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TESTING OF THE SIBERIA LANDSCAPE EVOLUTION MODEL USING THE TIN CAMP CREEK, NORTHERN TERRITORY, AUSTRALIA, FIELD CATCHMENT

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ABSTRACT

The SIBERIA landscape evolution model was used to simulate the geomorphic development of the Tin Camp Creek natural catchment over geological time. Measured hydrology, erosion and geomorphic data were used to calibrate the SIBERIA model, which was then used to make independent predictions of the landform geomorphology of the study site. The catchment, located in the Northern Territory, Australia is relatively untouched by Europeans so the hydrological and erosion processes that shaped the area can be assumed to be the same today as they have been in the past, subject to the caveats regarding long-term climate fluctuation. A qualitative, or visual comparison between the natural and simulated catchments indicates that SIBERIA can match hillslope length and hillslope profile of the natural catchments. A comparison of geomorphic and hydrological statistics such as the hypsometric curve, width function, cumulative area distribution and area–slope relationship indicates that SIBERIA can model the geomorphology of the selected Tin Camp Creek catchments. Copyright 2002 © Environmental Research Institute of the Supervising Scientist, Commonwealth of Australia.

KEY WORDS: landscape simulation; SIBERIA; digital elevation model; geomorphology; hydrology

INTRODUCTION

The establishment of stable geometry for the final post-mining landform at the Energy Resources of Australia Ranger Mine (ERARM) in the Northern Territory, Australia requires accurate erosion prediction for up to 1000 years through modelling. The SIBERIA landscape evolution model has been used as a tool for testing rehabilitation proposals for the ERARM after the completion of approximately 30 years of mining (Willgoose and Riley, 1998). Modelling to date has been based on input parameters derived from experimental data from the current ERARM waste rock dump (Willgoose and Riley, 1998; Evans *et al*., 2000; Evans and Willgoose, 2000). Although SIBERIA is able to predict the development of landscapes, few field studies have been performed to prove that the landforms predicted by SIBERIA for the waste rock dump are correct. Validation of the ability of SIBERIA to predict over a range of time scales and landscapes required by ERA's statutory obligation (i.e. up to 1000 years) is necessary.

Research on the waste rock dump at ERARM is limited to existing surfaces that are 5 to 8 years old. In terms of weathering and erosion processes the surfaces are not mature and may not resemble long-term surfaces. To ensure SIBERIA's ability to predict accurately the geomorphic development of the final rehabilitation design of the ERARM, SIBERIA needs to be validated for its ability to simulate natural landscape development over the short (1–10 years), medium (10–1000 years) and long term (>1000 years). Short- and medium-term predictions have been reported elsewhere (Bell JRW. 1997. *Monitoring of gully erosion at ERA Ranger Uranium Mine, Northern Territory, Australia*. Internal Report, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle: Callaghan, NSW; Hancock *et al*., 2000). The testing reported here aims to test SIBERIA predictions over the long term.

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This study forms part of a continuing research programme testing SIBERIA predictions against small-scale laboratory experimental and large-scale natural landscapes over a range of different landforms, geologies and climates. Studies in this programme include: (1) Willgoose (1994) who demonstrated that SIBERIA is able to simulate the development of the Pokolbin catchment; (2) Hancock and Willgoose (2001a) who demonstrated that SIBERIA is able to simulate the development of experimental model landscapes; and (3) Ibbitt *et al.* (1999) who demonstrated that SIBERIA can simulate natural landforms in a tectonically active region in New Zealand.

The ability of SIBERIA to predict over periods greater than 1000 years was examined by testing SIBERIA's ability to simulate the development of a natural landscape (Tin Camp Creek), which has similar geology to the ERARM and was considered to be an analogue for the future geomorphic development of the ERARM (Uren C. 1992. *An investigation of surface geology in the Alligator Rivers Region for possible analogues of uranium mine rehabilitation structures*. Unpublish Internal Report 56, Supervising Scientist for the Alligator Rivers Region: Jabiru, NT).

The SIBERIA landscape evolution model

The SIBERIA model is a physically based mathematical model that simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion and mass transport processes. The SIBERIA model links widely accepted hydrology and erosion models under the action of runoff and erosion over long time-scales. The SIBERIA model is an important tool in the understanding of the interactions between geomorphology and erosion and hydrologic process because of its ability to explore the sensitivity of a system to changes in physical conditions, without many of the difficulties of identification and generalization associated with the heterogeneity encountered in field studies.

The sediment transport equation of SIBERIA is

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

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:

$$q_{sf} = \beta_1 q^{m_1} S^{n_1} \tag{2}$$

where q is the discharge per unit width (m^3 s^{-1} m^{-1} width), S (m^{-1} m^{-1}) the slope in the steepest downslope direction and β_1, m_1 and n_1 are calibrated parameters.

The diffusive term, q_{sd}, is

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

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, rain splash and landsliding.

The SIBERIA model does not directly model runoff (Q, m^3 – for the area draining through a point) but uses a subgrid effective parameterization 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 β_3 is the runoff rate constant and m_3 is the exponent of area, both of which require calibration for the particular field site.

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. A more detailed description of SIBERIA can be found in Willgoose *et al.* (1991a–d).

Methods of comparison between SIBERIA and field observations

One subjective method of comparison is to compare visually a SIBERIA prediction with the observed landform to see if they appear similar. If model results do not look right then the model is likely to be incorrect. However, many landform evolution models give results that appear equally satisfactory to the untrained eye. More objective methods of comparison involve statistical tools. Four quantitative geomorphological descriptors have been shown to be important measures of catchment hydrology and geomorphology (Perera and Willgoose, 1998; Hancock and Willgoose, 2001a; Willgoose and Perera, 2001) and have been used in this study. These are the area–slope relationship, hypsometric curve, width function and cumulative area distribution. The use of these geomorphic statistics in testing landscape evolution models has been discussed elsewhere (Hancock and Willgoose, 2001a).

STUDY SITE

Tin Camp Creek is a natural site in Arnhem Land, Northern Territory, Australia (Figure 1). This site is an important test site for SIBERIA's ability to simulate natural landscapes as it is considered that Tin Camp Creek is one of the few sites worldwide where the management regime has not changed in recent history (the site has not been significantly impacted by European settlement), so the historical hydrology and erosion that shaped the landform reasonably can be assumed to be as today subject to caveats about long-term climate fluctuations. There is some geological heterogeneity over the region. Hydrology and erosion data (Riley SJ. 1994. *Hydrological monitoring of Tin Camp Creek mica and quartz catchments, 1993–94 Wet season.* Internal report 151, Supervising Scientist for the Alligator River Region, Australian Government Publishing

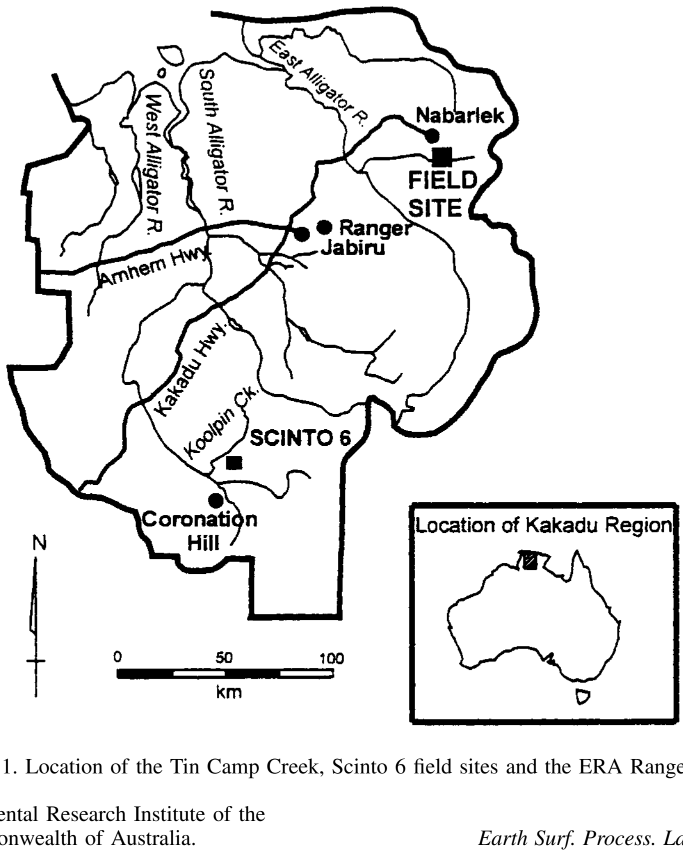

Figure 1. Location of the Tin Camp Creek, Scinto 6 field sites and the ERA Ranger Mine

Service (AGPS): Canberra; Moliere DR. 2000. *Temporal trends in erosion and hydrology characteristics for a post-mining rehabilitated landform at Energy Resources of Australia Ranger Mine, Northern Territory, Australia*. Master of Engineering Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia) have been collected for Tin Camp Creek allowing SIBERIA to be calibrated independently.

Tin Camp Creek digital elevation model

The SIBERIA model simulates an evolving landform by changing elevations defined on a regular grid by simulation of sediment transport downslope and sediment deposition from an upslope direction. Consequently, all landscape data for comparison with SIBERIA are required to be on a grid.

Tin Camp Creek landscape data (X, Y and Z coordinates) were determined by digital photogrammetry by Airesearch Pty Ltd, Darwin, and were supplied as 240 000 irregularly spaced data points within an irregularly shaped boundary. To place the data on to a regular grid, a gridding program was used to interpolate the landscape elevation data on to a 10 m by 10 m grid, producing a data set of approximately 82 000 points. This spacing was equivalent to the average spacing of the original Airesearch data.

Before the gridded elevation data can be analysed for geomorphic and hydrological statistics, artefacts of the gridding process need to be removed. This mainly involves pit removal. Pits within a digital elevation model (DEM) are defined as a single low point, or series of low points, surrounded by points of higher elevation. They are a common feature of gridded DEMs and are the result of (1) errors in the determination of elevations for the landscape surface, and (2) the lowest points in the landform not necessarily falling on grid points. There are numerous computer codes available for the removal of pits from DEMs. In this case the Tarboton *et al*. (Tarboton DG, Bras RL, Rodriguez-Iturbe I. 1989. *The analysis of river basins and channel networks using digital terrain data, TR 326*. Department of Civil and Environmental Engineering, Massachusetts Institute of Technology: Boston) method was used to remove all pits. The pit-filling code can be used on regular gridded data within an irregular boundary.

The entire Tin Camp Creek DEM data could not be modelled with SIBERIA owing to the large number of data points and consequent excessive computer requirements. Furthermore, the landscape also displayed large differences in catchment morphology as a result of spatially varying geology and erosion rates. It was not possible to model the erosionally complex data available for Tin Camp Creek. In order to simplify the modelling of the Tin Camp Creek landscape, smaller, geologically homogeneous catchments from within the data set were isolated and examined.

A series of smaller catchments were extracted from the Tin Camp Creek landscape. These catchments ranged in size from approximately 4 to 50 ha and encompassed a range of different landscape morphology, geology and shape. Examination of mapped geology, field examination of the landscape and examination of area–slope and hypsometric-curve data revealed two catchments with homogeneous geology and sufficiently large drainage networks to be useful test cases. They were also broadly indicative of the larger Tin Camp Creek area. Catchment 1 (C1) and Catchment 2 (C2) (Figures 2 and 3) contained within it the Mica and Quartz field sites, respectively, for which hydrology and erosion data had been collected (Riley SJ. 1994. *Hydrological monitoring of Tin Camp Creek mica and quartz catchments*. Internal report 151, Supervising Scientist for the Alligator River Region, AGPS: Canberra; Moliere DR. 2000. *Temporal trends in erosion and hydrology characteristics for a post-mining rehabilitated landform at Energy Resources of Australia Ranger Mine, Northern Territory, Australia*. Master of Engineering Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia). Catchments C1 and C2 were 50·9 and 23·5 hares respectively. Catchment C1 was roughly rectangular whereas C2 was roughly triangular.

CALIBRATION OF SIBERIA INPUT PARAMETERS

Before SIBERIA can be used to simulate landscape development, the sediment transport equation (Equation 1) and area–discharge relationship (Equation 4) require independent calibration. Calibration of the sediment transport equation can be performed by two methods. The first method requires the collection of hydrological and sediment transport data from study sites and calibrating the SIBERIA sediment transport equation from

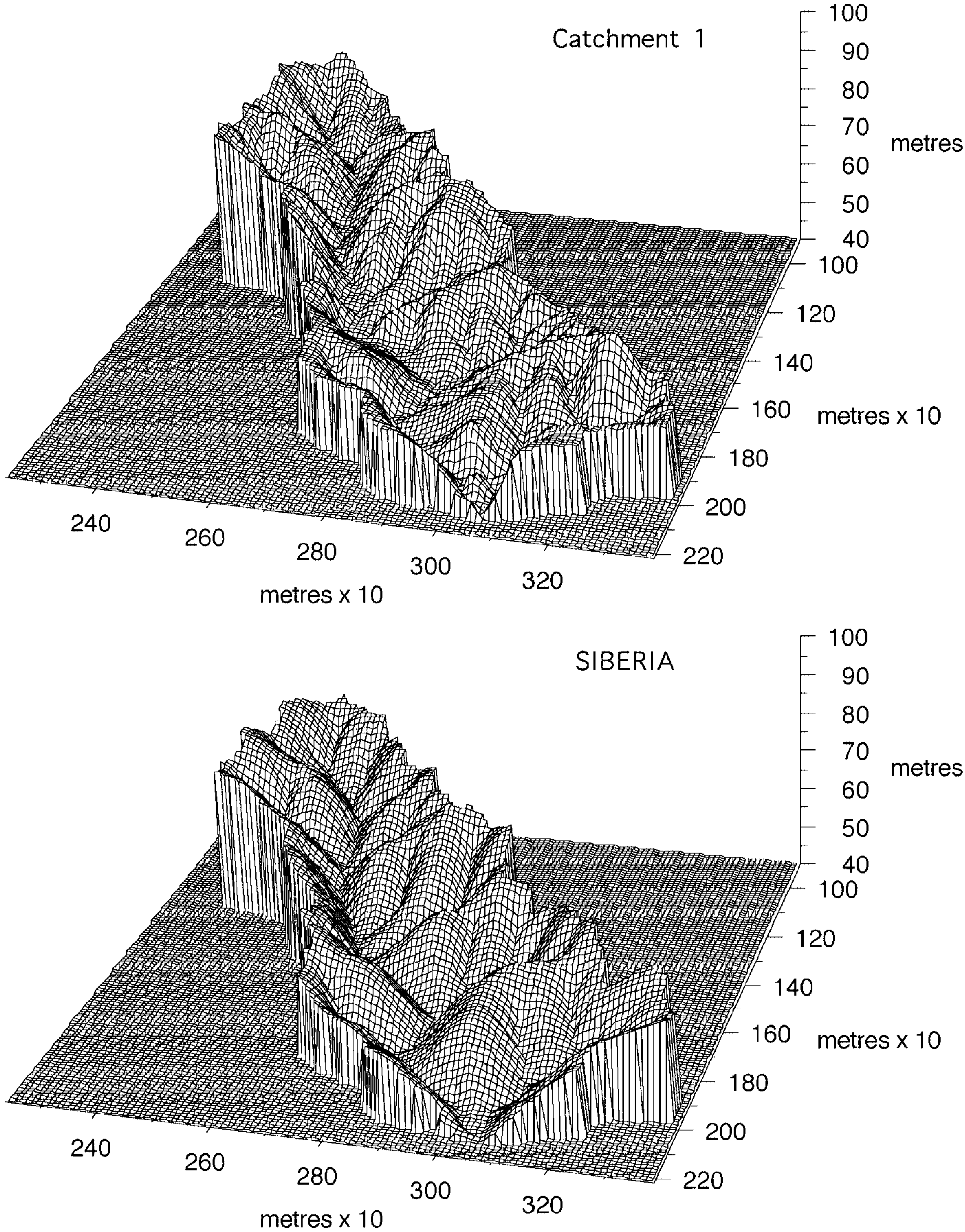

Figure 2. Catchment 1 (C1) and SIBERIA simulation of C1, Tin Camp Creek, Northern Territory Australia

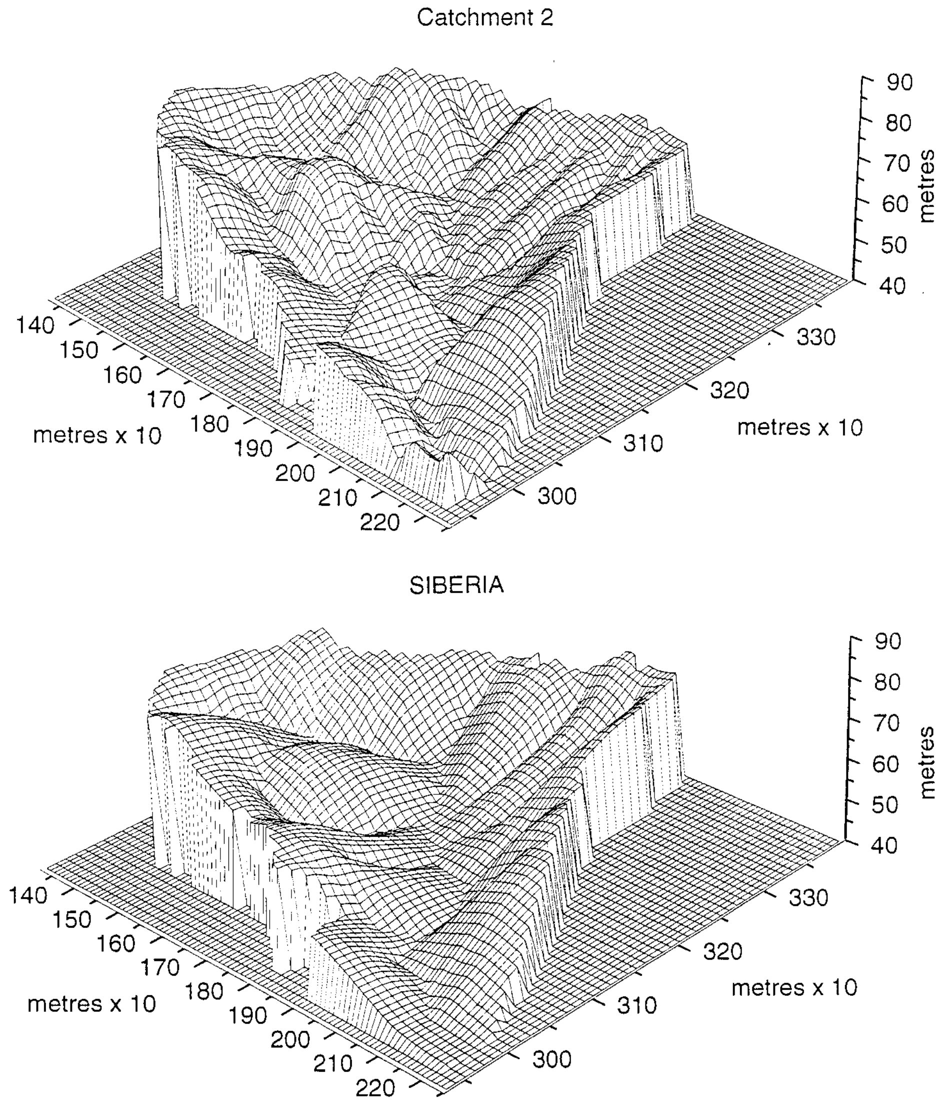

Figure 3. Catchment 2 (C2) and SIBERIA simulation of C2, Tin Camp Creek, Northern Territory Australia

these data. This method has been described in detail by Willgoose and Riley (1993. *Application of a catchment evolution model to the prediction of long-term erosion on the spoil heap at Ranger Uranium Mine*. Open File Report 107, The Office of the Supervising Scientist: Jabiru, NT) and Evans and Willgoose (2000). The second method is determination of parameter values through inference from DEMs. In this study the parameter values were determined using the second method.

Inferring SIBERIA parameters from DEMs

The area–slope relationship of a catchment is the relationship between area draining through a point versus the slope at that point (Figure 4). If the site is close to equilibrium then the catchment will comply with the log–log area–slope relationship discussed in Willgoose (1994).

Willgoose (1994) demonstrated that the slope of the fluvial section of the area–slope relationship (α) is

$$\alpha = (m_3 m_1 - 1)/n_1 \tag{5}$$

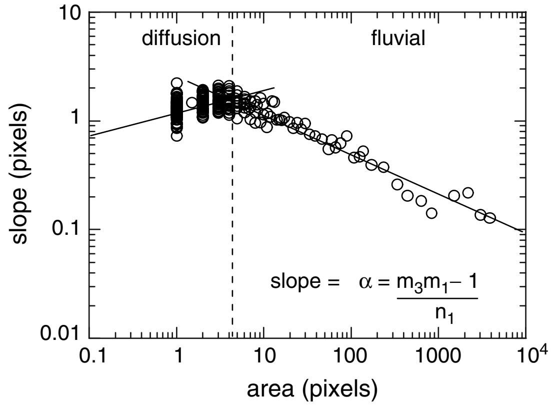

Figure 4. Area–slope relationship for C1, Tin Camp Creek

where m_3 is the exponent of discharge draining through a point in Equation 4 and m_1 and n_1 are exponents in the SIBERIA sediment transport (Equation 2, Figure 4).

Using an α value of 0·42 for the fluvial region of the area–slope relationship (fitted from the Tin Camp Creek DEM) for C1 only, and an assumed value of $n_1 = 2{\cdot}1$ for wide channel flow (Willgoose *et al.*, 1991a–d), and a value for m_3 of 1, the value for m_1 is 2·0. The value of $n_1 = 2{\cdot}1$ also is very close to the value of $n_1 = 2$ suggested by Henderson (1966). The values of m_1 and n_1 also are within the range of values for field catchments suggested by Kirkby (1971). The value of α of 0·42 is within the range found by Tarboton et al. (1989) for natural catchments. Moliere (2000, *Temporal trends in erosion and hydrology characteristics for a post-mining rehabilitated landform at Energy Resources of Australia Ranger Mine, Northern Territory, Australia*. Master of Engineering Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia) derived α values of $\alpha = 0{\cdot}47$ and 0·57 for Tin Camp Creek based on observed data of Riley (1994. *Hydrological monitoring of Tin Camp Creek mica and quartz catchments*. Internal report 151, Supervising Scientist for the Alligator River Region, AGPS: Canberra). The value of 0·47 for the hydrology and erosion data is consistent with the inferred value for α for Tin Camp Creek. To test the sensitivity of the simulated landscape to variation in the value of m_1, simulations were also run using values of $m_1 = 1{\cdot}8$ and 2·2 (corresponding to $\alpha = 0{\cdot}38$ and 0·57).

A further series of simulations were also conducted using very different erosion parameters to the Tin Camp Creek data. Erosion parameters determined by field monitoring from the Scinto 6 (Figure 1) former uranium mine were used (Hancock *et al.*, 2000). The values of $m_1 = 1{\cdot}68$, $n_1 = 0{\cdot}69$, and $m_3 = 0{\cdot}88$ ($\alpha = 0{\cdot}69$) for Scinto 6 are very similar to other erosion parameters determined for mined landscapes in the Northern Territory (Evans *et al.*, 2000; Evans and Willgoose, 2000). The literature suggests that the value of n_1 may be closer to 1 than what we have found in this study (Prosser and Rustomji, 2000) and these values are used to test the sensitivity of our results.

As it is extremely difficult to quantify the ability of rain splash to erode a surface, the diffusivity parameter D (Equation 3) was fitted by trial and error to C1 only. By fitting the slope of the diffusive dominated area of C1 a value for D of 0·03 was obtained, where length units are metres and time units are years. The validity of this value as a regional diffusivity parameter was tested using SIBERIA to model gully development at the Scinto 6 mine site located 180 km south-west of Tin Camp Creek (Figure 1) (Hancock *et al.*, 2000). The value of D, once corrected for the DEM grid spacing at Scinto 6 (0·5 m), demonstrated that this value can reliably predict diffusive erosion processes over a 50 year erosional history. To test the sensitivity of the Tin Camp Creek simulated landscape to variation in D, simulations were also run with values of $D = 0$ and 0·1.

Both C1 and C2 had similar area–slope relationships for large areas, which indicates that the ratio of $(m_3m_1 - 1)/n_1$ and the D value are the same for both catchments. This suggests that the fluvial and diffusive erosion physics are the same for both catchments. Therefore, parameters $m_1 = 2{\cdot}0$, $n_1 = 2{\cdot}1$ and $D = 0{\cdot}03$

were then used in an independent validation for C2. Catchment C2 therefore provides an independent validation of the SIBERIA erosion parameters derived using C1.

The determination of an exact value of β_1, or rate constant for the fluvial component of Equation 2, was not important for the SIBERIA simulation of the Tin Camp Creek landscape as the aim of this simulation was to demonstrate that SIBERIA could model the long-term landscape evolution. The value of β_1 only affects the rate at which landscapes evolve to equilibrium, not the shape once they have reached equilibrium (Willgoose, 1994). Owing to the limited data available from the Mica and Quartz sites, a β_1 value was unable to be determined. A β_1 value ($\beta_1 = 0{\cdot}05$) was used, which allowed the SIBERIA simulations to be completed in a minimum of computer time. As β_1 could not be derived, SIBERIA's ability to model the rate of landform evolution could not be tested for Tin Camp Creek.

RESULTS AND DISCUSSION

Initial conditions for SIBERIA simulations

The Tin Camp Creek area in Arnhem Land is presently tectonically inactive, or a stable area. Examination of the geology of the Tin Camp Creek area reveals a complex faulted landscape with spatially varying rock types. Catchments C1 and C2 were part of an area that was block uplifted around 1 000 000 to 2 000 000 years before present (Needham, 1988). To simulate the original Tin Camp Creek landscape for use as an initial condition for SIBERIA simulations this block uplift was modelled.

Initial conditions for the Tin Camp Creek landscape simulation were produced by using the C1 and C2 elevations, reducing the elevation differences (elevation minus the catchment outlet elevation) by two orders of magnitude (division by 100) and instantaneously uplifting the elevation data to the maximum height of the current catchment elevations. This procedure simulates the uplift event that occurred in the natural landscape. To create an outlet, a single node at the position of the present outlet was lowered to the value of the current outlet elevation value. This procedure has been used elsewhere (Ibbitt *et al*., 2000) and has the side-effect of conditioning the simulated drainage pattern to that currently occurring.

Reducing the elevations and uplifting provides a drainage network on the surface. Morisawa (1964), Parker (1977). *Experimental study of basin evolution and its hydrologic implications*. Unpublished PhD dissertation, Colorado State University: Fort Collins, CO and Hancock and Willgoose (2001a,b) have demonstrated that in the case of a single uplift event the present drainage network is representative of the original drainage network and that once a drainage network has developed it remains locked in place. Therefore, the current observed drainage network is likely to be representative of the original drainage network immediately after the block uplift. It is recognized that this method of construction for initial conditions is a simplistic realization of landscape history and it is unlikely that climate and vegetational history of the catchments have remained constant over geological time. Nevertheless this method provides the only method available for initial condition construction. Both C1 and C2 initial conditions were produced by this method.

SIBERIA simulations and comparison with observed catchments

The SIBERIA model simulations of C1 and C2 were run using the values of m_1, n_1 and D calibrated on C1 alone (previous section), and the initial catchments described in the previous sub-section. The simulations were continued until the total volume of the simulated landscape matched that of the field catchments and the hypsometric curve from SIBERIA simulations had reached a mature form (Strahler, 1952). Simulations were also run using $m_1 = 1{\cdot}8$ and $2{\cdot}2$ ($\alpha = 0{\cdot}38$ and $0{\cdot}57$) and $m_1 = 1{\cdot}68$, $n_1 = 0{\cdot}69$ and $m_3 = 0{\cdot}88$ ($\alpha = 0{\cdot}69$) as sensitivity studies.

Area–slope relationship. Comparison of C1 and C2 area–slope relationships with that of the SIBERIA simulations of C1 and C2 indicates that SIBERIA is able to closely match the natural catchment area–slope relationship using calibrated erosion parameters (Figures 5 and 6). This is to be expected as the SIBERIA erosion parameters have been derived from C1. However the good match for C2 is an independent test of the ability to match the area–slope relationship for the catchments.

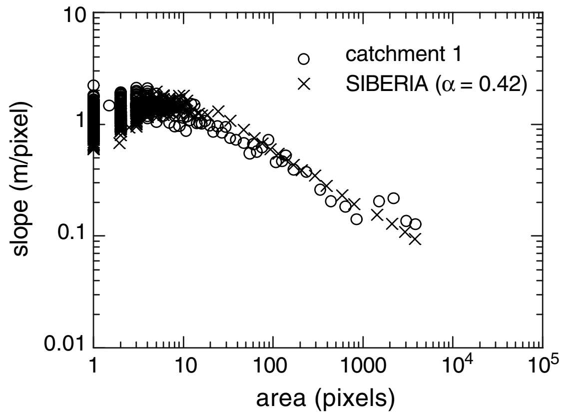

Figure 5. Fit of the area–slope relationship for C1 and SIBERIA simulation of C1

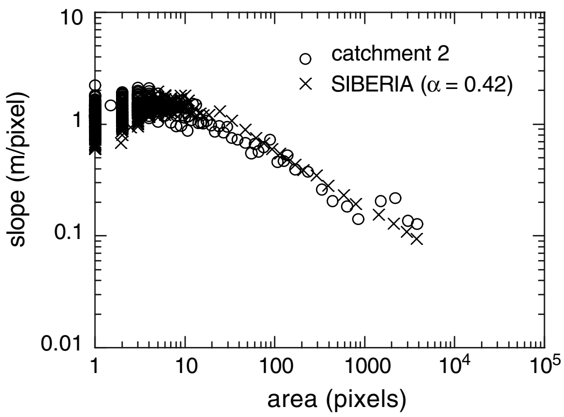

Figure 6. Prediction of the area–slope relationship for C2 and SIBERIA simulation of C2

Key characteristics reflecting a good match are:

(1) the gradient of the log–log linear right-hand part of the curve (this gradient reflects correct choice of fluvial erosion physics in the model);
(2) the area at which the data changes from a positive to negative slope at around area 10 (this reflects a good match of the relative magnitude of diffusive and fluvial erosion processes). (The area of 10 matches with the area of 10 in the cumulative area distribution, again reflecting the change from diffusive to fluvial dominance (discussed later, Figures 15 and 16).

The sensitivity study using values of $\alpha = 0{\cdot}38$, $0{\cdot}57$ and $0{\cdot}69$ demonstrates that the correct erosion parameter values are necessary for SIBERIA to match the observed area–slope data (Figures 7 and 8). Although the simulated data appear to be visually very close to each other, the slope of the simulated data matches the value of α used in the simulations. As expected, the simulations using $\alpha = 0{\cdot}38$ produce area–slope data that are less steep than the calibrated data, whereas the simulations using $\alpha = 0{\cdot}69$ produce data that are considerably steeper. Also, using a value of $D = 0$ produced an area–slope relationship that was log–log linear for its entirety, whereas a value of $D = 0{\cdot}1$ extended the diffusive region of the area–slope relationship to around 20 pixels, providing a poor match to the catchment data (Figure 9).

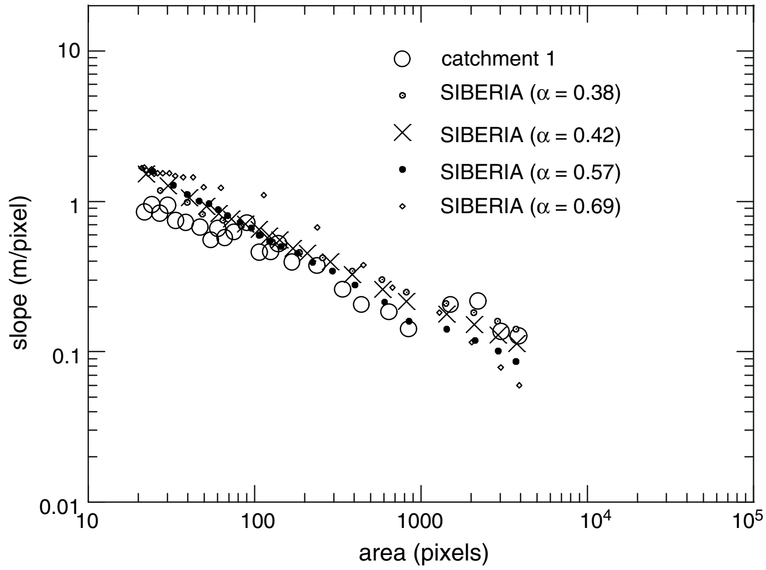

Figure 7. Sensitivity study using different values of α for C1. For clarity, only the fluvial component of the relationship is displayed

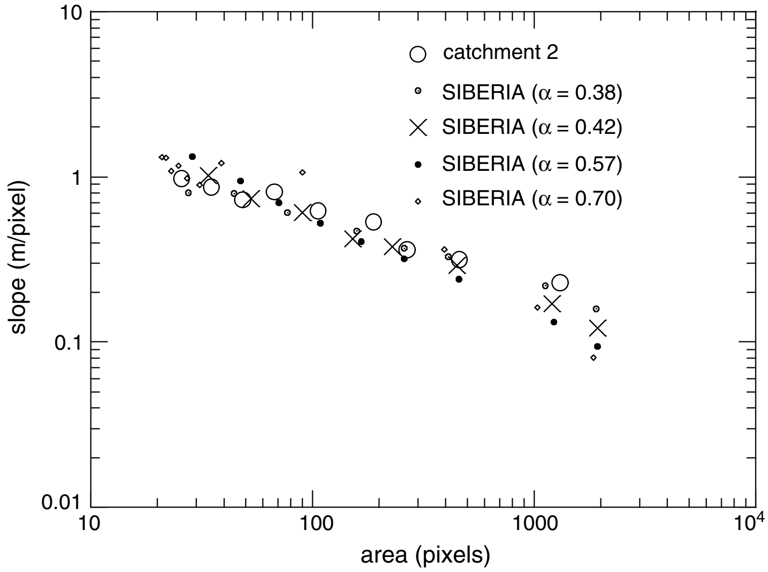

Figure 8. Sensitivity study using different values of α for C2. For clarity, only the fluvial component of the relationship is displayed

Although matching the area–slope relationship is not a strong test of SIBERIA, as it was used in calibration, it demonstrates that SIBERIA can reproduce the area–slope relationship from which the erosion equation was calibrated for different catchment geometries.

Hypsometric curve. The hypsometric curves generated by SIBERIA using calibrated erosion parameters match those for C1 and C2 (Figures 10 and 11). Both C1 and C2, and the simulations display hypsometric curves similar to Strahler's mature landscape. Both data are typical of a fluvially dominated catchment of roughly equal width and length (Willgoose and Hancock, 1998). Of particular note is that the concave-down region on the right-hand side (the toe) is well matched, which indicates that the networking characteristics of the landscapes are well matched.

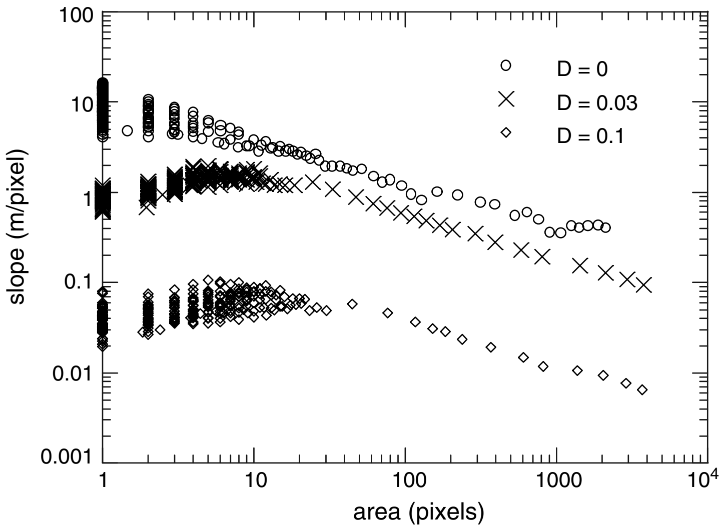

Figure 9. Effect of different diffusivity parameter D values on the area–slope relationship for C1. For clarity, slope (m pixel^{-1}) for $D = 0$ has been multiplied by 10, whereas slope (m pixel^{-1}) for $D = 0{\cdot}1$ has been divided by 10

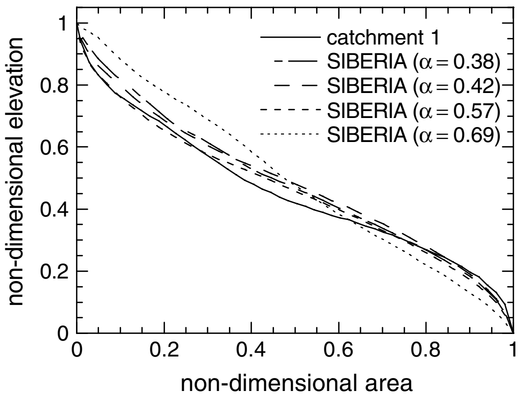

Figure 10. Fit of hypsometric curves for C1 and SIBERIA simulation of C1

The simulations using $\alpha = 0{\cdot}38$, $0{\cdot}42$ and $0{\cdot}57$ are very similar yet the simulations using $\alpha = 0{\cdot}69$ demonstrates the importance of correct erosion parameters for a match of the hypsometric curve to be obtained. Willgoose and Hancock (1998) demonstrated that the hypsometric curve is a sensitive indicator of drainage networks. They showed that different hypsometric curves will result with different values of α and that the hypsometric curve for a two-dimensional catchment is also dependent on n_1 and the planar geometry, not just the ratio of $(m_3 m_1 - 1)/n_1$. The variation of diffusivity parameter D also had an effect on the hypsometric curve (Willgoose and Hancock, 1998). No diffusion ($D = 0$) produced a curve that was very much higher than the fitted value whereas a higher diffusion value ($D = 0{\cdot}1$) produced a curve very much lower (Figure 12). This demonstrates that correct diffusivity is required for a match of the hypsometric curve.

These results demonstrate that SIBERIA is able to generate hypsometric curves that are qualitatively and quantitatively similar to the observed catchments. Willgoose and Hancock (1998) showed that the hypsometric curve is determined by the area–slope relationship and channel networking characterization. With the good match for the area–slope in the previous section, the close comparison here confirms a good match for the channel networking properties.

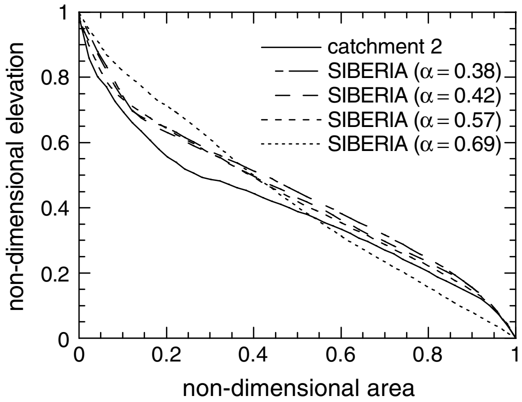

Figure 11. Prediction of hypsometric curves for C2 and SIBERIA simulation of C2

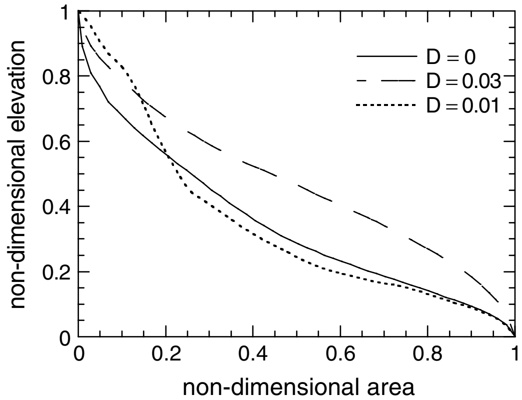

Figure 12. Effect of different diffusivity parameter D values on the hypsometric curve for C1

The width function. The width function, developed originally by Surkan (1968), is a plot of the number of channels at a given distance from the basin outlet, measured along the network (Naden, 1992). The width functions from C1 and C2 match those for the SIBERIA simulations using the calibrated erosion parameters (Figures 13 and 14) demonstrating that SIBERIA is able to match the distribution of flow networks in the natural catchment. It should be noted that the length and maximum width of the width function are almost identical and that the detail of the changes in width are also well matched. Some of this good match is in no doubt due to the fixed shape of the catchment (Rigon *et al*., 1993), but it nevertheless confirms that the model is satisfactory.

The simulated data ($\alpha = 0{\cdot}38$, 0·57 and 0·68) produces width functions that are slightly out of phase with the observed field data, with the peaks and troughs of the simulated data occurring slightly prior to the field data (Figures 13 and 14). The SIBERIA model produces a smoother landscape surface with slightly shorter flow paths than the field data, which have measurement errors inherent in the elevation data that increase flow-path length. The slightly smoother surface of the simulated landscape consequently produces a slightly shorter width function than the field catchments. This result is typical of other comparisons between field data and experimental data and simulated landscapes (Moglen and Bras 1995a,b; Hancock and Willgoose, 2001a).

There is little observed difference between width functions using $\alpha = 0{\cdot}38$ and 0·57 but there appears to be some deviation for $\alpha = 0{\cdot}69$, with the simulations of C1 and C2 both producing a shorter (in terms of

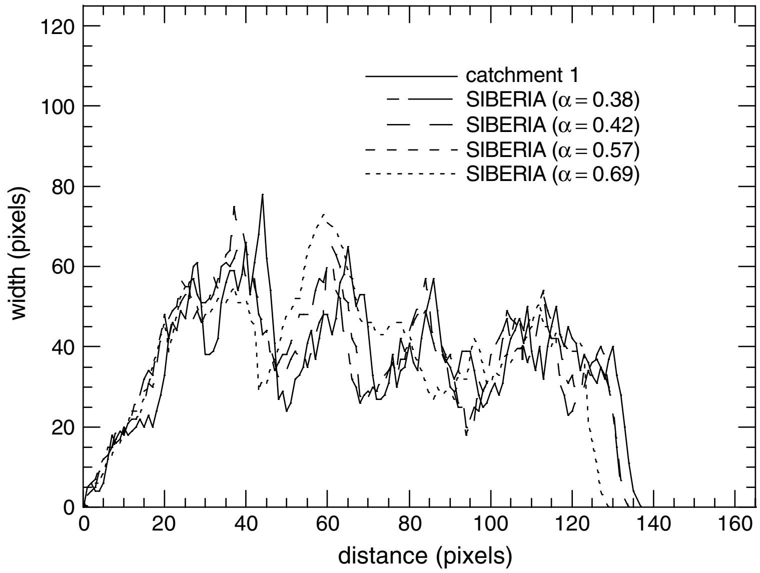

Figure 13. Fit of the width function for C1 and SIBERIA simulation of C1

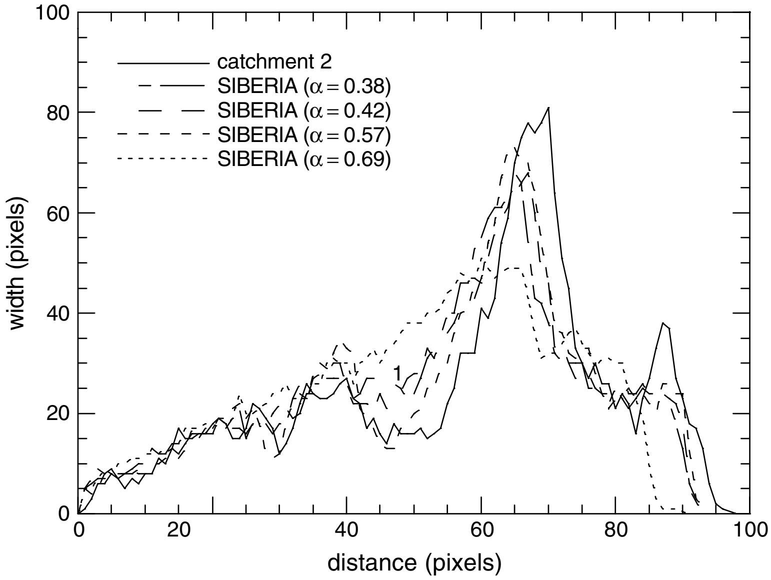

Figure 14. Prediction of the width function for C2 and SIBERIA simulation of C2

distance) and less tall (in terms of width) curve from the other simulations. At the present time we do not have the ability to determine whether this variation from the field data is statistically significant but this issue is currently being investigated (Hancock and Willgoose, 1999). The variation of diffusivity parameter D had little effect on the width function.

Consequently, the width function appears to be an insensitive indicator of catchment topography. As found by Moglen and Bras (1995a,b), the simulated systems examined all have observably different drainage patterns, yet the means and maxima of the width functions do not vary considerably. The shape of the width function appears to be constrained by catchment shape, and as the boundaries are fixed, the width functions are heavily constrained and similar (Rigon *et al*., 1993). The width function is thus a relatively weak comparison test.

It has long been recognized that the width function is a good measure of hydrologic response because it can be strongly correlated with the instantaneous unit hydrograph. If it is assumed that rainfall excess is routed with a constant velocity, then the width function can be linearly transformed into the instantaneous unit hydrograph. The result indicates that SIBERIA simulated catchments provide a good match to the observed catchments hydrology.

Cumulative area distribution. 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. The cumulative area distribution describes the spatial distribution of areas and drainage network aggregation properties within a catchment (Rodriguez *et al*., 1992; LaBarbera and Roth, 1994). The cumulative area distributions for the SIBERIA simulations and C1 and C2 match (Figures 15 and 16).

Important features of the match are:

(1) the intercept on the y axis – this tells us that we have matched the upstream part of the network and the number of runoff sources in the catchment;
(2) shape of the downward concave section of the left-hand section of the curve – this indicates that the drainage pattern on the hillslope is satisfactory;

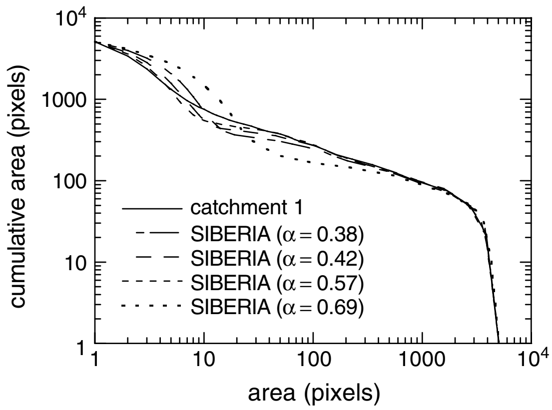

Figure 15. Fit of the cumulative area distribution for C1 and SIBERIA simulation of C1

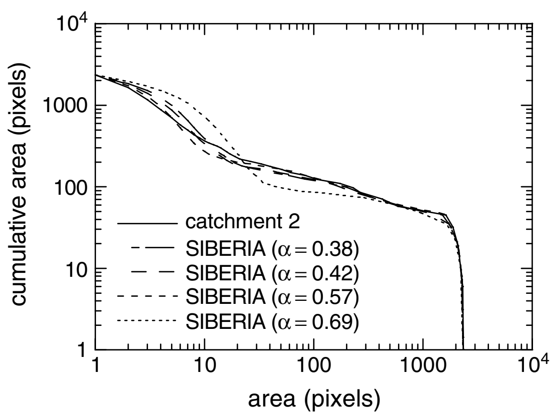

Figure 16. Prediction of the cumulative area distribution for C2 and SIBERIA simulation of C2

(3) the central linear component of the curve – this indicates that we have matched the tributary characteristics of the drainage network correctly.

The only part of the curve not well matched is that part around area equal to 10 pixels, which is the transition region between the hillslope and the valleys. Perera and Willgoose (1998) suggested poor matches in this region may reflect a lack of randomness in the size of valleys. Using a value of $D = 0$ produces a cumulative area distribution that is log–log linear with no diffusion dominated region at areas less than 10 pixels. Similar to the area–slope relationship, a value of $D = 0{\cdot}1$ extended the diffusive region of the cumulative area distribution to around 20 pixels, providing a poor match to the catchment data (Figure 17).

Subtle differences are observed between the simulations using $\alpha = 0{\cdot}38$, 0·57 and 0·68, with the transition between diffusion and fluvial dominated areas of the catchment occurring at smaller areas as α increases. Hancock and Willgoose (2001a) demonstrated that the cumulative area distribution is sensitive to changes in the value of α. In this case, however, the sensitivity study values of 0·38 and 0·57 are too close to the calibrated values of 0·42 (derived from the area–slope relationship) and 0·47 (derived from the hydrology data) for any strong differences to be observed. A distinct difference occurs for the simulations using $\alpha = 0{\cdot}69$ with a poor match observed between the diffusion and fluvial dominated areas of the curve indicating that correct erosion parameters are needed for a good match with the cumulative area distribution. We currently lack the ability to test for statistically significant differences between the simulations and field data (Hancock and Willgoose, 1999).

The cumulative area distribution is independent of the calibration process but may be influenced by the fixed boundary conditions and the imposed initial drainage network used in this study. Nevertheless we have demonstrated that the cumulative area distribution is sensitive to differences in both the erosion parameters and diffusivity value D, consequently we believe that the cumulative area distribution is a strong test of SIBERIA's ability to simulate the field catchments.

Visual comparison. Visual comparison of C1 and C2 with the SIBERIA simulations demonstrates that not only does SIBERIA successfully match the geomorphological and hydrological descriptors of C1 and C2 but it provides a good qualitative match as well (Figures 2 and 3). Although the simulation produces hillslopes and channels in slightly different positions compared with the natural catchments (that the main drainage lines correspond even approximately reflects the initial condition), SIBERIA is able to closely simulate the overall catchment shape, including hillslope length and convexity. In both cases SIBERIA produces catchments that are slightly smoother than observed. This suggests that our diffusivity value is marginally too high.

The simulations using $\alpha = 0{\cdot}38$, 0·57 and 0·69 provided a poor visual match with the observed natural data and are not displayed. The simulation using $m_1 = 1{\cdot}8$ ($\alpha = 0{\cdot}38$) produced a landscape that was insufficiently incised to visually match the Tin Camp Creek catchments, whereas the simulations using $m_1 = 2{\cdot}2$ ($\alpha = 0{\cdot}57$) produced highly incised landscapes, which also were a poor visual match. The poorer match by these

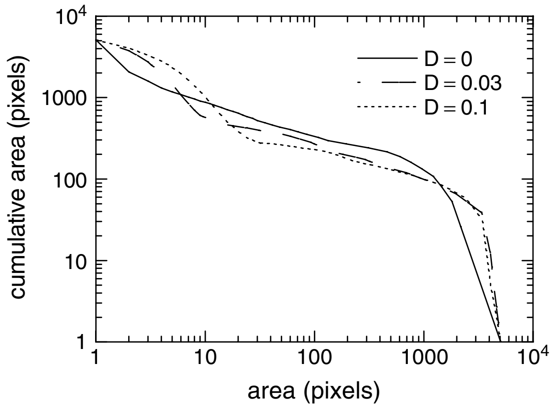

Figure 17. Effect of diffusivity parameter D on the cumulative area distribution for C1

parameters confirms that the model is sensitive to the effect of changing α and that visual comparison is a good test of SIBERIA's ability to simulate the field catchments.

The sensitivity of the simulated catchments to the diffusivity parameter is demonstrated in the SIBERIA simulations for C1 with no diffusion ($D = 0$, Figure 18) and with diffusion approximately three times the

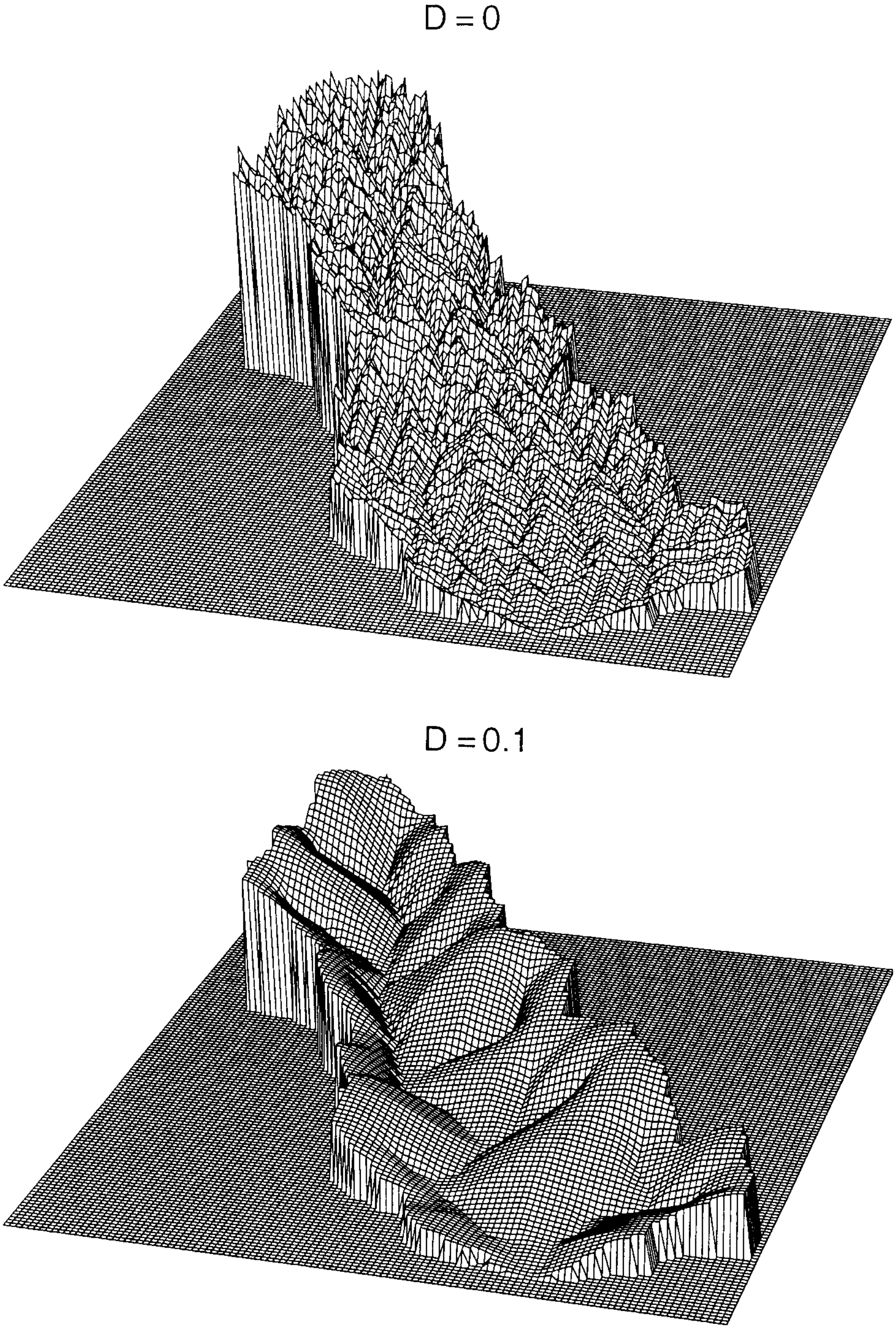

Figure 18. The SIBERIA model simulation for C1 with differing diffusivity

calibrated value ($D = 0{\cdot}1$, Figure 18). No diffusion produces a landscape that has an angular or jagged surface that is dominated by fluvial processes and with short hillslopes (the concave down regions). Increased diffusivity produces a landscape surface that is very smooth compared with the observed landscape and has much longer hillslopes. These results demonstrate the importance of the determination of an accurate diffusivity. Simulations for C2 using varying diffusion have the same effect.

CONCLUSION

The close match of the hypsometric curve, width function, cumulative area distribution and area–slope relationship between the Tin Camp Creek catchments and SIBERIA simulations of these catchments indicates that using the erosion parameters derived from the area–slope relationship and the assumed initial conditions, SIBERIA can match the geomorphology and erosion characteristics of these catchments. The simulated area–slope relationship is consistent with measured hydrology and erosion physics of the catchment (Moliere DR. 2000. *Temporal trends in erosion and hydrology characteristics for a post-mining rehabilitated landform at Energy Resources of Australia Ranger Mine, Northern Territory, Australia*. Master of Engineering Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia).

Using incorrect erosion parameters produces strong differences in the hypsometric curve, area–slope relationship and cumulative area distribution, indicating that calibrated erosion parameters are necessary. We currently do not have the ability to be able to test statistically whether the width function using the Scinto 6 parameters is different from the calibrated data and we are currently developing methods to address this deficiency (Hancock and Willgoose, 1999). The close qualitative match between the natural catchments and SIBERIA simulations provides confidence in the quantitative match. The results confirm SIBERIA's ability to simulate the long-term development of the catchments examined at Tin Camp Creek.

It has been demonstrated that given the erosion and hydrology data, SIBERIA erosion parameters can be calibrated independently for the site (Evans and Willgoose, 2000). Calibration of SIBERIA using the area–slope relationship provides an alternative method. This method has shown that given a catchment that is geologically and climatically homogeneous over its area with no change in land management practices, the area–slope relationship can provide a simple and effective method of determining erosion parameters. Although, field data are required to determine rate of erosion.

With further field data, a value for the fluvial erosion rate β_1 would be able to be determined. This would aid in the assessment of SIBERIA's ability to predict incision into a tailings cap at ERARM, for example. The determination of a rate constant was not considered essential for the SIBERIA simulation of the Tin Camp Creek landscape as the aim of this simulation was to demonstrate that SIBERIA could model the long-term landscape evolution. We recognize that the value of D/β_1 is important and a value was used that allowed the SIBERIA simulations to be completed to equilibrium in a minimum of computer time. There also is the difficulty of knowing the exact age of the Tin Camp Creek catchments and the initial conditions from which landscape development commenced. In this case we have assumed that the starting conditions were simply block uplifted catchments. We also recognize that the use of a block uplift as the initial conditions is simplistic and that the summits are likely to have been significantly lowered since uplift, but we do not have any other way of generating initial conditions given our present knowledge of the area.

Further work also is needed to determine diffusivity parameters. This study has demonstrated that correct values are required for both qualitative and quantitative matches to be obtained. The SIBERIA model simulations of the Scinto 6 former mine site demonstrate that the value of D used at Tin Camp Creek, when corrected for grid size, can be applied to a site 180 km away that is geologically and climatically similar to Tin Camp Creek (Hancock *et al*., 2000). It may be possible that diffusive erosion is a regional process as a result of rainfall type, frequency, intensity and ground cover.

We believe that area–slope relationship, hypsometric curve, width function and cumulative area distribution are the only defensible tools available at the present time for this type of analysis (Hancock and Willgoose, 2001a). We also recognize that the distribution of areas within the catchment is likely to be linked to the initial conditions and that the channel network is largely constrained by the fixed boundary and that the area–slope relationship is linked to the hypsometric curve. Consequently the methodological approach used in this paper is not a validation of SIBERIA in the strictest sense (Kirchner *et al*., 1996).

Although the sensitivity study investigated the effect of changing α values on the SIBERIA simulations, the ability of the area–slope relationship, hypsometric curve, width function and cumulative area distribution to be used as tools of calibration and comparison requires further study. The variability in the area–slope relationship, hypsometric curve, width function and cumulative area distribution is currently being investigated with a Monte Carlo analysis of the Tin Camp Creek catchment initial conditions (Hancock and Willgoose, 1999). The effect of different boundary conditions is currently being investigated by changing catchment aspect ratio.

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