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The measurement and modelling of rill erosion at angle of repose slopes in mine spoil

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Abstract

The process of rill erosion causes significant amounts of sediment to be moved in both undisturbed and disturbed environments and can be a significant issue for agriculture as well as mining lands. Rills also often develop very quickly (from a single rainfall event to a season) and can develop into gullies if sufficient runoff is available to continue their development. This study examines the ability of a terrestrial laser scanner to quantify rills that have developed on fresh and homogeneous mine spoil on an angle of repose slope. It also examines the ability of the SIBERIA erosion model to simulate the rill's spatial and temporal behaviour. While there has been considerable work done examining rill erosion on rehabilitated mine sites and agricultural fields, little work has been done to examine rill development at angle of repose sites. Results show that while the overall hillslope morphology was captured by the laser scanner, with the morphology of the rills being broadly captured, the characteristics of the rills were not well defined. The digital elevation model created by the laser scanner failed to capture the rill thalwegs and tops of the banks, therefore delineating a series of ill defined longitudinal downslope depressions. These results demonstrate that an even greater density of points is needed to capture sufficient rill morphology. Nevertheless, SIBERIA simulations of the hillslope demonstrated that the model was able to capture rill behaviour in both space and time when correct model parameters were used. This result provides confidence in the SIBERIA model and its parameterization. The results demonstrate the sensitivity of the model to changes in parameters and the importance of the calibration process. Copyright © 2007 John Wiley & Sons, Ltd.

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Introduction

Rill erosion has been demonstrated to be a major form of soil loss at many sites, with many attempts to both measure and model the volume of sediment transported. (Zhang *et al.*, 1998; Favis-Mortlock *et al.*, 2000; Sheridan *et al.*, 2000; Nicolau, 2002; Martinez-Casasnovas *et al.*, 2002; Polyakov and Nearing, 2003; Liu *et al.*, 2006; Parsons and Wainwright, in press). The Water Erosion Prediction Program (WEPP) (Laflen *et al.*, 1991; Flanagan and Livingston, 1995) is the most widely recognized sediment transport model for its ability to model both rill and interrill erosion. There have been few reported attempts to model small gullies or rills over the short-term (Hancock *et al.*, 2000) using digital-elevation-model-based soil erosion models. Computer-based landscape evolution models that employ digital elevation models to provide hillslope and catchment morphology at a variety of grid scales (Willgoose and Riley, 1998; Evans and Willgoose, 2000; Coulthard, 2001) offer the ability to evaluate landscape stability over the short (annual), medium (decades to hundreds of years) and long terms (thousands of years) (Hancock, 2004).

The modelling of soil erosion has many advantages over field studies (Evans, 2000). Modelling allows design ideas to be tested, different surface material properties to be evaluated and risk analyses to be carried out. Landscape evolution models allow the landscape surface to change through time, in contrast to other model types. Evolution

models also offer the advantage that the landscape can be evaluated visually as it develops through time, which is not possible with other approaches. Landscape evolution models can be used not only for soil loss assessment (i.e. tonnes/hectare/year), but also to evaluate the processes causing soil loss (i.e. rill or interrill erosion). Despite these numerous advantages, field studies are still needed as they provide base-line data to define hillslope and catchment soil loss, data for the calibration of predictive models and, importantly, field data with which to evaluate model effectiveness and accuracy.

One of the impediments to assessing the effectiveness of landscape evolutionary models has been the availability of accurate and dense spatial data to represent actual topography (Hancock, 2005). Methods used to measure surfaces have evolved radically and include techniques such as digital photogrammetry, motorized total stations, LIDAR and laser-scanning (Bellian *et al.*, 2005; Mitchell, 2007). Terrestrial laser scanners provide the ability to measure many thousands of data points per second, without needing to come into contact with the object. Two main classes of laser scanning systems can be identified (El-Hakim and Beraldin, 2006). 'Triangulation' based systems are most suited for close range applications (<10 m range) whilst 'time delay' systems are more flexible and operate at distances of 10–500 m (El-Hakim and Beraldin, 2006; Lim *et al.*, 2005).

This study examines the ability of a time delay laser scanner to quantify rills that have developed on fresh and homogeneous mine spoil on an angle of repose slope. It also examines the ability of the SIBERIA erosion model to simulate the rill's spatial and temporal behaviour. While there has been considerable work done examining rill erosion on rehabilitated mine sites (Sheridan *et al.*, 2000; Nicolau, 2002) and agricultural fields, little work has been done examining rill development on sites with angle of repose slopes. Rills often develop very quickly (timescales from a single rainfall event to a season) and can develop into gullies if sufficient runoff is available to continue their development (Martinez-Casasnovas *et al.*, 2002). Consequently, it is necessary to understand rill development if gully erosion is to be understood and modelled.

It is important that the erosional stability of angle of repose slopes be studied because of their importance in managing sediment production from temporary steep slopes, such as those on mine sites and major infrastructure development projects. More importantly, many mine sites have, or are proposing to use, such slopes for their post-mining landform (Hancock and Turley, 2005) and their stability needs to be evaluated to ensure that they can provide a functional and stable landform (Nicolau, 2002). Rills are also precursors to much larger erosional and site stability problems, such as gullies. Further, mine sites offer the opportunity to study 'new' landscapes created of fresh material where landforms are rapidly developing. Consequently, they are transient or non-equilibrium in their form and function and offer the rare opportunity to understand and quantify early or young landscape processes without the inbuilt memory of agricultural fields that have been utilized and/or modified over the years.

There appear to be few studies examining rill erosion at the hillslope scale on mine sites (Hancock *et al.*, 2000; Nicolau, 2002). Angle of repose slopes are of simple geometry and offer many advantages for post-mining landforms. They are inexpensive to construct and reduce elevation very quickly in relation to slope length. This reduces potential for runoff and so such slopes should be more stable and less susceptible to erosion. Nevertheless, angle of repose slopes have several problems in that they rarely resemble the surrounding undisturbed landscape, they cannot be accessed easily for revegetation work and also create long-term safety risks. Further, slopes created from mine spoil have different hydro-geological properties to natural hillslopes as the material grading and structure are different and the material is unweathered (Evans and Willgoose, 2000; Nicolau, 2002).

Study Site

Rix's Creek Coal Mine is located approximately ten kilometres west of the New South Wales town of Singleton (Figure 1). It is an open pit mine, which includes a tailings dam that has been in operation since 2002. The bank of this tailings dam was the site that was chosen for this project (Figure 2).

The study was conducted on a single continuous slope, which unlike bounded plot studies (Nicolau, 2002) provided spatial continuity of hillslope and runoff processes. The slope was originally formed by 'end dumping' from large haul trucks used at the mine. The slope was 20 m high at an angle of approximately 37 degrees and approximately 100 m long. The study focused upon one section, approximately 60 m in length. Beyond the crest of the slope, the ground surface rose up at an angle of 2–5 degrees; however, a small (1–1·5 m high) safety bund had been constructed, using the same spoil, along the top of the slope to prevent vehicles falling down the slope. This prevented any runoff from above the slope from running down the slope, and consequently rills developed only from runoff captured on the slope itself.

This site offered many advantages. Firstly, the site presented a very young landform that was only 3 years old and had remained undisturbed by subsequent mining activity. The slope was constructed of uniform and homogeneous

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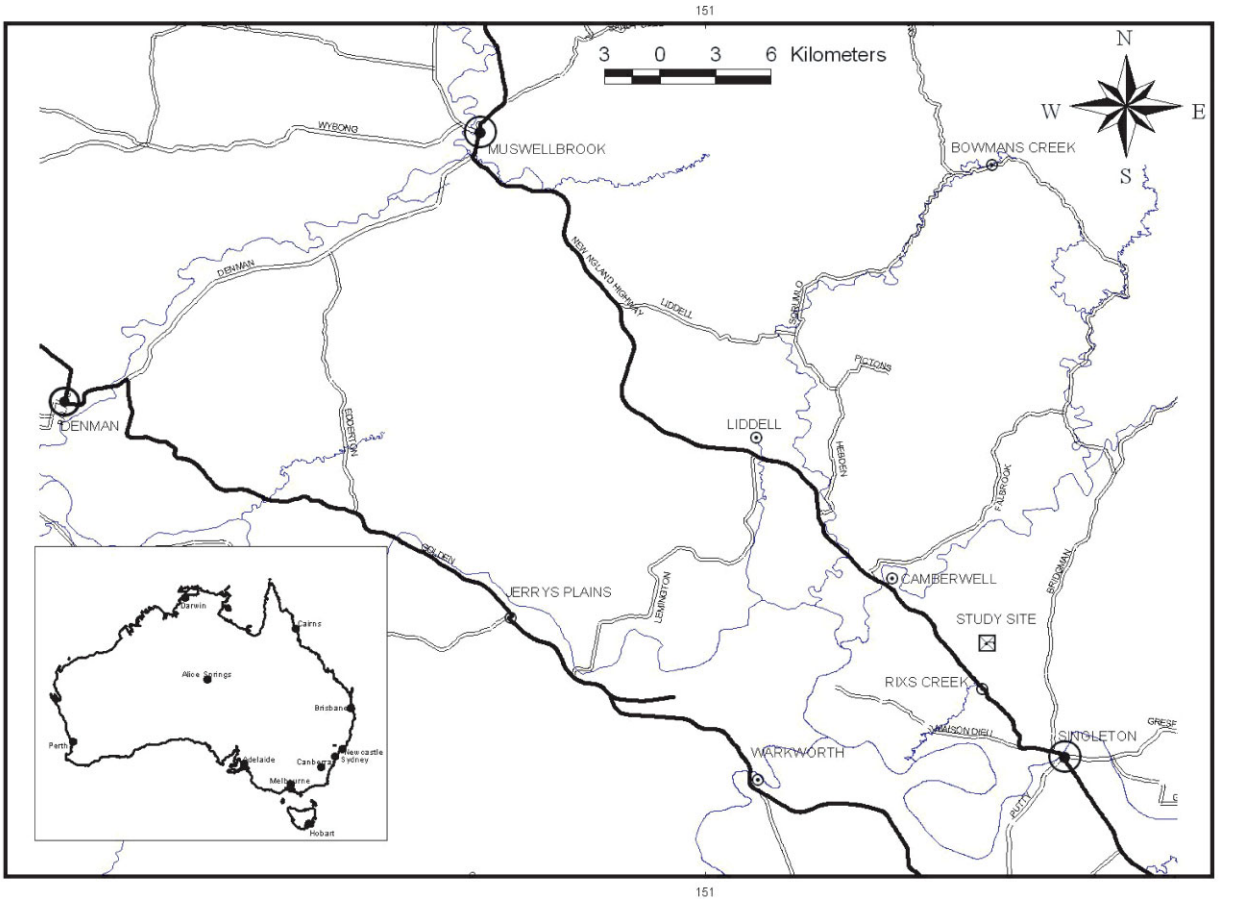

Figure 1. Location of the study site. This figure is available in colour online at www.interscience.wiley.com/journal/espl

material (mudstone spoil) with a relatively uniform particle size distribution. The site was also largely devoid of vegetation, which greatly simplified the model calibration. The lack of vegetation also meant that any measured surface truly represented the ground surface and not a combination of ground and bush, which is a practical difficulty associated with related studies (Martinez-Casasnovas *et al.*, 2002; Nicolau, 2002). Importantly, access to this site was very good, which is in contrast to the difficulties experienced on other mine sites due to safety concerns.

Another major advantage of this site was that the upslope contributing areas to each rill were equal, with only surface roughness and slight differences in plan form curvature across the study site. Slope length was also constant. This allowed for equal (and fair) competition between rills at the commencement of erosion.

Prior to the study the slope had not been surveyed. Nevertheless, due to the young age of the surface (3 years) and mine management assurance that the slope had been undisturbed during this time it can be confidently assumed that the original surface was uniform and planar. Subsequent erosion on the slope consisted of a network of rills, which ran down the length of the slope, and a single large gully, which was located off-centre from the middle of the slope (Figure 2). This large gully, which received the upslope runoff diverted by the slope crest bund, was not examined as part of this study as it was not possible to reliably determine the catchment area upslope of the site.

The rills commenced near the top of the slope and ran largely linearly down the slope, forming distinct drainage lines. They were regularly spaced, with no rills appearing to be significantly more successful than others (Favis-Mortlock *et al.*, 2000). There was some cross-grading and coalescing of rills. The cross-sectional profile of the rills was triangular with steep sidewalls. Examination of the sidewalls showed that the mine spoil was uniform with no hard layers, horizonization or surface armour to impede erosion. Previous site visits to the mine demonstrated that the rill patterns observed on this slope were very similar to that of other angle of repose slopes constructed of similar material.

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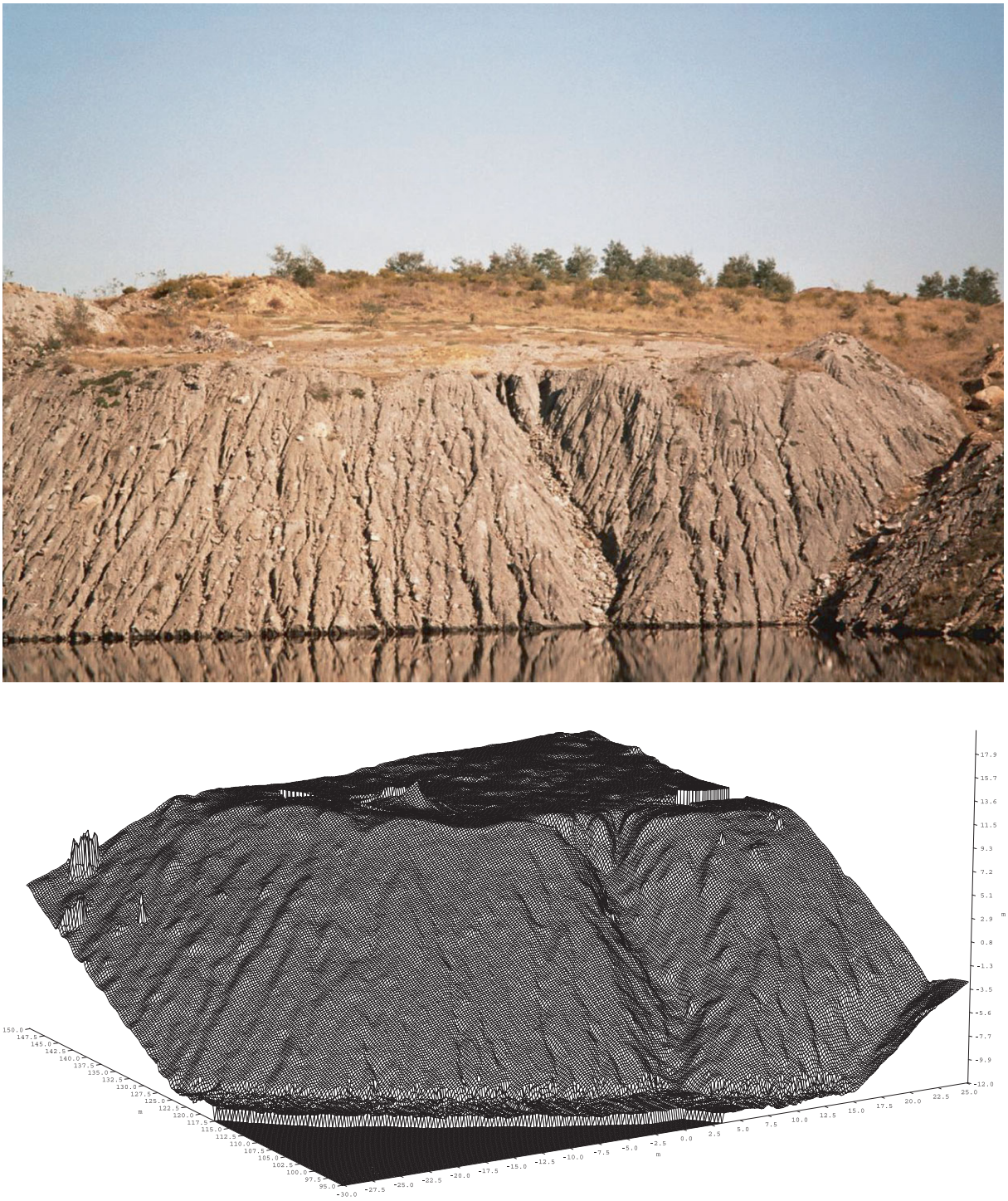

Figure 2. Photograph of the study site (top) with a digital elevation model (0·2 m by 0·2 m grid) (bottom). This figure is available in colour online at www.interscience.wiley.com/journal/espl

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Table I. Rill dimensions for the angle of repose slope. All dimensions are metres

	Rill depth	Rill width	Spacing between rills
Mean	0·38	0·27	1·69
Standard deviation	0·12	0·10	0·68
Minimum	0·10	0·10	0·7
Maximum	0·50	0·40	3·4

Due to safety considerations it was impossible to undertake a manual survey of the whole site in detail. Nevertheless, a limited survey was done using a hand tape (Zhang *et al.*, 1998). Rills were measured approximately half way down the slope and were found to have an average depth and width of 0·38 and 0·27 m, with an average spacing of 1·69 m (Table I).

Measurement of the Slope Using a Laser Scanner

In recent years a number of new techniques have developed to produce high resolution digital elevation models of landscape surfaces (Favis-Mortlock *et al.*, 1998; Chandler, 1999; Martinez-Casasnovas *et al.*, 2002; Bellian *et al.*, 2005). Modern 'reflectorless total stations' use an electromagnetic distance measurement device that measures the time that a laser pulse takes to travel from the instrument to the object surface and its return. By multiplying this time delay by the speed of light it is possible to estimate the 'double distance' (Uren and Price, 2005). Reflectorless total stations have been used to quantify soil erosion caused by rills on agricultural plots (Martinez-Casasnovas *et al.*, 2002), but these devices are relatively inefficient and more suited to targeting selected points than measuring large sets of arbitrary points on regularly spaced grids. In contrast, a terrestrial laser scanner is able to repeat the basic measurement very rapidly through the use of two rotating mirrors, which direct the laser pulse to different positions located on an object. By measuring the angular rotations of the mirrors and the distance to an object, it is possible to compute three dimensional coordinates, representing each point in an arbitrary 3D coordinate system. This procedure operates at very high rates, typically exceeding 5000 points per second, generating high resolution 'point clouds' (Uren and Price, 2005). Significantly, as the laser scanner does not require a field assistant to walk over the site holding a prism, the site does not experience any physical degradation and there are no safety issues related to accessing steep slopes. A further advantage of laser scanning over traditional total stations is that discrete points are not individually measured, drastically reducing the time the surveyor spends directing a telescope in the field. A final advantage of a laser scanner is the ability to produce data in near real-time and to see and assess the derived data in the field.

The I-Site laser measuring system used in this project is owned by the Laser Scanning Consortium Australia and New Zealand (LASCAN), of which the members are Curtin University of Technology, Perth, Australia; University of Melbourne, Australia; The University of Newcastle, Australia; University of Otago, Dunedin, New Zealand, and the University of Southern Queensland, Toowoomba, Australia (details can be found at www.cage.curtin.edu.au/lascan). The laser scanner used for this project was a Riegl LMS-Z210i acquired in 2002. The instrument has a field of 340 degrees horizontal and 80 degrees vertical and a range of up to 350 m @ ±25 mm accuracy and up to 700 m @ ±50 mm accuracy. The instrument can record points at a rate of up to 6000 pts/sec.

To operate, the scanner is set up, levelled and aligned like any other optical instrument. This generation of equipment uses a single mirror and a motorized head, which moves through the user defined field of view to ensure that the area of interest is fully covered. The scanner position and orientation can be input to locate the instrument into a specific ground coordinate system or to relocate the instrument for subsequent scans.

Table II. Effect of different erosion model parameters on erosion process (from Kirkby, 1971)

Erosion parameter		
M_1	n_1	Erosion process
1	1–2	soil wash without gullying
2	2	soil wash with gullying
>2	>2	gullying

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The SIBERIA Landscape Evolution Model

There have been several recent attempts to model rill erosion both in the field and under laboratory conditions, with each model having its strengths for different applications (Laflen *et al.*, 1991; Flanagan and Livingston, 1995; Nicolau, 2002; Polyakov and Nearing, 2003; Liu *et al.*, 2006; Parsons and Wainwright, 2006). In this study we use the SIBERIA (Willgoose *et al.*, 1991a, 1991b, 1991c, 1991d) model.

SIBERIA is a physically based mathematical model that simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion, and mass transport processes. SIBERIA links widely accepted hydrology and erosion models under the action of runoff and erosion over long timescales. 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 generalization associated with the heterogeneity encountered in field studies.

An advantage of the SIBERIA model over other erosion models, such as the USLE (and its derivatives) and WEPP, is that whole landscapes can be input to the model (x, y, z coordinates) as a regular grid digital elevation model. SIBERIA also has the ability to output whole landscapes as a regular grid digital elevation model.

The sediment transport equation of SIBERIA is

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

where q_s (m^3/s/m 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/m 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/m width), S (metre/metre) 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/m width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface and combines the effects of creep, rainsplash and landsliding.

SIBERIA does not directly model runoff (Q, m^3 – for the area draining through a point), but uses a sub-grid 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 appear, 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 erosion.

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

Digital elevation model

The SIBERIA erosion model requires a digital elevation model of the study hillslope. As the hillslope was originally a planar surface before the commencement of erosion, a digital elevation model based on the I-Site data was used. This required reconstruction of the hillslope without the major gully and rills.

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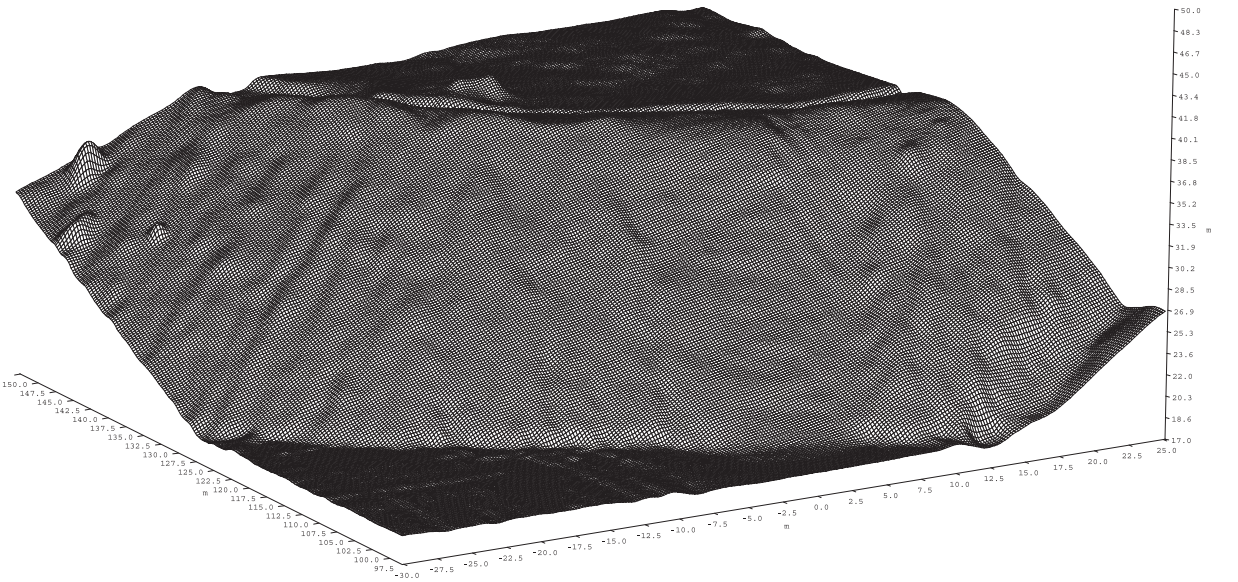

Figure 3. Initial hillslope used for the SIBERIA simulations. The digital elevation model grid size is 0·2 m by 0·2 m.

To create the digital elevation model representing its supposed original and un-eroded state, the ungridded point data representing the current hillslope was gridded at a resolution of 1 m using simple kriging. This created a dataset with the correct overall dimensions of the slope but without the fine detail of the rills and gully. This 1 m by 1 m grid was then gridded onto a 0·2 m by 0·2 m grid using kriging and a smoothing algorithm that generated an average elevation for each point based upon its height value and the elevations of its eight neighbors (Figure 3). This procedure effectively removed the fine detail of the rills whilst still capturing the overall length and proportions of the hillslope. It also maintained some of the surface roughness that might exist as a result of the end dumping of the waste rock by the haul trucks.

Parameterization of SIBERIA

Before SIBERIA could be used to simulate soil erosion, the sediment transport equation (Equation (2)) and area–discharge relationship (Equation (4)) required calibration. The fluvial sediment transport equation (Equation (2)) in SIBERIA was parameterized using input from field and laboratory sediment transport and hydrology data. This parameterization process is described in detail by Evans *et al.* (2000) and Hancock *et al.* (2000). A simple calibration can be performed using a database of SIBERIA erosion model parameters that has been developed from existing rainfall simulator and flume studies and relates soil particle size distribution and chemical properties to erosion rates (Hancock and Turley, 2005). The calibration can also use field data collected from rainfall–runoff plots or laboratory flume and/or rainfall simulator data (Evans *et al.*, 2000; Hancock *et al.*, 2002; Hancock, 2004). These methods are discussed below.

Calibration using soil physical properties. At this study site, there was an absence of field data to calibrate SIBERIA so the SIBERIA model parameter database was used. The erosion data of Sheridan *et al.* (2000) provides a database for spoil textural properties as well as its erodibility. It has long been recognized that soil properties influence erosion rates. While there are many factors, such as organic matter content, electrical conductivity, mineralogy and rock content that contribute to soil erodibility, one of the strongest influences on erodibility is soil particle size distribution. Consequently, the textural properties or particle size distribution of soil can be used to provide an indication of erodibility and can be used to calibrate the SIBERIA erosion model.

In this study, initial calibration data was derived from rainfall simulator and flume studies for a range of soil and spoil materials from the data of Sheridan *et al.* (2000). To calibrate Equation (3), the sediment concentration data was used in a multiple regression between sediment concentration, slope and discharge. This provides a range of values for β_1, m_1 and n_1. From this a database of input parameters for SIBERIA has been determined.

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Particle size distribution was determined by sieve analysis and hydrometer from nine spoil samples collected on the study site and showed that the spoil was classed as either sandy loam or loamy sand. Sand, silt and clay content ranged from 61 to 79%, 14 to 24% and 7 to 15%, respectively. Using the particle size data of the site and comparing it with the data of Sheridan *et al.* (2000) produced erosion parameters of $m_1 = 1{\cdot}5$, $n_1 = 2{\cdot}1$, $\beta_3 = 1$, $m_3 = 1$ and $\beta_1 = 0{\cdot}01$.

The value of $m_1 = 1{\cdot}5$ is not greatly different from the value of $m_1 = 1{\cdot}8$ derived mathematically by Willgoose *et al.* (1989) for wide channel flow, and is close to the value of $m_1 = 1{\cdot}6$ found experimentally by Moore and Burch (1986). The value of $m_1 = 1{\cdot}5$ is also within the range of $m_1 = 1{\cdot}45$–$1{\cdot}71$ found by Willgoose (1994) for the Pokolbin field catchment. The constant n_1 is the exponent on slope (S) and has been found by Willgoose *et al.* (1989) to vary only slightly between channel geometries. The value of $n_1 = 2{\cdot}1$ found to be applicable in this case is also the value previously determined mathematically by Willgoose *et al.* (1989) for wide channel flow. It is also very close to the value of $n_1 = 2$ suggested by Henderson (1966).

Generalizations can also be made about the erodibility of the surface materials and climate to assess best case/worst case scenarios of potential designs. Generic parameters can be used to provide a sensitivity analysis of different designs or erosion control structures (Kirkby, 1971). For example, the parameters m_1 and n_1, and the relationship between these parameters, are known to control whether a landscape will develop by either gullying or slope wash processes (Kirkby, 1971) (Table II). Consequently, if the erosive behaviour of the material is known, then an assessment of the erosive behaviour of the landform can be made by adjusting the values of m_1 and n_1. Values of $m_1 = 1$ and $n_1 = 1$ produce sheet wash erosion while $m_1 = 2$ and $n_1 = 2$ produce incision or gullying (Kirkby, 1971). Therefore, the parameters derived for this site using the data of Sheridan *et al.* (2000) suggest that the parameters are low, as the gully and rilling suggest that erosion is dominated by incisive type processes.

Calibration using a laboratory flume. To calibrate SIBERIA a small laboratory flume was used. This apparatus has been extensively used in previous studies for the calibration of SIBERIA (Hancock and Willgoose, 2001; Hancock *et al.*, 2006). This flume, with dimensions 1·4 m long by 0·4 m wide and 0·4 m deep, was located underneath rainfall microsprinklers, which produced rainfall with kinetic energy many times less than natural rain. This effectively eliminated diffusive erosion processes, producing a landscape dominated by fluvial erosion. The outlet of the catchment was the full catchment width, with a narrow covered flume external to the catchment, allowing water and sediment to be easily collected into bottles. To allow free draining, holes were drilled in the base of the box with geotextile material placed over the holes to prevent loss of soil. Rainfall rate was measured using four raingauges permanently mounted on the outside of the box. The flume and rainfall microsprinklers have been described in detail elsewhere (Hancock and Willgoose, 2001; Reid, 2004; Simic, 2005; Hancock *et al.*, 2006).

For this study the flume was set up at an angle of 15 degrees, as this was the slope used by Sheridan *et al.* (2000). Rix's Creek mine spoil was then placed up to the top of the box walls and smoothed with a straight edge. In this study a rainfall rate of 20 mm/hr was used. To obtain data for the calibration, rainfall was applied for a total period of 18 hours, in periods of 1 to 2 hours over a series of weeks, to represent a series of typical storm events. Grab samples of water and sediment from the outlet flume were collected in bottles at least once during each rainfall period for a duration of one minute, allowing the volume of water and sediment to be determined. The amount of sediment leaving the catchment was observed to be highly variable and was similar to other experimental geomorphological studies (Parker, 1977; Weaver, 1984). A total of 14 grab samples were collected, which produced a mean sediment load of 0·152 tonnes/year/m^2 (standard deviation = 0·068 tonnes/year/m^2, minimum = 0·042 tonnes/year/m^2, maximum = 0·263 tonnes/year/m^2).

To calibrate SIBERIA, the flume sediment data was then compared to SIBERIA simulations of the flume. To ensure any grid size scaling issues were minimized, a simulation grid size of 0·2 m by 0·2 m was used and the parameters described in the last subsection evaluated as a starting point, as these are indicative values. The simulations were run for a period of 10 years with the mean annual erosion rate determined. SIBERIA simulations using values of $m_1 = 1{\cdot}5$ produced a mean annual soil loss of 0·005 tonnes/year/m^2 while simulations using $m_1 = 2{\cdot}5$ produced 0·013 tonnes/year/m^2. These simulations provided a sensitivity analysis for the various values of m_1 and n_1. Consequently, the value of $m_1 = 1{\cdot}5$, as determined above, appears to be low, while a value of $m_1 = 2{\cdot}5$, while not matching the experimental data, is within the same order of magnitude as the flume data and is just outside the mean sediment loss minus two standard deviations for the flume data. In this study, the rate constant β_1 could have been adjusted upwards slightly to match the flume data, but in this case the calibration values were considered acceptable for our purposes.

It is important to recognize that, while many of the erosion and hydrology parameters are scale independent, some are not and need to be adjusted for the DEM grid size. The results presented here all use a 0·2 m by 0·2 m grid cell size and the parameters have been calibrated accordingly. If other grid sizes are needed, Evans and Willgoose (2000) provide a good discussion and the methodology for this adjustment, which is particularly important for the parameter β_1.

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Results

Laser scanning of the slope

Proximity to the studied slope was limited by the pond immediately in front of the slope. Initially, the instrument was set up at a location on the other side of the pond, approximately 300 m directly in front of the slope (Figure 4). This initial scan, while successfully capturing the gross morphology of the slope, generated a point cloud that was too sparse in relation to the rills. A second scan was done at a distance of approximately 100 m, but offset to the right of the slope (Figure 4). This location enabled the whole slope to be scanned at a higher resolution, and still without the presence of holes in the dataset created by features in the foreground obscuring more distant objects (known as 'occlusion effects'; Lim *et al.*, 2005; Lichti and Gordon, 2004).

I-Site was programmed so that it scanned the slope and surrounding area. This produced a point cloud consisting of approximately 76 000, points with the area containing the study slope represented by approximately 48 000 points. As SIBERIA uses a regular grid digital elevation model, the irregular spaced points within the point cloud needed to be resampled to a regular grid structure. Consequently, the data was gridded onto a regular grid of dimensions 0·2 m by 0·2 m using the simple kriging method available in the commercial package Surfer 7·0. This procedure generated a digital elevation model containing 76 176 points (276 by 276 points), represented in Figure 2. A grid size of 0·2 m by 0·2 m was selected because the majority of rills have a grid size spacing of 0·27 m, just greater than this value (Table I). Using a 0·2 m by 0·2 m provided approximately 0·6 points per 0·2 m by 0·2 m grid cell. A smaller resolution grid (i.e. 0·1 m by 0·1 m or less) could have been produced by interpolation, but as the 0·2 m by 0·2 m grid spacing approximately matches the average spacing of the original ungridded data, the 0·2 m by 0·2 m resolution provides a natural limit to the grid size reduction possible with the original captured data.

Overall hillslope morphology was captured by the I-Site data, with the major gully being clearly defined (Figure 2). The morphology of the rills was broadly captured; however, the smaller rills were not well defined. The digital elevation model failed to capture the rill thalweg and top of the banks, therefore creating a series of ill defined longitudinal downslope depressions.

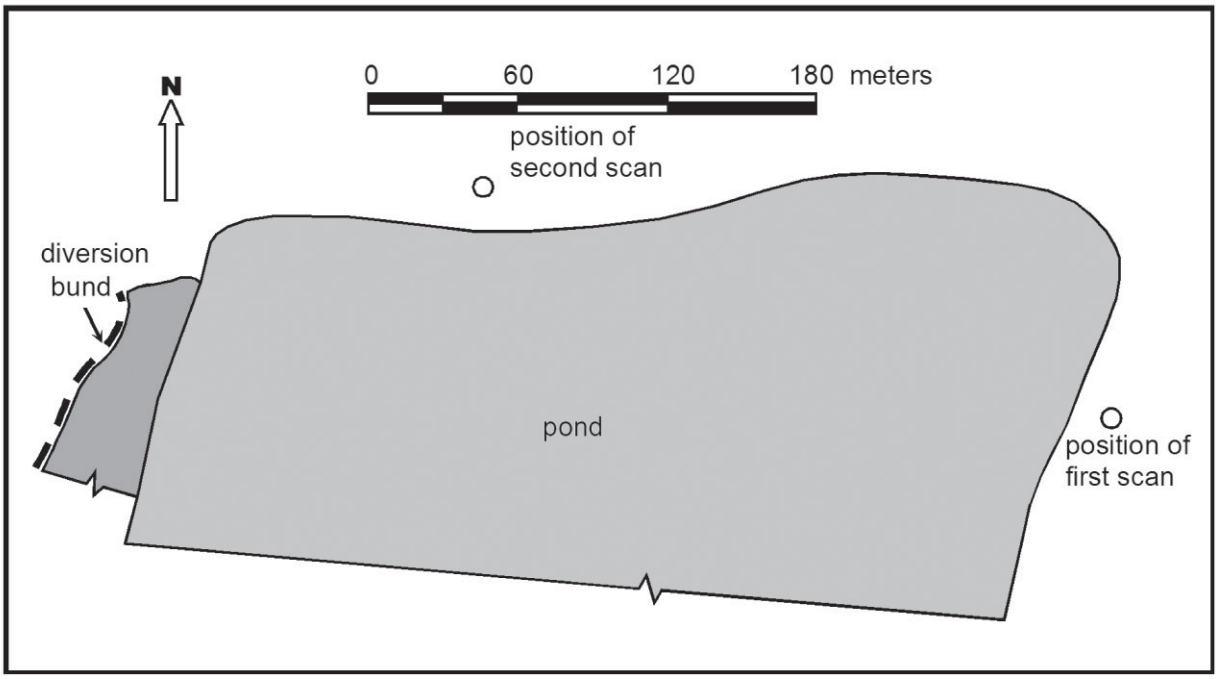

Figure 4. Site layout showing scanner locations.

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Table III. Parameters used for the SIBERIA simulations

Erosion process	m_1	n_1	β_1	β_3	m_3
Soil wash with gullying	1·5	2·0	0·01	1	1
Soil wash with gullying	2·0	2·0	0·01	1	1
Gullying	2·5	2·0	0·01	1	1

SIBERIA simulations

SIBERIA simulations were run using the 0·2 m by 0·2 m digital elevation model and the parameter values described above (Table III). The simulations were run for a time period of 3 years, this being the age of the study site.

Figure 5 shows that using values of $m_1 = 1{\cdot}5$ produces little erosion. Increasing m_1 to 2·0 produces small rills at the base of the slope while $m_1 = 2{\cdot}5$ produces rills that run from near the top of the slope down to its base. It is particularly gratifying that these visually match the rills developed in the field site after the simulation time of three years.

Discussion

The laser ranging system captured the morphology of the study hillslope at a level of detail and accuracy sufficient for an analysis of the SIBERIA system. While able to capture the large gully, the system was unable to capture the finest detail of the rills. This is a disadvantage of the automated system in scanning on a prescribed regular pattern, and not specifically collecting data points down the rill thalweg and along the banks. The thalweg and the banks are major features defining the slope characteristics and, without them correctly defined, morphology of the rills will not be captured.

These results demonstrate that a greater density of points is needed to capture the rill morphology in greater detail. This could theoretically be achieved by moving the scanner system closer to the object, but it was not possible in this case because the water of the tailings dam prevented access. An alternative is to perhaps use the I-Site system in conjunction with a total station and target breaks of slope representing the channel walls and thalweg (Martinez-Casasnovas *et al.*, 2002). The more expensive solution would be to adopt a more recent laser scanner capable of working at a higher spatial resolution (e.g. Leica HDS4500: 100 000–500 000 points per second; Leica, 2007).

Although a higher resolution scanner could achieve improved results, it is important to realize that any measuring system has limitations that fundamentally constrain what can be achieved. The idea that the full topographic surface can be measured is unrealistic, with any survey method being only capable of measuring a 'sample' of the full surface 'population'. If the survey is at a sufficiently high resolution for the needs of the study, then the survey methodology can be regarded as successful and 'fit for purpose'. For the case of validating the output of a landscape evolutionary model, the measured resolution should match and ideally coincide spatially with the resolution of the model output. This utopian situation would then also limit discrepancies arising from interpolation, which have not been addressed in this current study.

SIBERIA simulation using values of $m_1 = 2{\cdot}5$ and $n_1 = 2{\cdot}0$ was able to capture rill behaviour in both space and time. Using lower values of m_1 reduced the amount of incision predicted. This result provides confidence in the SIBERIA model and its parameterization. While unable to calibrate SIBERIA using the existing database of parameters, the process demonstrated here shows how existing information can be used as a basis for calibration. In this study the parameters β_1 and n_1 were kept constant and m_1 adjusted to capture the behaviour of the rills. The use of the laboratory flume can provide a more reliable calibration method. For calibration purposes for a particular site the SIBERIA model parameters could be based on the existing data set and individual parameters adjusted until the simulations match the observed/measured erosion, if initial surface conditions are reliably known.

Figure 6 demonstrates the effect of increasing m_1. Using values of $m_1 = 1{\cdot}5$ produced little incision. Higher values of m_1 produce more incised rills. Comparison of the measured rill size and spacing with the simulations (when the original surface has been subtracted from the simulated data) (Figure 7) shows that the field data has deeper and narrower rills than the simulated data. The simulations also produce fewer rills than are measured in the field. The results demonstrate the sensitivity of the model to changes in parameters and the importance of the calibration process. These differences are likely to be the result of several factors: first, the differences in roughness of the initial surface, which will affect the flow paths and coalescence of flows and consequent simulation pattern of erosion; second, the erosive process and therefore the inability of the model and parameterization to correctly capture the erosion processes particularly at high slopes. This is an area of ongoing research.

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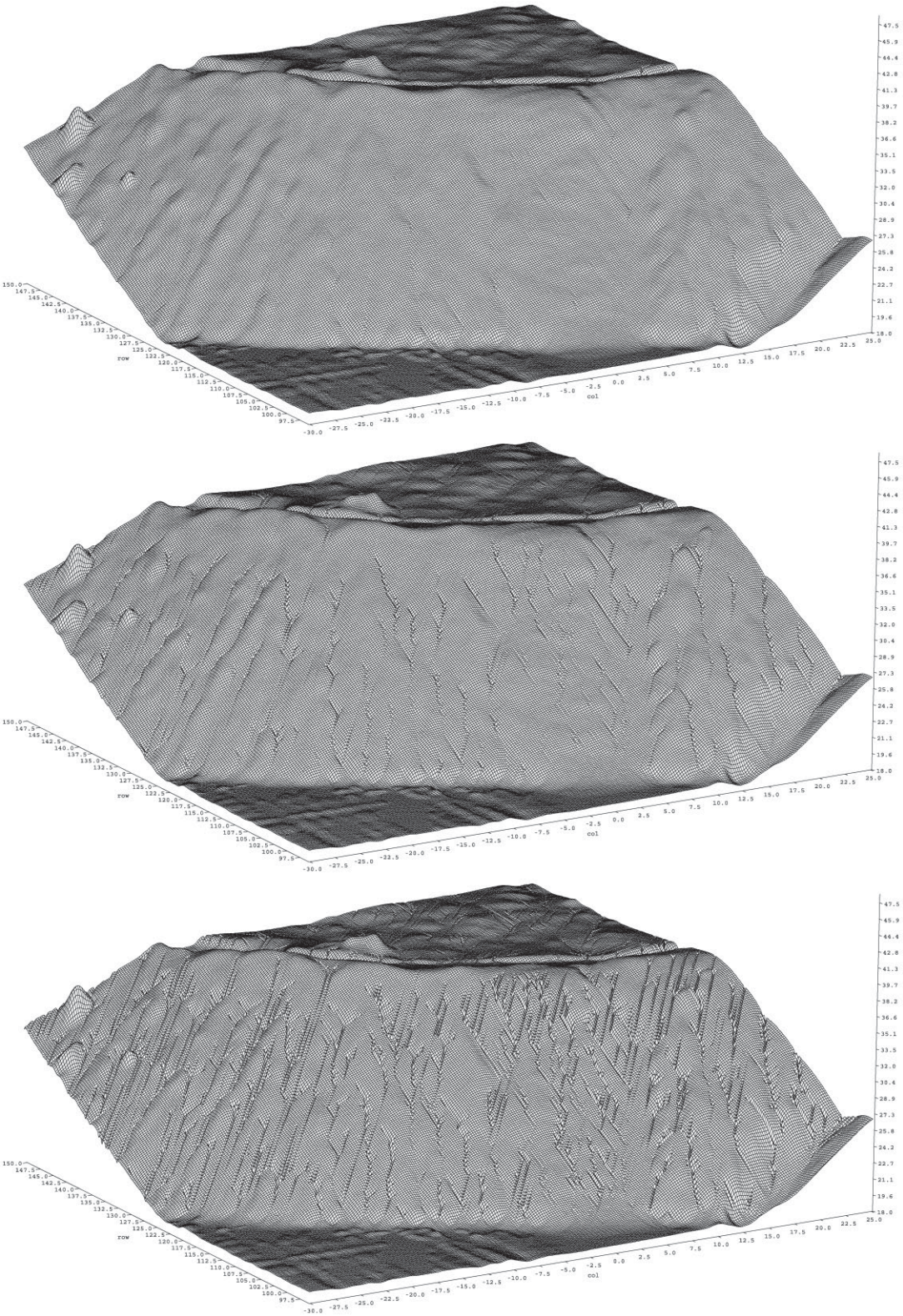

Figure 5. SIBERIA simulation of the angle of repose slope using $m_1 = 1{\cdot}5$ (top), $m_1 = 2{\cdot}0$ (middle) and $m_1 = 2{\cdot}5$ (bottom).

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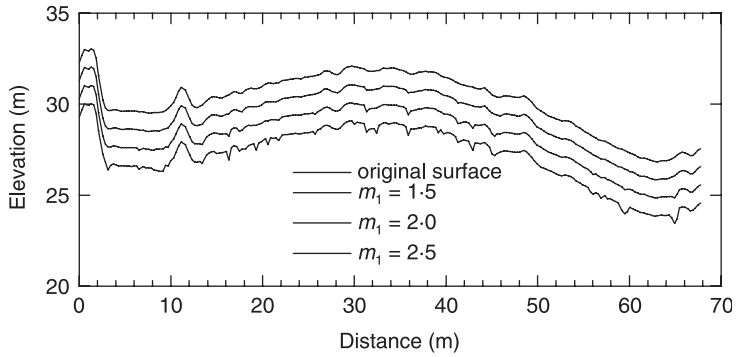

Figure 6. Sectional profiles (original surface at top) across the face of the slope and SIBERIA simulations after three years using increasing values of m_1. A value of 1, 2, and 3 m respectively has been subtracted from simulation sectional profiles for clarity.

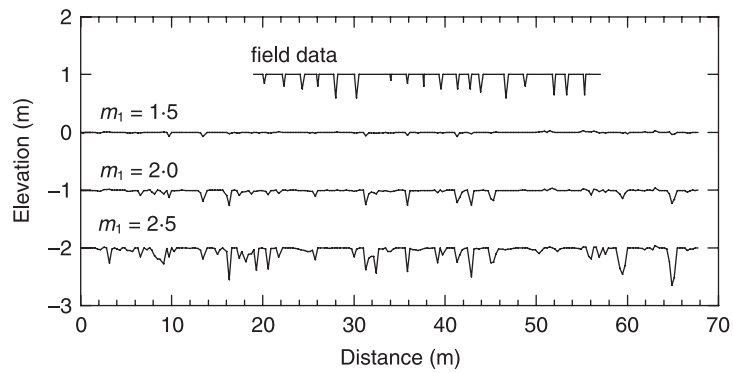

Figure 7. Sectional profiles across the face of the waste rock dump for the field data and SIBERIA simulations. A value of 1, 2 and 3 m respectively has been subtracted from the simulation data for clarity.

Further, the parameters in SIBERIA are derived from average annual data. The transferability of this data to model that of short-term hillslope features such as rills is unknown, with this being the first study of its kind to examine rills on angle of repose slopes in mine spoil. The results show that using parameters derived from coal mine spoil, such as those of Sheridan *et al.* (2000), underestimates erosion at the site. This is not surprising, as the Sheridan data was derived from flume studies and quantified total load exiting a flume. No attempt was made to quantify soil loss from incisive processes or to identify spoil that would readily rill. The study of Sheridan *et al.* (2000) also examined spoil erodibility at much lower slopes than our study site. Even though the site is very young, the role of armouring and sorting of sediment through time is unknown (Polyakov and Nearing, 2003).

This study was conducted on a single continuous slope providing spatial continuity of hillslope and runoff processes, unlike bounded plot studies (Nicolau, 2002). While not proposed for Rix's Creek mine, if angle of repose slope were to be used further, studies into short and long term erosion processes are needed. To provide a better calibration, long term plot studies are needed for the spoil material and climate, as there are few studies that have examined this issue on such high slopes. An alterative to long term plot studies is to use laser scanning to measure the hillslope through time, and these data coupled with rainfall records would allow a calibration to be performed with confidence. This process would require a higher resolution laser scanner than that which we currently have available. This would be quick and cost effective and have considerably fewer long term logistical issues than using field plots and the measurement of sediment transport and rill volumes.

It was impossible in this study to determine actual soil loss rates for the hillslope from the field data as we do not know the initial surface elevation, nor is it possible to conduct plot or hillslope studies over the long term (Martinez-Casasnovas *et al.*, 2002; Nicolau, 2002). Other methods such as ^{137}Cs (Zhang *et al.*, 1998) are not possible due to the young age of the site. It is likely that a considerable amount of material has been lost in the interrill space by surface wash. Nevertheless, the amount of material lost by rill erosion can be crudely calculated to be 18·5 m^3 for the site, based on the measured rill characteristics and assuming the tops of banks coincide with the initial surface. This value is likely to be a lower bound and a gross underestimate. It is also impossible to accurately quantify the amount of rill

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and interrill erosion for the model simulations, as any calculation includes both rill and interrill erosion, and sediment loss by SIBERIA does not explicitly differentiate between the two erosion processes. Totals for the simulations using $m_1 = 1{\cdot}5$, 2 and 2·5 are 5 m^3, 27 m^3 and 84 m^3 respectively, and these will be an overestimate when compared with the field data as they include both rill and interrill erosion components. While the field and simulation results cannot be compared, these figures show that the modelled results, when assumptions are made about the limitations of the volume calculations, are within the same order of magnitude and therefore respectably similar.

This study has examined the ability of an erosion model to capture the morphology and spacing of rills using a single set of initial conditions for the simulations. Other areas to explore as part of this modelling process include the role of initial surface roughness and microtopography (Favis-Mortlock *et al.*, 2000) in rill position, shape and spacing, as it has been demonstrated that different surface roughnesses can affect sediment transport rates (Hancock, 2005). Other important issues include interrill erosion rates, the role of rainsplash erosion on fresh mine spoil and how the new hillslope geomorphologically evolves over the medium (hundreds of years) to long term (thousands of years) as the hillslope dynamically adjusts in relation to vegetation, armouring and pedogenesis (Saco *et al.*, 2006). These issues are currently being addressed by the authors.

Conclusion

Soil erosion is a complex process, which is governed by the underlying geology and soil characteristics, rainfall, topography, vegetation, landuse and management practices. Consequently each hillslope and catchment has individual characteristics, which, if we are to model soil erosion, requires knowledge of many parameters, many of which are site specific. It is well recognized that soil erosion has both on-site and off-site impacts, and in recent years there has been a range of new predictive models and field measurement techniques used for prediction and measurement (Zhang *et al.*, 1998).

This study has examined rill development and morphology on a very young, angle of repose slope, constructed of homogeneous mine spoil and devoid of vegetation. Mine sites offer the ability to study 'new' or 'transient' landscapes created of fresh material where landforms are rapidly developing and offer the rare ability to understand and quantify early or young landscape processes. When able to be accessed safely, due to their relatively quick evolution they offer the valuable opportunity to evaluate models.

The rill patterns observed on this slope were very similar to that of other angle of repose slopes constructed of similar material, with the rills initiating near the top of the slope and running largely linearly down the slope, forming distinct drainage lines, and being regularly spaced. No rills appeared to be more successful than others, yet there was some cross-grading and coalescing of rills. The cross-sectional profile of the rills was triangular with steep sidewalls. The laser ranging system used was unable to capture the finest detail of the rills, and a greater density of points is needed to capture the rill morphology more fully. Nevertheless, the system used in an appropriate relative location correctly captured the morphology of the studied hillslope at the level of detail and accuracy sufficient for an analysis of the SIBERIA system. The results have shown that a digital-elevation-model-based soil erosion model can be used to simulate rill development. They also show that the model is very sensitive to different parameters and that reliable model calibration is needed to correctly capture rill morphology and sediment loss.

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