Sustainable mine rehabilitation – 25 years of the SIBERIA landform evolution and long-term erosion model

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ABSTRACT

Mine site rehabilitation is becoming increasingly sophisticated through improved knowledge as well as advances in technology. Computer-based landscape evolution and soil erosion models are tools that can greatly assist mine rehabilitation. This paper outlines where rehabilitation practices and the use of landscape evolution models can greatly improve rehabilitation outcomes and the rehabilitation design process. The focus here is on the SIBERIA landscape evolution model, which has been used by the mining industry for the past 25 years. The paper outlines the history of landscape evolution models and SIBERIA, the model functionality and model calibration process. A particular focus is placed on testing and evaluation of the model for both natural and post-mining landscapes. As the expectation is that the model can accurately and reliably predict soil erosion and landscape evolution at decadal time scales and longer, the need for long-term test sites to be established is also explained. Finally, future developments to the SIBERIA model are discussed.

INTRODUCTION

Cost-effective and environmentally sustainable rehabilitation design is crucial for the long-term stability of an engineered post-mining landform. Underlying any closure strategy is the need to engineer a rehabilitation program that allows for a walk away at the end of operations. To achieve a walk away result it is expected that a significant research effort will be required as waste rock dumps (WRD) and tailings facilities are considered one of the greatest long-term post-mining liabilities.

Rehabilitation practices of the mining industry are increasing in sophistication as community and government expectations of long-term landscape sustainability become necessarily increasingly rigorous. In particular, post-mining landscapes need to be designed using an understanding of geomorphic landscape processes together with best practice technology. In the rehabilitation of land systems affected by mining, the final result is largely controlled by topographic reconstruction (Toy and Hadley, 1987; Hancock, Loch and Willgoose, 2003). Understanding the geomorphology of the post-mining system is vital to successful rehabilitation as geomorphology influences soil and soil development down the slope (that is, the soil catena), landscape hydrology, establishment and maintenance of vegetation as well as erosion.

Post-mining rehabilitation projects fail because the landscape is unable to sustain functional ecosystems and/or because the export of sediments has and can affect ecosystems downslope and downstream (Evans, 2000, 2010; Nicolau, 2004). For any mine, a reconstructed landscape must be designed to achieve a long-term viable ecosystem while releasing sediment at a minimal rate and geochemically compatible with the surrounding undisturbed landscape. Consequently, landform stability over the long term is essential for a sustainable functioning ecosystem. Assessing the long-term behaviour of any rehabilitated site is difficult, as visual inspection after a few years may not reveal any longer-term issues. Computer-based landscape evolution models offer the ability to evaluate landscape stability over the short (annual), medium (hundreds of years) and long term (thousands of years). Modelling has advantages in that design ideas can be tested, different surface material properties and treatments can be evaluated, and risk analysis carried out. Landscape evolution models allow the landscape surface to change through time, in contrast to other models. These models also offer the advantage that the landscape can be evaluated visually as it develops through time, which is not possible with other models. Landscape evolution models can be used for not only soil loss assessment (tonnes/hectare/annum) but also to evaluate the method of soil loss (rill or interrill erosion) and the design life of erosion protection treatments.

LANDSCAPE DESIGN

The goal of any mine is to operate with minimal environmental impact (Evans, 2000, 2010). During mine operations, environmental impacts are largely planned and can be controlled. A major issue on any mine site is water management, with all sites having plans to manage and control water for all but the most extreme and unforeseen events. Implicit with this is that any contaminated water and/or sediment will be managed and controlled on-site. Post-closure, the goal is for the disturbed area to be rehabilitated such that the area blends in with the surrounds, has minimal off-site impact and is environmentally sustainable. This requires that hillslope shape and length be constructed to achieve these goals.

The first step of this process is to design a landform that is erosionally stable. This requires that a landscape have hillslope lengths and slopes that ensures erosion will be minimised. A significant issue with designing landforms that are in keeping with the surrounding non-mined landscape is the increased waste volume or bulking as a result of blasting and handling. In many operations the resource removed is only a small fraction of the material moved, leading to an increase in the volume of the waste rock or spoil, so that some structure above the premined elevations is inevitable.

If erosion from the landscape is minimised or in keeping with that of its surrounds then vegetation has a good chance of being established and maintained, nutrients stored and available for recycling on-site and soil development enhanced. This process could be considered a positive feedback loop. This also ensures that any sediment leaving the site (some soil loss is inevitable) is potentially at the same soil loss rate as the surrounding unmined landscape and that any pollution issues (excess sediment, incompatible sediment geochemistry) contributing to the surrounding landscape and waterways is minimised.

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If, however, slope length and slope angles are not suitable, together with a non-ideal growth medium (that is, poor topsoil) then rills and gullies will result. This then will ensure that any topsoil is lost, nutrients exported and gullies may develop. Even if viable soils subsequently form, the erosion rate may be too high to allow seeds to germinate and set root into the rehabilitation. If gullies form, these will depressurise any shallow groundwater system leading to a loss of soil water and nutrients. If the site has suboptimal material contained within the rehabilitation structure then gullies have the potential to expose this material. The overburden at any site can be relatively benign with no harmful characteristics; however, at many mine sites material with a high salt content, acid generating potential or other unacceptable content (for example low-grade ore, tailings) needs to be managed. Ideally, the waste stream and construction of the WRD need to be designed and constructed with any contaminant issues being considered. This means that any contaminant can be contained and/or encapsulated within the WRD in a planned manner. Therefore post-mining erosional and landscape stability is key for any post-mining land use to obtain its integration with its surrounding undisturbed landscape system.

LANDSCAPE EVOLUTION MODELS

It is mandatory that mines in Australia demonstrate that they have a stable and ecologically sustainable post-mining structure (Australian and New Zealand Minerals and Energy Council / Minerals Council of Australia, 2000). At most sites erosional stability is largely determined by visual or qualitative assessment after a time period of years to at most a few decades and may be insufficient given the larger climate extremes of more arid Australian environments (Peel, McMahon and Finlayson, 2004).

There are a number of modelling tools that can be used to assess erosional stability. First, models such as the RUSLE and derivatives (Wischmeier and Smith, 1978; Laflen *et al*, 1991) have been widely employed. The RUSLE has been used globally and there is a large database of parameters available for most situations. Further model developments such as WEPP (Laflen *et al*, 1991) provide a more sophisticated analysis capability with many additional features, such as plant growth modules, variable climate (via climate file input), as well as being able to be linked to other hillslopes and catchments. These models, while very reliable and useful when calibrated and used appropriately do not predict both erosion and deposition patterns and they do not dynamically adjust hillslope elevation in response to erosion and deposition (Laflen *et al*, 1991; Willgoose, Bras and Rodriguez-Iturbe, 1991a–1991d; Riley, 1994; Evans and Riley, 1994; Flanagan and Livingston, 1995; Evans and Loch, 1996; Willgoose and Riley, 1998; Evans, 2000; Evans and Willgoose, 2000; Loch *et al*, 2000).

An advance on the above models is landform evolution models (LEMs). There are numerous soil erosion and landform evolution models developed and employed for a wide range of uses (Willgoose, Bras and Rodriguez-Iturbe, 1991a–1991c; Braun and Sambridge, 1997; Coulthard, 2001; Tucker *et al*, 2001; Coulthard and Van De Wiel, 2006). Originally developed to assess landforms over geological time (Ahnert, 1976), the usefulness of LEMs for engineering applications was quickly realised. Coulthard (2001), Willgoose (2005) and Tucker and Hancock (2010) provide a review of most available models.

Here the focus is on the SIBERIA LEM, which is the model most widely used internationally for mine rehabilitation assessment. SIBERIA is a computer model for simulating the evolution of landscapes under the action of run-off and erosion over long times scales (typically more than a few years) (Willgoose, Bras and Rodriguez-Iturbe, 1991a–1991c). SIBERIA is both a very simple model and a very sophisticated one. The hydrology and erosion models are based on ones that are simple and that have been widely accepted in the hydrology and agricultural communities since the 1960s. These models are based on widely accepted erosion physics and have been successfully calibrated in a range of environments. The sophistication of SIBERIA lies in its use of digital terrain maps for the determination of drainage areas and geomorphology and its ability to efficiently adjust the landform with time in response to the erosion that occurs on it.

A very brief (and necessarily incomplete) summary of its key capabilities follows.

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 capacity per unit width
q_{sf}	is the fluvial sediment transport term
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) is the slope in the steepest downslope direction
β_1, m_1 and n_1	are calibrated parameters

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

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

where:

D (m^3/s/m width)	is diffusivity
S	is slope

The diffusive term models smoothing of the land surface and combines the effects of creep and rainsplash. SIBERIA does not directly model run-off (Q, m^3/s – for the area draining through a point) but uses a subgrid 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 run-off rate constant
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 (SIBERIA is currently being extended to allow the modelling of a climate series and this will be made generally available in due course), but rather the average effect of many aggregated events over time are quantified. 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 and deposition that occurs on it.

The most basic function of SIBERIA is that of linked erosion and deposition models that route sediment in the steepest downslope direction. However, since its original development there have been several important additions that greatly increase functionality. The most significant of these are described below.

Spatially variable erosion

There are very few landscapes, whether they are natural catchments or rehabilitation structures, that have uniform surface materials and therefore uniform erosion properties. In most cases only one set of parameters is available and therefore a uniform set is employed across the entire modelled landform. However, SIBERIA offers the capability to spatially distribute different fluvial erosion model parameters (that is, β_1, m_1 and n_1) on a grid cell by grid cell basis if the differences in erosion are known. This function has been demonstrated successfully at the former Nabarlek uranium mine (Hancock *et al*, 2008b). This is a model function that quite often surpasses the field data available.

Hydrology – discharge from off-site and spatial variability

A further functionality is that the model can optionally input discharge from off-site and spatially variable run-off. If there is a large flow coming from off-site then this inflow can be introduced at any grid point. This feature is particularly useful if there is a large domain and only a specific area needs modelling. It also allows large domains to be modelled efficiently. This feature has been demonstrated by Hancock *et al* (2000) for a WRD that used a high resolution digital elevation model (DEM), where discharge from upslope was input to the DEM from an undisturbed hillslope to which the DEM was linked (Hancock *et al*, 2000).

Similar to erodibility, there are very few landscapes, whether they are natural catchments or rehabilitation structures, that have uniform surface materials and therefore uniform run-off. SIBERIA offers the capability to spatially distribute discharge parameters (that is, β_3 and m_3) on a grid cell by grid cell basis if the data is known. This function has been demonstrated successfully at the former Nabarlek uranium mine (Hancock *et al*, 2008b). Similar to the spatial variability of erosion, this is a model capability that quite often surpasses the field data available.

Tectonics model

While not of critical importance for Australia, in many parts of the world tectonic uplift is an important component of long-term landscape evolution. SIBERIA can easily apply uplift at any defined rate at each node. The model can also apply a time varying sinusoidal function if this behaviour is appropriate.

Layer model

Similar to differences in surface erodibilities, there are few natural or reconstructed landscapes where erodibility is constant down the soil profile. For a natural landscape, soil horizons and resultant soil profile is well encapsulated by a single set of erosion parameters as the landscape has evolved as a single entity. However, post-mining landscapes often are constructed of layers of different materials and in some cases have constructed caps and barriers to encapsulate suboptimal material.

SIBERIA allows different layers of material with different erodibilities and is represented by a series of layers of material with specified characteristics (for example erosion, run-off). Fluvial erosion and hydrology properties can be changed from layer to layer and as the landform erodes the model tracks the flow and the characteristics of the material being transported. This has the consequence that the material being transported by the flow determines the transport capabilities of the flow. The characteristics of the flow reflect the mixing of material being transported from upstream and the material being eroded at that point. This capability is essential to be able to correctly model localised regions of rock armouring.

At present SIBERIA determines erosion characteristics based on a characteristic diameter of the eroded sediment (for example d_{50}) and a mixing model is provided to allow simulation of different kinds of diameter dependency of sediment transport. When deposition occurs the characteristics of the material being deposited are those of the material in the flow at that point and time. Deposition is assumed to be instantaneous. Since the characteristics of the material being deposited typically change over time and space (and with cumulative upstream erosion exposing new layers, or eroding previously deposited material), the changing characteristics of the deposited material are tracked and a profile of layers of deposited material is created at that point. If an area of previous deposition is eroded at some later stage of the evolution then the characteristics of the entrained sediment are those of the layer currently being eroded. As the layers are eroded the characteristics of the entrained sediment change to reflect the current layer being eroded.

The layers are applied, deposited, eroded etc at each point independently of any other point. The model does not explicitly impose any spatial layering structure (that is, linking of a layer at one location with some layer at another location) as deposition simply reflects deposition characteristics at each individual location. However, since sediment characteristics change slowly as you proceed down a drainage path there is likely to be some spatial layering pattern that arises naturally from the deposited sediment. This reflects the physics, not any structure imposed by the layering model.

Armouring model

Armouring of a soil surface is the process whereby the surface coarsens by the removal of readily transportable fines. The fluvial process that occurs on the surface is one of winnowing of fine materials, leaving behind coarser material that provides some level of protection against further erosion. Any increase in overland flow will either destroy the armour or further coarsen it. Once the fines have been removed this provides a stable layer that will remain unless overland flow increases (which may lead to destabilisation of the armour layer). Surface armour therefore provides protection against rainsplash and associated detachment and a reduction inflow velocity due to an increase in surface roughness (Brakensiek and Rawls, 1994; Poesen, Torri and Bunte, 1994; Rieke-Zapp, Poesen and Nearing, 2007).

The effect of armouring has been incorporated into the SIBERIA sediment transport equation where the fluvial sediment transport term employs a depth dependent armouring and erosion submodel within fluvial sediment transport equation, which is a simple approximation to an armouring reduction of erodibility. The logic of the model is that in a well graded soil the greater the erosion at a point, the quicker the erosion at that point will reduce due to the development of an armour layer. Willgoose and Sharmeen (2006) showed that the armouring process greatly affects the erosion rate and also has the effect of reducing the SIBERIA erodibility parameter β_1 (Equation 1) through time.

The model ensures that for the initial conditions of a simulation, the erodibility starts at the default β_1 value for erodibility (chosen by the user and described previously, Equation 2) but that as the depth of erosion increases the erodibility reduces asymptotically to zero. To determine the depth of erosion, Z_e, the elevation at the start of the simulation is subtracted from the current elevation at that point. If there is net deposition at that point on the hillslope then no adjustment is made. The advantage here is that the SIBERIA model self-adjusts the β_1 value in response to erosion and deposition without any external user input. This approach, embedded within the SIBERIA model is both spatially and temporally dynamic and negates the need to quantify a soil surface particle size distribution and related shear stress (Parker and Klingeman, 1982; Wilcock and Crowe, 2003). For rocky spoils this improves the match with field data for the depth of gullies (Bell and Willgoose, 1998; Willgoose, in press).

The model is simple and easily employed and recent work has demonstrated that site-specific calibration is necessary (Hancock *et al*, 2016a).

CALIBRATION AND SIBERIA INPUT PARAMETERS

An important part of any modelling assessment is the determination of input parameters. SIBERIA is no different. There are a number of ways that SIBERIA input parameters can be calibrated. These are discussed below in order of increasing sophistication.

Soil textural properties or particle size distribution as well as the physical attributes of soil (that is, organic matter content, electrical conductivity and rock content) can be used to provide a measure of erodibility and derive SIBERIA parameters. This erodibility data can be derived from rainfall simulator and flume studies for a range of soil materials (Sheridan *et al*, 2000). The erosion data can then be used in a multiple regression between sediment concentration, slope and discharge as well as soil physical properties, producing parameters that predict annual erosion. Several SIBERIA erosion parameter databases have been developed based on this approach. Studies such as that of Sheridan *et al* (2000) provide an erosion parameter resource as well as a method for future parameter derivation.

For natural catchment assessments, the fluvial erosion sediment transport equation parameters m_1 and n_1 (Equation 2) can be determined from DEMs and the catchment area-slope relationship. The area-slope relationship of a catchment is the relationship between upslope area draining through a point versus the slope at that point. If the site is at or 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:

$$S \propto A^{-\alpha}$$

$$\alpha = (m_3 m_1 - 1)/n_1 \qquad (5)$$

where:

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

By determining the slope of the fluvial region of the area-slope relationship and an assumed value for n_1 (equal to 2), then m_1 can be determined. In most studies a value of $n_1 = 2$, for wide channel flow as suggested by Henderson (1966) and described in Willgoose *et al* (1991a–1991b), and a value for m_3 of 1, are appropriate (Kirkby, 1971). Soil textural properties can be used to calculate a K based on the RUSLE methodology or database (see K values listed for different soils listed in Hazelton and Murphy, 2007) (Evan and Loch, 1996). The RUSLE K value can be considered to be equivalent to the SIBERIA β_1 (Equation 2) (Willgoose, 2012).

An alternative approach that has been used is to calibrate SIBERIA to the outputs from a traditional agricultural erosion model such as WEPP or RUSLE. This can be convenient if this other model has already been set up and used for the site, though it is an approach that can be fraught with danger. The main issue is that these traditional agricultural erosion models typically make implicit assumptions about the dependency of erosion on discharge and slope that are satisfactory for short-term erosion simulations (that is, a few years) but do not reflect important processes that may develop over a number of years (for example rilling, surface armouring; Willgoose and Riley, 1998; Sharmeen and Willgoose, 2007). Willgoose and Gyasi-Agyei (1995) and Solyum and Tucker (2007) have shown how changes in the discharge-slope dependency of erosion (within the range assumed by agricultural erosion models) can make dramatic differences in the predictions of the depth and location of gullies.

However, the most reliable SIBERIA parameters are derived from field data where there are known catchment areas and slopes, and all water and sediment discharge are collected for a series of significant storms. To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall and run-off for discrete rainfall events are collected. The data is then used in a multiple regression of rainfall, hillslope discharge and sediment output to optimise the hydrology and sediment transport equation parameters. This method is the most reliable as it is site based and therefore is representative of the site materials and sediment transport processes. It also can capture change in surface materials as a new surface evolves (Hancock *et al*, 2016a). Vegetation growth can be monitored and vegetation removed by fire if required and assessed (Evans, 2000; Evans *et al*, 2000). However, this field-based approach requires many rainfall events and therefore time. Such field plots are costly to set up and maintain. This parameterisation process is described in detail by Evans *et al* (1999); Evans, Saynor and Willgoose (2000) and Hancock *et al* (2000).

LANDSCAPE INPUT – DIGITAL ELEVATION MODELS

Landscape evolution models such as SIBERIA require a DEM to represent the landscape surface. There are four important issues with DEMs:

1. The DEM needs to be accurate and reliable. That is, each coordinate needs to be true with no errors, such as high and low points. The SIBERIA model (or any other model) cannot differentiate between a reliable or unreliable set of coordinates. Any error will influence how erosion and deposition occurs as well as the erosion rate and ultimately landform evolution. In a worst-case scenario gullies may occur due to erroneous low points that wrongly concentrate flow. A DEM, particularly if derived from digital photogrammetry, should not have any systematic bias that twists or warps the DEM (Moreno de Las Heras, Saco and Willgoose, 2012). Such bias can be difficult to determine without sufficient and reliable control points.
2. The DEM needs to be at a resolution (have a grid cell size) that represents the landform feature of interest (Hancock *et al*, 2006). Hancock (2005) showed that a 5–10 m grid cell size is sufficient to capture hillslope length and curvature for catchments with rolling topography and hillslope lengths of 100–150 m (a rule of thumb is to use a minimum grid size one-tenth of the average hillslope length). However, for a mining landscape where benches and contour banks are an integral part of the landform, a grid size must be used that can capture these features. Therefore, if a contour bank or constructed drainage line is 3–4 m wide, a DEM grid scale must be used that can reliably capture these features (for example 2 m or better DEM).
3. The coordinate data for WRD, reconstructed catchment of hillslope can be derived from a wide range of techniques and processes from field survey using a theodolite (the simplest approach, Hancock *et al*, 2000) through to laser scanning, light detection and ranging (LiDAR) and digital photogrammetry (Hancock, Willgoose and Evans, 2002; Hancock, Willgoose and Evans, 2007). In the initial planning process, coordinate data can come from programs such as AutoCAD (and derivatives) as well as specific mine planning software such as Vulcan. In many cases the grid points can be sparse and irregularly spaced, requiring extreme care in data preparation. Choice of gridding algorithm (that is, kriging, Delaunay triangulation, linear interpolation) is absolutely critical in providing the correct representation of the landscape surface (Hancock, 2006).

4. A further issue not largely recognised is that DEM preparation can be very time consuming. This issue cannot be stressed highly enough. The authors have found that this landscape file preparation process can take days to weeks to complete and quite often is the most significant time component of any project. Particularly problematic are coordinate data sets of WRDs, which were originally captured for volume estimation only. These data sets rarely have sufficient numbers and density of points from which contour banks, benches and roads can be reliably derived.

Ultimately, SIBERIA is a computer model that will utilise its input and cannot discriminate between good or poor data. That is, the landscape model output is only as good as the landscape model input.

TESTING LANDSCAPE EVOLUTION MODELS

A significant issue with long-term LEMs is how do you evaluate a model that has the capability to make both short- and long-term landscape predictions? Is the model reliable over both short and long time scales?

Landscape evolution models have mostly been tested using landforms at long-term equilibrium or steady-state (Willgoose, 1994; Willgoose, Hancock and Kuczera, 2003), and where the time evolving aspects of the model can be ignored (for example Hancock, Willgoose and Evans, 2002). The rationale behind using equilibrium landforms is that the data requirements are less, and that if the models cannot do well in this case, they are unlikely to do well in the more difficult case of transient or evolving landforms. Tests on equilibrium landforms do not provide a very rigorous test of model adequacy as, for a given set of model parameters, the equilibrium steady-state form of an uplifting landscape is readily described by a simple relationship between slope at the catchment outlet, and the drainage area of that catchment; the area-slope relationship (Willgoose, 1994). If there is no uplift, then the area-slope relationship also involves catchment elevation.

However, there is considerable variation in model behaviour in the period before landforms achieve steady-state. Thus, more powerful model tests can be applied by looking at transient behaviour. For instance, published models for transport – and detachment-limited processes can yield an indistinguishable area-slope relationship in a dynamic equilibrium, when erosion balances uplift. Recent work has indicated that in the absence of uplift, when the landform is declining towards the Davisian peneplain, transport-limitation will yield characteristic non-dimensional forms for a broad range of process parameters (Willgoose, 1994), while detachment-limitation will not (Sinclair and Bell, 1996). This is irrespective of whether, over the long term, they both converge to the same area-slope relationship (Solyum and Tucker, 2007). Another reason for an interest in transient landforms is that applications of landform evolution models for long-term erosion modelling (Willgoose and Riley, 1998) require validation at timescales where transient behaviour is dominant. Equilibrium validations are unlikely to be able to guarantee the correct behaviour of models in the transient regime.

Over the past 25 years the authors have spent considerable time calibrating and evaluating SIBERIA using a range of approaches. The approaches used are described below.

Long-term evaluation

Initially SIBERIA was compared with laboratory scale experimental model landforms, which provided confidence in the model's long-term predictive capabilities (Hancock and Willgoose, 2001, 2002). This approach involved a sand box and rainfall simulator and examined a number of different landscapes with different catchment geometries. SIBERIA was also shown to match erosion rates and hillslope profiles in the experimental catchments (Hancock, Nuake and Fityus, 2006). The results demonstrated that SIBERIA simulated landscapes approximated the experimental systems. However, there are always questions of scale and boundary conditions when using laboratory scale apparatus.

Millennial time scale evaluations are difficult given the issues with dating and/or quantifying pre-existing landscape conditions. Long-term evaluations have been conducted by comparing SIBERIA with other LEMs such as CAESAR. These tests, mostly at the Ranger and Tin Camp Creek sites, have demonstrated that both models predict broadly similar outcomes (Hancock, Willgoose and Evans, 2002; Hancock *et al*, 2010). Therefore at the sites examined, the models can be considered reliable.

Further evaluation of the model was undertaken using assumed initial catchment conditions with SIBERIA run over geological time until the catchment reached equilibrium, matching the natural catchment (Hancock, Willgoose and Evans, 2002; Willgoose, Hancock and Kuczera, 2003). This study, conducted at Tin Camp Creek demonstrated the theoretical long-term (geological time scale) reliability of the model (see below for further detail).

Ibbitt, Willgoose and Duncan (1999) also demonstrated the reliability of the model for undisturbed field sites in New Zealand. They compared SIBERIA and another geomorphology model, the optimal channel network (OCN) model, against the Ashley River Catchment in the southern Alps. They found that SIBERIA consistently provided a better reproduction of the topography, channel network geometry and age of the catchment than the OCN.

Field assessment – the Ranger uranium mine

The first use of SIBERIA in an engineering application was at the Ranger uranium mine (Willgoose and Riley, 1993, 1998). The mine is heavily environmentally scrutinised as it is surrounded by Kakadu National Park and associated environmental and heritage sites of global significance. Legislative requirements are such that the site must demonstrate that no contaminants will leave the site for millennia (Commonwealth of Australia, 1987). At this site there are significant volumes of waste rock as well as low-grade uranium ore and tailings that require encapsulation for millennia. Therefore, design of any rehabilitation structure is of extreme importance for long-term containment of encapsulated materials. At Ranger, SIBERIA was employed to evaluate a series of initial designs (Unger *et al*, 1996; Willgoose and Riley, 1993, 1998).

However, it was quickly realised that while the model can be easily applied and the results valuable, the model required site-specific calibration. Further, it was realised that a single set of parameters derived from the initial landform surface may not be representative of the long-term surface. As a result of this realisation, a series of plots were established, which were maintained and monitored over a number of years.

This was pioneering work because there were few, if any, data sets available globally to calibrate and/or quantitatively validate a LEM (Evans, 2000; Evans and Willgoose, 2000; Evans *et al*, 2000). The plots at Ranger included bare waste rock, vegetated waste rock as well as a series of plots that were vegetated and subject to fire. The field plots were monitored for rainfall, water and sediment discharge including both suspended and bed load (total load) with the data collected on a storm-by-storm basis. These plots were maintained and monitored for a number of years with as many storms monitored as possible.

It was quickly realised that a newly constructed and rehabilitated surface quickly armours, pedogenesis commences and vegetation establishment quickly changes erosion properties of the surface. Therefore, after a survey of degraded mine sites in the Alligator Rivers region (Willgoose and Loch, 1996), a new field site was established at the Scinto 6 former uranium mine, a site that had been abandoned in the 1950s (Hancock *et al*, 2000; Moliere *et al*, 2002; Evans, 2000). At this site, two plots were established from which hydrology and erosion parameters were determined for the 60-year-old surface.

Also, Tin Camp Creek (TCC) was identified as a surrogate for the likely rehabilitated structure of the Ranger mine due to its geochemical similarity, as well as having slope lengths and angles similar to any rehabilitation design (Riley and Rich, 1998). Here a series of rainfall run-off plots were established from which natural or analogue site parameters were derived (Moliere *et al*, 2002). Using these plot data, Hancock, Willgoose and Evans (2002) demonstrated that SIBERIA could predict long-term landscape evolution for the site. Medium-term (decadal times scale) SIBERIA validation was performed at TCC by comparing erosion rates determined from environmental tracer data (^{137}Cs determined erosion rates) as well as the RUSLE (Hancock *et al*, 2008a). Further work has examined SIBERIA's ability to predict gullying at the site (Hancock *et al*, 2010; Hancock, Willgoose and Lowry, 2013). Further long-term work has also evaluated SIBERIA against other LEMs (Hancock *et al*, 2010, 2011a). The Ranger, Scinto and TCC data provide three sets of parameters for the initial surface (0–10 years), medium time scale (50–60 years) through to geological time scale or natural time scale parameters (effectively the age of the soils, about 100 000 years).

Coupled with this is the extensive work of Duggan (1991), Cull *et al* (1992) and Erskine and Saynor (2000) who developed denudation rates for the area based on a range of data including stream sediment measurements. Hancock and Lowry (2015) have also determined decadal scale hillslope erosion rates using erosion pins. This denudation rate or rate of geological lowering provides a guide to the natural or background erosion rate. Decadal-scale SIBERIA-determined erosion rates are compared to this catchment scale data and therefore provide a test of SIBERIA's ability to predict long-term erosion rates (Hancock, 2009; Hancock *et al*, 2010, 2015; Hancock, Lowry and Coulthard, 2015; Hancock, Lowry and Saynor, 2016).

A further evaluation of the model was undertaken at TCC to assess the ability of the SIBERIA model to predict gullies (Hancock, Willgoose and Lowry, 2013). This was considered an important confirmation of SIBERIA's capabilities as the LEMs have been employed to evaluate the likely occurrence of gullies, particularly for sites where suboptimal material is encapsulated and cannot be exposed.

Recent work has used a large trial landform plot at the Ranger site. At this site, four plots (30 m by 30 m) have been established and both bed load and suspended sediment measured over a six year period. Using the previously established parameters (Evans and Willgoose, 2000; Evans *et al*, 2000), SIBERIA demonstrated a good match to this plot data (Hancock, Lowry and Saynor, 2016). Further work tested and confirmed the armouring capacity of the model discussed earlier (Hancock, Verdon-Kidd and Lowry, in press).

Other sites

Further evaluation of SIBERIA across a range of geomorphology and climates has been conducted using both field data and modelling approaches.

One of the outcomes of the Queensland Coal Association Post-Mining Landscapes Project (So *et al*, 1998) was the development of a parameters database for SIBERIA for the spoils and soils in the Bowen Basin tested during this project. This is commonly referred to as the QCA database and is distributed as part of the EAMS-SIBERIA software package.

Hancock *et al* (2007) used laser scanning to measure rill and gully erosion on a steep slope batter on a coalmine in the Hunter Valley, New South Wales. Using a combination of this laser scan data and field measurements, SIBERIA was shown to reliably capture the erosion process at the site. Importantly, this was the first reported use of laser scanning to calibrate the model. Previous projects at other sites have used digital photogrammetry over a number of years to backfigure cumulative erosion rates on WRDs, though parameter estimation for the erosion processes using these data can sometimes be difficult and depends, among other factors, on the accuracy of the DEMs and how accurately the differences between the DEMs at different times can be determined (Willgoose, 1998).

Martinez, Hancock and Kalma (2009) found that SIBERIA-predicted erosion rates were very similar to erosion rates determined using ^{137}Cs and the RUSLE for a basalt soil grazing land use catchment with 550 mm rainfall in south-eastern New South Wales. Hancock *et al* (2011a) found that both SIBERIA and the CAESAR LEM predicted similar erosion rates in a larger basalt soil catchment that contained the subcatchment of Martinez, Hancock and Kalma (2009).

Recent work has evaluated SIBERIA against catchment-scale erosion rates for undisturbed catchments in south-eastern Australia (Hugo, 2016). These high slope and high rainfall catchments (~1600 mm/a) were compared against approximately ten years of sediment total load data. SIBERIA approximated sediment output very well for this previously untested environment and demonstrated its potential for application in forestry situations.

WHERE HAS SIBERIA BEEN USED?

The SIBERIA model has been used widely across a range of climates, land use and mine operations both nationally and internationally. The authors have been personally involved in significant projects using SIBERIA to assess both existing and proposed post-mining landscapes in Australia, Argentina (Hancock and Turley, 2005), Canada, Namibia, Papua New Guinea, Tanzania and the USA. The authors are aware of many other applications by consultants worldwide.

In Australia, the model has been employed in coalmines in New South Wales (Hancock *et al*, 2007) and Queensland (So *et al*, 1998), mineral sands mines in Victoria, metalliferous mines in South Australia, Queensland, Western Australia and New South Wales, the bauxite mines of northern Australia as well as south-western Western Australia (Hancock, Loch and Willgoose, 2003). In particular, the model has been extensively used to assess WRD designs for iron ore mines in the Pilbara region of Western Australia (Willgoose, 1998; Hancock, Loch and Willgoose, 2003).

As described above, SIBERIA has been particularly heavily used in the Northern Territory for assessment of the former Nabarlek uranium mine and the Ranger mine rehabilitation designs. The Nabarlek site was initially assessed using the RUSLE (Hancock *et al*, 2006a); however, a more advanced assessment was performed when a DEM became available for the site (Hancock *et al*, 2008a). The RUSLE assessment also included a water quality and radionuclide transport assessment. The assessment using SIBERIA was the first application of the model using spatially distributed erosion and hydrology model parameters for the different rehabilitated surfaces across this site. Both the RUSLE and SIBERIA demonstrated that while there would be considerable erosion at the site, the encapsulated radionuclides would remain covered for millennia.

SIBERIA has been extensively employed for assessment of proposed rehabilitated WRD designs at the Ranger mine. Initially SIBERIA was used for a whole of landscape assessment (Willgoose and Riley, 1993, 1998; Unger *et al*, 1996; Evans and Willgoose, 2000; Evans *et al*, 2000; Moliere *et al*, 2002) using a low resolution (30 m grid size) DEM. This assessment, using a series of field plot parameters (waste rock material and vegetated surface), demonstrated extensive gullying was likely to occur across the site with a high likelihood of tailings containment failure (Morgan and Willgoose, 1994).

Due to new rehabilitation plans and the availability of higher resolution DEMs of rehabilitation designs, recent work has focused on individual rehabilitated catchments. In this case, the Corridor Creek catchment at Ranger has been examined as it will be one of the first to be rehabilitated. SIBERIA has been employed to examine a proposed design for its erosion rate, depth and type of erosion (gullying) for a simulation time of 10 000 years (Hancock, Lowry and Coulthard, 2015; Hancock, Coulthard and Lowry, 2016). Induced surface roughness (ripping) together with construction error has also been examined.

SIBERIA has been used to design and evaluate containment structures for low-level nuclear waste (Wilson, Crowell and Lane, 2006; Bredehoeft *et al*, 2006; NYSERDA, 2010). These containment structures are required to be stable for 10 000 years. While this design lifetime is longer than expected for most mining operations, it is the design lifetime criteria adopted for uranium mill tailings repositories in Australia. This work has been a spinoff of the authors' mine rehabilitation applications (Willgoose, 2010) and has been the justification of a number of recent improvements in the technical capabilities of SIBERIA (for example the layers capability was introduced to model the multilayer caps that are commonly used on low-level nuclear waste repositories).

OTHER APPLICATIONS

SIBERIA is a soil erosion and landform evolution model that has the ability to predict type of erosion (that is, sheet wash and/or gullying) and an important use of SIBERIA has been to predict gully initiation and evolution (Hancock and Evans; 2006, 2010; Hancock, Willgoose and Lowry, 2013). As previously discussed the model has been shown to capture gully dynamics at Tin Camp Creek (Hancock, Willgoose and Lowry, 2013) and also at the Scinto 6 former uranium mine (Hancock *et al*, 2010). Importantly, SIBERIA has demonstrated *not* to produce gullies for environments where gullies do not exist (Hancock *et al*, 2011a).

While primarily a LEM, SIBERIA can be easily adapted for other uses and applications. For the mining industry, contour banks, engineering drainage lines as well as channel armouring can easily be incorporated and evaluated (Gyasi-Agyei and Willgoose 1996; Hancock, 2004). Surface roughness to capture the effects of ripping can also easily be incorporated into a DEM (Hancock, Lowry and Coulthard, 2015). This allows the assessment of different surface properties for both the determination of erosion rates as well as erosion process.

The model has also shown its adaptability by being able to assess the impact of tree-throw on erosion and landscape evolution (that is, an extreme climate event) as well as the role of animal disturbance (feral pigs) on soil erosion (Hancock *et al*, 2011b; Hancock, Lowry and Saynor, 2015).

The tree-throw assessment was performed by incorporating the pit-mound topography (measured from field data) associated with tree-throw into the DEM (Hancock *et al*, 2011b). The SIBERIA model was used to assess this disturbance by incorporating the effects of both the pit-mound topography as well as the tree trunk on hillslope hydrology and erosion.

A further study examined the effects of extensive pig disturbance on soil erosion (Hancock *et al*, 2015). This study determined the size and extent of pig digs over a number of years and then incorporated this field data into a high resolution DEM. Both studies demonstrated how easily SIBERIA could be adapted to other important environmental applications.

RISK ASSESSMENT – PROBABILISTIC APPROACH

Landscape evolution models can provide a risk assessment for any design based on a statistical approach that aims to capture parameter variability, error or variability in landscape construction and climate variability. Calibration can be viewed stochastically, where the input data, such as the DEM and/or model calibration data can be uncertain. As a result, this data variability produces landscape and erosion parameters that are uncertain so that the predictions are uncertain. A model with a small amount of calibration data will be highly uncertain (that is, have a large variance on its predictions) with increased data availability typically reducing uncertainty in model predictions.

Generally it is not possible to perform repeated sets of field experiments or collect long-term data due to logistics and cost. As a result it is not possible to determine the variance of calibration inputs directly from the data. However, if the main sources of variability and the ranges of variability can be characterised, then landform evolution projections can be randomly simulated by sampling from this variability.

This involves Monte Carlo simulation of landforms, where parameters are randomly selected within their feasible range, another set of random parameters is selected and another landform projection is simulated, and so on. Each landform is a product of the statistically derived data and each landform realisation varies randomly because of the random inputs. After running a number of these realisations (for example Willgoose, Hancock and Kuczera, 2003 and Hancock *et al*, 2016b both used 100 replicates to examine landform variability, while Hancock, Verdon-Kidd and Lowry, in press, used ten rainfall replicates), the outputs to determine the probability limits of the model predictions can be statistically assessed.

This probabilistic assessment can be performed by:

- If it is known how the slope is to be constructed and accuracy of construction then that error can be incorporated into a DEM of the initial landscape surface and assess the impact of construction error on the stability of the landform (Morgan and Willgoose, 1994; Hancock, 2003; Willgoose, Hancock and Kuczera, 2003; Hancock, Coulthard and Lowry, 2015). Multiple hillslopes can be constructed incorporating this error. For example, Hancock, Coulthard and Lowry (2015) demonstrated that at any point on a slope there may be a construction error of ±0.1 m due to ripping. Other errors may result due to slumping and settlement. This type of error can be easily incorporated into the initial or starting surface DEM.
- If the model input parameter distribution is known then hydrology and erosion parameters can be randomly selected from within this distribution.

The results can be assessed by a sensitivity analysis of the impact of maximum and minimum parameter values while the incorporation of both DEM and hydrology and erosion equation parameter variability could be performed. However, this approach is numerically intense (Willgoose, Hancock and Kuczera, 2003). The common availability of multicore desktop computers has made these simulation capabilities increasingly easy to access outside the research environment.

Using this approach a landform design can be assessed statistically using a robust and defensible methodology. This can provide not only average data, such as average soil loss rates for a slope, but also maximum gully depth, position of gully commencement and average maximum and minimum gully volumes, and probabilities of containment failure. Such an assessment may prove extremely valuable when assessing novel rehabilitation design options where the probability of failure and consequence of that failure need to be characterised (Hancock, Lowry and Saynor, 2016).

CONCLUSION AND FUTURE DEVELOPMENT

Mining has and always will be a central part of the Australian economy.

In the past, mining in terms of footprint was relatively small; however, with increasing technology and resultant economies of scale, mines and their infrastructure are becoming larger and have the potential to be a significant long-term legacy if not environmentally well-planned and managed. It has become increasingly recognised that environmental planning and management will pay economic dividends to the mining company and the community. Therefore with large and ever increasing size of mines, together with the associated waste stream, long-term planning and post-closure rehabilitation is of key importance.

A key issue is that once mining spoil has been placed or a landscape has been constructed, it is relatively costly to make any significant changes. It is even more difficult post-closure if any unforeseen erosion issues emerge. Any constructed landform will be different to the prior undisturbed or natural surface and have some environmental impact. This reconstructed landform will be present forever post-mine closure. It is therefore of critical importance that we as a community get the design right. SIBERIA can provide significantly improved environmental outcomes.

The SIBERIA model is the most widely tested and used landscape evolution model in the world. It offers unparalleled capability as a design assessment tool and erosion model together with its ability to assess different surface materials and hydrological conditions. Its speed of operation allows landscape assessment to be conducted over relatively short computing times (minutes versus days compared to other models) and can be operated over a relatively large domain. The paper concludes with three important issues.

The need for a long-term study site

The authors have spent the past 25 years using, testing the SIBERIA model on constructed landforms, extending SIBERIA with mine rehabilitation specific capabilities and developing the associated tools for assessing constructed landforms. However, as discussed above, the testing and evaluation has focused on a limited number of sites. Long-term trial sites are needed for both natural and rehabilitated landscape systems.

No model is a perfect representation of field processes and the reliability of any predictions made using LEMS are open to question. Questions regarding how the material and erodibility properties of the landscape temporally change (that is, armouring and weathering), leading to pedogenesis and how this affects the long-term stability of the landform are very difficult questions to answer and each landform will be different due to its differences in material properties (Cohen, Willgoose and Hancock, 2009; Welivitiya *et al*, 2016). Long-term field plots (decadal time scale) are needed to assess such important questions (Hancock, Lowry and Saynor, 2016).

A further important question is – what is an acceptable erosion rate (Evans 2000, 2010)? No reconstructed landscape will be geomorphically the same as it was premining. Nor should it be expected to be, since in many cases the hydrology and erosion properties are different from the premining condition. SIBERIA allows alternative designs to be assessed so that sediment loss is minimised. There is also the increasingly important issue of how landscapes will perform under different climate scenarios and enhanced climate variability (Hancock, 2009, 2012). There is an increasing realisation that any climate understanding that we have is based on relatively short-term data and that any constructed landform has to be stable for geomorphic time. From an engineering design perspective, a conservative approach should always be taken. In the majority of rehabilitation design cases, it is likely that the newly disturbed and exposed surface material is more erodible than the long-term weathered and armoured surface. Consequently, there is likely to be a built-in conservatism with any erosion model parameter calibration performed using fresh spoil. However, field assessment of materials is required to fully establish any long-term erosion behaviour.

Future developments

Coupled with the need for further evaluation is the ongoing development of SIBERIA (Willgoose, in press). SIBERIA employs well accepted hydrology and erosion models. However, as discussed above, for many situations the evolution of the new surface can occur relatively rapidly as material weathers, pedogenesis begins and vegetation establishes. There is also potential for further mine rehabilitation specific capabilities (for example engineered erosion control structures).

The next generation of SIBERIA will incorporate a full pedogenesis (that is, soil evolution) functionality based on spinoffs of the pure science work of Cohen, Willgoose and Hancock (2009), Welivitiya *et al* (2016) and Willgoose (in press). This enhanced model will allow a combined landscape and soil evolution that is fully coupled. That is, as the hillslope evolves, the soil co-evolves. This will be particularly useful for rehabilitation design and assessment where there is a constructed soil profile, engineered caps (for example capillary break layers over tailings) or where a soil profile (with consequent impacts of ecosystem sustainability) is expected to develop naturally post-rehabilitation. The difficulty with such a model is that there is a near complete absence of mining specific field data with which to calibrate the physically based pedogenesis model parameters. This is where long-term field sites would provide invaluable data either to calibrate or test the new capabilities.

At present the model can employ spatially distributed but static with time parameters to represent a landscape surface. However, it is well recognised that erosion for an undisturbed or natural surface that vegetation is not static. Accompanying the pedogenesis functionality is a vegetation growth model based on well understood growth functions. However, for natural systems, field data at the hillslope scale regarding biomass change and its influence on erodibility is scarce for natural systems, let alone for rehabilitated post-mining landscapes (see discussion by Nicolau, 2004).

SIBERIA has now developed to where the landscape, soils and vegetation are integrated and the system can co-evolve. Finally, it is expected that this enhanced model may well be useful for assessing mine offset lands, where it is common to acquire land on the basis that the offset land will be rehabilitated back to something approaching natural conditions. This may involve gully remediation, soil modification and/or revegetation, all with uncertain outcomes long term.

SIBERIA availability

SIBERIA is distributed, free of charge, either as:

- part of a design assessment tool called EAMS, the combination is commonly referred to as EAMS-SIBERIA (currently Windows only) even though it also includes other tools, or
- as the bare standalone executable code SIBERIA with no graphical interface (Windows, Linux, OSX).

A number of users have developed their own workflow for landform assessment and the bare code without the graphical interface works better for them. Some advanced capabilities (for example Monte Carlo assessment) are only available with the bare SIBERIA. Either of these packages can be downloaded at <http://www.telluricresearch.com> or by contacting the authors. Currently EAMS-SIBERIA is limited to Windows XP (a critical third-party library for the graphical interface has not been updated for Windows 7 and beyond). A new version of EAMS is currently being tested which removes the Windows XP limitation and will allow EAMS to run on all Windows variants, as well as Linux and OSX. It is anticipated that the new version of EAMS will be released for general community use in 2017. The bare SIBERIA can be run on any platform that has a FORTRAN 90 compiler. If users need the FORTRAN source code for SIBERIA they should contact the developer (the second author) to discuss their requirements.

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REFERENCES

Ahnert, F, 1976. Brief description of a comprehensive three-dimensional model of landform development, *Zeitschrift fur Geomorphologie Supplement Band*, 25:29–49.

Australian and New Zealand Minerals and Energy Council / Minerals Council of Australia, 2000. Strategic framework for mine closure, 22 p (Australian and New Zealand Minerals and Energy Council / Minerals Council of Australia: Canberra).

Bell, J R W and Willgoose, G R, 1998. Monitoring of gully erosion at ERA Ranger Uranium Mine, Northern Territory, Australia, internal report 274, Environmental Research Institute of the Supervising Scientist, Jabiru.

Brakensiek, D and Rawls, W, 1994. Soil containing rock fragments: effects on infiltration, *Catena Supplement*, 23:99–110.

Braun, J and Sambridge, M, 1997. Modelling landscape evolution on geological time scales: a new method based on irregular spatial discretization, *Basin Research*, 9:27–52.

Bredehoeft, J D, Fakundiny, R H, Neuman, S P, Poston, J W and Whipple, C H, 2006. Peer review of draft environmental impact statement for decommissioning and/or long-term stewardship at the West Valley Demonstration Project and Western New York Nuclear Service Center.

Cohen, S, Willgoose, G R and Hancock, G R, 2009. The mARM spatially distributed soil evolution model: a computationally efficient modelling framework and analysis of hillslope soil surface organization, *Journal Geophysical Research*, 114:F03001.

Coulthard, T J, 2001. Landscape evolution models: a software review, *Hydrological Processes*, 15:165–173.

Commonwealth of Australia (Department of Arts, Sports, the Environment, Tourism and Territories), 1987. *Code of Practice on the Management of Radioactive Wastes from Mining of Radioactive Ores 1982, Guidelines* (Australian Government Printing Service: Canberra).

Coulthard, T J and Van De Wiel, M J, 2006. A cellular model of river meandering, *Earth Surface Processes and Landforms*, 31:123–132.

Cull, R, Hancock, G R, Johnston, A, Martin, P, Marten, R, Murray, A S, Pfitzner, J, Warner, R F and Wasson, R J, 1992. Past, present and future sedimentation on the Magela plain and its catchment, in *Modern Sedimentation and Late Quaternary Evolution of the Magela Plain*, Supervising Scientist for the Alligator Rivers Region research report 6 (ed: R J Wasson), pp 226–268 (Australian Government Publishing Service: Canberra).

Duggan, K, 1991. Mining and erosion in the Alligator Rivers Region of northern Australia, Part 1, open file record 81 (Supervising Scientist for the Alligator Rivers Region: Canberra).

Erskine, W D and Saynor, M J, 2000. *Assessment of the Off-site Geomorphic Impacts of Uranium Mining on Magela Creek, Northern Territory, Australia*, Supervising Scientist report 156 (Supervising Scientist: Darwin).

Evans, K G, 2000, Methods for assessing mine site rehabilitation design for erosion impact, *Australian Journal of Soil Research*, 38:231–247.

Evans, K G, 2010. Development of trigger levels to assess catchment disturbance on stream suspended sediment loads in on stream suspended sediment loads in the Magela Creek, Northern Territory, Australia, *Geographical Research*, 48:370–385.

Evans, K G and Loch, R J, 1996. Using the RUSLE to identify factors controlling erosion rates of mine soils, *Land Degradation and Development*, 7(3):267–277.

Evans, K G, Loch, R J, Bell, L C and Aspinall, T O, 1997. Laboratory rainfall simulator studies of selected open-cut coal mine overburden spoils from Central Queensland, Australia, *Australian Journal of Soil Research*, 35:15–30.

Evans, K G and Riley, S J, 1994. Planning stable post-mining landforms: the application of erosion modelling, in *Proceedings AusIMM Annual Conference,* pp 411–414 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Evans, K G, Saynor, M J and Willgoose, G R, 1999. Changes in hydrology, sediment loss and micro-topography of a vegetated mine waste rock dump impacted by fire, *Land Degradation and Development*, 10:507–522.

Evans, K G and Willgoose, G R, 2000. Post-mining landform evolution modeling: 2. Effects of vegetation and surface ripping, *Earth Surface Processes and Landforms*, 25(8):803–823.

Evans, K G, Willgoose, G R, Saynor, M J and House, T, 1998. *Effect of Vegetation and Surface Amelioration on Simulated Landform Evolution of the Post-mining Landscape at ERA Ranger Mine, Northern Territory*, Supervising Scientist report 134 (Australian Government Publishing Service: Canberra).

Evans, K G, Willgoose, G R, Saynor, M J and Riley, S J, 2000. Post-mining landform evolution modelling, Derivation of sediment transport model and rainfall-runoff model parameters, *Earth Surface Processes and Landforms*, 25(7):743–763.

Flanagan, D C and Livingston, S J, 1995. Water erosion prediction project (WEPP), Version 95.7, user summary, in WEPP User Summary (eds: D C Flanagan and S J Livingston), NSERL report No 11, July 1995.

Gyasi-Agyei, Y, Willgoose, G R and Troch, P, 1995. Effects of vertical resolution and map scale of digital elevation models on geomorphological parameters used in hydrology, *Hydrological Processes*, 9(3/4):121–140.

Hack, J T, 1957. Studies of longitudinal stream profiles in Virginia and Maryland, *United States Geological Survey Professional Paper*, 292(B):45–97.

Hancock, G R, 2003. The effect of catchment aspect ratio on geomorphological descriptors, in *Prediction in Geomorphology* (eds: P Wilcock and R Iverson), Geophysical Monograph Series volume 135 (American Geophysical Union: Washington).

Hancock, G R, 2004. The use of landscape evolution models in mining rehabilitation design, *Environmental Geology*, 46:561–573.

Hancock, G R, 2005. The use of digital elevation models in the identification and characterisation of catchments, *Hydrological Processes*, 19:1727–1749.

Hancock, G R, 2006. The impact of different gridding methods on catchment geomorphology and soil erosion over long time scales, *Earth Surface Processes and Landforms*, 31(8):1035–1050.

Hancock, G R, 2009. A catchment scale assessment of increased rainfall and storm intensity on erosion and sediment transport for Northern Australia, *Geoderma*, 152:350–360.

Hancock, G R, 2012. Modelling stream sediment concentration: an assessment of enhanced rainfall and storm frequency, *Journal of Hydrology*, 430–431:1–12.

Hancock, G R, Coulthard, T J and Lowry, J B C, 2016. Long-term landscape trajectory — can we make predictions about landscape form and function for post-mining landforms?, *Geomorphology*, 266:121–132.

Hancock, G R, Coulthard, T J, Martinez, C and Kalma, J D, 2011a. An evaluation of landscape evolution models to simulate decadal and centennial scale soil erosion in grassland catchments, *Journal of Hydrology*, 398:171–183.

Hancock, G R, Crawter, D, Fityus, S G, Chandler, J and Wells, T, 2007. The measurement and modelling of rill erosion at angle of repose slopes in mine spoil, *Earth Surface Processes and Landforms*, 33(7):1006–1020.

Hancock, G R and Evans, K G, 2006. Gully position, characteristics and geomorphic thresholds in an undisturbed catchment in Northern Australia, *Hydrological Processes*, 20:2935–2951.

Hancock, G R and Evans, K G, 2010. Channel and hillslope erosion – an assessment for a traditionally managed catchment, *Earth Surface Processes and Landforms*, 13:1468–1479.

Hancock, G R, Evans, K G, McDonnell, J J and Hopp, L, 2011b. Ecohydrological controls on soil erosion and landscape evolution, *Ecohydrology*, 5(4):478–490.

Hancock, G R, Grabham, M K, Martin, P, Evans, K G and Bollhöfer, A, 2006a. A methodology for the assessment of rehabilitation success of post mining landscapes – sediment and radionuclide transport at the former Nabarlek uranium mine, Northern Territory, Australia, *Science of the Total Environment*, 354:103–119.

Hancock, G R, Loch, R J and Willgoose, G R, 2003. The design of post-mining landscapes using geomorphic guidelines, *Earth Surface Processes and Landforms*, 28:1097–1110.

Hancock, G R, Loughran, R J, Evans, K G and Balog, R M, 2008a. Estimation of soil erosion using field and modelling approaches in an undisturbed Arnhem Land catchment, Northern Territory, Australia, *Geographical Research*, 46(3):333–349.

Hancock, G R and Lowry, J B C, 2015. Hillslope erosion measurement—a simple approach to a complex process, *Hydrological Processes*, 29(22):4809–4816.

Hancock, G R, Lowry, J B C and Coulthard, T J, 2015. Predicting uncertainty in sediment transport and landscape evolution – the influence of initial surface conditions, *Computers and Geosciences*, 90(B):117–130.

Hancock, G R, Lowry, J B C, Coulthard, T J, Evans, K G and Moliere, D R, 2010. A catchment scale evaluation of the SIBERIA and CAESAR landscape evolution models, *Earth Surface Processes and Landforms*, 35:863–875.

Hancock, G R, Lowry, J B C, Dever, C and Braggins, M, 2015. Does introduced fauna influence soil erosion? A field and modelling assessment, *Science of the Total Environment*, 518–519:189–200.

Hancock, G R, Lowry, J B C, Moliere, D R and Evans, K G, 2008b. An evaluation of an enhanced soil erosion and landscape evolution model: a case study assessment of the former Nabarlek uranium mine, Northern Territory, Australia, *Earth Surface Processes and Landforms*, 33(13):2045–2063.

Hancock, G R, Lowry, J B C and Saynor, M J, 2016. Early landscape evolution — a field and modelling assessment for a post-mining landform, *Catena*, 147:699–708.

Hancock, G R, Martinez, C, Evans, K G and Moliere, D R, 2006b. A comparison of SRTM and high-resolution digital elevation models and their use in catchment geomorphology and hydrology – Australian examples, *Earth Surface Processes and Landforms*, 31:1394–1412.

Hancock, G R, Nuake, J and Fityus, S G, 2006. Modelling of sediment dynamics in a laboratory scale experimental catchment, *Hydrological Processes*, 20:67–84.

Hancock, G R and Turley, E, 2005. Evaluation of proposed waste rock dump designs using the SIBERIA erosion model, *Environmental Geology*, 49(5):765–779.

Hancock, G R and Willgoose, G R, 2001. The use of a landscape simulator in the validation of the SIBERIA landscape evolution model: steady state landforms, *Water Resources Research*, 37(7):1981–1992.

Hancock, G R and Willgoose, G R, 2002. The use of a landscape simulator in the validation of the SIBERIA landscape evolution model: transient landforms, *Earth Surface Processes and Landforms*, 27(12):1321–1334.

Hancock, G R, Willgoose, G R and Evans, K G, 2002. Testing of the SIBERIA landscape evolution model using the Tin Camp Creek, Northern Territory, Australia field catchment, *Earth Surface Processes and Landforms*, 27:125–143.

Hancock, G R, Willgoose, G R, Evans, K G, Moliere, D R and Saynor, M J, 2000. Medium term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model, *Australian Journal of Soil Research*, 38:249–263.

Hancock, G R, Willgoose, G R and Lowry, J B C, 2013. Transient landscapes: gully development and evolution using a landscape evolution model, *Stochastic Environmental Research and Risk Assessment*, 28(1):83–98.

Hancock, G R, Verdon-Kidd, D and Lowry, J B C, in press. Sediment output from a post-mining catchment – centennial impacts using stochastically generated rainfall, *Journal of Hydrology*.

Hazelton, P and Murphy, B, 2007. *Interpreting Soil Tests: What Do all the Numbers Mean?* second edition (CSIRO Publishing: Melbourne).

Hugo, J, 2016. Sediment transport rates in forested headwater catchments of the Telegherry River, New South Wales: the role of disturbance and scale, BSc Honours thesis (unpublished), Earth Sciences Department, The University of Newcastle, Newcastle.

Ibbitt, R P, Willgoose, G R and Duncan, M J, 1999. Channel network simulation models compared with data from the Ashley River, New Zealand, *Water Resources Research*, 35(12):3875–3890.

Kirkby, M S, 1971. Hillslope process-response models based on the continuity equation, *Slopes: Form and Process*, serial publication 3, pp 15–30 (Institute of British Geographers).

Laflen, J M, Elliot, W J, Simanton, J R, Holzhey, C S and Kohl, K D, 1991. WEPP soil erodibility experiments for rangeland and cropland soils, *Journal of Soil and Water Conservation*, 46(1):39–34.

Martinez, C, Hancock, G R and Kalma, J, 2009. Comparison of fallout radionuclide (caesium-137) and modelling approaches for the assessment of soil erosion rates for an uncultivated site in south-eastern Australia, *Geoderma*, 151:128–140.

Moliere, D R, Evans, K G, Willgoose, G R and Saynor, M J, 2002. Temporal trends in erosion and hydrology for a post-mining landform at Ranger Mine, Northern Territory, Supervising Scientist report 165, Supervising Scientist, Darwin.

Moreno de Las Heras, M, Saco, P M and Willgoose, G R, 2012. A comparison of SRTM V4 and ASTER GDEM for hydrological applications in low relief terrain, *Photogrammetric Engineering and Remote Sensing*, 78(7):757–766.

Morgan, A R and Willgoose, G R, 1994. *Erosional Stability of Mine Rehabilitation*, ERISS internal report 135 (Supervising Scientist for the Alligator Rivers Region: Canberra).

Needham, R S, 1988. *Geology of the Alligator Rivers Uranium Field, Northern Territory*, Bulletin 224 (Australian Government Publishing Service: Canberra).

Nicolau, J M, 2004. Trends in relief design and construction in opencast mining reclamation, *Land Degradation and Development*, 14(2):215–226.

NYSERDA, 2010. Decommissioning and/or long-term stewardship at the West Valley demonstration project and western New York nuclear service center, volume 2, US Department of Energy, Washington DC.

Parker, G and Klingeman, P C, 1982. On why gravel beds streams are paved, *Water Resources Research*, 18(5):1409–1423.

Peel, M C, McMahon, T A and Finlayson, B L, 2004. Continental differences in the variability of annual runoff – update and reassessment, *Journal of Hydrology*, 295(1–4):185–197.

Poesen, J W, Torri, D and Bunte, K, 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review, *Catena*, 23(1–2):141–166.

Rieke-Zapp, D J, Poesen, J and Nearing, M A, 2007. Effects of rock fragments incorporated in the soil matrix on concentrated flow hydraulics and erosion, *Earth Surface Processes and Landforms*, 32:1063–1076.

Riley, S J and Rich, J F, 1998. Geochemical assessment of an analogue site for an engineered landform at Ranger Uranium Mine, Northern Territory, Australia, *Environmental Geology*, 34:203–213.

Sharmeen, S and Willgoose, G R, 2007. A one-dimensional model for simulating armouring and erosion on hillslopes. 2. Long-term erosion and armouring predictions for two contrasting mine spoils, *Earth Surface Processes and Landforms*, 32(10):1437–1453.

Sheridan, G J, So, H B, Loch, R J, Pocknee, C and Walker, C M, 2000. Use of laboratory scale rill and interrill erodibility measurements for the prediction of hillslope–scale erosion on rehabilitated coal mines soils and overburden, *Australian Journal of Soil Research*, 38(2):285–298.

Sinclair, K and Bell, R C, 1996. A mechanism for global optimization of river networks from local erosion rules, *Physical Review Letters*, 76:3360–3363.

So, H B, Sheridan, G J, Loch, R J, Carroll, C, Willgoose, G R, Short, M and Grabski, A, 1998. Post mining landscape parameters for erosion and water quality control, final report on projects 1629 and 4011, Volume 1: Executive summary, Volume 2: Main report, The University of Queensland, Brisbane.

Solyom, P B and Tucker, G, 2007. The importance of the catchment area–length relationship in governing non-steady state hydrology, optimal junction angles and drainage network pattern, *Geomorphology*, 88:84–108.

Staben, G W and Evans, K G, 2008. Estimates of tree canopy loss as a result of Cyclone Monica, in the Magela Creek catchment northern Australia, *Austral Ecology*, 33:562–569.

Story, R, Galloway, R W, McAlpine, J R, Aldrick, J M and Williams, M A J, 1976. *Lands of the Alligator Rivers Area, Northern Territory*, Land Research Series 38 (CSIRO: Canberra).

Strahler, A N, 1952. Hypsometric (area-altitude) analysis of erosional topography, *Geological Society of America Bulletin*, 63:1117–1142.

Surkan, A J, 1968. Synthetic hydrographs: effects of network geometry, *Water Resources Research*, 5(1):112–128.

Tarboton, D G, Bras, R L and Rodriguez-Iturbe, I, 1989a. *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).

Tarboton, D G, Bras, R L and Rodriguez-Iturbe, I, 1989b. Scaling and elevation in river networks, *Water Resources Research*, 25(9):2037–2052.

Toy, T J and Hadley, R F, 1987. *Geomorphology of Disturbed Lands* (Academic Press: New York).

Tucker, G and Hancock, G R, 2010. Modelling landscape evolution, *Earth Surface Processes and Landforms*, 35:28–50.

Tucker, G, Lancaster, S, Gasparini, N and Bras, R L, 2001. The Channel-Hillslope Integrated Landscape Development model (CHILD), in *Landscape Erosion and Evolution Modelling* (ed: R Harmon), pp 349–388 (Kluwer Academic/Plenum Publishers: New York).

Unger, C, Evans, K G, Saynor, M J and Willgoose, G R, 1996. Incorporation of landform design and erosion modelling in mine planning at the Ranger Uranium Mine, Jabiru, NT, paper presented to Minerals Council of Australia Environmental Workshop.

Uren, C, 1992. An investigation of surface geology in the Alligator Rivers region for possible analogues of uranium mine rehabilitation structures, internal report 56, Supervising Scientist for the Alligator Rivers Region, Canberra.

Welivitiya, W D P, Willgoose, G R, Hancock, G R and Cohen, S, 2016. Exploring the sensitivity on a soil area-slope-grading relationship to changes in process parameters using a pedogenesis model, *Earth Surface Dynamics*, 4:607–625.

Wilcock, P R and Crowe, J C, 2003. Surface-based transport model for mixed-size sediment, *Journal of Hydraulic Engineering*, 129(2):120–128.

Willgoose, G R, 1994. A physical explanation for an observed area-slope-elevation relationship for catchments with declining relief, *Water Resources Research*, 30(2):151–159.

Willgoose, G R, 1998. SIBERIA parameter estimates from Argyle Diamond mine escarpment dump, report provided in confidence to Coffey and Partners.

Willgoose, G R, 2000. SIBERIA parameter estimates and landform simulations of rehabilitation proposals for the Three Sisters escarpment dumps at Mount Tom Price Mine, report provided in confidence to Hamersley Iron.

Willgoose, G R, 2005. Mathematical modeling of whole-landscape evolution, *Annual Review of Earth and Planetary Sciences*, 33:443–459.

Willgoose, G R, 2010. Assessment of the erosional stability of encapsulation caps and covers at the millennial timescale: current capabilities, research issues and operational needs, paper presented to Workshop on Engineered Barrier Performance Related to Low-level Radioactive Waste, Decommissioning, and Uranium Mill Tailings facilities, 3–5 August.

Willgoose, G R, 2012. User manual for SIBERIA, Version 8.33 [online], 115 p. Available from: <http://www.telluricresearch.com/siberia_8.33_manual.pdf>.

Willgoose, G R, in press. *Modeling Soilscape and Landscape Evolution* (Cambridge Press: Cambridge).

Willgoose, G R, Bras, R L and Rodriguez-Iturbe, I, 1991a. A physically based coupled network growth and hillslope evolution model: 1 Theory, *Water Resources Research*, 27(7):1671–1684.

Willgoose, G R, Bras, R L and Rodriguez-Iturbe, I, 1991b. A physically based coupled network growth and hillslope evolution model: 2 Applications, *Water Resources Research*, 27(7):1685–1696.

Willgoose, G R, Bras, R L and Rodriguez-Iturbe, I, 1991c. A physical explanation of an observed link area-slope relationship, *Water Resources Research*, 27(7):1697–1702.

Willgoose, G R, Bras, R L and Rodriguez-Iturbe, I, 1991d. Results from a new model of river basin evolution, *Earth Surface Processes and Landforms*, 16:237–254.

Willgoose, G R and Gyasi-Agyei, Y, 1995. New technology in hydrology and erosion modeling for mine rehabilitation, paper presented to APCOM XXV Application of Computers and Operations Research in the Mineral Industries.

Willgoose, G R, Hancock, G R and Kuczera, G, 2003. Variability of catchment statistics, in *Prediction in Geomorphology* (ed: P Wilcock and R Iverson), Geophysical Monograph Series 135 (American Geophysical Union: Washington).

Willgoose, G R and Loch, R J, 1996. An assessment of the Nabarlek rehabilitation, Tin Camp Creek and other mine sites in the Alligator Rivers Region as test sites for examining long-term erosion processes and the validation of the SIBERIA model, internal report 229, Environmental Research Institute of the Supervising Scientist, Canberra.

Willgoose, G R and Riley, S J, 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. Also published with minor revisions as: Willgoose, G R and Riley, S F, 1998. Application of a catchment evolution model to the prediction of long term erosion on the spoil heap at Ranger Uranium Mines: initial analysis, Supervising Scientist report 132 (Australian Government Publishing Service: Canberra).

Willgoose, G R and Riley, S J, 1998. An assessment of the long-term erosional stability of a proposed mine rehabilitation, *Earth Surface Processes and Landforms*, 23:237–259.

Willgoose, G R and Sharmeen, S, 2006. A one-dimensional model for simulating armouring and erosion on hillslopes. 1. Model development and event-scale dynamics, *Earth Surface Processes and Landforms*, 31(8):970–991.

Wilson, C J, Crowell, K J and Lane, L J, 2006. *Surface Erosion Modelling for the Repository Waste Cover at Los Alamos National Laboratory Technical Area 54, Material Disposal Area* G (Los Alamos National Lab: Los Alamos).

Wischmeier, W H and Smith, D D, 1978. Predicting rainfall erosion losses – a guide to conservation planning, US Department of Agriculture, Agriculture Handbook 537.2.