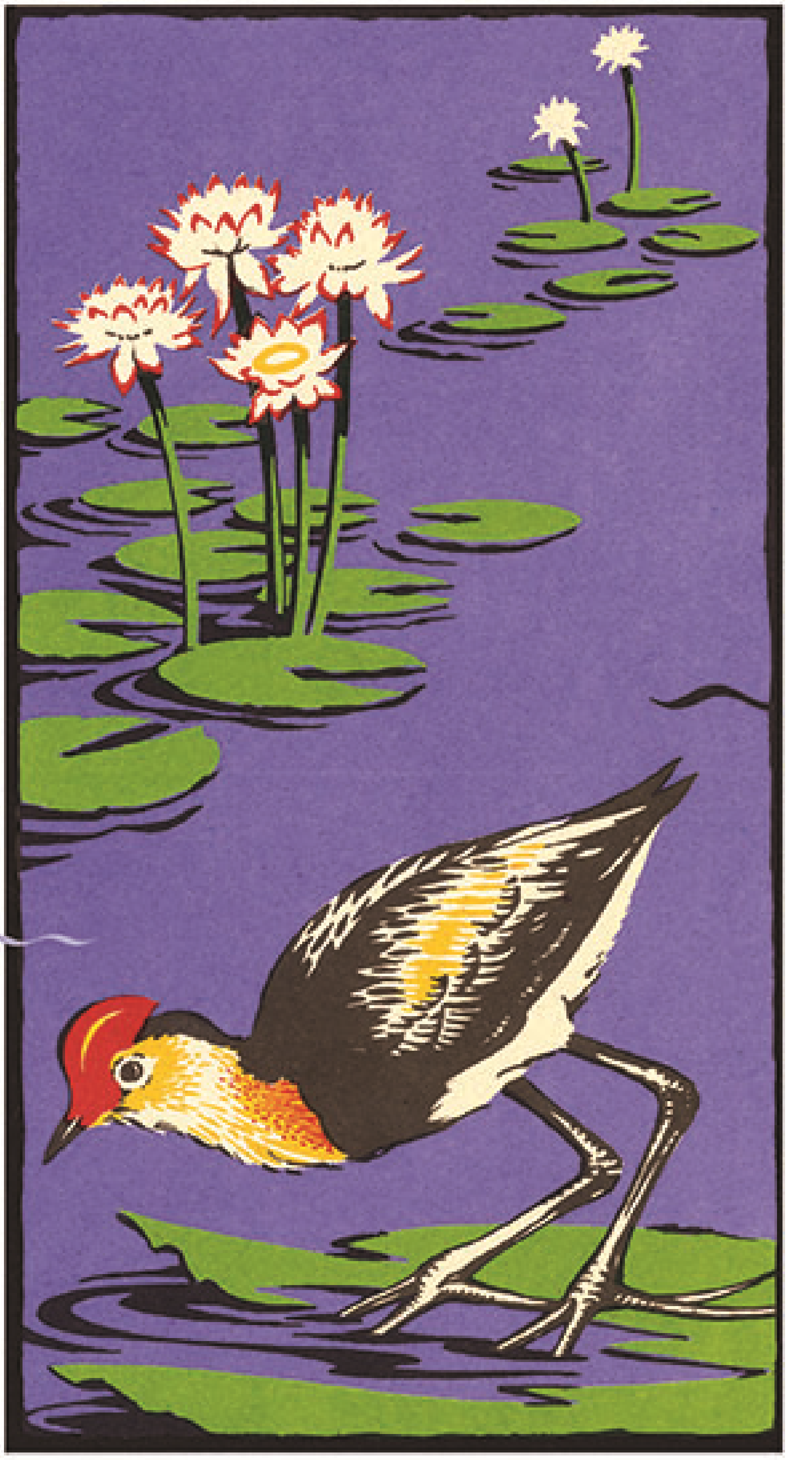
supervising scientist report

210



Future Directions for Application of Landform Modelling by the Supervising Scientist: Response to the Review of the application of the CAESAR-Lisflood model by the eriss Hydrologic, Geomorphic and Chemical Processes program

J Lowry, W Erskine, G Pickup, T Coulthard & G Hancock

Australian Government
Department of the Environment
Supervising Scientist

Typically, it is Supervising Scientist policy for reports in the SSR series to be reviewed as part of the publications process. This Supervising Scientist Report is a summary of an external review of landform modelling procedures at the Supervising Scientist and, although not externally peer-reviewed, it has been reviewed internally by senior staff.

Author of this report:

Mr John Lowry – Hydrologic, Geomorphic and Chemical Processes group, Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia

Dr Wayne Erskine – Hydrologic, Geomorphic and Chemical Processes group Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia,

Dr Geoff Pickup - 1538 Sutton Road, Sutton, New South Wales 2620, Australia

Professor Tom Coulthard, Department of Geography, University of Hull, HU 6 7RX, United Kingdom,

Associate Professor Greg Hancock, Discipline of Earth Sciences, University of Newcastle, Callaghan, NSW 2308, Australia

This report should be cited as follows:

Lowry J, Erskine W, Pickup G, Coulthard T & Hancock G 2015. *Future Directions for Application of Landform Modelling by the Supervising Scientist: Response to the Review of the application of the CAESAR-Lisflood model by the eriss Hydrologic, Geomorphic and Chemical Processes program*. Supervising Scientist Report 210, Supervising Scientist, Darwin NT.

The Supervising Scientist is part of the Australian Government Department of the Environment.

ISSN-2203-4781 (online)

ISBN-13: 978-1-921069-27-7

environment.gov.au/science/supervising-scientist

Contents

Executive summary

In January 2014, the Supervising Scientist commissioned an external review of the landform evolution modelling (LEM) methods in use by the Hydrologic, Geomorphic and Chemical Processes (HGCP) research program, focussing particularly on the use of the CAESAR-Lisflood software application. This report integrates the document produced by the external reviewer, Dr Geoff Pickup, with comments and feedback on review recommendations by the CAESAR-Lisflood application developer, Professor Tom Coulthard (University of Hull) and a leading practitioner of landform evolution modeling, Associate Professor Greg Hancock (University of Newcastle). Finally, it documents the Supervising Scientist response to the review recommendations and the subsequent feedback. It outlines the next steps and the priorities for future research in landform evolution modelling by the Supervising Scientist.

In his review, Dr Pickup assessed how the landform evolution modelling methods in use by the HGCP program compare with international best practice. He also reported on additional and emerging approaches in landform evolution modelling on mine sites that might be used by the HGCP program. While he notes that there are a number of alternatives to the CAESAR-Lisflood model, none offer the comprehensive approach to long-term landform evolution offered by specialised models such as CAESAR-Lisflood and SIBERIA (also used by ***eriss***). However Dr Pickup observed that SIBERIA, while offering shorter modelling time for long-term model simulations, does not model gully development and channel erosion (both critical processes for assessing or modellingthe stability of rehabilitated landforms at Ranger) as well as CAESAR-Lisflood.

Overall, Dr Pickup found that the landform evolution models in use at ***eriss*** represent world best practice and are largely suitable to the task in hand. The methods by which the models are employed are also consistent with world best practice. He found that there are some areas where modelling and erosion research procedures could be enhanced. These include more checking of DEMs for artefacts, sensitivity analysis of model parameters, and improved long term rainfall record generation procedures. Dr Pickup also suggested that future applications of the model could benefit from further development to incorporate greater spatial variability to reflect vegetation growth influences on runoff, erosion and deposition.

Professor Coulthard and Associate Professor Hancock endorsed Dr Pickups comments and recommendations. In addition, they provided supplementary information outlining the means by which Dr Pickups and their own recommendations could be prioritised and undertaken.

Crucially, Dr Pickup, Professor Coulthard and Associate Professor Hancock all stress the importance of landform modelling work continuing at the Supervising Scientist, particularly as the Ranger mine approaches the closure and rehabilitation phase.

The HGCP research program believes that the recommendations made by Dr Pickup will enhance landform modelling capabilities by enabling ***eriss*** to focus future LEM activities and research into specific areas. The priority areas for future landform modelling research at ***eriss*** are seen as:

- Calibrating the input parameters and variables to the CAESAR-Lisflood model to ensure it provides meaningful and useful results with confidence;

- Identifying and developing a rainfall dataset that could be used for long-term model simulations which would be representative of the range of global climatic extremes that may occur within a timeframe of 10,000 years;
- Continue to engage and consult with leading practitioners and developers of landform evolution models to ensure that the CAESAR-Lisflood model is updated to incorporate additional parameters as required, and to ensure procedures, processes and outputs from landform modelling represent best practice and are scientifically sound.
- Investigate the development and inclusion of additional parameters, such as chemical weathering and vegetation into the CAESAR-Lisflood model and the broader HGCP research program.

Acknowledgments

Dr Mike Saynor, Dr Rick van Dam and Ms Lucy Lytton from the Supervising Scientist and Dr Anita Chalmers from the University of Newcastle discussed various aspects of this work with the authors and helped improve the report.

Part 1: Background to the landform modelling review at the Supervising Scientist

J Lowry & W Erskine

1.1 Background

The 27th meeting of the Alligator Rivers Region Technical Committee (ARRTC) in November 2011 identified the assessment of the geomorphic stability of the proposed rehabilitated Ranger landform as a priority research activity of the Environmental Research Institute of the Supervising Scientist (***eriss***). This information is required for use by Energy Resources of Australia (ERA) in the finalisation of the landform design, and to assist with the development of closure criteria. To expedite this process ERA firstly identified from the company's perspective the key closure-related tasks, and their associated knowledge requirements and prioritised these against the current Key Knowledge Needs (KKNs). This was then followed by working meetings between ERA and the Supervising Scientist (SS) to map these needs against current KKNs, and to assign organisational responsibilities for the execution of the required work. Among the identified priority needs was an assessment of the geomorphic stability of the proposed landform (KKN 2.2.1 *Landform Design* and KKN 2.2.4 *Geomorphic Behaviour and Evolution of the Final Landform)*.

Within its membership, ARRTC includes a number of independent scientific experts in fields of relevance to mine environmental impacts, mine operations and mine rehabilitation. At the time of the 27th meeting, the independent member of ARRTC with expertise in geomorphology was Professor Colin Woodroffe of the University of Wollongong. While ARRTC plays a key role in setting research priorities and advising on appropriate methods and techniques, it does not have the resources and time to undertake detailed formal reviews of individual research programs. Similarly, representatives of the different scientific disciplines are not necessarily experts in all aspects or fields of that discipline. Therefore, with the increased importance of landform modelling as Ranger mine rehabilitation started, Professor Woodroffe encouraged SS to seek input and guidance on the research approach undertaken by the Hydrologic, Geomorphic and Chemical Processes (HGCP) research program from an external source who is an expert in the field of landform modelling.

In response to the recommendation of Professor Woodroffe, a review of the use of landform evolution modelling technologies to assess the geomorphic stability of a rehabilitated landform by the HGCP program was undertaken by Dr Geoff Pickup, an independent consulting geomorphologist.

1.2 Landform modelling at the Supervising Scientist

Historically, landform evolution modelling assessments of rehabilitated mine landforms have been done by SS, with SS having invested substantially in the development and application of the SIBERIA and CAESAR-Lisflood models.

Landform evolution modelling provides a means for assessing the potential performance of constructed mine landforms. Over the last 40 years a variety of models have been used to evaluate erosion and simulate post-mining landscape stability (Evans 2000, Loch et al. 2000). These models include the water erosion prediction programme or WEPP (Laflen et al. 1991), the universal soil loss equation (USLE) and its variants, the modified universal soil loss equation (MUSLE), the revised universal soil loss equation (RUSLE) (Onstad & Foster 1975, Wischmeier & Smith 1978, Renard et al. 1994) and SIBERIA (Willgoose et al. 1989). Importantly, much of the developmental work with the SIBERIA landform model was undertaken by projects associated with the Supervising Scientist and /or the Ranger mine site i.e.Willgoose & Riley 1998, Evans et al. 2000.

The CAESAR model (Coulthard et al. 2000, 2002) was originally developed to examine the effects of environmental change on river evolution and to study the movement of contaminated river sediments through drainage networks. Recently, SS has invested significant resources in assessing, developing and adapting the CAESAR (and succeeding CAESAR-Lisflood) landform evolution modelling software program to assess the geomorphic stability and evolution of proposed rehabilitated mine landforms in northern Australia (Hancock et al. 2010; Lowry et al. 2011; 2013; Saynor et al. 2012a).

1.3 Why CAESAR?

CAESAR-Lisflood is the latest version of the CAESAR model. It combines the Lisflood-FP 2d hydrodynamic flow model (Bates et al. 2010) with the CAESAR geomorphic model (Coulthard et al. 2000, 2002, 2005, Van De Wiel et al. 2007) to simulate erosion and deposition in river catchments and reaches over time scales from hours to thousands of years. The model does this by routing water over a regular grid of cells and altering elevations according to erosion and deposition from the operation of fluvial and slope processes. CAESAR-Lisflood can be run in two modes: a catchment mode (as used here), with no external influxes other than rainfall, and a reach mode, with one or more points where sediment and water enter the system. For both modes the model requires the specification of several parameters or initial conditions, including elevation, grain sizes and rainfall (catchment mode), or a flow input (reach mode). The initial topography of the landscape drives fluvial and hillslope processes that determine the spatial distribution of erosion (loss) and deposition (gain) that occurs during a given time step. This altered topography becomes the starting point for the next time step. Outputs of the model are elevation and sediment distributions through space and time and discharges and sediment fluxes at the outlet(s) through time. There are four main components to CAESAR-Lisflood: a hydrological model, a flow model, fluvial erosion and deposition and slope processes.

When running in catchment mode, runoff over the catchment is generated through the input of rainfall data. This is calculated using an adaptation of TOPMODEL (Bevan & Kirkby 1979) that contains a lumped soil moisture store which when it exceeds a threshold value generates surface runoff. The surface runoff generated by the hydrological model is then routed using a flow model.

Although flow is the main driver of the model, morphological changes result from entrainment, transport and deposition of sediments. CAESAR-Lisflood can accept up to nine size-based fractions of sediment that are transported either as bed load or as suspended load, depending on the grain sizes. CAESAR-Lisflood provides two different methods of calculating sediment transport, based on the Einstein (1950) and the Wilcock & Crowe (2003) equations.

A key attribute of the CAESAR-Lisflood model is the ability to utilise recorded rainfall data from the study area, enabling the modelling of the effects of specific rainfall events.

The model enables rainfall data to be input at a range of temporal intervals, ranging from 10-minutes to 1 hour. Event modelling is critical, especially for the early stages of landform evolution, since it is recognised that the majority of erosion typically occurs during a limited number of high-intensity events (Moliere et al. 2002). As the climatic region in which the Ranger mine occurs is dominated by seasonal, high-intensity rainfall events (McQuade et al. 1996), the ability to model specific rainfall events has meant that CAESAR-Lisflood model is the model of choice by SS for this region.

1.4 Report Structure

This report is divided into four parts:

- Part 1 provides the background and rationale for this report.
- Part 2 contains the review of landform modelling activities at Supervising Scientist by Dr Geoff Pickup.
- Part 3 contains a response to the recommendations contained in Part 2 by Professor Tom Coulthard and Associate Professor Greg Hancock, developer of the CAESER-Lisflood model and long-term landform modelling collaborators with the SS, respectively.
- Part 4 contains the response to the recommendations and comments of Dr Pickup and Professor Coulthard and Associate Professor Hancock by the Hydrologic, Geomorphic and Chemical Processes program, and outlines the priorities and future direction that landform modelling will take.

Part 2: Review of landform modelling at the Supervising Scientist

G Pickup

2.1 Project Brief

The project brief specifies a review of the landform evolution modelling activities of ***eriss***, in order to address the following questions:

1. How do the approaches and methods - specifically the use of the CAESAR-Lisflood software - currently employed by the Hydrologic, Geomorphic and Chemical Processes Research Program compare to current international leading practice for assessing landform evolution, especially in relation to erosion, of a rehabilitated mine site?
2. What additional or emerging approaches could be utilised by the Hydrologic, Geomorphic and Chemical Processes Program for its research and assessment activities for assessing landform evolution, especially in relation to erosion, of a rehabilitated mine site?

The environmental requirements for mine closure specify that the final landform should possess:

"erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas" (Supervising Scientist Division 1999).

Rehabilitation planning and landform design should therefore aim to produce landform shapes and surface treatments that reduce erosion and minimise release of contaminants. Specifically, erosion should not result in gullying, which may expose contained waste material to the environment within a specified time period (Lowry et al. 2013).

The objective of modelling is to facilitate the design of the final landform by testing a range of alternative designs. However, given the requirements for mine closure, modellingshould not only evaluate erosion potential, it should also encompass downstream impacts. The review material below considers both of these issues.

The report consists of four sections. These are:

- A brief description of current practices in mine landform erosion modelling either used or with potential for use by ***eriss***.
- A review of how *CAESAR-Lisflood* is being applied, including data issues, parameter selection and model limitations
- Suggestions on how *CAESAR-Lisflood* results may be used with complementary models to overcome *CAESAR-Lisflood's* limitations.
- Comments on emerging approaches that may be used by the Hydrologic, Geomorphic and Chemical Processes program.

2.2 Comparison with International Practice

The Hydrologic, Geomorphic and Chemical Processes research program has a long history of landform evolution modelling and, in my opinion, currently represents world best practice. Over time, the program and associated scientists have carried out extensive research on rates of erosion and sediment transport on both natural landforms and mine-affected areas. Methods have included direct measurement of streamflow and sediment transport, use of rainfall simulators and plot trials, and almost two decades of two-dimensional landform evolution modeling. Indeed, the two landform evolution models, most commonly-used worldwide, *(SIBERIA and CAESAR/CAESAR-Lisflood)* owe at least some of their development to work in the Alligator Rivers Region.

In my experience, most attempts to model the final (and rehabilitated) landforms produced by mining rely on parameters derived from elsewhere or, at best, short runs of plot measurements at much smaller scales than the actual landforms. Scaling up is fraught with difficulty and prone to substantial error because the plot rarely represents the hillslope or small catchment. The Alligator Rivers Region datasets include erosion measurements at a variety of spatial scales and provide an unusual opportunity to both calibrate and validate landform process models. Furthermore, short-run datasets often do not include results from rare and extreme events yet these events may do much of the work in causing erosion and generating rapid landscape change. Some of the Alligator Rivers Region datasets include the effects of one or more severe tropical cyclones and, once again, provide an unusual opportunity to calibrate and validate models.

2.2.1 Models

While the review specifically calls for comments on the *CAESAR-Lisflood* model, it is worth adding a few comments on what else is available. These comments are restricted to models and procedures that are readily-available, either at no cost or commercially. I have only commented here on models that are sufficiently developed to be publicly available and regarded as operational. There are, of course, many models that are research tools developed by individuals but these are rarely supported and have had little or no testing making them inappropriate for operational use.

Landform evolution models that are potentially of use or have been applied in the eriss Hydrologic, Geomorphic and Chemical Processes Program fall into a number of categories:

Hillslope models such as the *USLE* and its variants. Essentially, these model plots or one dimensional planar hillslopes and do not allow for sediment storage due to factors such as slope curvature. They have a large database derived from many years of plot studies but do not readily scale up to two-dimensional landforms or larger areas. While they may be useful when calibrated for providing point or localized inputs into more complex and spatially distributed models, they are unsuitable for generating downstream impacts.

Variations of hillslope models that allow for sediment storage and non-planar, more complex, slopes such as WEPP. Essentially, these models are still one dimensional and not especially suited to more complex, two dimensional landforms although a 2-D effect can sometimes by represented by subdividing the landform into sub-areas. They are, however, a significant advance on the simple hillslope models.

Both pure hillslope models and their variations have been used by ***eriss*** *and its forerunners. Where this review is concerned, they are essentially a historical development and are already used in the* ***eriss*** *program where appropriate.*

Physically based 2-D and 3-D hydraulic models such as TUFLOW and SRH-2D. These models focus on in-channel and/or floodplain hydraulics with sediment transport as an add-on, usually based on a range of bedload equations. They require sediment inflow data as an upstream boundary condition and sometimes allow for lateral inflow of sediment. This means that a decoupled hillslope model is required. Such models can reproduce or forecast channel changes and may be used in modellingof downstream effects. However, they are not good at reproducing wash load which may be the main component of sediment load in cases of soil and gully erosion upstream. They are also only as good as the bedload equation in use and therefore potentially subject to large errors. The commercial models are also very expensive.

The hydraulic model approach described here is too restrictive to meet eriss's objectives as it lacks a hillslope component.

Lumped Parameter, Semi-Distributed Catchment and Sub-Catchment Models such as Source and MUSIC *(both products of the eWater CRC).*

MUSIC is a conceptual design tool to simulate runoff in catchments and predict the performance of water quality treatments. It has mainly been used in urban catchments in Australia in water-sensitive urban designs, although it is increasingly being adopted in non-urban settings including mining environments. It has a rainfall-runoff component based on soil properties and a sediment yield component that may be calibrated from observed data. The model uses a sediment accounting and delivery approach and allows for basin storage including the effect of sediment detention basins. It is a semi-distributed model and uses sub-catchments and/or sub-areas with different types of surface such as undisturbed zones, roads, quarries, rock dumps, etc. However each of these requires calibrated runoff and erosion parameters so the model is highly empirical and best used in a data-rich environment. While it may be used to generate water quality parameters such as suspended load, it does not reproduce the behaviour of specific landforms such as gullies. However, as long as calibration data are available, it may be used to evaluate a range of alternative treatments on runoff and water quality. The model is available commercially and is supported.

Source has some similarities to *MUSIC* but is a more complex and more sophisticated model. It also requires more input data and, like *MUSIC*, performs best when data are available for model calibration. The *eWater CRC* describes *Source* as follows:

'Source is highly flexible and is able to create an overall integrated model that is tailored to the problem. Constructing a model for a particular catchment management situation involves selecting appropriate component models and linking them in the software.

The model is based on the following building blocks:

- Sub-catchments: The sub-catchment is the basic spatial unit, which is then divided into hydrological response units (or functional units) based on a common response or behaviour such as land use. Within each functional unit, three models can be assigned: a rainfall-runoff model, a constituent generation model and a filter model.

- Nodes: Nodes represent sub-catchment outlets, stream confluences or other places of interest such as stream gauges or dam walls. Nodes are connected by links, forming a representation of the stream network.
- Links: Links represent the river reaches. Within each link, a selection of models can be applied to:
  - route or delay the movement of water along the link
  - modify the contaminant loads due to processes occurring within the links, such as decay of a particular constituent over time.

Source features a wide range of data pre-processing and analysis functions that allows users to create and compare multiple scenarios, assess the consequences, and report on the finding.

The contribution of a particular constituent on areas of the catchment can be viewed, and various visualisation methods used to show uncertainty including bar charts, line graphs, tables and maps such as rasters or polygons."

Source is particularly interesting because it allows for the use of a variety of dynamic *Sednet*[1] plugins covering hillslopes, gullies, streams and nutrients. It uses an ensemble of spatial and point models that produce outputs that are fed into *Source* for load generation. These can represent different soils, climates, land uses and land management scenarios. Once loads are generated, downstream effects of sediment storage and in-stream deposition and decay may be applied through the link models.

Source is available commercially and is supported with regular training sessions and conferences.

While Source and MUSIC are not landform evolution models per se they may offer potential for use together with distributed hillslope/channel models such as CAESAR-Lisflood since they make it possible to deal with spatially variable landscapes containing a wide range of soil and vegetation types and a different set of management treatments. I provide more comments on this in a later section.

Spatially Distributed Landform Evolution Models: while a number of models exist, only two are widely available and suitable for operational use. These are *SIBERIA* and *CAESAR* plus *CAESAR-Lisflood* which is the current version. Both have been applied by ***eriss***. A number of other spatially distributed models exist such as *EUROSEM, TREX, CASC2D* (now included in the *GRASS GIS)* and *LISEM*. However, these are more focused on estimating flood runoff and sediment yield from specific landforms and land use treatments rather than taking the longer term perspective of the landform evolution models.

SIBERIA has been used in the Alligator Rivers Region since the mid-1990s. It generates erosion and deposition using a simple sediment transport relationship based on slope and contributing runoff area. There are many other parameters including diffusion, rates of uplift or subsidence, etc. All these parameters require calibration and there is a small library of suitable parameters. However, usually only the slope and area parameters that control runoff and erosion are used while all other parameters are held constant. Indeed, in many cases, virtually nothing is known about what these other parameters do in

---

[1] *Sednet* is a relatively simple sediment yield model originally developed by CSIRO for Australia's National Land and Water Audit in 2001 and subsequently developed as part of the eWater toolkit.

practice and changing them can sometimes produce quite unpredictable results. *SIBERIA* allows for a bedrock surface which limits downward erosion. It can also handle spatially variable ground and runoff conditions by having different parameter values for several sub-areas. However, boundaries between sub-areas may result in sharp differences in erosion rates and produce large steps in elevation as there is only basic sediment routing and very little smoothing. *SIBERIA* has also been used on landforms containing layers with different sediment and erosion conditions, notably at Los Alamos. However, this is not a simple process and is undocumented.

SIBERIA is perhaps the most widely used landform evolution model and a simplified version of it has been built into *CAESAR-Lisflood*. However, the model has not been developed further for some years and the support is minimal. It has also been widely misused and I have seen a number of cases where it has been used to evaluate a range of landform designs with no calibration or validation and parameters based on guesswork.

My personal experience of *SIBERIA* has been under steep slopes and very high rainfalls with high quality calibration datasets. While the hillslope profiles generated were reasonably convincing, the model did not handle concentrated flow in potential gullies. Once sediment loads were high enough, these became blocked and became pits from which no outflow occurred. Thus, most streams stopped dead. This meant that downstream erosion rates were severely underestimated and the distribution of erosion and deposition did not match what was observed. However, it was possible to calibrate the model to generate overall observed sediment loss rates.

While the SIBERIA model has a somewhat dated interface and is not an easy model to use, it still offers some potential for ***eriss****, particularly for hillslopes and situations where erosion rates are not too high to generate the pitting problem. It is much faster to run than CAESAR-Lisflood and is currently better suited to handling sub-catchments with different characteristics as part of the same model run. It may also be used to quickly generate results from a range of management treatments and landform shapes as long as defensible values for the slope and area runoff and sediment transport parameters are available.*

CAESAR-Lisflood is the current model in use by ***eriss***. It combines the *LISFLOOD-FP* flow model for unsteady flow routing across a landscape with the *CAESAR* landscape evolution model. There are four main parts to *CAESAR*, a hydrological model, a flow model, a fluvial erosion and deposition model, and slope process models. The hydrology model is a variant of the *TOPMODEL* procedure and is used to generate a combined surface and subsurface discharge using rainfall inputs, evaporation and a soil moisture store. *TOPMODEL* incorporates landform shapes through the use of a Topographic Index which is a measure of the extent of flow accumulation at the given point on the topographic surface. *LISFLOOD-FP* is a one-dimensional inertial model derived from the full shallow water equations that is applied in the x and y directions to simulate two dimensional flow over a raster grid. It combines both unsteady and spatially-varied flow. Erosion and deposition are modelled using either the Wilcocks and Crowe sediment transport model or the Einstein procedure. The model is capable of handling multiple grain sizes and uses multiple bed layers to provide a capacity for bed armouring. Slope processes consist of a slow soil creep model and a landslide threshold procedure based on angle of rest. In what is something of a first, *CAESAR-Lisflood* also contains a simple vegetation growth model allowing a grass surface to develop over time which inhibits erosion. However, it apparently occurs at a uniform rate over the whole catchment. Vegetation effects on runoff may also be represented through a parameter in the runoff model. A further advantage of *CAESAR-Lisflood* is that it has been shown to operate successfully on small plots and therefore has a capacity to scale up although careful attention to parameter values is needed to see if they are scale-invariant.

CAESAR-Lisflood represents current international best practice and eriss is a world leader in applying it to landforms rehabilitated after mining. *It provides estimates and locations of erosion and deposition, topographic change, and development and decay of gullies. It also calculates sediment loads at various locations and times within the catchment and at catchment boundaries. This meets many of the criteria specified for the rehabilitated landform after mine closure so it is fit for purpose. The model is also much more tolerant of the pits and flats that limit or halt downslope movement of sediment and water in SIBERIA.*

While *CAESAR-Listflood* is probably the best model currently available, there are a number of things it does not do, or capacities it does not have. These include:

- Inability to handle spatial variability in soil type and vegetation type and cover except through the use of sub-catchments which must be linked post-facto. This feature did exist in early versions of the CAESAR model but has been dropped in later versions.
- The model does not handle layers in landforms apart from an erosion-limiting bedrock surface.
- Limited capacity to generate the fine sediment that makes up wash load except, perhaps through the slope erosion parameter or by running the model in reach mode with fine sediment inputs from upstream.
- While many of the model parameters are based on measurable properties or have values that that can be reasonably estimated, some, such as the lateral erosion rate, ideally require calibration as they can make a significant difference to model results. Unfortunately this requires long term data on landscape change which may not exist.
- Reliance on sediment transport equations which are notoriously unreliable. Also, only two bedload equations are available. It is, however, relatively easy to modify calculated transport rates through a few lines of code that introduce a simple transport rate multiplier.
- The model is computationally intensive and, while running much faster than comparable 2-D hydraulic models, it still requires long computer times. These may be prohibitive on large areas or fine grids.

One problem with landform evolution models more generally is the lack of long term validation data on landform change. Models often run for long periods but there are few datasets available that show sufficient observed changes in elevation over time at the whole landform scale to validate model results against. Information on river channel changes over time (usually from sequences of aerial photographs) is more common and this has been used at times for model validation. However, there not enough change in mine area small catchments to make use of this approach.

Other datasets that have proved useful for model validation over long periods of time include concentrations of trace metals in sediment deposits from historical mining operations. Some of these have already been investigated in southern Alligator Rivers Region. Early versions of *CAESAR* included the *TRACER* model which allowed tracking of heavy metals down through river systems and identification of deposits. Unfortunately, this capacity is no longer present. It would be useful if this capacity was reintroduced by the model developer as it would allow more model validation in the local region.

2.3 *eriss* modelling procedures with *CAESAR-Lisflood*

The modelling procedures reported by eriss in recent publications are both thorough and sound and are consistent with best practice. *They are also still developing as final landform designs become available and as cooperation with the model developer continues. However, I do have some suggestions that might enhance the work.*

1. There are few examples in the general *CAESAR* literature (not just from the Alligator Rivers Region) where runoff rates from the *TOPMODEL* component are reported and compared with observed discharges. This should be done if possible even if the location of stream gauges does not quite match the current area of interest.

2. I would like to see more investigation of how changes in *CAESAR-Lisflood* parameters affect model results. In my own work with the model, I have found that changes in the soil creep parameter and the lateral erosion rate can make quite a difference to results. In fact, it may be desirable to conduct a formal sensitivity analysis to determine which parameters matter most under local conditions.

3. The long term simulation reported in the most recent exercise to determine the long term stability of the rehabilitated landform used a rainfall series built from repeating the observed 22 year rainfall but excluded the 2007 cyclone. Given the importance of extreme events in the Alligator Rivers Region reported elsewhere in the literature, this approach is open to debate. A more defensible approach might be to use the standard methods for generating rainfall series in Australia to produce a long term synthetic record. Several approaches may be necessary to accommodate extreme outliers. Indeed, stress testing of alternative landform designs might be carried out using a rainfall series with a fairly high frequency of extreme events.

4. Model results throughout the *CAESAR* literature (not just from the Alligator Rivers Region) tend to show the initial landform and the final landform but do not provide figures showing the amount of change between them. This can hide a variety of sins. I would prefer to see results of modelling runs expressed as change in elevation as well as elevation itself. This gives a much better indication of model performance. Just using elevation (as a grey scale) does not give a very clear impression of what is happening and tends to mask model flaws. I note that eriss has shown change values in modelling of pit stability but it would be useful to provide these values more widely.

5. All of the 2D models I have used (including *CAESAR-Lisflood*) are potentially affected by DEM artefacts. These are small irregularities in the topographic surface caused when gridding LiDAR point datasets or when gridding from contours (which may produce steps in the landscape). Gridding from contours via fitted TINs may also produce artefacts. Once a model is run, it may generate rills in some of the irregularities which subsequently become gullies under high rainfall conditions. DEMs should be checked to see whether these problems occur before running a model. A good way of carrying out this check is to calculate and view topographic curvature. The LiDAR-derived DEM of current landforms in the mine area seems reasonably free of major artefacts. However, if datasets of final landforms are delivered in the form of contours, this may cause problems.

6. *CAESAR-Lisflood* uses a single angle of rest to determine whether slope failure and subsequent landsliding can occur. On slopes containing fine sediment, waterlogging and possible even fluidisation may occur, producing landslips. Events of this nature have been reported from the Alligator Rivers Region on natural hillslopes. Presumably, the engineers designing the final landforms at Ranger will subject them to the normal range of geotechnical analyses. However, it may also be worth applying a shallow landsliding model such as *SHALSTAB* to investigate potential for areas of slope failure in steeper zones of flow convergence even if final landforms have fairly low slopes. Potential areas of interest may be valley sidewalls if local creeks affected by final landform construction re-establish themselves.
7. *CAESAR-Lisflood* assumes no change over time in particle size distribution from that of initially emplaced material except through sorting and bed armouring. However, there may well be some particle breakdown to fines with weathering. There may be a need to allow for the weathering characteristics of cap material during long term modelling runs. Some rock types, if fresh, can weather very quickly in tropical environments when exposed to oxidation. ***eriss*** is currently in the process of acquiring these data and a time series covering several years should soon be available.
8. Assuming that feral buffalo survive in the area, their tracks create a risk of gullying, especially if constructed landforms or the mine area provide a source of dry season drinking water (in pit lakes for example) or when rehabilitated landforms are sown with palatable grasses. Feral pigs may be an even greater problem as they can disturb soils with their foraging behaviour. These issues may be worth investigating as they could cause significant localised erosion.
9. When designing or testing landforms, it is common to use a safety factor, especially where model parameters or behaviour involves uncertainties. The *eriss* program has gone a considerable distance with this approach by modelling with and without vegetation cover and for surcharged and non-surcharged landforms. However, I would like to see wider use of safety factors, perhaps by varying the most important and least certain model parameters. Loss of vegetation through fire should be expected and modelling without vegetation cover will give a measure of safety.
10. Waste rock may contain sulphides. Potential for acid generation should be examined and mitigation strategies such as mixing with limestone may need investigation.

2.4 Potential for combining *CAESAR-Lisflood* with sediment accounting models

CAESAR-Lisflood does not handle spatial variability in soil types and vegetation growth cover easily. Sub-catchments need to be set up and model runs carried out and subsequently linked. Variations in rehabilitated landscape shape also need to be set up from new DEMs. *Given the relatively long computation times associated with CAESAR-Lisflood runs, it may be worth examining whether the model might be used to generate parameter sets suitable for use in sediment accounting models such as Source and thereby applied to larger areas and more heterogeneous landform assemblages.* I am not aware of any instances where this has been done with *CAESAR-Lisflood* but it is worth considering where a range of landforms or vegetation growth patterns needs to be investigated.

I note that eriss has already taken this approach by using CAESAR-Lisflood to help in selecting parameters for SIBERIA which allows for model runs over very long time periods.

2.5 Emerging approaches

While currently being state-of-the art, *CAESAR-Lisflood* is essentially a physical process model with a very simple grass growth model added on. However, recent trends in landform rehabilitation science show increasing concentration on biological processes. Some early work was done on soil turnover by termites in the Alligator Rivers Region but the biological component does not appear to have been incorporated within the sediment modelling program beyond the simple grass growth model in *CAESAR-Lisflood*. This reflects the lack of available models & reflects the lack of biology in the training of most geomorphologists more generally.

Most studies I have seen of rehabilitated mine landscapes in the semi-arid and seasonally wet tropics in Australia emphasise the importance of colonisation by plants and maintenance of vegetation cover in developing a stable landform. However, this is not a spatially uniform process as modelled in *CAESAR-Lisflood*. Instead, it is a highly variable process and is locally dominated by zones of water runoff and runon, and the level of loss, disturbance and accumulation of sediment and nutrients within a slope or landform. This is especially true of newly created or disturbed rehabilitated mine landforms where patterns of runoff and vegetation cover are developing from scratch. Here, recently constructed slopes or landform cover materials develop source zones which shed runoff, sediment, nutrients and plant material. Source zones feed into transfer zones which are areas which only show limited net loss or gain of material but are regularly disturbed as material is intermittently transported across them. Transfer zones feed into sinks where material accumulates and plant growth may be vigorous. Source zones often develop on the upper sections of hillslopes, transfer zones may occupy mid-slopes, and sinks occur on lower slopes. However this is a simplistic model and all three zones may occur anywhere on a slope. Indeed, they may exist simultaneously at a variety of spatial scales and small scale features may be nested within larger features making up erosion cell mosaics. The theory of these mosaics suggests that the finer scale features operate during smaller rainfalls whereas the larger source zones, transfer zones and sinks operate and develop connectivity during high rainfall events.

Over the last two decades, a great deal of work has been done in Australian rangeland research on this type of landscape patchiness and it has been shown that patch structures greatly influence landscape stability by modulating loss of water, sediment and nutrients (also termed leakiness). Leaky landscapes tend to have large patches (or erosion cells) and are regarded as degraded and low in resilience under variable climatic conditions such as those of the savannah landscapes of northern Australia. The more resilient landscapes and those which are trending towards stability tend to develop fine-scale patchiness.

One technique that has been developed for assessing landscape condition is *Landscape Function Analysis (LFA)*. This is essentially a ground survey technique based on one-dimensional transects. While initially developed for range assessment, it is increasingly being used on mine waste dumps and rehabilitated landforms, initially to understand how they are evolving through time, but also as a measure to assess whether the rehabilitation scheme was successful. Indeed, it is currently being considered by several States, both as a measure of successful rehabilitation, and, when a suitable level of landscape functioning is achieved, as a possible trigger for the return of post rehabilitation bonds.

A manual and full description of the LFA techniques is available here:

http://live.greeningaustralia.org.au/nativevegetation/pages/pdf/Authors%20T/7a_Tongway.pdf and other resources are available here: http://www.csiro.au/Organisation-Structure/Divisions/Ecosystem-Sciences/EcosystemFunctionAnalysis.aspx

A presentation on application to minesites is available here:

http://www.cse.csiro.au/research/ras/efa/resources/EFA_Overview_Minesite.pdf

The concepts behind *LFA* involve identifying those features in a landscape that regulate the availability of vital resources such as soil, water and nutrients in space and time. Many landscapes are naturally heterogeneous in terms of resource control and possess areas where resources tend to be lost or are only available intermittently (source and transfer zones) or patches where they accumulate (sinks). Between them are inter-patches which the resources flow more freely across. The patches may form "runon" zones where overland flow tends to accumulate, due to flats or depressions in the landscape, or plant patches that accumulate resources by acting as wind or water flow obstructions. Patches are richer in resources and have enhanced soil properties such as better infiltration, higher nutrient concentrations and greater physical stability. Inter-patches tend to be poorer in resources and have low soil property values compared with the patch. Source zones consistently shed water soil and nutrients and develop rills, sheetflow zones and gullies. Many rehabilitated landforms develop these features on their slopes or have them built in (often accidentally) during construction. Indeed, the development of patch structures is often how areas of disturbance restabilise.

Without going into the detail of the *LFA* procedure, stabilising slopes tend to develop fine scale patchiness or have low sediment loss and maintain uniformity of plant cover and retain resources. Degrading or dysfunctional slopes tend to develop large scale patchiness and largely consist of source or transfer zones with large sinks at their base.

Field application of *LFA* involves a range of measurements including soil surface parameters such as crusts and cryptogam covers, plant composition and recognition of patches. However, *CAESAR-Lisflood* also generates a range of source zones, transfer zones and sinks both initially in the *TOPMODEL* topographic index, and subsequently as erosion and deposition proceeds. These also develop at changing spatial scales as rainfall event magnitude increases. Indeed, it has been suggested that the topographic index controls flow accumulation, soil moisture, distribution of saturation zones, depth of water table, evapotranspiration, thickness of soil horizons, organic matter, pH, silt and sand content, and plant cover distribution.

It would seem that there is some capacity for improving the biological component of CAESAR-Lisflood by incorporating some of the LFA ideas on patchiness and resource leakage into both the plant growth model and into local erosion/deposition rates over time. Thus, water and sediment sinks or patches have more rapid or enhanced vegetation growth and stronger runoff and sediment trapping properties. Source or eroding zones, on the other hand, have reduced plant growth and runoff trapping properties and enhanced rates of sediment loss even during periods of general vegetation growth. No doubt, these changes would have to be made by the model developer or perhaps within a sediment accounting framework such as *Source*. However, it is a prospect and there is now probably enough multi-temporal high resolution remotely sensed data available to carry out some testing on existing landforms. I don't believe this has been done with an LEM as yet but I suspect that may become the way forward when trying to generate stable or resilient landforms.

2.6 Conclusions

The review brief called for assessments of:

1. How the Hydrologic, Geomorphic and Chemical Processes landform evolution research program compares with current international leading practice, especially in relation to erosion of a rehabilitated mine site?

In my opinion, the program is world-class and consistent with international best practice. The methods in use with the models are sound and also represent best practice.

2. What additional or emerging approaches could be utilised by the Hydrologic, Geomorphic and Chemical Processes Program for its research and assessment activities for assessing landform evolution.

The program may wish to examine whether the current generation of Lumped Parameter, Semi-Distributed Catchment and Sub-Catchment Models offer potential for developing more generalized approaches. However, this may not be necessary if available computer facilities are able to handle long term runs with CAESAR-Lisflood over larger areas.

There is potential for enhancing the program through incorporation of recent developments in knowledge of how slopes function by developing spatial patterns of distribution in runoff, erosion and deposition, and nutrient cycling, and the feedbacks between vegetation growth and these processes.

2.7 Credentials of reviewer

Dr. Geoff Pickup is geomorphologist of more than 30 years' experience with a background in fluvial geomorphology, remote sensing and engineering hydrology. Prior to becoming a private consultant in 2001, he was Chief of the CSIRO Division of Water Resources and Chief Research Scientist, CSIRO Land and Water. He currently specialises in sediment transport and erosion modellingin mining environments and has worked in Australia, Asia, Africa, North America and the Pacific. Over the last decade, he been responsible for most of Ok Tedi Mining Ltd's sediment transport modellingand recently, in association with EGI Ltd, pioneered the merging of sediment transport and ARD modeling. He has applied both the *CAESAR-Lisflood* and *SIBERIA* models at various locations, including the Ok Tedi and Hidden Valley Mines in Papua New Guinea. He has extensive experience in northern and central Australia in areas including palaeoflood analysis, erosion modeling and the use of high resolution imagery and airborne geophysical techniques for mapping of sedimentary environments. He also led the team that designed much of the Alligator Rivers Research Institute geomorphology program in the 1980s. He has had no connection with ***eriss*** since then.

Part 3: Comments by Tom Coulthard and Greg Hancock

T Coulthard & G Hancock

3.1 Introduction

The above comprehensive review describes how eriss is using state of the art models and world-best practice for simulating the future behaviour of the Ranger mine site. It also highlights a number of advantages of the methods used – and how this 'best practice' methodology is to be commended. The review also contained a series of comments and insights that are highly constructive to consider when moving the project forward.

In this chapter, Professor Coulthard (University of Hull) and Associate Professor Hancock (University of Newcastle) respond to all of the comments and suggestions made by Dr Pickup. The chapter has been broken into three broad sections:

- An integrated section which contains a joint response to general/technical comments;
- The response of Professor Coulthard, from the perspective of model developer, to three key areas picked up by Dr Pickup with respect to climate, soil development and vegetation; and
- The response of Associate Professor Hancock to Dr Pickup's comments from the perspective of a landform modelling practitioner.

3.1.1 Integrated general/technical comments

The review noted that CAESAR-Lisflood was unable to simulate spatially variable soil and vegetation. For soil/sediment type this is not correct. There is a utility called grainfilemaker (downloadable from the CAESAR website) where separate areas of soil/sediment composition can be created for the catchment / study area. This was used in 2012/13 by ***eriss*** to show how different surface treatments of the landform (in different locations – i.e. along streamlines) could impact upon erosion rates. Further Hancock and Coulthard (2012) have employed this function and shown that soil and particle size has a direct impact on erosion rate and erosion position. Vegetation growth can vary spatially across the modelled area – but the properties of the vegetation community do not change (i.e. it is the same type of vegetation) – although this is something that could be readily modified.

A further comment was that CAESAR-Lisflood does not handle layers of different type or competence of sediment. The model can handle this – but it is not implemented by ***eriss***. As CAESAR-Lisflood has ten 'strata' layers below the surface it is quite possible to define these differently – so capping layers can be underlain by different grade/formation sediments. This could readily be changed if such a scenario was required. If the field data was available this could be easily included in any simulation.

The review also noted that while some model parameters were based on measurable properties or values that could be calculated, other model parameters relied upon being calibrated (for example lateral erosion rates). Unfortunately, this is an issue with all forms of morphodynamic landform modelling and is not unique to CAESAR-Lisflood.

Similarly, the review correctly noted a reliance on sediment transport equations that have a high degree of uncertainty. When applying all morphodynamic models outside of a theoretical framework this criticism is true. A generic solution to this reliance in sediment transport equations is a long way from realisation.

Specific dot points raised by Dr Pickup are addressed below:

- *There are few examples in the general CAESAR literature (not just in the Alligator Rivers Region) where runoff rates from the TOPModel component are reported and compared with observed discharges. This should be done if possible even if the location of stream gauges does not quite match the current area of interest.*

Bevan (1997) compares predicted runoff rates from TOPModel with observed discharges. CAESAR-Lisflood utilises a largely unmodified version of TOPMODEL. Therefore, it is quite possible that TOPMODEL literature i.e. Beven & Kirkby (1979) may be used to parameterise the key 'm' value within TOPMODEL.

- *I would like to see more investigation of how changes in CAESAR_LISFLOOD parameters affect model results. In my own work with the model, I have found that changes in the soil creep parameter and the lateral erosion rate can make quite a difference to results. In fact, it may be desirable to conduct a formal sensitivity analysis to determine which parameters matter most under local conditions.*

This is a very valid criticism. A full evaluation of the sensitivity and uncertainty of CAESAR-Lisflood would be a very useful and instructive exercise. There are a range of previous studies which have considered and tested various aspects of CAESAR and CAESAR-Lisflood parameters (Coulthard & Van de Wiel 2013; Coulthard et al. 2012a; Hancock & Coulthard 2012; Hancock et al. 2011; Ziliani et al. 2013)

- *Model results throughout the CAESAR literature (not just from the Alligator Rivers Region) tend to show the initial landform and the final landform but do not provide figures showing the amount of change between them. This can hide a variety of sins. I would prefer to see results of modelling runs expressed as change in elevation as well as elevation itself. This gives a much better indication of model performance. Just using elevation (as a grey scale) does not give a very clear impression of what is happening and tends to mask model flaws. I note that eriss have shown change values in modelling of pit stability but it would be useful to provide these values more widely.*

Agreed. This is largely down to the data provided. Output data can be provided in a variety of forms from annual erosion rates through to 3-D plots of the evolving landscape at any time step required. At all times we have endeavoured to provide the most relevant and useful data.

- *All of the 2-D models I have used (including CAESAR-Lisflood) are potentially affected by DEM artefacts. These are small irregularities in the topographic surface caused when gridding LiDAR point datasets or when gridding from contours (which may produce steps in the landscape. Gridding from contours via fitted TINs may also produce artefacts. Once a model is run, it may generate rills in some of the irregularities which subsequently become gullies under high rainfall conditions. DEMs should be checked to see whether these problems occur before running a model. A good way of carrying out this check is to calculate and view topographic curvature.*

Agreed. This is a significant concern – albeit primarily the responsibility of the landform designer – in this context, the mining company ERA and/or its contractors. It is important that the reliability/robustness of the initial landform be assessed before any modelling occurs. From the perspective of the software developer / practitioner, while we may have little control over the initial landform as it is a product of the mass-balance issues of the landscape reshaping and that of the skill of the designer and their knowledge of geomorphology, we are currently developing a method for assessing landscape construction error and its long-term influence on landform behaviour.

- *CAESAR-Lisflood uses a single angle of rest to determine whether slope failure and subsequent landsliding can occur. On slopes containing fine sediment, waterlogging and possible even fluidisation may occur producing landslips. Events of this nature have been reported in the Jabiru area on natural hillslopes. Presumably, the engineers designing the final landforms at Ranger will subject them to the normal range of geotechnical analyses. However, it may also be worth applying a shallow landsliding model such as SHALSTAB to investigate potential for areas of slope failure in steeper zones of flow convergence.*

This could indeed be added – though given the low slopes on the landform for all scenarios proposed to date – this may not be necessary. However, it is an issue that should be considered with any proposed design.

Saynor et al. (2012b) found that landslides on Oenpelli Dolerite in the Magela Creek catchment during the extreme event of February/March 2007 were restricted to slopes equal to or steeper than 17° and the designed rehabilitated mine site would need to be checked for such threshold slopes.

- *Assuming that feral buffalo survive in the area, their tracks create a risk of gullying, especially if constructed landforms or the mine area provides a source of dry season drinking water (in pit lakes for example) or when rehabilitated landforms are sown with palatable grasses. This may be worth investigating.*

It is considered unlikely that the impacts and affects of feral buffalo will feature heavily in rehabilitation / remediation plans and activities for the Ranger mine. Hancock et al. (2011) demonstrated that tree throw after cyclones did not increase erosion for a nearby undisturbed catchment. Further work by Hancock et al. (in press) has found again that pigs do not increase erosion rates in a natural catchment despite exhuming considerable soil each year. How these findings translate to post-mining materials is not yet known.

- *CAESAR-Lisflood does not handle spatial variability in soil types and vegetation growth cover easily. Sub-catchments need to be set up and model runs carried out and subsequently linked. Variations in rehabilitated landscape shape also need to be set up from new DEMs. Given the relatively long computation times associated with CAESAR-Lisflood runs, it is worth examining whether the model might be used to generate parameter sets suitable for use in sediment accounting models such as Source and thereby applied to larger areas and more heterogeneous landform assemblages. I am not aware of any instances where this has been done with CAESAR-Lisflood but it is worth considering where a range of landforms or vegetation growth patterns needs to be investigated.*
- *I note that eriss have already taken this approach by using CAESAR-Lisflood to help in selecting parameters for SIBERIA which allows for model runs over very long time periods.*

This is a realistic and practical option. The current method employed is to use CAESAR for sub-annual and short term assessment with SIBERIA having the capacity to operate at longer (millennial) time scales.

3.2 Tom Coulthard's perspective

3.2.1 Climate

The reviewer rightly identifies limitations with how climate and climate change are represented in the modelling program. Changes in rainfall driving the model will be one of the main causes of change in output. We have conservatively used existing rainfall data (augmented by the 2007 cyclone event when required) as a baseline for our existing studies but when looking to simulate up to 10,000 years into the future a methodology should be developed for simulating rainfall for this period. Using synthetic rainfall data raises new issues – weather generators and other methods for creating rainfall time series largely sample statistical representations of existing rainfall tweaked to give different future distributions of events. These rainfall data are generated stochastically, by randomly sampling the distribution of past events and means a probabilistic approach is required for future simulations. This means that multiple repeats with different rainfall time series (from the same scenario) need to be used and average values (with variance) of resultant changes forming the output. This has been carried out over shorter time scales (30-100 years) on one UK based catchment (Coulthard et al. 2012b) and such a methodology could form a framework for future simulations here. Unfortunately, the need to run multiple simulations with a model that can have considerable run times generates a computational overhead. However, this need for improved rainfall data is coupled with understanding the armour/soil development and resultant feedbacks with vegetation growth and dynamics.

3.2.2 Soil development

The review rightly identifies that the present ***eriss*** modelling capability assumes no breakdown in the grainsize of sediment. Changes in surface grainsize are solely driven by selective erosion and deposition. Rates of mostly physical weathering on the trial landform test plots are currently being determined. Nevertheless, the physical and chemical breakdown of the surface material and soil is an important process that should be integrated within the ***eriss*** modelling approach.

Trial work has already begun on this approach by integrating the physical and chemical weathering components of the soil development model of Vanwalleghem et al. (2013). This is a dynamic 3d soil development model that takes into account how moisture and temperature vary with depth when determining the breakdown of sediment clasts. For example equation 1 describes how particle size reduction is contingent upon particle size, depth and rates of reduction for that grain size.

$$a_{jit} = -k_1 e^{(-c_1 D_j)} \frac{c_2}{\log(PD_i)} \Delta t \quad (1)$$

where a_{jit} is the amount each particle size class (i) breaks down by, k_1 the rate constant of physical weathering, D_j the depth below the soil surface for layer(j), c_1 the depth rate constant for physical weathering, PD_i the mean particle size, c_2 the size rate constant for physical weathering and Δt the model time step.

Vanwalleghem et al. (2013) also identify an equation which could be used to represent the chemical weathering of a landform surface.

The scheme of Vanwalleghem et al. (2013) uses multiple grainsizes and a series of layers to represent horizons within the soil, so can easily be integrated within CAESAR-Lisflood as this already contains an active layer system and works with multiple grainsizes.

Initial simulations are encouraging – and show the model reducing surface grainsizes over time. However, the parameters used to predict rates of weathering will require calibrating and the model testing with field data. Such work is already being carried out by ***eriss*** who have been monitoring surface grainsizes on the trial landform plots to show how the grain size distributions change over time. In the course of the coming few years this will give rise to a valuable data set from which the above schemes in CAESAR-Lisflood can be tested/calibrated.

3.2.3 Vegetation

The review rightly noted the limitations of the vegetation model used within CAESAR-Lisflood. The importance of vegetation on altering erosion rates in this environment is undeniable and needs to be accounted for. The existing vegetation model within CAESAR-Lisflood is simple and adequate for some purposes, but is probably too simplistic in its present form for this application.

The review suggested looking at the use of Landscape Function Analysis (LFA) for rehabilitated landforms and for integrating such approaches within numerical models of mine rehabilitated landforms. Reviewing the LFA manual and some example papers suggests that LFA is an excellent tool for *assessing* mine site rehabilitation and *measuring* vegetation recovery.

However, whether LFA approaches would translate into providing parameters and process rates that can be fed into a numerical model is not so clear. LFA gives good indicators of recovery, but how this could be used as a predictor within numerical code is not clear. Certainly it could provide data to parameterise numerical schemes, but it does not readily provide information on the processes or interactions operating. Therefore, we would suggest that methods like LFA would be an excellent procedure to use when assessing the performance of the landform and landform models post rehabilitation but less suitable for using to develop a numerical vegetation model component. However, if LFA is seen as a good way forward changes could easily be made within CAESAR-Lisflood with the aim of using LFA as a comparator metric/methodology and model outputs designed accordingly.

However, this still leaves a clear need for a dynamic vegetation model to be developed/integrated within CAESAR-Lisflood. Dynamic vegetation models have been developed within landscape evolution models (Cohen et al. 2013; Saco 2007; Saco & Moreno-de las Heras 2013) whereby soil moisture is linked to a biomass growth and seed dispersal model. Biomass levels can then be used to restrict surface erosion rates. In environments such as those found at Ranger with strongly seasonal vegetation responses this approach may be ideal and by lumping all vegetation within a biomass term it reduces the need to have different types of vegetation represented. Tests have already been carried out integrating this approach into CAESAR-Lisflood and shown that it works and can generate a dynamic vegetation pattern who's biomass density follows overall moisture but also soil moisture. Therefore you get a concentration of vegetation within gulleys and depressions reducing the likelihood of erosion in these areas. Initial tests show that for the Ranger application seed dispersal is not a significant issue (we must assume that there is widespread planting) and that the model is sensitive to two terms accounting for biomass decay and biomass growth rates. Values for these can be taken from previous studies - but getting appropriate values could be measured/calculated for vegetation endemic to the NT.

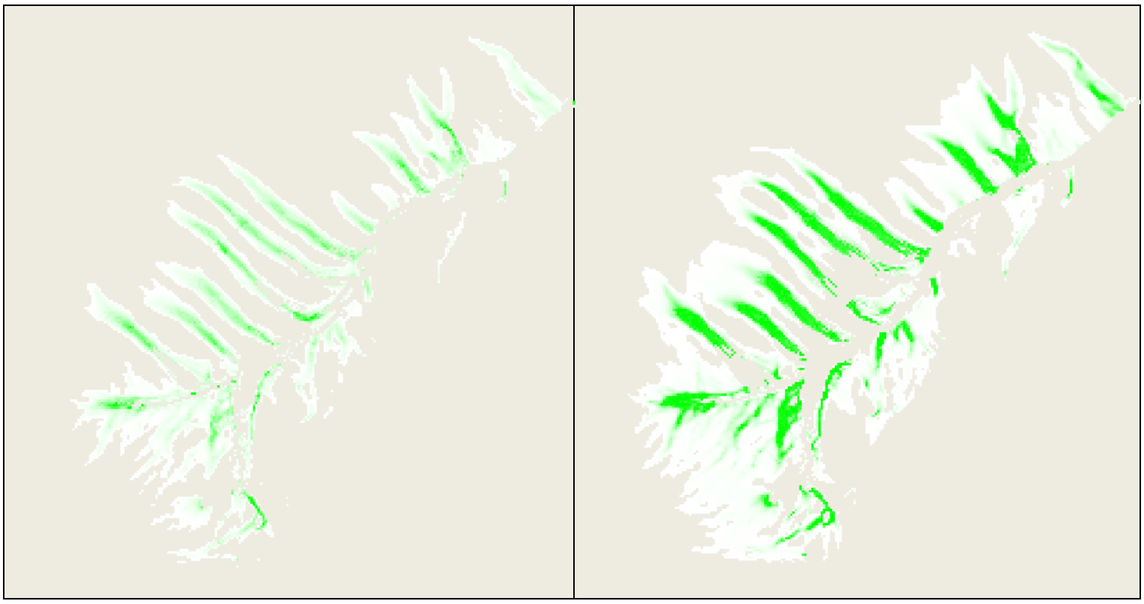


Figure 3.1 Images from preliminary runs showing the development of vegetation along drainage lines within the Corridor Creek catchment based on the Saco et al. (2007) model.

3.2.4 Future recommendations

I would suggest that the addition, testing and if necessary modification of the Vanwalleghem pedogenis model and Saco vegetation growth, in addition to an appropriate methodology for generating future rainfall for the region could be a suitable way of addressing the bulk of the issues outlined by the reviewer moving forward.

3.3 Greg Hancock's perspective

There is no question that the ERA Ranger site will be rehabilitated in some form and that the central tenet of any rehabilitation is a stable self-sustaining landscape. Given the length of time that the landscape is required to perform (10,000 years), innovative assessment approaches are required.

Over the past decade ***eriss*** has been visionary in using LEMs to assess a range of proposed landforms. These LEMs have been calibrated and developed to the point where they are now limited by input data and a consensus on design and climate scenarios. Both SIBERIA and CAESAR are very advanced models and it can be argued that they have more functionality than the field data with which to calibrate them. For example, if vegetation growth and its influence on hydrology was quantified along with pedogenesis then sub models within SIBERIA and CAESAR could be further developed and implemented.

Previous world-class work by Evans et al. (2000) developed LEM input parameters based on what was proposed to be the surface materials of the final landform. These parameters were for waste rock as well as for a vegetated surface. The effect of fire was also examined. However the extent, nature and composition of the final landform surface is still being evaluated. If the surface is very different to that of past materials then new LEM model parameters for the new material will be needed. This will require field plots to be constructed for a range of slopes and slope length and monitored for many years. If this is not done then any LEM predictions may have considerable error.

A significant issue is reliable prediction at time scales up to 10,000 years. Both SIBERIA and CAESAR are capable of running to this length of time, however this requirement has several implications such as model calibration at these time scales, validation at these time scales and the practicalities of model run times for 10,000 years. These and other issues are discussed below

3.3.1 Model calibration

At present any LEM parameters have been developed for surfaces that are several years old. We know very little about how these new surfaces evolve and how erodibility changes in this or any post-mining environment. It is well recognised that armouring and weathering of waste rock is extremely rapid at the ERA Ranger mine. However, we have a near complete lack of data on this process and therefore this is not included in LEM parameterisation. The outcome from this lack of data is that any model prediction may be grossly over or underestimating erosion at the 10,000 year time scales needed here. Significant issues are weathering and armouring and pedogenesis. A further issue is the trial landform.

3.3.2 Weathering and armouring

They should be at least examined on the surface of the trial landform and on any material that is likely to be used as part of the rehabilitation. Weathering trials for the proposed materials under controlled conditions (i.e. such as that performed by Wells et al. 2005) will provide important information on weathering process and rate.

3.3.3 Pedogenesis

Pedogenesis can be examined by use of soil pits at sites of different ages on rehabilitated areas of the mine or areas that have not been disturbed so that soil production rates and process can be determined.

3.3.4 Trial Landform

The Trial Landform, while a world class facility in its size and setup, is more suited for the determination of vegetation establishment and management than hydrology and sediment transport and has very limited potential for the reliable determination of long-term erosion parameters. This is due to the simple very low slopes on the plots that are not representative of the typical slopes and slope lengths on the rehabilitated site. Hydrology and sediment transport is recognised to be highly non-linear especially at higher slopes and a single low slope provides very limited calibration and validation potential.

It is recommended that further trial plots be established over a greater range of slopes so that more robust parameterisation and validation can be determined.

A further significant issue is that aside from the world-class work of Evans (2000) and Evans et al. (2000), there are few external data sets available for both post-mining and natural surfaces. Denudation rates exist but only provide a broad expected range of landscape lowering for the region. These denudation rates need to be re-examined and updated.

Further, data exists for the Gulungul Creek catchment adjacent to the mine as well as suspended sediment data from the trial landform, however, these data sets have not been fully processed, assessed and made available. While recognising that some data for the 2012-13 year is available in the *eriss* research summary (Erskine et al 2014a), the total dataset required is incomplete. Given the particular importance of the Gulungul Creek data, these data should be made available as soon as possible.

Other techniques using environmental tracers such as ^{137}Cs and ^{210}Pb should be employed to determine background hillslope erosion rates. ^{7}Be can provide data on storm scale erosion. These techniques are well-established and ^{137}Cs has been used successfully in the region. The employment of environmental tracers would provide indicative erosion rates over a 50-60 (^{137}Cs) and 200 (^{210}Pb) year periods. They need to be employed at suitable sites as close to the mine as possible.

3.3.5 The role of vegetation

Conceptually, vegetation is recognised to have a large influence on erosion and consequently landscape evolution. However, there is very little quantitative data on the role of vegetation and how this interacts with the new surface especially in this environment. While there is some data from the work of Evans et al. (1996, 1998) on this issue, there are no data for time periods greater than 5 years. This is especially important as how vegetation will influence hydrology and sediment transport at timescales greater than this will ultimately determine the performance of the landform. Therefore, field data is needed for proposed vegetation types and assemblages and how this temporally changes at both the initial and longer term periods. Long–term established analogue sites such as Tin Camp Creek provide a long-term end member for vegetation succession and should be examined.

The region also has a regular fire regime. In the initial stages of vegetation establishment fire will be excluded. However, over the longer term fire will be an inevitable part of the landscape evolution process.

At present, both the CAESAR-Lisflood and SIBERIA landform evolution models allow for incorporation of vegetation cover through the use of lumped parameter approaches. The vegetation parameter values used in both of these models need to be better defined to better account for the effects of developing vegetation cover over an area. Given its role in the north Australian landscape, the role of fire, which may disrupt or prevent the development of specific vegetation communities, will also need to be considered. The rate and effects of this process in the Kakadu region has been extensively studied in the Kapalga fire studies (Anderson et al., 2003). The impact of fire on the landscape and tree cover of Kakadu National Park has also been described in Lehmann et al. (2009).

Consequently, further studies into the role and impact of fire on vegetation development cannot be neglected and should be investigated in conjunction with studies into weathering and soils evolution. Consequently, field and plot studies are recommended to investigate how weathering and resultant soils interact.

3.3.6 Climate

At present all model parameterisation is carried out assuming a static climate. This is not a practical scenario given the time scales required here. Climate models predict an increase in frequency and intensity of rainfall in the area. Any future landscape design must take this into account and it is important that a consensus on future climate and thus rainfall scenarios is met, so that future designs can be assessed. This will allow model parameters to be developed that reflect expected events.

3.3.7 The significance of 10 000 year simulations

This is the first time that LEMs have been employed for 10 000 year simulations to assess rehabilitation strategies. The change in prediction time scales from 1 000 to 10 000 years presents a fresh set of challenges. Both models are capable running for these lengths of time however due to the additional processes modelled in CAESAR-Lisflood run times can be considerably longer than SIBERIA. The SIBERIA model, based on its framework of annual input data and annual output of sediment and landscape coordinates can provide a result for a Corridor Creek size catchment in approximately one hour for a simulated period of 10 000 years. In contrast CAESAR, with its high resolution hour time steps and similar output time steps allows much more detailed analysis of sediment transport and landscape form. However for a Corridor Creek size catchment it takes approximately 150 hours for 1000 years.

Therefore, a method could be established and protocol developed where, for example, CAESAR is run for the first 10–100 years and SIBERIA is employed for the landscape for the remaining time period. This would allow fine scale detail in the initial stages of landscape development and less detail but long-term trajectory to be examined at longer time periods by SIBERIA. Additionally, SIBERIA parameter values for future climates and vegetation levels could be developed from CAESAR-Lisflood simulations of 10–100 year periods under these future climate/vegetation scenarios.

3.3.8 Validation of predictions

If the models are to be employed at 10 000 year time scales then they require much more extensive validation than that currently undertaken. This validation is required for the short-term (annual to decadal) through to millennial time scales. This requires not just validation against erosion rates but also erosion process (i.e. sheetwash, rilling and gullying). Environmental tracers provide data on hillslope scale erosion rates while the Gulungul Creek data will help provide catchment scale data.

Older sites on the mine itself may provide areas where rilling and gullying exist and provide vital calibration and validation data for erosion process. The work at Scinto 6 provides a template for this type of analysis. Longer term data can be obtained from analogue sites such as Myra Camp where gullies have been quantified and hillslope plots established. Other approaches such as slack water deposits and the quantification of probable maximum floods would also be of benefit to quantify extremes.

3.3.9 Personnel

A critical issue with the effective use of LEMs is well trained and motivated personnel. The LEMs employed by ***eriss*** are state of the art. However, they are continually being developed and refined. To ensure that this development continues, it is vital that the skills base at ***eriss*** is continued and supported. It is also important that ***eriss*** continues to engage with the developers and practitioners of LEMs.

Part 4 : Response by Supervising Scientist – future directions and priorities for landform evolution modelling

J Lowry & W Erskine

This section provides a summary of current research projects and applications of the CAESAR-Lisflood model within the Supervising Scientist Branch, followed by a detailed response to the recommendations made by the reviewer and the external collaborators, including priorities for future work.

4.1 Research projects

Landform evolution modelling currently supports two research projects at the Supervising Scientist:

1. Assessing the geomorphic stability of the Ranger trial landform (RES-2010-007); and
2. Modelling the geomorphic stability of the Ranger landform for a period of 10,000 years (RES-2012-005).

It is envisaged that both of these projects will extend through to the end of 2015 at least.

As part of these projects, it is anticipated that the model will be used to assess the geomorphic stability of individual elements of the rehabilitated landform as they are designed.

In addition, it is anticipated that the CAESAR-Lisflood model will be used on an opportunistic as-needs basis, where new opportunities and requirements for landform and erosion modelling occur. Potential scenarios could include assessing the stability of containment structures in the South Alligator Valley; and the provision of advice to external stakeholders and consultants.

4.2 Response to review and external collaborators feedback

4.2.1 Reviewer recommendations

Dr Pickup reviewed the use and application of CAESAR-Lisflood favourably. All of his suggestions and recommendations were helpful. Responses to each of his suggestions and recommendations are provided below.

1. There are few examples in the general *CAESAR* literature (not just from the Alligator Rivers Region) where runoff rates from the *TOPMODEL* component are reported and compared with observed discharges. This should be done if possible even if the location of stream gauges does not quite match the current area of interest.

As noted by Dr Pickup, some information is available in the literature about the most appropriate runoff values to use to parameterise the 'm' value in TOPMODEL and consequently CAESAR-Lisflood. The suggestion by Dr Pickup is a valid and important one. ***eriss*** has been comparing field data collected on the trial landform with the model predictions of discharge from the trial landform since 2012, which goes some way to addressing this point. Observations to date indicate that an 'm' value of 0.02 is most appropriate to use for simulations on the landform, representing relatively low flood peaks and long duration hydrographs. The runoff / discharge data for Plot 2 are the most complete to date. Utilisation of an 'm' value of 0.02 in simulations shows a very high correspondence with measured discharge. Gaps in the field data for the other erosion plots means that it has not been possible to do a direct comparison with model data yet. It is anticipated that field collection of discharge data on the landform will continue for several more years, which will provide a valuable resource for assessing the accuracy of the predicted discharge data from the CAESAR-Lisflood model across all plots on the landform. Additional work is planned to utilise the data collected at gauging stations in Gulungul Creek to assess the accuracy of model predictions after the accuracy of the rating curves have been checked, as recommended by Erskine et al. (2014a). Continuing to compare model and measured discharge is seen as an important activity to ensure confidence that model simulations will provide meaningful and realistic predictions over longer time frames. Given the results to date, this is seen as a **low-medium** priority activity.

2. I would like to see more investigation of how changes in CAESAR-Lisflood parameters affect model results. In my own work with the model, I have found that changes in the soil creep parameter and the lateral erosion rate can make quite a difference to results. In fact, it may be desirable to conduct a formal sensitivity analysis to determine which parameters matter most under local conditions.

Sensitivity tests are currently being run to assess the impact and significance of the lateral erosion and soil creep parameters on simulations on both the trial landform and on the conceptual rehabilitated Ranger landform design prepared by ERA, over simulated time periods ranging from 4 years to 45 years. Longer term simulations up to 10,000 years are planned. This is recognised as an important part of calibrating model simulations and ensuring that model outputs are reliable and realistic. As such, this is considered an important **high priority** activity that should continue while the Ranger final rehabilitated landform is in development.

3. The long-term simulation reported in the most recent exercise to determine the long term stability of the rehabilitated landform used a rainfall series built from repeating the observed 22 year rainfall but excluded the 2007 cyclone. Given the importance of extreme events in the Alligator Rivers Region reported elsewhere in the literature, this approach is open to debate. A more defensible approach might be to use the standard methods for generating rainfall series in Australia to produce a long term synthetic record. Several approaches may be necessary to accommodate extreme outliers. Indeed, stress testing of alternative landform designs might be carried out using a rainfall series with a fairly high frequency of extreme events.

The point raised by Dr Pickup about the importance of a sound rainfall dataset on which simulations is based is very important. However, the material he reviewed may not have contained a comprehensive explanation of the lineage of the range of rainfall records used by ***eriss*** to date. Rainfall data recorded at Jabiru airport over the period from 1972-2006 has been used to generate a 22-year contiguous rainfall dataset. This contiguous dataset has been used to generate several rainfall files ranging in length from 44 up to 1000 years. Furthermore, data for the 2006-2007 rainfall year, which included a greater than 1-in-100 year extreme event in February-March 2007, has been recorded. In combination with the 22 year contiguous rainfall dataset, the 2007 rainfall dataset has been used to generate a number of rainfall files representing different rainfall scenarios. However, it is also recognised that generating a 10 000 year rainfall dataset using the 22 years worth of contiguous rainfall data currently available would limit the range of climate scenarios potentially modelled. It is recognised that simulating 10 000 years will require a dataset that would enable a wide range of scenarios to be modelled. Consequently, the creation and generation of a rainfall dataset to use in conjunction with 10,000 year modelling is recognised as an **important milestone and a high priority** for modelling a rehabilitated landform. Importantly, it is believed that such a dataset should form a common resource which could be utilised by other research programs, such as for groundwater and surface water modeling. The identification and sourcing of such a dataset is currently underway with ERA.

4. Model results throughout the *CAESAR* literature (not just from the Alligator Rivers Region) tend to show the initial landform and the final landform but do not provide figures showing the amount of change between them. This can hide a variety of sins. I would prefer to see results of modelling runs expressed as change in elevation as well as elevation itself. This gives a much better indication of model performance. Just using elevation (as a grey scale) does not give a very clear impression of what is happening and tends to mask model flaws. I note that ***eriss*** has shown change values in modelling of pit stability but it would be useful to provide these values more widely.

Simulations run by ***eriss*** have included the generation of output surfaces at a series of regular intervals between the commencement and the conclusion of the simulation. This has been demonstrated to have been particularly useful in modelling the changes in elevation and evolution of landscape and erosion features i.e. gullies over time, particularly in the period immediately after the rehabilitation of the mine site. This is recognised as an important output of the model simulations and ***eriss*** will continue to produce these as model outputs for simulations into the future.

5. All of the 2-D models I have used (including *CAESAR-Lisflood*) are potentially affected by DEM artefacts. These are small irregularities in the topographic surface caused when gridding LiDAR point datasets or when gridding from contours (which may produce steps in the landscape). Gridding from contours via fitted TINs may also produce artefacts. Once a model is run, it may generate rills in some of the irregularities which subsequently become gullies under high rainfall conditions. DEMs should be checked to see whether these problems occur before running a model. A good way of carrying out this check is to calculate and view topographic curvature. The LiDAR-derived DEM of current landforms in the mine area seems reasonably free of major artefacts. However, if datasets of final landforms are delivered in the form of contours, this may cause problems.

The comments about the need to check the DEM used to represent the rehabilitated surface for errors and artifacts are well founded and important. It is hoped that many of these issues can be eliminated when the DEM is generated by ERA or its contractors. However, the recommendation to assess and test any DEM before modelling has and will continue to be undertaken by ***eriss*** as a **high priority** before any simulations are run. Given that the most recent DEMs supplied by ERA have been generated from contour data, the suggestion to calculate and view topographic curvature will be incorporated into any pre-modelling preparations undertaken by ***eriss***.

6. *CAESAR-Lisflood* uses a single angle of rest to determine whether slope failure and subsequent landsliding can occur. On slopes containing fine sediment, waterlogging and possible even fluidisation may occur, producing landslips. Events of this nature have been reported from the Alligator Rivers Region on natural hillslopes. Presumably, the engineers designing the final landforms at Ranger will subject them to the normal range of geotechnical analyses. However, it may also be worth applying a shallow landsliding model such as *SHALSTAB* to investigate potential for areas of slope failure in steeper zones of flow convergence even if final landforms have fairly low slopes. Potential areas of interest may be valley sidewalls if local creeks affected by final landform construction re-establish themselves.

This inclusion of a dedicated landsliding model into long-term simulations using CAESAR-Lisflood is being considered. It should be noted that the landslide studies in the Alligator Rivers Region referenced by Dr Pickup occurred on Oenpelli Dolerite on slopes greater than 17° (Saynor et al. 2012b). Such a slope or material is not expected to be represented on a final rehabilitated landform at Ranger. The expansion of the CAESAR-Lisflood model to include a dedicated landslide component would require the involvement and participation of Professor Coulthard, as the developer of the model. Subject to the availability of Professor Coulthard, such a development is seen as a medium – long term goal and as such is considered a **medium priority** in the application of landform modelling technologies at ***eriss***.

7. *CAESAR-Lisflood* assumes no change over time in particle size distribution from that of initially emplaced material except through sorting and bed armouring. However, there may well be some particle breakdown to fines with weathering. There may be a need to allow for the weathering characteristics of cap material during long-term modelling runs. Some rock types, if fresh, can weather very quickly in tropical environments when exposed to oxidation. ***eriss*** is currently in the process of acquiring these data and a time series covering several years should soon be available.

As noted by Dr Pickup, ***eriss*** is currently in the process of collecting particle size data from the trial landform, as well as particle size data from other areas representing potential surface conditions (waste rock, Koolpinyah erosion surface) in the Alligator Rivers Region, such as the Nabarlek mine site. More significantly, ***eriss*** contracted Professor Coulthard to incorporate a weathering function into the CAESAR-Lisflood model to account for the weathering and breakdown of the surface materials over time. The weathering function incorporated into the model by Professor Coulthard is currently being tested. This forms a major part of the current landform modelling activity at ***eriss*** is seen as a **very high priority**. In addition, further ongoing engagement with Professor Coulthard and Associate Professor Hancock is required in this area.

8. Assuming that feral buffalo survive in the area, their tracks create a risk of gullying, especially if constructed landforms or the mine area provide a source of dry season drinking water (in pit lakes for example) or when rehabilitated landforms are sown with palatable grasses. Feral pigs may be an even greater problem as they can disturb soils with their foraging behaviour. These issues may be worth investigating as they could cause significant localised erosion.

Feral buffalo are not expected to be a major factor in a post-mining environment. Furthermore, Associate Professor Hancock notes studies conducted in western Arnhem Land which indicate that feral pigs may actually have little effect on soil erosion in a natural or undisturbed environment. However, modelling from the same study shows that simulated pig disturbance on a rehabilitated landform may lead to an increase in erosion. From this, it could be inferred that simulated pig disturbance should be included in the modelling assessment of a rehabilitated landform. However, it should be noted that the resolution of the data required to simulate pig disturbance (0.25m grid size) is much finer than the current and likely resolution of the DEM of the final landform (10m). Further work would be required to determine if pig disturbance could be modelled at a resolution of 10 metres. This aspect of landform modelling is seen as **low-medium** priority by ***eriss***.

9. When designing or testing landforms, it is common to use a safety factor, especially where model parameters or behaviour involves uncertainties. The ***eriss*** program has gone a considerable distance with this approach by modelling with and without vegetation cover and for surcharged and non-surcharged landforms. However, I would like to see wider use of safety factors, perhaps by varying the most important and least certain model parameters. Loss of vegetation through fire should be expected and modelling without vegetation cover will give a measure of safety.

The role of vegetation and fire on the landscape are recognised as important factors that will need to be incorporated into any final assessment of a rehabilitated landform for any extended period, particularly one potentially extending out to 10,000 years. ***eriss*** is currently looking at ways of better representing the role of vegetation communities and their development into the modelling process in collaboration with Professor Coulthard and regards this recommendation as a **high priority** for future activity. At the same time, ***eriss*** recognise the value of continuing to conduct some simulations without a vegetation component, as these provide a conservative estimate of landform response.

10. Waste rock may contain sulphides. Potential for acid generation should be examined and mitigation strategies such as mixing with limestone may need investigation.

The current waste rock material used on the trial landform has not yielded large quantities of sulphides. Similarly, data and observations from the trial landform have indicated that acid rock drainage is currently not an issue or concern. However, while it is assumed that the final rehabilitated landform will be primarily composed of similar material, the actual composition has not been defined. Consequently, it is recognised that there maybe the potential for acid generation and/or other chemical processes to occur. This is seen as an area for future research and development of the CAESAR-Lisflood model, which would need to be done in conjunction with Professor Coulthard and potentially other researchers with expertise in chemical weathering. At this stage, this is seen as a **low-medium** priority with respect to developing and enhancing the CAESAR-Lisflood model. However, it is recognised that there is a knowledge gap in chemical weathering expertise within the HGCP group. Consequently, the development and acquisition of this knowledge and capability is seen as important.

4.2.2 Additional Reviewer recommendations

11. *CAESAR-Lisflood* does not handle spatial variability in soil types and vegetation growth cover easily. Sub-catchments need to be set up and model runs carried out and subsequently linked. Variations in rehabilitated landscape shape also need to be

set up from new DEMs. *Given the relatively long computation times associated with CAESAR-Lisflood runs, it may be worth examining whether the model might be used to generate parameter sets suitable for use in sediment accounting models such as Source and thereby applied to larger areas and more heterogeneous landform assemblages.* I am not aware of any instances where this has been done with *CAESAR-Lisflood* but it is worth considering where a range of landforms or vegetation growth patterns needs to be investigated.

CAESAR-Lisflood is able to model spatial variability in soil or surface covers and ***eriss*** has been successfully running a series of simulations on conceptual landforms in which different surfaces covers (representing waste rock, natural or Koolpinyah erosion surface) have been modelled. ***eriss*** sees the collection of additional material which could be used to describe/classify new and existing surface classes as a **high priority** and an appropriate way of addressing this recommendation. This activity would integrate with those landform modelling tasks looking at understanding the effects of weathering on the particle size composition of landform surface.

12. It would seem that there is some capacity for improving the biological component of CAESAR-Lisflood by incorporating some of the LFA ideas on patchiness and resource leakage into both the plant growth model and into local erosion/deposition rates over time.

eriss has applied LFA techniques in earlier studies relating to landscape ecology and mine rehabilitation, but has not considered integrating or applying them in a landform evolution model. This is something which would have to be done in collaboration with Professor Coulthard, as the developer of CAESAR-Lisflood. Without the involvement or participation of Professor Coulthard, this would be considered a **low priority** for landform modelling activities at ***eriss***.

4.2.2 Collaborators feedback and recommendations

As discussed in Part 3, Professor Coulthard and Associate Professor Hancock both support the suggestions and recommendations of Dr Pickup for the use and direction of landform modelling research at ***eriss***, whilst noting some alternatives and additions to some of the recommendations.

Specifically, Professor Coulthard recommends that the addition, testing and if necessary modification of the Vanwalleghem pedogenis and Saco vegetation growth models be incorporated into future versions of the CAESAR-Lisflood model. He also recommends the adoption of an appropriate methodology for generating future rainfall for the region as an appropriate way of both adopting the reviewer recommendations and moving forward with landform modelling at ***eriss***.

From an ***eriss*** perspective, this appears an eminently practical and reasonable suggestion to move forward with long-term landform modelling.

Associate Professor Hancock notes that the extent, nature and composition of the final landform surface is still being evaluated. If the surface is very different to that of past materials then model parameters for the new material will be required. However, this is highly unlikely because the rehabilitated mine site will be constructed principally of waste rock and a range of slopes and slope lengths have been monitored by ***eriss*** over many years. While ***eriss*** recognises there may be benefit in the establishment of additional trial plots with a greater ranger of slopes, it also notes that much work has been done in the past which could provide useful information to address this issue. Examples of these studies include East et al. (1994), Riley (1995), Evans & Loch (1996), Evans et al. (1998), Saynor & Evans (2001) and Moliere et al. 2002).

Associate Professor Hancock also re-iterates that studies be undertaken on the weathering of the surface of the trial landform and on any material that is likely to be used as part of the rehabilitation. He further suggests that soil formation or pedogenesis should be included as part of the model parameterisation. This information could be determined by examining soil pits at sites representing different ages on rehabilitated areas of the mine or areas that have not been disturbed so that soil production rates and process be determined. ***eriss*** has already commenced this work.

> ***eriss*** recognises the value of additional data from a range of slopes and surface materials. However, ***eriss*** does not currently have the resources to lead the construction of new trial plots and therefore, any trial plot development would have to be done in collaboration with ERA. Professor Steven Riley, who undertook geomorphology research on the Ranger site and surrounds in the 1990s at ***eriss*** recently provided his notes on his research and Dr Saynor will collate and process this material.

Another issue noted by Associate Professor Hancock is that aside from the work of Evans et al. (2000), there are few external data sets available for parameterising post-mining and natural surfaces. Denudation rates exist but only provide a broad expected range of landscape lowering for the region. These denudation rates need to be re-examined and updated. Erskine et al. (2014b) partly addressed this issue in their review of the available data that they used to construct a revised total sediment load sediment budget for all of Magela Creek.

> ***eriss*** recognises the need to collect additional and updated information on background rates of landscape lowering or denudation in the ARR. For example, while Erskine & Saynor (2014) have recently calculated bedload yields for streams at Jabiluka using over 30 techniques, they conclude that additional work is required to understand background denudation rates of the landscape.

How regular fire events influence vegetation, water quality and landscape evolution have been researched extensively at Kapalga and Munmarlary within Kakadu National Park. This is an important issue that now needs to be integrated with the weathering and soils evolution. Earlier work, such as that of Evans et al (1999) will advise how the impacts of fire may affect vegetation community development, and any subsequent erosion and evolution of a post-mining landscape. The comment that long–term established analogue sites such as Tin Camp Creek provide a long-term end member for vegetation succession and should be examined has been noted and will be investigated further through studying the available literature at those sites.

> ***eriss*** hopes to be able to investigate the role of fire through monitoring the impact of fire on vegetation communities during a planned burn of the trial landform in several years time. In the interim, ***eriss*** will be opportunistically looking to gather this information as a high priority.

Associate Professor Hancock also notes that earlier / historic work conducted at mine sites in the Alligator Rivers Region may be useful for calibrating and validating work on erosion processes. Other approaches such as slackwater deposits and the quantification of probable maximum floods would also be of benefit to quantify extremes when developing input parameter values for modelling purposes.

eriss agrees that the use of historic data collected at mine sites in the ARR, along with data collected in related geomorphic studies, such as those analysing slackwater deposits should be used to support the calibration and validation of datasets used in simulations of landform stability.

Finally, Associate Professor Hancock notes that it is vital that the skills base at ***eriss*** for landform evolution modelling is continued and supported.

eriss plan to continue to engage external support and expertise to provide guidance and support in the development and application of landform modelling skills and techniques by ***eriss*** staff.

4.2.3 Summary of priority areas for further and future development

Dr Pickup has made a number of recommendations that will enhance landform modelling capabilities at ***eriss*** through focussing future landform research and activities into specific areas. These recommendations have been supported by comments from Professor Coulthard and Associate Professor Hancock. In addition, both provided additional suggestions and recommendations regarding the direction and applications of landform modelling research at ***eriss***. Based on the recommendations of Dr Pickup and Professor Coulthard and Associate Professor Hancock, the priority areas for future landform modelling research at ***eriss*** are seen as:

1. Calibrating the input parameters and variables to the CAESAR-Lisflood model to ensure it provides meaningful and useful results with confidence. A number of activities can be grouped into this area, including
   i. Collecting, developing and calibrating information on weathering rates of different surface types in the ARR to use with the weathering function that has been recently incorporated into the CAESAR-Lisflood model.
   ii. Undertaking sensitivity tests to determine the most appropriate input variables for parameters such as soil creep and lateral erosion, for the different surface types that may feature on a rehabilitated landform. Performing the sensitivity tests will identify the optimum parameter ranges to use for the ARR environment and enhance confidence in the outputs from the CAESAR-Lisflood model. This activity will include utilising relevant existing historic information collected in the ARR.
   iii. Study and collect information on the impact of vegetation communities and fire on the stability of a rehabilitated landform. This information will be used to as a guide for further developments to the CAESAR-Lisflood model itself, and as inputs to enhanced vegetation parameters.
   iv. Continuing to assess the reliability of CAESAR-Lisflood predictions by comparing model predictions of sediment transport and discharge with field-based observations of sediment transport from the Ranger trial landform. This is particulary important in helping understand the natural rates of weathering in the landscape.

2. In conjunction with ERA and external research collaborators identify and develop a rainfall dataset that could be used for long term model simulations which would be representative of the range of climatic extremes that may occur within a timeframe of 10 000 years.

3. Continue to engage and consult with Professor Coulthard to ensure that the CAESAR-Lisflood model is updated to incorporate additional parameters that are required to comprehensively model the long stability of a rehabilitated landform; and with Associate Professor Hancock to ensure procedures, processes and outputs from landform modelling are best practice and scientifically sound.
4. Investigate the development and inclusion of additional parameters, such as chemical weathering into the CAESAR-Lisflood model and the broader HGCP research program.

References

Andersen AN, Cook GD & Williams RJ 2003. Fire in Tropical Savannas: the Kapalga experiment. Springer-Verlag, New York.

Bates PD, Horrit MS & Fewtrell TJ 2010. A simple initial formulation of the shallow water equation for efficient two-dimensional flood inundation modelling, *Journal of Hydrology*, Vol. 387, pp. 33–45.

Bevan K & Kirkby M J 1979. A physically based contributing area model of basin hydrology. *Hydrological Science Bulletin*, 24:43-69.

Bevan KJ 1997. TOPMODEL: a critique. *Hydrological Processes* 11(9): 1069–1086

Cohen S, Willgoose G & Hancock G 2013. Soil–landscape response to mid and late Quaternary climate fluctuations based on numerical simulations. *Quaternary Research* 79 : 452–457. DOI: 10.1016/j.yqres.2013.01.001

Coulthard TJ, Kirkby MJ & Macklin MG 2000. Modelling geomorphic response to environmental change in an upland catchment, *Hydrological Processes*, Vol. 14, pp. 2031–2045.

Coulthard TJ, Macklin MG & Kirkby MJ 2002. Simulating upland river catchment and alluvial fan evolution, *Earth Surface Processes and Landforms*, Vol. 27, pp. 269–288.

Coulthard TJ, Lewin J & Macklin MG 2005. Modelling differential and complex catchment response to environmental change. *Geomorphology*. 69. 224-241.

Coulthard TJ, Hancock GR & Lowry JBC 2012a. Modelling soil erosion with a downscaled landscape evolution model. *Earth Surface Processes and Landforms* 37 : 1046–1055. DOI: 10.1002/esp.3226

Coulthard TJ, Ramirez J, Fowler HJ & Glenis V 2012. Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield. *Hydrology and Earth System Sciences* 16 : 4401–4416. DOI: 10.5194/hess-16-4401-2012

Coulthard TJ & Van de Wiel MJ. 2013. Climate, tectonics or morphology: what signals can we see in drainage basin sediment yields? *Earth Surface Dynamics Discussions* 1 : 67–91. DOI: 10.5194/esurfd-1-67-2013.

East TJ, Uren CJ, Noller BN, Cull CF & Curley PM 1994. Erosional stability of rehabilitated uranium mine structures incorporating natural landform characteristics, northern tropical Australia. *Zeitschrift fur Geomorphologie*, 38: 283-298

Einstein HA 1950. The Bedload Function for Sediment Transport in Open Channel Flow, Soil Conservation Technical Bulletin No. 1026, U.S. Department of Agriculture, Washington, DC.

Erskine WD & Saynor MJ 2000. Assessment of the off-site geomorphic impacts of uranium mining on Magela Creek, Northern Territory, Australia, Supervising Scientist Report 156, Supervising Scientist, Darwin.

Erskine WD & Saynor MJ 2014. Bedload yields for sand-bed streams in the Ngarradj Creek catchment, Northern Territory, Australia. *Hydrological Processes*, in press.

Erskine WD, Saynor MJ, Turner K, Fagan S. & Chalmers A. 2014a. Geomorphic characteristics of the Gulungul Creek catchment. In: ***eriss*** Research Summary 2012-2013. Supervising Scientist Report 205, Supervising Scientist, Darwin, NT, 98-115.

Erskine WD, Saynor MJ, Turner K, Whiteside T, Boyden J & Evans KG. 2014b. Do suspended sediment and bedload move progressively from the summit to the sea along Magela Creek, northern Australia? In: Xu YJ, Allison MA, Bentley SJ, Collins AL, Erskine WD, Golosov V, Horowitz A & Stone M. (Eds), *Sediment Dynamics from the Summit to the Sea*. International Association of Hydrological Sciences, Wallingford, 283-290.

Evans KG and Loch RJ 1996. Using the RUSLE to identify factors controlling erosion rates of mine soils. Land Degradation and Development. 7(3) pp267-277.

Evans KG, Saynor MJ & Willgoose 1996. *The effect of vegetation on waste rock erosion, Ranger uranium mine*, Northern Territory, Bulletin of the AusIMM, pp 21-24

Evans KG, Willgoose GR, Saynor MJ & 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, Supervising Scientist, Canberra.

Evans KG, Saynor MJ & Willgoose 1999. Changes in hydrology, sediment loss and microtopography of a vegetated mine wast rock dump impacted by fire. *Land Degradation and Development*. 10 : 507-522. DOI 10.1002/(SICI)1099-145X(199911/12)10:6<507::AID-LDR341>3.0.CO;2-#

Evans KG 2000. Methods for assessing mine site rehabilitation design for erosion impact, *Australian Journal of Soil Research*, Vol. 38(2), pp. 231–248.

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

Hancock GR, Lowry JBC, Coulthard TJ, Evans KG & Moliere DR 2010. A catchment scale evaluation of the SIBERIA and CAESAR landscape evolution models, *Earth Surface Processes and Landforms*, Vol. 35, pp. 863–875.

Hancock GR, Coulthard TJ, Martinez C & Kalma JD 2011. An evaluation of landscape evolution models to simulate decadal and centennial scale soil erosion in grassland catchments. *Journal of Hydrology* 398 : 171–183. DOI: 10.1016/j.jhydrol.2010.12.002

Hancock GR & Coulthard TJ 2012. Channel movement and erosion response to rainfall variability in southeast Australia. *Hydrological Processes* 26 : 663–673. DOI: 10.1002/hyp.8166

Hancock GR, Lowry JBC, Dever C & Braggins M *In press*. Do introduced fauna influence soil erosion ? A field and modelling assessment. *Science of the Total Environment*

Laflen JM, Elliot WJ, Simanton JR, Holzhey CS & Kohl KD 1991. WEPP soil erodibility experiments for rangeland and cropland soils, *Journal of Soil and Water Conservation*, Vol. 46(1), pp. 39–44.

Lehmann CER, Prior LD &Bowman DMJS 2009. Decadal dynamics of tree cover in an Australian tropical savanna. *Austral Ecology*, 34 (6) 601-612

Loch RJ, Connolly RD & Littleboy M 2000. Using rainfall simulation to guide planning and management of rehabilitated areas: Part 2, Computer simulations using parameters from rainfall simulation, *Land Degradation and Development*, Vol. 11(3), pp. 241–255.

Lowry JBC, Coulthard TJ, Hancock GR & Jones DR 2011. Assessing soil erosion on a rehabilitated landform using the CAESAR landscape evolution model, in Proceedings of the 6th International Conference on Mine Closure, A.B. Fourie, M. Tibbett and A. Beersing (eds) 18–21 September 2011, Australian Centre for Geomechanics, Perth, pp. 613–621.

Lowry JBC, Coulthard TJ & Hancock GR 2013. Assessing the long-term geomorphic stability of a rehabilitated landform using the CAESAR-Lisflood landscape evolution model, in Proceedings Eighth International Conference on Mine Closure (Mine Closure 2013), M Tibbett, AB Fourie & C Digby (eds), 18-20 September 2013, Eden Project, United Kingdom, Australian Centre for Geomechanics, Perth, pp .611-624

McQuade CV, Arthur JT & Butterworth IJ 1996. Climate and hydrology, in Landscape and Vegetation of the Kakadu Region, Northern Australia. C.M. Finlayson and I. von Oertzen (eds), Kluwer Academic Publishers, Dordrecht, pp. 17–35.

Moliere DR, Evans KG, Willgoose GR & Saynor MJ 2002. Temporal trends in erosion and hydrology for a post-mining landform at Ranger Mine. Northern Territory. Supervising Scientist Report 165, Supervising Scientist, Darwin.

Onstad CA & Foster GR 1975. Erosion modelling on a watershed, Transactions of the American Society of Agricultural Engineers, Vol. 26, pp. 1102–1104.

Renard KG, Laflen JM, Foster GR & McCool DK 1994. The revised universal soil loss equation, in Soil Erosion Research Methods, R. Lal (ed.), *Soil and Water Conservation Society*, Ankeny, Iowa, 2nd ed., pp. 105–124.

Riley SJ 1995. Aspects of the differences in the erodibility of the waste rock dump and natural surfaces, Ranger Uranium Mine, Northern Territory, Australia. Applied Geography 15(4) pp 309-323. DOI http://dx.doi.org/10.1016/0143-6228(95)00014-U

Saco P 2007. Eco-geomorphology of banded vegetation patterns in arid and semi-arid regions. *Hydrology & Earth System Science* : 1717–1730.

Saco PM & Moreno-de las Heras M 2013. Ecogeomorphic coevolution of semiarid hillslopes: Emergence of banded and striped vegetation patterns through interaction of biotic and abiotic processes. *Water Resources Research* 49 : 115–126. DOI: 10.1029/2012WR012001

Saynor MJ & Evans KG 2001. Sediment loss from a waste rock dump, ERA Ranger mine, northern Australia. *Australian Geographical Studies*, 39(1) pp 34-51. DOI 10.1111/1467-8470.00128

Saynor MJ, Lowry J, Erskine WD, Coulthard T, Hancock G, Jones D & Lu P 2012a Assessing erosion and run-off performance of a trial rehabilitated mining landform. Life of Mine Conference, Brisbane Queensland 10–12 July 2012, pp 123-134.

Saynor MJ, Erskine WD, Staben G, & Lowry J 2012b. A rare occurrence of landslides initiated by an extreme event in March 2007 in the Alligator Rivers Region, Australia. In: Collins AL, Golosov V, Horowitz AJ, Lu X, Stone M, Walling DE & Zhang X (Eds). *Erosion and Sediment Yields in the Changing Environment*. International Association of Hydrological Sciences, Wallingford, pp. 303-310.

Supervising Scientist Division 1999. Environmental Requirements for the Ranger Uranium Mine, Department of Sustainability, Environment, Water, Populations and Communities, viewed 3 April 2013,http://www.environment.gov.au/ssd/about/legislation/pubs/ranger-ers.pdf.

Van De Wiel MJ, Coulthard TJ, Macklin MG & Lewin J 2007. Embedding reach-scale fluvial dynamics within the CAESAR cellular automaton landscape evolution model. *Geomorphology*, Vol. 90 (3–4), pp. 283–301.

Vanwalleghem T, Stockmann U, Minasny B & McBratney AB 2013. A quantitative model for integrating landscape evolution and soil formation. *Journal of Geophysical Research: Earth Surface* 118 : 331–347. DOI: 10.1029/2011JF002296.

Wells A, Binning P &Willgoose G 2005. The role of moisture cycling in the weathering of a quartz chlorite schist in a tropical environment: findings of a laboratory simulation. *Earth Surface Processes and Landforms*, 30: 413–428. DOI: 10.1002/esp1149

Wilcock PR & Crowe JC 2003. Surface-based transport model for mixed-size sediment, *Journal of Hydraulic Engineering*, Vol. 129, pp. 120–128.

Willgoose GR, Bras RL & Rodriguez-Iturbe I 1989. A physically based channel network and catchment evolution model, TR 322, Ralph M. Parsons Laboratory, Department of Civil Engineering, Massachusetts Institute of Technology, Boston, Mass., 464 p.

Willgoose G & Riley S 1998. The long term stability of engineered landforms of the Ranger Uranium Mine, Northern Territory, Australia: application of a catchment evolution model, Earth Surface Processes and Landforms, 23 : pp. 237-259. DOI: 10.1002/(SICI)1096-9837(199803)23:3<237::AID-ESP846>3.0.CO;2-X

Wischmeier WH & Smith DD 1978. Predicting rainfall erosion losses – a guide to conservation planning, Agriculture Handbook No. 537.2, U.S. Department of Agriculture, Washington, DC, 85 p

Ziliani L, Surian N, Coulthard TJ &Tarantola S 2013. Reduced-complexity modellingof braided rivers: Assessing model performance by sensitivity analysis, calibration, and validation. *Journal of Geophysical Research: Earth Surface* 118: 2243–2262. DOI: 10.1002/jgrf.20154.