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Medium-term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model

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Abstract

This study forms part of a collaborative project designed to validate the long-term erosion predictions of the SIBERIA landform evolution model on rehabilitated mine sites. The SIBERIA catchment evolution model can simulate the evolution of landforms resulting from runoff and erosion over many years. SIBERIA needs to be calibrated before evaluating whether it correctly models the observed evolution of rehabilitated mine landforms. A field study to collect data to calibrate SIBERIA was conducted at the abandoned Scinto 6 uranium mine located in the Kakadu Region, Northern Territory, Australia. The data were used to fit parameter values to a sediment loss model and a rainfall–runoff model. The derived runoff and erosion model parameter values were used in SIBERIA to simulate 50 years of erosion by concentrated flow on the batters of the abandoned site. The SIBERIA runs correctly simulated the geomorphic development of the gullies on the man-made batters of the waste rock dump. The observed gully position, depth, volume, and morphology on the waste rock dump were quantitatively compared with the SIBERIA simulations. The close similarities between the observed and simulated gully features indicate that SIBERIA can accurately predict the rate of gully development on a man-made post-mining landscape over periods of up to 50 years. SIBERIA is an appropriate model for assessment of erosional stability of rehabilitated mine sites over time spans of around 50 years.

Additional keywords: landscape simulation, mine rehabilitation.

Introduction

The SIBERIA landscape evolution model has been used as a tool for assessing the impact of erosion rehabilitation proposals for the Energy Resources of Australia (ERA) Ranger Mine after the completion of mining (Willgoose and Riley 1993*a*, 1993*b*; Evans 1997; Willgoose and Riley 1998). To date, modelling has been based on parameters derived from experimental data from the current ERA Ranger Mine waste rock dump. This study was performed to test 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, Fox *et al*. 1977) is necessary. This study is one of a number of experiments carried out by the collaborators to test SIBERIA predictions.

Research on the waste rock dump at ERA Ranger Mine is limited to existing surfaces that are 5–8 years old. In terms of weathering and erosion processes the surfaces are not mature and may not resemble the long-term surface. To ensure SIBERIA's ability to accurately predict the geomorphic development of the final rehabilitation design for the

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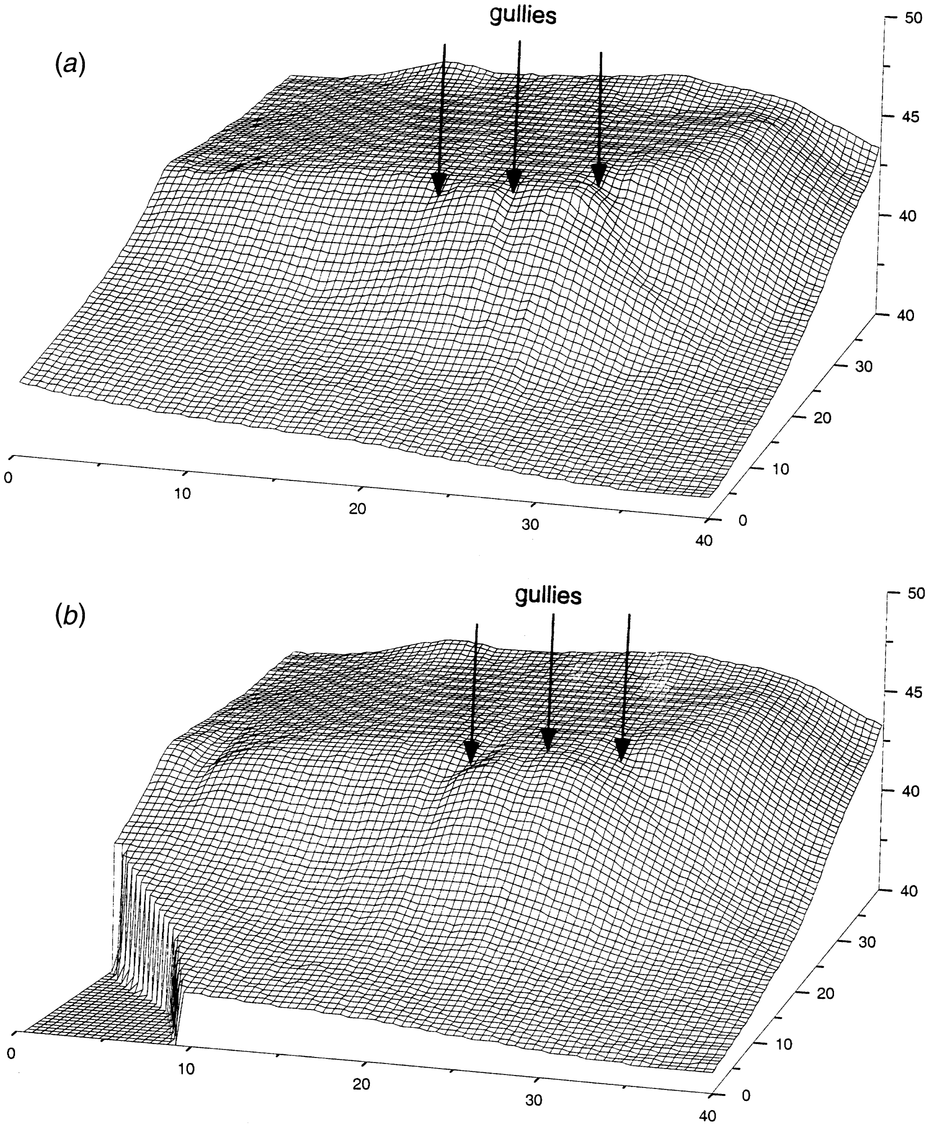

Fig. 1. (*a*) Digital terrain map of the Scinto 6 waste rock dump. (*b*) SIBERIA simulation of gullies at the Scinto 6 waste rock dump (this figure should be compared with (*a*)). All dimensions are in metres. The corner of the digital terrain map was not part of the waste rock dump and has been removed to increase the speed of the simulation.

ERA Ranger Mine, SIBERIA needs to be validated for its ability to simulate landscape development under natural processes over longer time spans.

The abandoned Scinto 6 mine in the Northern Territory, Australia, offers an opportunity to test SIBERIA. The mine has a flat-topped waste rock dump (Fig. 1) contributing water to the steep surrounding batters, and mimics the main features of one of the proposed water-shedding rehabilitation designs for the ERA Ranger Mine (Unger *et al.* 1996). Willgoose and Riley (1993*a*, 1993*b*, 1998) and Evans (1997) highlighted

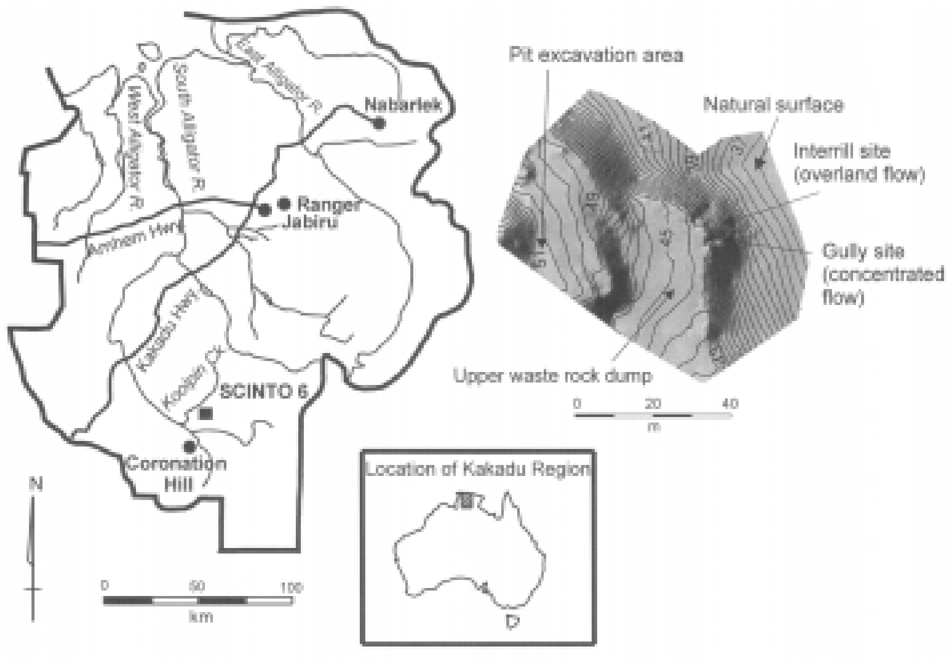

Fig. 2. Location of the Scinto 6 mine site.

this as a problem for the above-grade rehabilitation plan because of the gullies that form at the change in slope between the low-gradient upper cap surface and the high-gradient batter slopes. Qualitatively, erosion features at Scinto 6 are similar to those predicted at ERA Ranger Mine by SIBERIA. This study provided quantitative data to test the model's ability to simulate these erosional features over the medium-term (approximately 50 years).

Further studies have been conducted to test SIBERIA's ability to predict landform development over the short term (i.e. one wet season) and geological time (Hancock *et al.* 1999), and also within a controlled laboratory setting (Hancock 1997). This paper focuses only on medium-term landscape development at the Scinto 6 mine.

Study site

Scinto 6 is an abandoned open cut Uranium mine in the South Alligator River Valley in the Northern Territory, Australia (Fig. 2). Mining ceased at Scinto 6 approximately 50 years ago (P Waggitt, Environmental Research Institute of the Supervising Scientist, pers. comm.). The mine excavation was 50 m by 25 m by 20 m deep, and waste rock was dumped adjacent to the entrance of the excavation resulting in a flat-topped waste rock dump with angle-of-repose batters (Fig. 2). The site has been undisturbed since mining ceased. The waste rock comprises Precambrian volcanics (Crick *et al.* 1980). The area receives high-intensity storms and rain depressions between October and April (wet season) with little rain falling during the remainder of the year (dry season) (McQuade *et al.* 1996). The site, located in Kakadu National Park, is approximately 100 km south from the town of Jabiru, which has an average annual rainfall of 1480 mm (1971–1996), 150 km south-west of Oenpelli with an average annual rainfall of 1390 mm (1910–1996), and approximately 110 km north of Katherine, which has an average annual rainfall of 973 mm (1973–1996).

The Scinto 6 mine site was surveyed using a TOPCON Geodetic Total Station (GTS-3C) theodolite. Approximately 400 points were measured with an irregular spacing over the Scinto 6 waste rock dump and surrounding natural landscape. These irregularly spaced coordinates were then placed on a regular grid of 0.5 m by 0.5 m using the SURFER plotting package (Fig. 1).

The waste rock dump selected for study was flat topped with steep batters at the edges, and was butted against the natural hill, which had not been mined. Runoff from this natural hill was directed onto a haul road at the back of the waste rock dump, directing the runoff from the natural hill away from the cap along the side of the waste rock dump. As the focus of the Scinto 6 study was to model the development of the waste rock dump, and not the natural landscape, the waste rock dump was extracted from the surrounding natural landscape and contained the two significant data collection sites on the waste rock dump batters, which were monitored during the 1996–97 wet season (Fig. 1).

The first data collection site, the gully plot, had an average slope of 0.52 m/m (52%). This plot defined a shallow gully on the batter slope that appeared to have formed as water discharged from the low-gradient cap area of the waste rock dump to the high-gradient batter slope. The surface of the gully was armoured with large competent rock fragments. This plot was used to measure concentrated flow runoff and sediment loss. The second area data collection site, the interrill plot, was on the batter slope and had an average slope of 0.58 m/m (58%). The interrill plot surface was armoured with coarse rock fragments of rhyolite, the predominant material of the dump. This plot was used to measure overland flow runoff and sediment loss. Both plots had negligible vegetation cover at the beginning of the monitoring season. However, by the end of the monitoring season, both plots had a dense covering of native sorghum. Studies at ERA Ranger Mine on a ripped and vegetated site found that increasing vegetation cover (predominantly native sorghum) during the wet season had little effect on hydrology (George and Willgoose 1997).

The SIBERIA landscape evolution model

SIBERIA is a physically based predictive model that can simulate the geomorphic evolution of landforms subjected to fluvial erosion and mass transport processes (Willgoose *et al*. 1989, 1991*a–d*). SIBERIA links widely accepted hydrology and erosion models under the action of runoff and erosion over variable-time scales. SIBERIA is an important tool in the understanding of the interactions between geomorphology, 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 generalisation associated with the heterogeneity encountered in field studies.

The sediment transport equation of SIBERIA consists of 2 terms:

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

where q_s is the sediment transport rate per unit width, q_{sf} is the fluvial or rill sediment transport term, and q_{sd} is the diffusive or interrill transport term.

The fluvial sediment transport term (q_{sf}) is based on the Einstein-Brown model, which is:

$$q_{sf} = \beta_1 q^{m_1} S^{n_1} (\tau - \tau_c) \tag{2}$$

where q is the discharge per unit width, S the slope in the steepest downslope direction, β_1, m_1, and n_1 are parameters of the model, τ is bottom shear stress for the flow, and τ_c is a shear stress threshold (critical shear stress).

The diffusive transport term is expressed as:

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

where D is diffusivity and S is slope. The diffusive term can model creep, rainsplash, and landsliding.

For long-term elevation changes it is convenient to model the average effect of these processes with time. Accordingly, individual events are not normally modelled, but rather the average effect of many aggregated events over time are modelled. Consequently, SIBERIA output describes how the catchment is expected to look, on average, at any given time. Long-term landscape evolution is the balance between fluvial processes that incise the landscape and diffusive processes that round or smooth the landscape (Willgoose 1994). The sophistication of SIBERIA lies in its use of digital terrain models for the determination of drainage areas and geomorphology as well as its ability to efficiently adjust the landform with time in response to the erosion that occurs on it.

Derivation of SIBERIA input hydrology and erosion model parameter values

The fluvial sediment transport equation (Eqn 2) in SIBERIA is parameterised using input from a sediment transport equation and a hydrology model. This parameterisation process is illustrated in Fig. 3 and described in detail by Evans *et al.* (1998).

The gully and interrill sites on the batters of the Scinto 6 waste rock dump were instrumented and monitored for the 1996–97 wet season. The rainfall, runoff, and sediment data were used to derive input erosion and hydrology model parameter values for SIBERIA, as outlined below.

Monitoring of natural rainfall events

The study sites were monitored during natural rainfall events from December 1996 until March 1997. In the study area, the seasonal rainfall of the wet/dry tropics provided a good opportunity to obtain natural rainfall data. To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall, and runoff for discrete events are required. This necessitated an observer being present on-site during rainfall events as high humidity, rainfall, and temperatures produce regular equipment failure. Complete data sets were collected for 9 events for each plot. Because of the remoteness of the study site and high rainfall during the study period, which made access by land impossible, all staff and supplies were transported by helicopter on a 7-day rotation.

The gully plot had a length of 10 m and variable width (area of 24.2 m^2), while the interrill plot had a length of 9.8 m with variable width (area of 34.3 m^2). The plot borders were constructed using wide damp course. A 0.304-m HS flume was placed at the outlet of the gully plot to measure discharge and a 90° V-notch sharp-crested weir was placed at the outlet of the interrill plot to measure discharge. The up-slope end of the gully plot was open to the low-gradient upper cap surface so that discharge from this area could be included in analysis. However, during monitoring there was no observed discharge from the upper surface into the gully. The up-slope end of the interrill plot had a border in place to prevent flow entering. Rainfall on each plot was measured using a tipping bucket rain gauge.

Total rainfall, maximum 10-min rainfall intensity (I_{10}), total discharge, runoff coefficient for the monitored rainfalls, and suspended and bedload sediment are given in

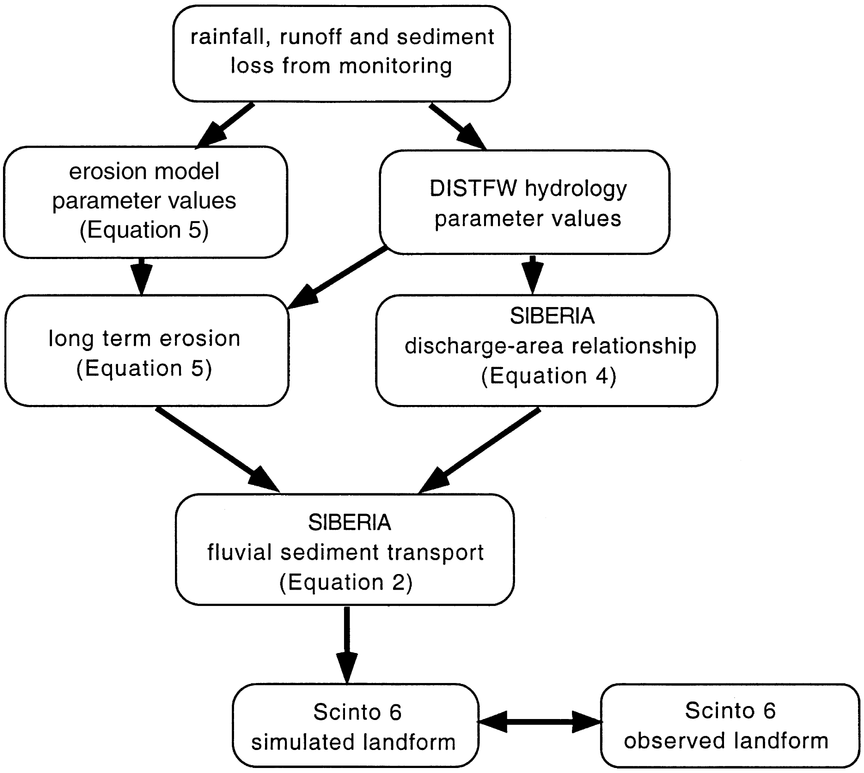

Fig. 3. Flow chart describing the process of parameter derivation for SIBERIA.

Table 1. Total rainfall and I_{10} were the same for both sites, except for the event monitored on 9 January 1997. Total rainfall ranged from 5.2 to 46.4 mm, and I_{10} ranged from 28.8 to 90.0 mm/h. The mean runoff coefficients (and standard deviations) for the sites were gully 0.28 (0.18), and interrill 0.22 (0.11). The event on 20 Febuary 1997 on the interrill site had a low runoff coefficient (0.07) compared with the other events on that site. Total discharge per unit surface area was greater from the gully plot than from the interrill plot (Table 1).

Derivation of hydrology model parameter values

The monitoring data were used to parameterise the DISTFW rainfall–runoff model. The parameterised model was used to derive long-term average parameters for the SIBERIA landform evolution model for the Scinto 6 waste rock dump.

DISTFW rainfall–runoff model parameters

The DISTFW model is a rainfall–runoff model based on the sub-catchment based Field-Williams Generalised Kinematic Wave Model (Field and Williams 1983). Willgoose and Riley (1993*a*) described the model and its application to mine spoils and waste rock in detail. DISTFW divides a catchment into a number of sub-catchments connected together by a channel network draining to a single catchment outlet. Hortonian runoff is modelled and drainage through the sub-catchments occurs by a kinematic wave on the overland flow. For this study, it was assumed that infiltration drained to a very deep aquifer and

Table 1. Monitored data at Scinto 6

Site	Date	Total rainfall (mm)	I_{10} (mm/h)	Total runoff (l) [peak discharge (L/s)]	Suspended sediment loss (g) [loss per unit runoff (g/L)]	Bedload loss (g) [loss per unit runoff (g)]	Total sediment loss (g) [loss per unit runoff (g)]
Gully	07/01/97	42.4	68.4	261.6 [0.23]	117.71 [0.45]	328.19 [1.25]	445.90 [1.70]
	09/01/97[A]	5.8	34.8	29.9 [0.14]	13.99 [0.97]	33.52 [1.12]	47.51 [1.59]
	17/02/97	46.4	90.0	677.2 [0.60]	419.43 [0.62]	853.09 [1.26]	1272.52 [1.88]
	18/02/97	36.4	76.8	351.0 [0.42]	118.99 [0.34]	229.24 [0.65]	348.23 [0.99]
	19/02/97	13.4	51.6	88.9 [0.19]	16.41 [0.48]	42.83 [0.48]	59.24 [0.67]
	20/02/97[A]	15.0	28.8	79.1 [0.7]	8.89 [0.11]	16.44 [0.21]	25.33 [0.32]
	21/02/97	30.2	30.0	200.8 [0.19]	40.33 [0.20]	39.12 [0.19]	79.45 [0.40]
	26/02/97	33.8	58.8	316.2 [0.33]	100.07 [0.32]	72.54 [0.23]	172.61 [0.55]
	05/03/97	16.2	56.4	174.6 [0.57]	57.56 [0.33]	91.41 [0.52]	148.97 [0.85]
Interrill	07/01/97	42.4	68.4	205.9 [0.20]	30.60 [0.15]	320.87 [1.56]	351.47 [1.71]
	09/01/97[A]	5.2	31.2	24.9 [0.07]	1.00 [0.04]	55.02 [2.21]	56.02 [2.25]
	17/02/97	46.4	90.0	754.6 [0.63]	208.44 [0.28]	292.12 [0.39]	500.56 [0.66]
	18/02/97	36.4	76.8	286.0 [0.39]	48.60 [0.17]	107.54 [0.38]	156.14 [0.55]
	19/02/97	13.4	51.6	99.5 [0.15]	8.25 [0.08]	30.82 [0.31]	39.08 [0.39]
	20/02/97[A]	15.0	28.8	35.4 [0.05]	3.96 [0.11]	10.70 [0.30]	14.66 [0.41]
	21/02/97	30.2	30.0	181.8 [0.15]	36.23 [0.20]	23.08 [0.13]	59.31 [0.33]
	26/02/97	33.8	58.8	312.7 [0.37]	38.58 [0.12]	51.87 [0.17]	90.45 [0.29]
	05/03/97	16.2	56.4	147.4 [0.55]	35.91 [0.24]	41.13 [0.28]	77.04 [0.52]

[A] These events were not used for erosion modelling (Eqns 7 and 8) so that large events were accurately predicted as discussed by Evans *et al*. (1988).

Table 2. Fitted parameter values (mean±s.d.) for 1997 events in parallel on the gully and the interrill sites

Parameter (units)	7, 9 Jan.; 17, 18 Feb.	20, 21, 26 Feb.; 5 Mar.
	Gully	
c_r ($\mathrm{m}^{(3-2e_m)}$/s)	1.330±1.34	2.354±2.05
e_m	1.663±0.24	1.761±0.21
S_ϕ ($\mathrm{mm/h}^{0.5}$)	1.758±0.43	0.905±0.54
ϕ (mm/h)	38.22±1.09	18.24±1.36
	Interrill	
c_r	0.823±13.37	0.359±0.10
e_m	1.546±4.22	1.500±0.07
S_ϕ	1.464±10.57	2.877±0.30
ϕ	38.67±27.97	18.84±0.59

did not discharge to the surface within a study site, so the groundwater component of the model was disabled.

The parameters fitted in this study were (1) sorptivity (initial infiltration), S_ϕ ($\mathrm{mm/h}^{0.5}$); (2) long-term infiltration, ϕ (mm/h), and kinematic wave coefficient and exponent, c_r ($\mathrm{m}^{(3-2e_m)}$/s) and e_m. Parameter values were fitted to observed rainfall and runoff for the monitored rainfall events using a non-linear regression package, DISTFW-NLFIT (Willgoose *et al*. 1995).

The DISTFW-NLFIT interface allows the user to fit (1) parameter values to a single rainfall event for a single site; (2) a number of events at a single site; or (3) parameter values across a number of sites. Method (2) was used to fit parameter values to observed hydrographs for observed rainfalls by fitting a single parameter value set that provided a good fit to 4 hydrographs for each site simultaneously. Firstly, a single parameter value set was fitted to the first 4 events that occurred on the sites (Table 1). Secondly, a single parameter value set was fitted to the last 4 events on the sites (Table 1). Fitted parameter values are given in Table 2.

The fitted parameter values (Table 2) were used to predict the hydrograph for the events in parallel. These predicted hydrographs compared reasonably well with observed data for each event.

The parameter values fitted for the first 4 storms on the interrill site (overland flow) had very large standard deviations and were thus considered unreliable. The parameter values fitted for the first 4 storms on the gully site (concentrated flow) were used to predict hydrographs for the rest of the events at that site. The events were under-predicted and did not fit the observed data well. The parameter values fitted for the last 4 storms on the interrill and gully sites were used to fit hydrographs to the rest of the events on those sites. The predicted hydrographs using parameter values for the last 4 storms generally compared well with observed hydrographs, although there was some over-prediction. The observed and predicted hydrographs with 90% prediction limits for both sites for the event on 17 February 1997 are given in Fig. 4. This event, one of the first 4 events, had the greatest rainfall and the highest I_{10} and it is important that large events are accurately predicted (Duggan 1988, 1994; Evans 1997). For the interrill site, the rising stage of the hydrograph is generally well predicted but there is some over-prediction in the receding

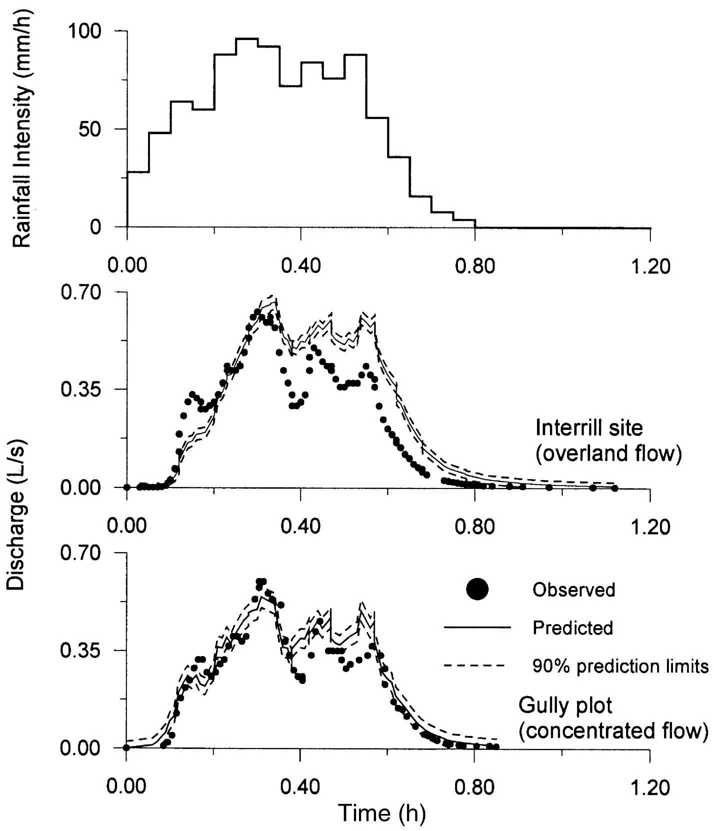

Fig. 4. Hyetograph and hydrographs for the interrill (overland flow) and gully (concentrated flow) plots for the event on 17 February 1997 predicted using adopted parameter values for the site (Table 2). Gully plot parameter values are c_r = 2.35, e_m = 1.76, S_ϕ, = 0.91 and ϕ = 18.2. Interrill plot parameter values are c_r = 0.36, e_m = 1.50, S_ϕ, = 2.88 and ϕ = 18.8.

stage of the hydrograph. The peak discharge from both sites was well predicted, but there was some over-prediction of rise and fall of secondary peaks in the hydrographs.

The parameter uncertainty code within the NLFIT package (Kuczera 1994), COMPAT, was used to assess the statistical compatibility of parameters calibrated to the model. The program uses the parameter values derived for the different sites and produces uncertainty regions in which the parameters lie with 95% certainty (Fig. 5). The kinematic wave parameter values are not significantly different, as the 95% confidence limits for the interrill and gully site overlap (Fig. 5*a*). The infiltration parameters for the interrill (overland flow) and gully (concentrated flow) sites are statistically different, as the confidence regions do not overlap (Fig. 5*b*). However, the long-term infiltration rates, ϕ, for the gully (18.2±1.36) and interrill (18.8±0.59) sites are similar.

There is a significant difference between the variation of cumulative infiltration with time for the interrill and gully sites. This indicates that sorptivity, S_ϕ, controls the difference in discharges between the sites with the lower S_ϕ on the gully site generally resulting in higher total runoff than the interrill site (Table 1). This occurs even though the gully plot area is less than the interrill plot area. The gully plot cross-section, ‘V’ shaped, would result in a smaller wetted surface per unit of plot area. The smaller surface

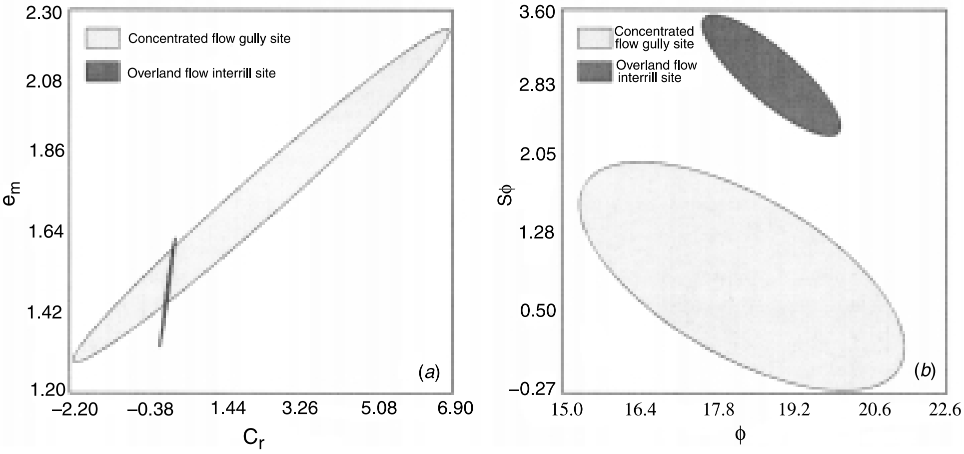

Fig. 5.(*a*) 95% compatibility regions for simultaneously fitted kinematic wave parameter values, and (*b*) 95% compatibility regions for simultaneously fitted infiltration parameter values.

area provides less area for initial infiltration giving a smaller S_ϕ. However, ϕ is similar because the two plots are adjacent and examination has demonstrated that they comprise the same material.

Derivation of SIBERIA input parameter values from hydrology data

The parameters of SIBERIA represent temporal average properties of the runoff and erosion processes occurring on the landscapes. The parameter values derived above for the DISTFW model represent instantaneous values and must be integrated over time to yield temporal average values. SIBERIA does not directly model runoff 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 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.

Examination of flow paths derived from the digital terrain map for the waste rock dump indicated that the gully and interrill sites appeared to be fed by runoff from the natural landscape at the rear of the waste rock dump. However, it was observed that during rainfall events little, if any, of this runoff reached the gully and batters of the waste rock dump, and that the only runoff reaching the gully and interrill sites was that generated from the waste rock dump cap and the batters. The runoff from the natural landscape at the rear of the waste rock dump infiltrated through the much coarser waste rock dump mine spoil at the junction of the natural hill and waste rock dump. This runoff exited as groundwater downslope of the waste rock dump at a point that was unable to be determined during the study period. The gully, and its development, was the main feature of interest; therefore, to simplify the determination of runoff parameters from the waste rock dump, the gully and its supporting catchment without the area contributed by the natural hill was used to determine the runoff parameters.

Equation 4 was fitted using the peak discharges and areas for both gully and interrill catchments using both sets of parameters of c_r, e_m, S_ϕ, ϕ. Storms of various duration for a 1-

in-2 year average return interval (ARI) were used, using rainfall data from Jabiru. The storm durations were 10, 15, 20, 25, 30, 45, and 60 min. The ARI of the storm that most closely relates the instantaneous erosion physics with long-term erosion physics is 2.33 years (Willgoose *et al.* 1989). Since the ARI is used solely to determine the value of m_3 in Eqn 4, use of the 1-in-2 year rather than 2.33 year is considered satisfactory, and consistent with the index flood approach to flood frequency analysis (Pilgrim 1987). To examine the effect of parameter variation, both gully and interrill values of c_r, e_m, S_ϕ, ϕ were used. Values for β_3 and m_3 were 0.0005 and 0.89, and 0.0004 and 0.87, for the gully and interrill plots, respectively. As there was only a small difference between values and this has been shown to have little effect on the simulations, the gully values were adopted for all further work.

Derivation of erosion model parameter values from sediment data

Equation 2 can be rearranged to determine the total sediment loss in grams (T) during a rainfall event (Evans *et al.* 1998). This is described by the following equation:

$$T(\mathrm{g}) = \beta_2 S^{n_1} \int Q^{m_1} \mathrm{d}t \tag{5}$$

where, $\int Q^{m_1} \mathrm{d}t$ is a function of cumulative runoff over the duration of the event.

However, as there is only one slope value for the gully and interrill sites, the slope parameter, n_1, could not be fitted. As a result the following equation was fitted for total sediment output T(g) (Table 1):

$$T(\mathrm{g}) = K \int Q^{m_1} \mathrm{d}t \tag{6}$$

where

$$K = \beta_2 S^{n_1}$$

The parameters m_1 and K were fitted to the sediment transport model (Eqn 6) for both sites using log–log regression. Table 1 demonstrates that bedload dominates suspended load in this geographical area with the same result reported by others (Duggan 1988; Roberts 1991; Evans 1997):

Willgoose and Riley (1993*a*) used rainfall simulation data on cap and batter site plots at ERA Ranger Mine to derive a value of the slope parameter of $n_1 = 0.69$. Using this value, an n_1 parameter value was determined for Eqns 7 and 8. The slope of the gully and interrill sites are 0.52 m/m and 0.58 m/m, respectively, producing equations for total sediment loss from the gully and interrill plots as follows (Moliere *et al.* 1997):

$$T(\text{gully}) = 4.732 \mathrm{S}^{0.69} \int Q^{1.64} \mathrm{d}t \tag{7}$$

$$T(\text{interrill}) = 1.014 \mathrm{S}^{0.69} \int Q^{1.14} \mathrm{d}t \tag{8}$$

Simulations were run using the parameters described in Eqns 7 and 8 with values of m_1 and n_1, respectively, 1.64 and 0.69, and 1.14 and 0.69 for gully and interrill plots.

The SIBERIA input parameter β_1 was determined using

$$\beta_1 = q_s / \beta_3^{m_1} A^{m_1 m_3} \tag{9}$$

where A is the area draining the waste rock dump and q_s is the total sediment loss over the monitoring period (Table 1). This produced a value of 0.003 for β_1, which was used in all simulations.

A second series of simulations was also run using parameters determined from the ERA Ranger Mine waste rock dump (Willgoose and Riley 1993*a*). These values were calibrated to a geomorphic analogue of the Scinto 6 waste rock dump and allowed the testing of these parameters on an analogue of the ERA Ranger Mine waste rock dump over the medium term. The ERA Ranger Mine values were $m_1 = 1.68$, $n_1 = 0.69$, $\beta_1 = 0.003$, and $m_3 = 0.88$. These values approximate the calibrated values from the hydrological analysis.

Diffusion parameters

Previous SIBERIA simulations of the ERA Ranger Mine waste rock dump had not used a diffusion mass transport process as the appropriate diffusivity could not be determined either theoretically or in the field. Diffusion has the effect of rounding the landform over the long-term.

Scinto 6 provided the opportunity to fit diffusivity to the degraded landform and was fitted by trial and error to provide the best visual comparison with the Scinto 6 landform. Diffusivity was adjusted until the appropriate degree of rounding of the gully bottom and tops was found. This trial and error value compared well with a value for diffusivity from Tin Camp Creek in Arnhem Land derived from the catchment area–slope relationship (Hancock *et al*. 1999). A sensitivity study of the value for diffusivity demonstrated that large changes in gully morphology can occur with small variation in diffusivity (Hancock *et al.* 1999).

SIBERIA simulations

Initial conditions

As the waste rock dump at Scinto 6 is a flat-topped structure with relatively steep batters constructed from dumped rock and is a simple design with only localised erosion, it is possible to estimate the landscape dimensions and proportions immediately after the completion of mining. This ability to determine the initial landscape is reinforced by the extremely low natural denudation rate for the Jabiluka, Ranger, and Narbalek areas in the Northern Territory of 0.04 mm/year (Cull *et al.* 1992).

The major feature of interest is the two gullies that have formed on the batter (Fig. 1). Field inspection of the dump indicated that the flat top of the waste rock dump has not eroded significantly from its original height, with no evidence of erosion such as rills or small channels, although it is impossible to visually estimate the amount of diffusive processes operating. There may have been some slight deposition of material from the natural hill at the back of the waste rock dump.

The section of the waste rock dump where significant visible erosion has occurred is on the batters. Here, the major erosional features are two gullies that start at the top of the batter and run down to the base, where a small alluvial fan has been deposited. For the initial conditions the two gullies were removed from the batters by filling them in. As it is extremely difficult to estimate the amount of erosion that has occurred on the batter excluding the gullies, and, assuming that the batters had eroded uniformly over the surface, it could be assumed that the batters between the gullies had changed little in shape from their original surface. Consequently, the initial conditions adopted for the SIBERIA simulation consisted of the Scinto 6 waste rock dump with the two gullies filled in.

Comparison of SIBERIA simulated catchment with natural catchment

SIBERIA simulations modelled the whole waste rock dump and used the parameter values and initial conditions described previously. The comparison concentrated on the ability of SIBERIA to match the small-scale features of the landform, in particular the position, shape, depth, volume, and number of the gullies on the batter.

Using the gully parameters, Fig. 1 shows that SIBERIA is able to predict the correct number and spacing of gullies along the batter. A simular result is obtained using the ERA Ranger Mine parameters. The shape of the SIBERIA gullies also approximates that of the Scinto 6 gullies. SIBERIA is also able to match the Scinto 6 maximum gully depth of 0.45 mm and volume of 7.71 m^3.

Using the calibrated erosion parameters for Scinto 6, SIBERIA also independently predicted the gully depth and volume at the same age as that of the current landform. By matching the total erosion SIBERIA predicted that the age of the landform was about 40 years, which is a close match to the actual age of approximately 46 years. By comparison, simulations using the interrill values produce only small gullies on the batters over the same time period.

Correctly estimating the correct runoff area for the waste rock dump proved to be essential in the accurate modelling of the gullies. Including runoff from the natural hill at the back of the waste rock dump provided excess runoff and the gullies developed much more quickly and were too deep. When this runoff from the natural hill was not included, the simulated gullies developed to the required depth and at the same rate as those observed. Furthermore, evidence from the field site suggested that most of the runoff from the natural hill followed an old haul road and did not contribute to the waste rock dump. These results indicate that gullies developed from runoff generated on the waste rock dump itself, and reinforce the observation that runoff from the natural hill does not contribute to the waste rock dump but becomes groundwater at the junction of the waste rock dump and the natural hill.

Conclusion

Erosion and hydrology parameters were calibrated from data from two sites on an abandoned waste rock dump. The derived hydrology model parameter values (Table 2) were used in the DISTFW rainfall/runoff model to predict hydrographs for each monitored event using the observed rainfall for the event as input to the model. The NLFIT-DISTFW package allows the fitting of hydrology model parameter values to 4 runoff events simultaneously. The results indicate that this method gives robust parameter values that result in an accurate prediction of discharge that is representative of the observed situation on small-scale sites. This method has potential to refine design of post-mining rehabilitated landforms. Hydrology modelling is an integral part of landform evolution modeling using SIBERIA.

These calibrated hydrology parameter values were then used with sediment data collected from the site in an erosion model to derive mean annual erosion parameter values for SIBERIA. These values were used to test the ability of SIBERIA to simulate landscape development on a man-made landform over 50 years. The good match between the observed Scinto 6 waste rock dump and SIBERIA simulations demonstrates that SIBERIA can satisfactorily simulate the rate and form of the geomorphic development of the waste rock dump. SIBERIA simulations dated the Scinto site at approximately 40 years old, correctly matching the age of the Scinto 6 site. The good match of the gully position, volume, and depth indicate that the independently calibrated SIBERIA can accurately simulate the development of gullies on the batters of the Scinto 6 waste rock dump. This work has also demonstrated that SIBERIA can match the rate at which the gullies develop and their geometry if the erosion and runoff characteristics of the gully are known.

This study as well as other research examining short-term erosion on mine sites, natural catchments (Hancock *et al*. 1999), and also experimental catchments (Hancock

1997) has demonstrated that SIBERIA is validated for the landscapes examined. SIBERIA provides a new tool for predicting erosion of post-mining landscapes.

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