to establish how resilient a proposed rehabilitated landform sculpted over the existing mine landform will be. Guidelines (Commonwealth of Australia, 1987) recommend that in Australia mine sites should be able to withstand erosion, and models such as SIBERIA and CAESAR provide a useful method for assessing this likelihood. For this purpose and for validating their worth it is necessary that numerical models of soil erosion be compared with each other, validated against field data and their strengths and weaknesses assessed for the prediction of sediment fluxes and geomorphic change (Roering, 2008). Comparison also provides insights into which subcomponents of the model formulation are doing a better job, leading to improved understandings of the underlying science of sediment transport and the models predictive capability. Areas for improvement are also highlighted.

In this paper we compare the SIBERIA and CAESAR erosion models for their ability to predict sediment transport in a small catchment in western Arnhem Land, Northern Territory, selected as it is a good analogue for the pre-mined Ranger site. The simulation results are compared with each other and with field-determined values of soil erosion determined for the catchment. The merits of each model, their formulation and ease of application are also discussed.

## Study Site

Located in the catchment of Tin Camp Creek (TCC) in western Arnhem Land, Northern Territory, Australia (Figure 1), the study site lies in the Myra Falls Inlier in Lower Member Cahill Formation (Needham, 1988). This metamorphosed schist formation also hosts the Energy Resources of Australia Ranger Uranium Mine (RUM) and the surface properties may possibly be analogous to rehabilitated landforms at the RUM in the long term (Uren, 1992). Other studies in the region have [1] examined gully development on the waste rock dumps of the Scinto 6 former uranium mine (Hancock *et al.*, 2000).

The TCC catchment is located in the wet-dry tropics of northern Australia. The mean annual rainfall for the region is approximately 1400 mm, almost all of which falls in the wet season months from November to April. Short, high intensity storms are common, consequently fluvial erosion is the primary erosion process (Saynor *et al.*, 2004). Generally, most of the erosion occurs during a small number of high intensity tropical storms.

The area is presently tectonically inactive (Needham, 1988). TCC is part of the Ararat Land System (Story *et al.*, 1976) and developed in the late Cainozoic by the retreat of the Arnhem Land escarpment, resulting in a landscape dissected by active gully erosion (Hancock and Evans, 2006). For the purposes of this study, a smaller 50 ha catchment, representative of many others in the area was selected (Figure 2). The catchment consists of closely dissected short, steep slopes 10–100 m long with gradients generally between 15 and 50%. The soils are red loamy earths and shallow gravely loam with some micaceous silty yellow earths and minor solodic soils on alluvial flats (Riley and Williams, 1991). Much of the surface of slopes and hill crests is covered by a gravelly cobble quartz lag.

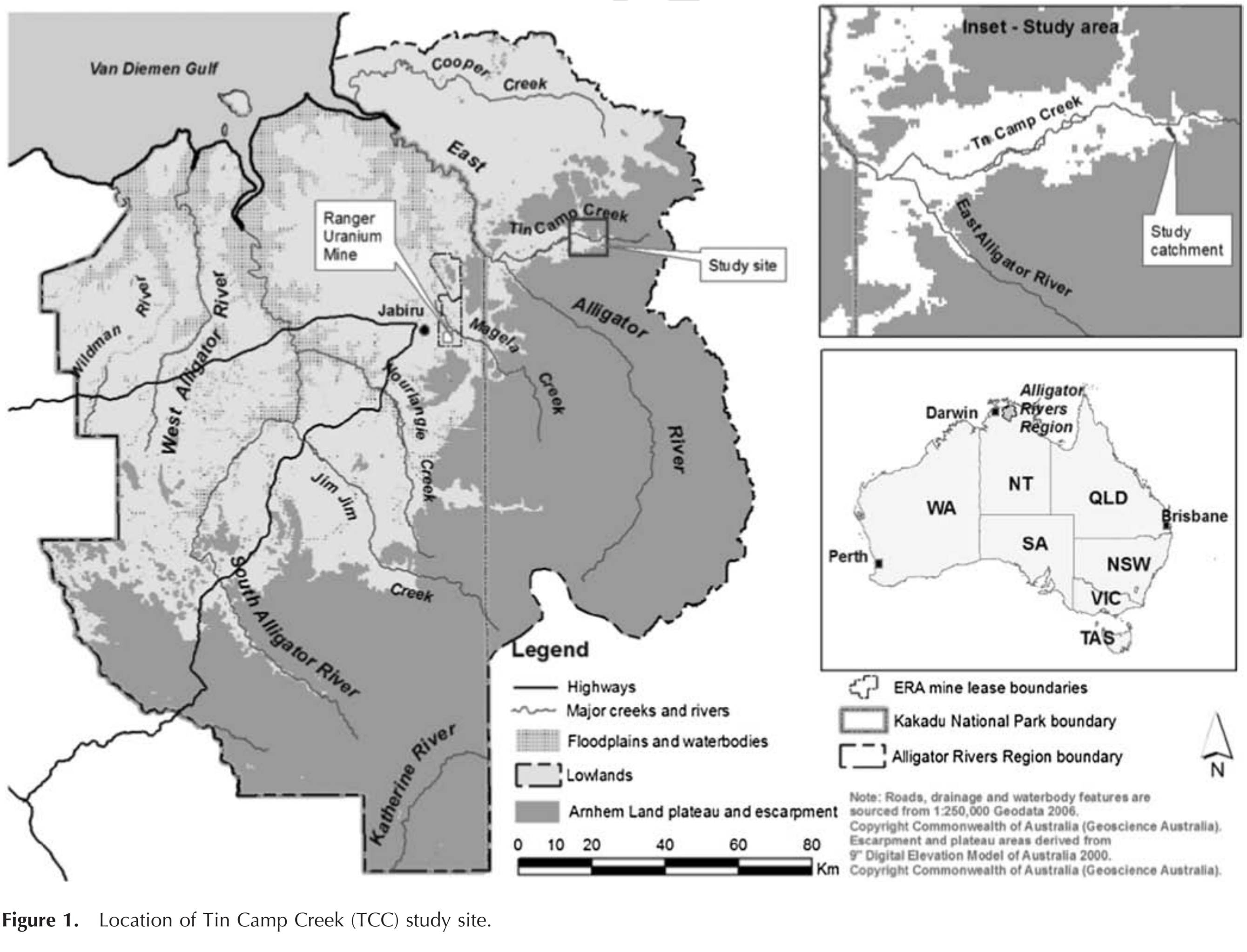

**Figure 1.** Location of Tin Camp Creek (TCC) study site.

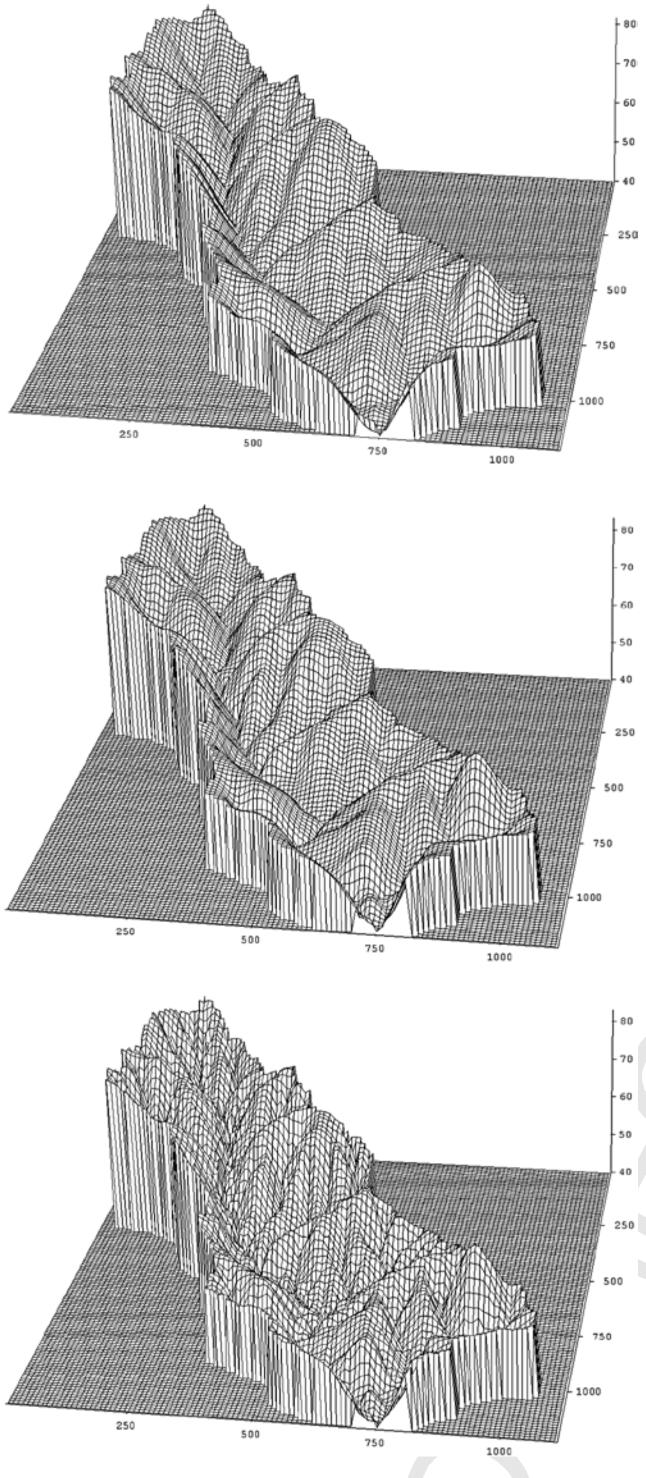

**Figure 2.** Digital elevation model of the Tin Camp Creek catchment gridded at 10 m after 10 000 years of erosion using SIBERIA and C1 parameters with diffusion (top), CAESAR using QT1 parameters and diffusion (middle) and SIBERIA with C1 parameters and no diffusion (bottom).

The native vegetation is open dry-sclerophyll forests and, although composed of a mixture of species, is dominated by *Eucalyptus* and *Acacia* species (Story *et al.*, 1976). *Melaleuca* spp. and *Pandanus spiralus* are also found in the low-lying riparian areas with an understorey dominated by *Heteropogon contortus* and *Sorghum* spp. There is vigorous growth of annual grasses during the early stages of the wet season. These grasses often fall over during the wet season, providing a thick mulch which causes high reductions in erosion rates of bare soil. Cover afforded by vegetation is often reduced by fire during the dry season, which enhances the potential for fluvial erosion following burning events (Saynor *et al.*, 2004).

## Measured erosion rates

Erosion and denudation rates have been established for the catchment using a variety of different methods. An assessment using the fallout environmental radioisotope caesium-137 ($^{137}$Cs) as an indicator of soil erosion status for two transects in the catchment produced net soil redistribution rates between 2 and 13 t ha$^{-1}$year$^{-1}$ (0·013–0·86 mm year$^{-1}$) (Hancock *et al.*, 2008). Erosion pins located at the base of hillslopes (representative of erosion rates for the lower hillslope) produced rates of 14 t ha$^{-1}$year$^{-1}$ (~1 mm year$^{-1}$) over a 2 year period (Hancock *et al.*, 2008). Estimated rates using the Revised Universal Soil Loss Equation (RUSLE) produced erosion rates of 10 t ha$^{-1}$year$^{-1}$ (0·67 mm year$^{-1}$). The RUSLE input parameter values were derived from field data collected from the area for that specific purpose.

The measured erosion rates, using $^{137}$Cs, for the upper hillslopes of the study area compare favourably with that of overall denudation rates for the area (0·01 to 0·04 mm year$^{-1}$) determined using stream sediment data from a range of catchments of different sizes in the general region (Cull *et al.*, 1992; Erskine and Saynor, 2000). The variation between measured rates above and denudation rates derived using stream sediment data may result from (i) the value of the bulk density of surface material (which varies between 1 and 1·4 g cm$^3$ across the catchment) applied when converting mass to volume to derive a denudation rate, and (ii) the application of a sedimentary delivery ratio (which is the percentage of the annual gross erosion from within a catchment that arrives at the catchment outlet each year) to the hillslope measurements to derive catchment output as all sediment mobilised on the hillslope is unlikely to leave the catchment each year.

# The SIBERIA Landscape Evolution Model

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

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

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

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

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

where $Q$ is the discharge per unit width (m$^3$ s$^{-1}$ m$^{-1}$ width), $S$ (m m$^{-1}$) the slope in the steepest downslope direction and $\beta_1$, $m_1$ and $n_1$ are calibrated parameters.

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

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

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

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

$$Q = \beta_3 A^{m_3} \tag{4}$$

where $\beta_3$ is the runoff rate constant and $m_3$ is the exponent of area, both of which require calibration for the particular field site. SIBERIA uses the D8 routing algorithm.

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

The SIBERIA erosion model has recently been tested and evaluated for erosion assessment of proposed post-mining landforms (Willgoose and Riley 1998; Evans *et al.,* 1999, 2000; Boggs *et al.*, 2000, 2001; Evans and Willgoose 2000; Hancock *et al.,* 2000, 2002; Lowry *et al.* 2006.,). A more detailed description of SIBERIA can be found in Willgoose *et al.* (1991a–d).

## SIBERIA input parameters

Before SIBERIA can be used to simulate soil erosion the sediment transport and area–discharge relationships require calibration. The fluvial sediment transport equation is parameterised using input from field sediment transport and hydrology data. For this study the SIBERIA model was calibrated using field data collected at Tin Camp Creek from a series of rainfall events. Two catchments of size 2032 m$^2$ (catchment C1) and 2947 m$^2$ (catchment C2) with average slopes of 19% and 22%, respectively, were instrumented during the wet season of 1990 (Moliere *et al.*, 2002). Both sites are incised and channelised and are representative of the overall 50 ha catchment. The study sites were monitored during rainfall events from December 1992. At this time the catchments had a good covering of speargrass, which quickly regenerates each wet season.

To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall and runoff for discrete rainfall events in both catchments were collected allowing calibration for the two individual catchments. Using these individual data sets parameter values were determined, thus producing parameter sets for the two catchments representing annual hydrology and sediment transport rates (Table I) (Moliere *et al.*, 2002). This data will be referred to as the C1 and C2 parameter sets in all text below. While no field data exists for diffusion or hillslope creep for the area, a value of 0·0025, where length units are metres and time units are years (Hancock *et al.*, 2000, 2002), has been used for previous studies in the area and is also used here. A description of the parameters and the parameterisation process is described in detail by Evans *et al.* (1998), Hancock *et al.* (2000) and Moliere *et al.* (2002). Boundary conditions for the simulations were such that all areas within the catchment boundary were allowed to erode and a series of outlets (11 in total) allowed sediment to exit from the domain. The calibration of SIBERIA for the Tin Camp Creek is described in detail elsewhere (Moliere *et al.*, 2002; Hancock, 2006).

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

| | C1 | C2 |
|---|---|---|
| $m_1$ | 1·70 | 1·69 |
| $n_1$ | 0·69 | 0·69 |
| $\beta_3$ | 0·000186 | 0·000144 |
| $m_3$ | 0·79 | 0·83 |
| $\beta_1$ | 1067 | 384 |

## The CAESAR Landscape and Erosion Model

CAESAR is a cellular landscape and river reach evolution model (Coulthard *et al.*, 2006). It allows the user to input a DEM of a river catchment or reach, enter water and sediment fluxes, and/or rainfall data to drive catchment evolution. It features slope processes (soil creep, mass movement), hydrological processes, multidirectional routing of river flow and fluvial erosion and deposition over a range of different grainsizes. Furthermore, it has a tracing component embedded, so that users can input a different type of sediment and watch its movement, diffusion and concentration downstream. A full description of CAESAR can be found in Coulthard *et al.* (2002), Coulthard and Macklin (2003) and Van de Wiel *et al.* (2007).

CAESAR, similar to SIBERIA, represents a landscape with a mesh of grid cells. For each cell, further values are stored representing hydrological parameters, grainsize, water discharge, vegetation levels etc. Then, for every model iteration, these are altered according to a set of rules, loosely grouped into (1) hydraulic routing, (2) fluvial erosion and deposition, and (3) slope processes.

A modification of TOPMODEL (Bevan and Kirkby, 1979) is [2] used to generate a combined surface and subsurface discharge. For hydraulic routing the model takes a discharge either prescribed from a point, or determined via the in built hydrological model and then routes this to neighbouring cells with boundary conditions and catchment outlet being set similar to SIBERIA. This is carried out through a ‘scanning’ procedure that works across the catchment in four directions (left to right, right to left, up to down, down to up) pushing flow to the three cells in front – in a manner akin to Murray and Paola’s (1994) braided river model. In CAESAR, however, a depth is calculated for this discharge, which allows flow to be routed over, as well as around, obstacles.

After the hydraulic model has determined flow depths and inundation locations for the reach/catchment, fluvial erosion is calculated using nine different grainsizes embedded within a series of active layers. This allows bed armouring effects and the development of a limited stratigraphy. Soil creep is calculated and mass movement (landslides) occur when a critical slope threshold is exceeded based on slope alone and a diffusivity coefficient.

The main difference between CAESAR and SIBERIA is that CAESAR simulates individual storm events (driven by the hourly rainfall record) whereas SIBERA determines erosion based on average annual rates. Furthermore, CAESAR has a greater focus on shorter time scale fluvial processes (using multiple grainsizes and calculating flow patterns using multiple flow directions) and SIBERIA longer time scale slope and catchment wide processes.

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### CAESAR input parameters

CAESAR requires a DEM of the study site or catchment, rainfall data (mm $h^{-1}$) and soil/sediment particle distribution data. For this study, 22 years of complete hourly rainfall data from Jabiru (Figure 1) were used. The rainfall station at Jabiru is the closest station to TCC with long-term rainfall intensity data.

Soil particle size data were obtained from soil pits dug at two representative sites close to the catchment described earlier (Glindeman, 1992). The soil profile at these pits had a high quartz content of the parent mica schist formation. The first pit (QT1) was situated on a lower hillslope and had large rock fragments covering 30–40% of the surface with a slope of 12°. QT1 had a maximum depth of 900 mm. The second pit (QT3) was located on the upper hillslope with a slope of 11° and had a maximum depth of 1100 mm. The surface had an 80–90% cover of quartz fragments.

Soil particle size distribution was determined using both hydrometer and sieve methods (Hall *et al.*, 1992) and were classified into 18 ranges. As CAESAR uses nine ranges the data was re-grouped to suit (Table II). The two data sets allowed an assessment of the sensitivity of the CAESAR model to different particle size data input. These data will be referred to as the QT1 and QT3 parameter sets in all text below. A value for hillslope diffusion or creep of 0·0025 was used where length units are metres and time units are years. Similar to SIBERIA, boundary conditions for the simulations were such that all areas within the catchment boundary were allowed to erode and a series of outlets (11 in total) allowed sediment to exit from the domain.

## Catchment Digital Elevation Models

Both SIBERIA and CAESAR use DEMs to capture hillslope and catchment geomorphology. A high quality DEM of the area was created from 240 000 irregularly spaced data points using digital photogrammetry by AIRESEARCH Pty Ltd, Darwin. The DEM has been used extensively in past studies (Hancock 3 *et al.*, 2002; Hancock 2003, 2005; Willgoose *et al.*, 2003).

In this study the irregularly spaced data was gridded onto a 10 m by 10 m spacing by the commercially available and widely used Surfer 7·04 (Golden Software Inc) program using a simple Kriging technique. Hancock (2005) has demonstrated that a 10 m by 10 m digital elevation model grid size is a suitable size to capture the catchment hillslope properties at TCC. This 10 m by 10 m spacing was equivalent to the average spacing of the original AIRESEARCH data over the area and provides a natural limit to the grid size reduction. All elevation depressions (pits – an anomalous low surrounded by highs) were removed from the DEM using the Tarboton *et al.* (1989) method.

**Table II.** Soil particle size data from Quartz Trench 1 and 3 (QT1, QT3) used for input into CAESAR

| Size range (m) | QT1 | QT3 |
|---|---|---|
| 0·1 | 0·125 | 0·09 |
| 0·050 | 0·14 | 0·15 |
| 0·01 | 0·125 | 0·15 |
| 0·004 | 0·07 | 0·07 |
| 0·002 | 0·03 | 0·03 |
| 0·001 | 0·04 | 0·04 |
| 0·0005 | 0·20 | 0·20 |
| 0·0002 | 0·09 | 0·09 |
| 0·0001 | 0·18 | 0·18 |

## Methods and Results

As both CAESAR and SIBERIA have the ability to predict sediment transport and catchment evolution over the long term it is appropriate that they be evaluated over long time periods. As Australian guidelines recommend a design life for rehabilitated mine caps of 200 years and a structural life of at least 1000 years for uranium mines (Commonwealth of Australia, 1987), SIBERIA and CAESAR were run for 10 000 years to assess both erosion properties as well as geomorphic evolution of the catchment. For CAESAR this required running the 22 years of rainfall data end to end.

To assess the models, the catchments and their evolution are assessed using both a range of measures such as erosion and deposition rates as well as cross-sectional profiles. Geomorphic measures such as the area–slope relationship, hypsometric curve, cumulative area distribution, width function together with network descriptors such as Strahler (1964) stream statistics, network convergence and Optimal Channel Network (OCN) energy are also used as tools of comparison.

### Qualitative assessment

Visually there is little difference in hillslope morphology between the SIBERIA and CAESAR simulations with hillslope length and shape indistinguishable after 1000 years, this being the period over which rehabilitated mines should be able to withstand erosion (Commonwealth of Australia, 1987). After 10 000 years, subtle differences occur along the main drainage line where the SIBERIA simulations can be observed to produce a more incised drainage line than CAESAR. For the CAESAR simulation there appears to be some deposition in the main channels (Figure 2). Using no diffusion results in a much more incised channel network.

Erosion and deposition patterns show that differences exist between the models at 10 000 years (Figure 3). Overall, SIBERIA has a greater range of erosion and deposition than the CAESAR predictions but patterns of erosion and deposition are generally similar. For both SIBERIA and CAESAR the deepest erosion occurs along the main channel whereas deposition occurs in the first-order streams receiving eroded sediment from the surrounding hillslope.

An examination of cross-sectional profiles of the catchments at approximately one-fifth (T1), two-fifths (T2), three-fifths (T3) and four-fifths (T4) up from the catchment outlet demonstrates that both the SIBERIA and CAESAR simulations predict changes to the profile of the original catchment surface with SIBERIA having a more incised channel profile than that of the CAESAR simulations (Figure 4 top and middle). Overall, hillslope and catchment morphology resulting from the two simulations are closely matched in shape but SIBERIA has eroded considerably more than CAESAR (Figure 4, bottom).

### Quantitative assessment (erosion rates)

Examination of erosion rates (Figure 5) shows that both models have high initial erosion rates that decline. SIBERIA displays a uniform decline as a result of the temporally constant erosion and hydrology parameters while CAESAR sediment output is episodic in response to the temporally variable hourly rainfall. While not displayed in Figure 5, SIBERIA starts with a total catchment output of 121 $m^3$ (0·23 mm $year^1$) and 56 $m^3$ (0·12 mm $year^{-1}$), for C1 and C2 parameters respectively and CAESAR starts with a total catchment output of 6580 $m^3$ (13·2 mm $year^1$) and 4504 $m^3$ (9·0 mm $year^1$) for QT1 and

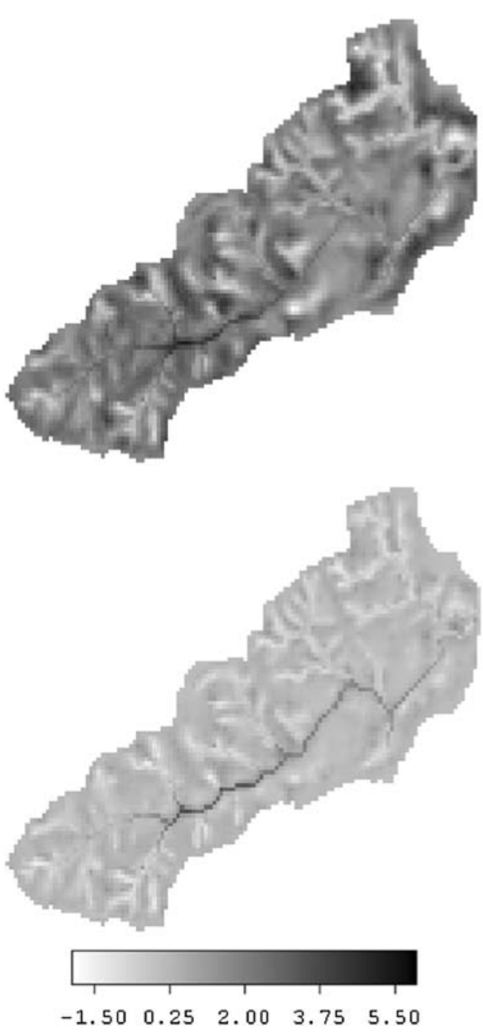

**Figure 3.** Erosion and deposition plots of the Tin Camp Creek catchment for SIBERIA using C1 parameters (top) and CAESAR simulation using QT1 parameters (bottom) after 10 000 years. Depth of erosion is in metres with positive values being erosion and negative values being deposition. The catchment outlet is on the right-hand side of each plot.

QT3 parameters, respectively. While the SIBERIA values are near field measured erosion rates the CAESAR erosion rates are higher.

Consequently, predicted erosion rates in the first 10 years are different, with CAESAR being much higher than SIBERIA (Table III). Erosion rates for both models at 10–100 years (Table IIIa and b) are very similar while erosion rates at 100–1000 years have CAESAR an order of magnitude lower than SIBERIA. Similar patterns are observed for minimum (deposition) and maximum (erosion) denudation rates (Table IIIa) with CAESAR having higher maximum erosion depths than SIBERIA. Interestingly maximum erosion depth decreases through time for CAESAR while the opposite occurs for the SIBERIA simulations with maximum erosion depth increasing. Minimum erosion (deposition) follows the same pattern for both models.

To evaluate the effect of diffusion on erosion rates, the simulations were repeated using fluvial erosion only and no diffusion (Table IIIc and d). Similar to the runs with diffusion, both models have high initial erosion rates that decline with a total catchment output of 161 m$^3$ (0·32 mm year$^1$) and 71 m$^3$ (0·14 mm year$^{-1}$), for C1 and C2 parameters, respectively, and CAESAR starts with a total catchment output of 6686 m$^3$ (13·2 mm year$^1$) and 7283 m$^3$ (14·4 mm year$^1$) for QT1 and QT3 parameters, respectively, demonstrating that diffusion has an effect on initial sediment output.

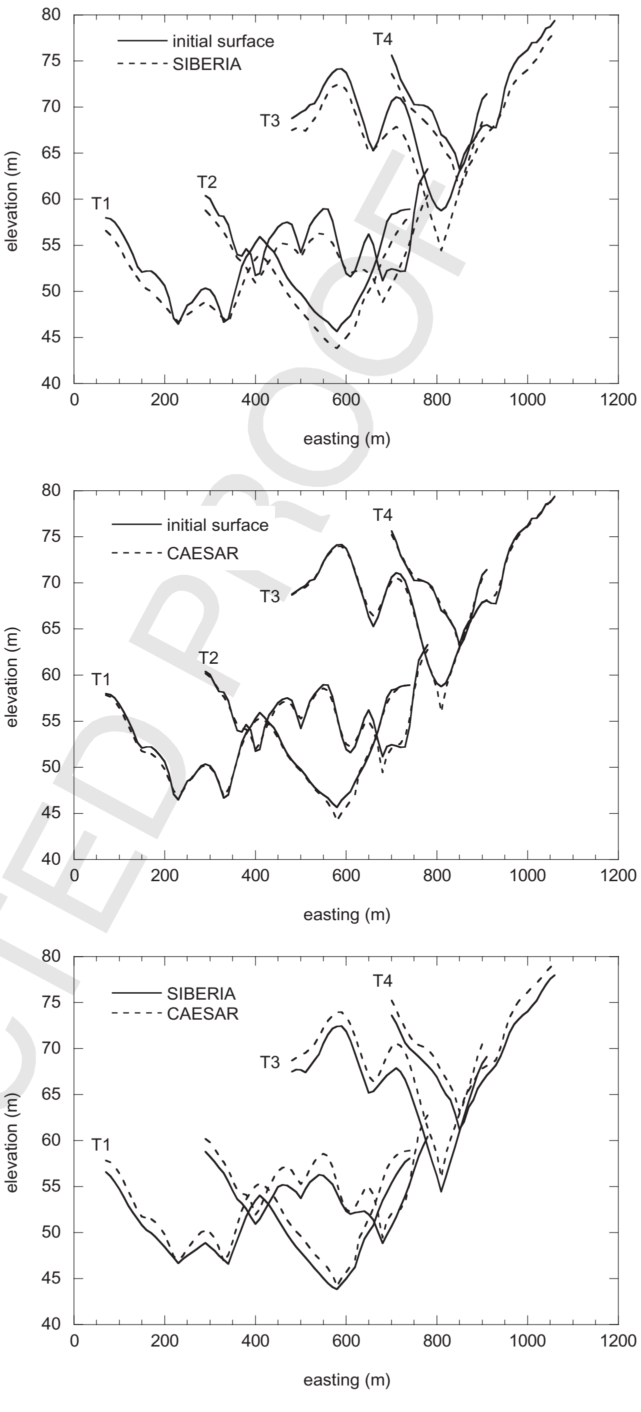

**Figure 4.** Cross-sections of initial surface at approximately one fifth (T1), two-fifths (T2), three-fifths (T3), four-fifths (T4) up the Tin Camp Ck catchment and SIBERIA (top) and CAESAR (middle) simulation after 10 000 years of erosion using C1 and QT1 parameters, respectively. Comparison of the SIBERIA and CAESAR predictions at 10 000 years is displayed at bottom.

## Quantitative assessment (geomorphology)

Catchment area–elevation properties examined here are the area–slope relationship, hypsometric curve and the cumulative area distribution.

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

$$A^{\alpha}S = \text{constant} \tag{5}$$

where $A$ is the contributing area to the point of interest, $S$ is the slope of the point of interest and $\alpha$ is a constant (Hack, 1957; Flint, 1974; Willgoose, 1994).

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

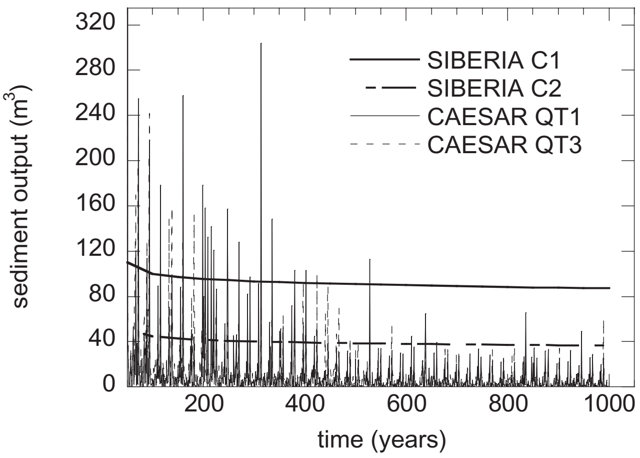

**Figure 5.** Erosion rates for SIBERIA (using C1 and C2 parameters) and CAESAR simulations (using QT1 and Qt3 parameters) of Tin Camp Creek.

The cumulative area distribution is a function defining the proportion of the catchment that has a drainage area greater than or equal to a specified drainage area and describes the spatial distribution of areas and drainage network aggregation properties within a catchment. The cumulative area distribution has been used as a means of characterising the flow aggregation structure of channel networks (Rodriguez *et al.*, 1992; LaBarbera and Roth, 1994). The cumulative area distribution is similar to the area–slope relationship in that it provides the ability to examine the relationship between diffusive and fluvial processes. Similar to the hypsometric curve, the cumulative area distribution is indirectly related to the area–slope relationship as the distribution of areas in a catchment is related to its area–elevation properties.

After 1000 years of erosion, the hypsometric curve and integral (Table IV), area–slope relationship, cumulative area distribution and width function displayed no difference between parameters data sets or models but at 10 000 years differences emerge (Figure 6). The hypsometric curve and integral from the SIBERIA simulations are lower than the CASEAR simulations indicating that the catchment has eroded faster. This is confirmed by the average elevations in Table IV, which demonstrate that the landscape has significantly lowered for the SIBERIA simulations. While difficult to observe in Figure 6 the fluvial region of the area–slope relationship also differs, with the exponent of Equation (5) being approximately 0·5 for the SIBERIA simulations and approximately 0·36 for CAESAR. This difference demonstrates that the two models produce landscapes that begin to diverge through time in terms of area–slope properties. Subtle differences can also be observed in the cumulative area distribution in both the

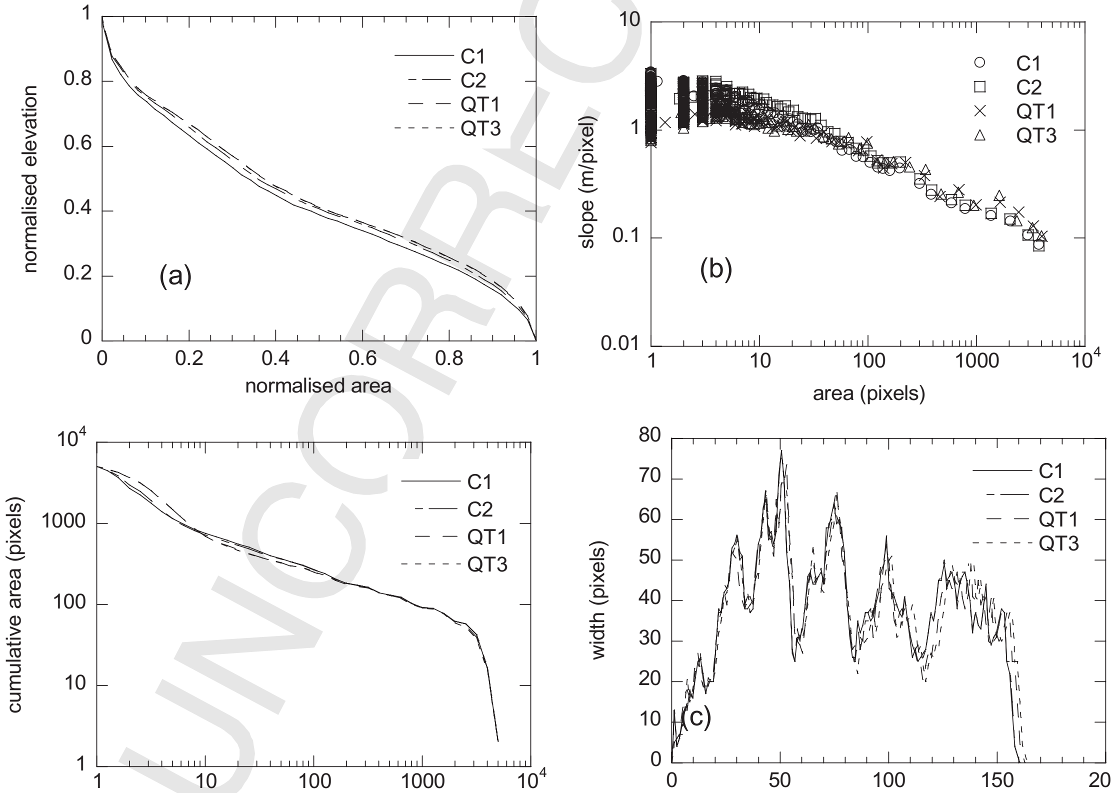

**Figure 6.** Hypsometric curve (a), area-slope relationship (b), cumulative area distribution (c) and width function (d) for SIBERIA simulations using parameters sets C1 and C2 and CAESAR simulations using parameter sets QT1 and QT3 at 10 000 years.

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**Table III.** Results from the SIBERIA and CAESAR simulations for the Tin Camp Creek catchment using C1 and C2 and QT1 and QT3 parameters, respectively, with diffusion (a and b) and without diffusion (c and d)

a.

| | SIBERIA C1 | | | SIBERIA C2 | | |
|---|---|---|---|---|---|---|
| Year | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) |
| 0–10 | 0·25 | –0·53 | 0·78 | 0·10 | –0·43 | 0·44 |
| 10–100 | 0·21 | –0·44 | 0·91 | 0·09 | –037 | 0·86 |
| 100–1000 | 0·19 | –0·99 | 1·55 | 0·08 | –1·05 | 1·25 |
| 1000–10000 | 0·18 | –0·10 | 4·41 | 0·07 | –1·92 | 3·60 |
| 0–10000 | 0·18 | –1·76 | 5·27 | 0·08 | –2·93 | 4·22 |

b.

| | CAESAR QT1 | | | CAESAR QT3 | | |
|---|---|---|---|---|---|---|
| Year | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) |
| 0–10 | 2·11 | –0·58 | 1·88 | 1·52 | –0·34 | 1·25 |
| 10–100 | 0·16 | –0·17 | 1·78 | 0·09 | –0·11 | 1·70 |
| 100–1000 | 0·02 | –0·28 | 1·76 | 0·02 | –0·38 | 1·11 |
| 1000–10000 | 0·01 | –1·23 | 1·29 | 0·02 | –1·34 | 1·01 |
| 0–10000 | 0·01 | –1·45 | 3·71 | 0·02 | –1·56 | 3·84 |

c.

| | SIBERIA C1 | | | SIBERIA C2 | | |
|---|---|---|---|---|---|---|
| Year | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) |
| 0–10 | 0·59 | –0·50 | 0·81 | 0·56 | –0·50 | 0·61 |
| 10–100 | 0·17 | –0·40 | 0·90 | 0·07 | –0·30 | 0·80 |
| 100–1000 | 0·180 | –0·60 | 2·30 | 0·07 | –0·40 | 1·90 |
| 1000–10000 | 0·15 | –0·11 | 5·09 | 0·06 | –0·47 | 4·44 |
| 0–10000 | 0·16 | –0·73 | 7·58 | 0·064 | –0·78 | 7·44 |

d.

| | CAESAR QT1 | | | CAESAR QT3 | | |
|---|---|---|---|---|---|---|
| Year | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) | Average erosion (mm year$^{-1}$) | Min. erosion (m) | Max. erosion (m) |
| 0–10 | 2·10 | –0·49 | 1·83 | 2·39 | –0·61 | 1·87 |
| 10–100 | 0·14 | –0·25 | 1·35 | 0·27 | –0·19 | 2·05 |
| 100–1000 | 0·01 | –0·09 | 0·89 | 0·02 | –0·09 | 1·61 |
| 1000–10000 | 0·004 | –0·10 | 1·98 | 0·003 | –0·24 | 1·19 |
| 0–10000 | 0·009 | –0·40 | 2·63 | 0·01 | –0·69 | 3·95 |

diffusive and fluvial regions of the data which confirm the differences observed in the area–slope relationship.

The width function (Surkan, 1968) is a plot of the number of channels at a given distance from the basin outlet, measured along the network (Naden, 1992). A slightly more general interpretation is adopted here, which is easier to apply for digital terrain maps. The width function used here is the number of drainage paths (whether they be channel or hillslope) at a given distance from the outlet as it is difficult to determine what is channel and what is hillslope on a DEM. The width function is sensitive to changes in network structure and catchment shape. There was no discernible difference in the width function at 1000 or 10 000 years between simulations demonstrating that the two models produce catchments with very similar network structures.

Other descriptors of channel networking properties used here are network convergence and Optimal Channel Network (OCN) energy. Catchment drainage network convergence for a gridded DEM is the average number of channels draining into a point in a catchment (Ibbitt *et al.*, 1999). Convergence statistics provide, in addition to the width function and the cumulative area distribution, an additional metric for analysing catchment drainage and network properties (Perera and Willgoose, 1998; Ibbitt *et al.*, 1999).

Catchments differ in potential energy as a result of catchment size and relief and the differences can be examined

**Table IV.** Geomorphic statistics for the SIBERIA and CAESAR simulations of Tin Camp Creek after 10 000 years. Tables a and b include diffusion while Tables c and d exclude diffusion

a.

| | | SIBERIA 1000 years | | SIBERIA 10000 years | |
|---|---|---|---|---|---|
| | 0 years | C1 | C2 | C1 | C2 |
| hypsometric integral | 0·456 | 0·453 | 0·456 | 0·437 | 0·454 |
| network convergence | 1·47 | 1·41 | 1·37 | 1·31 | 1·25 |
| OCN energy | 17068 | 16600 | 16694 | 16798 | 17118 |
| mean elevation | 60·05 | 59·86 | 59·97 | 58·28 | 59·26 |

b.

| | | CAESAR 1000 years | | CAESAR 10000 years | |
|---|---|---|---|---|---|
| | 0 years | QT1 | QT3 | QT1 | QT3 |
| hypsometric integral | 0·456 | 0·455 | 0·454 | 0·451 | 0·450 |
| network convergence | 1·47 | 1·48 | 1·48 | 1·37 | 1·38 |
| OCN energy | 17068 | 16871 | 16610 | 16719 | 16662 |
| mean elevation | 60·05 | 60·00 | 60·01 | 59·93 | 59·90 |

c.

| | | SIBERIA 1000 years | | SIBERIA 10000 years | |
|---|---|---|---|---|---|
| | 0 years | C1 | C2 | C1 | C2 |
| hypsometric integral | 0·456 | 0·452 | 0·454 | 0·423 | 0·442 |
| network convergence | 1·47 | 1·54 | 1·51 | 1·874 | 1·69 |
| OCN energy | 17068 | 16470 | 16531 | 16234 | 16320 |
| mean elevation | 60·05 | 59·87 | 59·98 | 58·49 | 59·42 |

d.

| | | CAESAR 1000 years | | CAESAR 10000 years | |
|---|---|---|---|---|---|
| | 0 years | QT1 | QT3 | QT1 | QT3 |
| hypsometric integral | 0·456 | 0·454 | 0·454 | 0·452 | 0·452 |
| network convergence | 1·47 | 1·50 | 1·50 | 1·49 | 1·50 |
| OCN energy | 17068 | 16562 | 16456 | 16555 | 16445 |
| mean elevation | 60·05 | 60·01 | 59·88 | 59·59 | 59·87 |

using the OCN concept of Rodriguez-Iturbe and Rinaldo (1997). In this study OCN energy is defined as

$$\sum_{i}^{N} l_i A_i^{0\cdot5} \tag{6}$$

where $i$ is the link index, $N$ the number of links and $l$ and $A$ are the length and area of each link. It is normally defined for the channel network only (Rigon *et al.*, 1993), but is used here over the whole catchment to eliminate the energy's sensitivity to the drainage density of the catchment.

At 10 000 years network convergence and OCN energy (Table IVa and b) were very similar for both models, suggesting that SIBERIA and CAESAR produce similar channel networks. This finding, along with the similarity of the width function, suggests that the runoff properties of both catchments are very similar at 10 000 years. Examination of other catchment statistics (Table IV) demonstrates that SIBERIA simulated catchments have eroded slightly less than CAESAR simulated catchments as relief and mean elevation are slightly higher.

Simulations with fluvial erosion only and no diffusion produced catchments with similar erosion rates and average elevations but a more highly branched channel network. The increased network convergence is a result of enhanced fluvial incision whereas the inclusion of diffusion acts to smooth or round the landscape resulting in a less incised channel network (Table 9). Overall, the similarity of the network convergence values for both the simulations with and without diffusion indicate that the fluvial and diffusive transport model in both SIBERIA and CAESAR operate similarly.

## Discussion

Soil erosion and landscape evolution models offer the ability to better understand and manage hillslope and catchment disturbance. It is important that these landform evolution models and modelling procedures be compared and evaluated so that first, the validity of each model can be ascertained and, second, the strengths and weaknesses of each model formulation can be better understood (Roering, 2008). Evaluation and improved understanding will allow better application and resultant prediction of erosion and sediment transport. Numerical modelling is the only quantitative method which allows predictions to be made about effects of landuse and climate variability on catchment processes. It is also necessary that model results be validated against field data so that there is confidence in simulated results.

## Model comparison

The results from both the SIBERIA and CAESAR models are comparable with independent field data determined for the site. Importantly, SIBERIA was calibrated using field data (see SIBERIA input parameters) independent of the erosion and denudation rates described earlier to which the model outputs are compared. At all stages of the 10 000 year simulation the SIBERIA model predicted sediment outputs within the range of field denudation rates predicted using the RUSLE or measured using $^{137}$Cs for the study catchment, but higher than the regional values reported by Cull *et al.* (1992) and that of Erskine and Saynor (2000) (Table III). Both models predict an initial high pulse of sediment output in the first (approximately) 10 years of the simulation and then settle down. SIBERIA produces a steady temporal drop in sediment output as a result of the temporally constant hydrology and erosion parameters while CAESAR produces episodic output as a result of temporally variable hourly rainfall data. During this 10 year period the maximum deposition depth is very similar for SIBERIA and CAESAR but the maximum erosion simulated by CAESAR is an order of magnitude greater that SIBERIA (Table III). However, after the first 10 years, the catchment conditioning phase, CAESAR simulated denudation rates within the ranges of the field rates.

The initial high pulse of sediment output in the first few years of the simulation is a result of the DEM being smoothed by the erosion models and in the case of CAESAR, fine material being removed. This is a result of CAESAR starting these simulations with a uniform grainsize distribution across the whole catchment. In the first few years of operation fines and sands within the channel cells are preferentially eroded until they become armoured. The elevation data show that the differences in topography generated in this spin-up[1] time are really very small despite the higher sediment outputs. This process also involves ‘rounding the edges’ from sharp steps between cells – predominantly in the channel cells. This is largely an artefact from the DEM creation process – where some cells will have disproportionately high gradients between them – due to the inaccuracies in the creation of the DEM (which is a smoothing of many elevations within an area). Furthermore, in CAESAR we get a disproportionately high sediment output not so much from topographic adjustment but more from removal of the fines from most cells where there is fluvial erosion. This is so the CAESAR model can develop a bed surface grainsize and is a clear difference between how the models operate.

One element that is likely to produce increased sediment loads at the start of each simulation is DEM surface roughness. To examine this issue the DEM was smoothed by one pass of an algorithm that averaged each elevation with its eight neighbours. There was no statistical difference in the area–slope relationship or hypsometry between the non-smoothed and smoothed catchment but differences occurred in network statistics and the width function as the channel network was simplified. This new smoothed DEM was used as input into the SIBERIA and CAESAR models (using C1, C2 and QT1 and QT3 parameters, respectively) and this reduced erosion rates by approximately 10% for SIBERIA and 40% for the CAESAR simulations. This demonstrates that initial topography has an impact on sediment output but for CAESAR the rainfall and sorting of the soil particle size distribution has a much stronger role in this environment. Model spin-up time and the role of different input parameters is an area of ongoing research.

Neither model includes a soil cohesion component at present but CAESAR does have the ability to simulate vegetation growth. Both of these factors will affect erosion rates. The effect of plant growth was not examined here as the catchment has been burnt every second year since the site was first studied. This is a typical fire frequency for the area and also when not burnt, the vegetation at the end of the dry season has senesced to the point where it provides little cover. The role of soil cohesion and vegetation is also an area for considerable further research.

Between 10 and 100 years both models produce very similar average annual denudation rates. Maximum erosion depth for the CAESAR simulations is approximately double that of SIBERIA during this period. It is suggested that in this case the models have a 10 year minimum ‘spin-up’ period with the models after this time predicting sediment transport rates within field data estimates discussed earlier. Nevertheless it may be that more conservative long-term estimates are achieved after a spin-up time of 100 years. Interestingly, never during the 10 000 years of simulation are the erosion rates of SIBERIA within the regional range 0·01–0·04 mm year$^{-1}$ (Cull *et al.*, 1992; Erskine and Saynor, 2000) while CAESAR output is within this range after 100 years.

Hillslope cross-sections are very similar between model simulations and show a demonstrable change from the initial surface (Figure 4). Enhanced incision in the catchment predicted by SIBERIA is likely to be the result of the model using the D8 flow direction algorithm while CAESAR uses multiple paths. Also, while both SIBERIA and CAESAR have the ability to model diffusion processes there are no field data with which to parameterise the models for both fluvial and diffusive/creep erosion transport processes. In the parameter derivation process described earlier any sediment transported by diffusion/creep including rainsplash was collected in catchments C1 and C2 and became part of the fluvial sediment transport parameters. Therefore SIBERIA is potentially overestimating erosion. Field data is required to specifically evaluate diffusion processes such as rainsplash for input into soil erosion and landscape evolution models. Hancock *et al.* (2002) demonstrated that diffusion is necessary to correctly capture hillslope morphology over long-term landscape simulations. SIBERIA currently does not implement multiple flow directions so the effect of this difference with CAESAR is difficult to quantify.

The analysis using geomorphic statistics showed that there was little difference between the resulting landscapes after 1000 years but differences begin to occur after this. A comparison of the hypsometric integral, area–slope relationship, cumulative area distribution demonstrate geomorphic differences (Figure 6). Both models and their parameterisation appear to result in similar landforms over the 1000 year simulation period but the differences here are potentially the result of the SIBERIA simulated landforms eroding at a faster rate than the CAESAR simulated landforms. Little difference was

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[1] ‘Spin-up’ describes the period of self-adjustment during which the model establishes a form of internal equilibrium. For example, the DEM may have ‘sharper’ edges between cells representing unrealistically steep gradients due to the method of DEM production. During the spin-up period, these edges and gradients are softened by erosion and deposition processes within the model. In CAESAR we are forced to define homogenous grainsize distributions across the catchment. In the first period of model operation this leads to fines being eroded away from channel areas leaving an armoured channel. This ‘flush’ of fines is not representative of catchment behaviour, more of the internal re-adjustment of the model parameters (surface grainsize distribution) and so this period of output is ignored.

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observed in the width function due to the fixed boundaries of the simulation. It should also be noted that both models are routing sediment through the already existing channel network. How the networks would evolve de-novo (i.e. Hancock *et al*, 2002) by the two models without any pre-existing network condition is an area to be examined. This suggests that both models can be used with some confidence for applications where the period of interest is 1000 years but for longer periods it is not known at present which model produces the more reliable prediction. Other factors such as soil production are likely to be needed to be included in the models to be able to simulate landscape processes over such a long time scale. (Roering, 2008). The correctness of the models over the long term is an area of ongoing research.

Interestingly, these geomorphic models display many of the characteristics exhibited by climate and atmosphere General Circulation Models, requiring a spin up time and also showing diverging results after a period of simulation. In some ways this is not surprising as both climate and landscape system processes are complex, distributed and non-linear. This current work does provide us with a first interesting insight into how long we might expect to reasonably predict geomorphic change and landscape evolution before model results diverge. The use of geomorphic descriptors to evaluate landforms is an area of ongoing research with a need to develop more sensitive tools to assess morphometric change particularly to evaluate subtle differences in landscape evolution models.

The 22 years of event rainfall data used for the CAESAR simulations span rainfall conditions that have historically occurred in the study area. For SIBERIA, the hydrology and erosion parameters were derived using rainfall and runoff data measured for a series of storms in the middle of the wet season when the catchment was fully vegetated. The particle size data used for the CAESAR modelling were obtained from the QT1 and QT3 soil pits close to the catchments where the erosion and hydrology data were collected for the SIBERIA parameter calibration. Consequently, despite the differences in model formulation and input parameters both CAESAR and SIBERIA simulate similar denudation rates and landform change compared with field data. Both of these scenarios effectively represent static climates. Rates for SIBERA do not change as a result of any climate forcing as the input parameters are static while CAESAR is driven by an unchanging, repeated 22 year rainfall sequence. However, the opportunity does exist to simulate changes in climate through simply increasing rainfall intensity and duration in CAESAR or altering erosion parameters in SIBERA.

Both models show that they are sensitive to input parameters. The initial and long-term sediment output for SIBERIA using the C1 parameters is approximately twice that of C2. Nevertheless minimum and maximum erosion depth predictions are similar for the SIBERIA parameter sets. This demonstrates that hydrology and erosion parameter derivation has long-term implications for catchment sediment export prediction (Table 3a). For CAESAR the initial denudation rate using QT1 parameters was approximately 1·4 times greater than when using QT3 parameters with diffusion (Table 3b). After 100 years the denudation rate using QT1 parameters is approximately 1·7 times greater than when using QT3 parameter values. Maximum depth of deposition is of the same order of magnitude for QT1 and QT3 parameters and the maximum depth of erosion is very similar. For CAESAR this suggests that the soil particle size distribution is important for simulations however, it was the only input variable as both simulations used the same climate data. It also shows the effect of the point source nature of the data and in this study two nearby sites with the same geology were used and resulted in different simulation results. Table IIIc and d also demonstrates that the absence of diffusion can change erosion rates together with minimum and maximum erosion.

## Model application

In terms of ease of application both models have their strengths and weaknesses. The calibration of SIBERIA can be time consuming if using field hydrology and sediment transport data to derive model parameters in advance of using the model. The use of flumes and sediment traps at the catchment outlet provide an integrated measure of hydrology, sediment transport and the effect of vegetation growth spatially and temporally (Hancock *et al.*, 2000; Moliere *et al.*, 2002). A much simpler approach for calibration uses a database of hydrology and erosion parameters derived from the work of Sheridan *et al.* (2000), which allows data to be derived for a range of soils and hydrology conditions. Alternatively SIBERIA erosion and hydrology parameters can be fitted using catchment area–slope relationship (Willgoose, 1994; Hancock *et al*, 2002) and erosion rate fitted using local data from field studies (Hancock *et al.* 2007). Both are generalist approaches and the reliability of the parameters with regard to the site need to be evaluated.

The calibration of CAESAR is much simpler with only hourly rainfall data and soil particle size data required as input parameters. The difficulty with this is the point specific nature of the soil particle size data that can be used and the availability of hourly rainfall data. Soil particle size data varies considerably on the hillslope and catchment scale (both laterally and with depth) and we have demonstrated here that it can affect sediment transport rates. Therefore, it may be wise to evaluate the impacts of having areas with different grain size characteristics on the model performance. Long-term hourly rainfall data may not be available for study catchments especially in remote locations. The sampling of soil and the approach to using particle size distribution data from discrete location for catchment wide assessment and the effect of rainfall variability, is an area for further research to assess the effect on sediment transport rates and landscape morphology.

The SIBERIA model, when calibrated for use with average annual data is considerably quicker in terms of run time. For example, SIBERIA takes approximately 1 h per 1000 years while CAESAR takes approximately 100 h for 1000 years (with both models run using a computer with an AMD 2·4 GHz processor with 2GB RAM). The reason for the time difference is that SIBERIA uses average annual hydrology and sediment transport data while CAESAR uses hourly rainfall data and has a more sophisticated representation of hydraulics and sediment transport, which requires considerably more calculations. CAESAR also calculates the erosion and deposition of each soil size fraction. Consequently, if average annual erosion rates are required then SIBERIA can provide the required output while if sediment transport rates down to the scale of individual storm events is required then CAESAR can provide this data on an hourly output.

## Conclusion

This paper demonstrates that two different landscape evolution models (CAESAR and SIBERIA) can produce quantitatively and qualitatively similar outputs despite having significant differences in their design, process representation, parameterisation and operation. It also shows how the different approaches taken by these two models, one event based and one using longer- term averages, can be complimentary depending upon the research question to be addressed. Interestingly, by comparing two quite different numerical models, this study provides a rigorous test of the metrics often used to calibrate and validate landscape evolution models, such as the area–slope relationship, width function, hypsometric curve as well as erosion rates. The findings imply that the geomorphic metrics used in Figure 6 may be of little use for determining more subtle differences in the geomorphology that may occur over shorter time scales and are useful at longer time scales only. An alternative interpretation is that this provides evidence that smaller, event based fluctuations (that CAESAR models using hourly time steps) leads to the same landscape (as tested by the geomorphic metrics: Figure 6) as that when using average erosion rates (such as that employed in SIBERIA).

This study also provides a good example of how different models may better suit different applications or research questions. For example, if detail on the impact of individual events (e.g. extreme rainfall) is required then CAESAR will provide results with more detail, at the expense of longer run times. Alternatively, if longer time scale, multiple runs are required then SIBERIA may be better suited. However, the user needs to be confident that the model is correctly simulating what is occurring in the modelled system. This confidence arises from a combination of the ease of application and calibration and accuracy of simulated outputs.

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