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A comparison of landscape evolution models for waste landform closure designs

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Abstract

Waste dumps are the largest feature to remain after the cessation of mining and pose a significant risk in terms of potential risks to the environment, particularly from accelerated erosion. Traditional approaches (such as rehabilitation trials) can take years to yield useful data which may be available after important factors in waste dump stability such as height and batter gradients have been set.

Landscape evolution models (LEM) are able to simulate the geomorphic environment of waste dumps and understand the erosional performance of a design. Two LEMs that have been used in the Australian mining environment are SIBERIA and CAESAR. SIBERIA is a 3-dimensional model that predicts the long-term evolution of channels and hillslopes in a catchment from averaged annual estimates of runoff and erosion. CAESAR is a landscape and river channel evolution model driven by hillslope and fluvial processes which determine the spatial pattern of erosion and deposition, and, therefore, changes to the land surface.

A comparison of the two LEMs was undertaken by running a 100 year simulation over a previously studied Goldfields catchment that includes low level waste dumps features. The SIBERIA 100 year model result predicted a low level of erosion, while CAESAR predicted extensive incision by drainage lines in as little as 5 years. Observation of the catchment and material characterisation of the topsoil tends to support the view that SIBERIA is more closely aligned with actual field conditions. The CAESAR model is an attractive alternative to SIBERIA because of its low parameter input requirements and its ability to simulate and visualise single storm events as well as long-term landscape evolution. However, having are limited parameters to describe the hillslope processes that strongly influence the predicted rate of erosion without comparison to accurate long term erosion plot data may lead to erroneous results.

Introduction

Waste dumps that remain a permanent feature on the landscape after the cessation of mining operation pose a risk to the environment that must be managed. The closure outcomes for waste dumps expected by environmental stakeholders include that they be safe, stable, and sustainable. In practical terms, it is expected that a waste dump design will be an erosionally stable feature that will not release sediment and other contaminants into the receiving environment and in WA, that its rehabilitation will allow vegetation to re-establish and support fauna without long-term ongoing maintenance.

Many aspects of mining are conducted in a data rich environment. For example, block models of the target ore and associated waste are used to visualise and plan mining of the deposit. Mining fleet movements are also well planned and optimised using a range of data from the nature of the deposit, the fleet available, and workforce requirements.

For mine rehabilitation, the same data rich environment has traditionally not been available. Data on rehabilitation success often take a long time to collect and many decisions affecting closure outcomes have been made before it is available. For example, assessment of rehabilitation waste dump shapes often yields results well after the dump shape is set through mining operations making decisions on lift heights and lift offset distances, and the landforms that result are often subject to accelerated rates of erosion (Howard and Roddy, 2012).

This evident need to increase the available data for rehabilitation planning has resulted in an increase in the use of models to assist closure planning. Landscape evolution models (LEMS) are increasingly popular and provide a powerful tool in the area of waste dump rehabilitation planning. The critical aspect of ensuring erosional stability of proposed waste dumps can be simulated at a range of time scales (decadal, centurial, or millennial). Increases in computing power mean that new LEMs are able to better simulate the geomorphic environment of waste dumps and understand the performance of a design. This paper will introduce two LEMs – SIBERIA and CAESAR – and outline a case study to compare the performance of the models and highlight the issues associated with their use.

Landscape evolution models

Landscape evolution models represent the entire landscape as a 3 dimensional grid (or cell) structure and seek to predict movement of sediment through fluvial networks that link hillslopes to streams. The movement of water through a cell network and the sediment it deposits or entrains in each cell is calculated by mathematical equations. The 3 dimensional landscape is adjusted iteratively as a result of sediment movement to represent the new surface as flows migrate or are concentrated, rills and gullies are incised, and sediment fans are formed (Tucker & Hancock 2010). Many LEMs are applied to geomorphic questions of catchment evolution, but in the mining industry the catchment size is often confined to looking at discrete features such as waste dumps. Although LEMs were originally designed for larger catchment scale studies, it is at this dump scale and the associated hillslope processes that LEMs are used to rapidly obtain data for determining the suitability of a proposed design.

SIBERIA and CAESAR are two such LEMs that have been applied to waste dump design in the Australian mining industry. The SIBERIA model was developed in Australia and has been widely applied since it was published in 1991 to consider long-term changes in landform shape. CAESAR was developed in England to study long-term changes in river catchments on an event basis (i.e. much shorter time frames than SIBERIA). The development of a catchment mode in CAESAR along with factors such as regolith weathering has meant that CAESAR has been attracting wider attention and assessment of its applicability to mining landscapes.

SIBERIA

SIBERIA simulates changes to landform shape as it evolves in response to predicted erosion and deposition. It is a 3-dimensional model that predicts the long-term evolution of channels and hillslopes in a catchment. It has been successfully applied to explain aspects of geomorphology of natural landforms (Willgoose 1994). SIBERIA does not input actual rainfall or material erodibility parameters. Channel development is governed by an activation threshold that is dependent on discharge and slope gradient. When the activation threshold is exceeded, a channel is predicted to develop. It is possible for a modelled surface to initially have no gullies, and for channels to develop when the activation threshold is exceeded.

The parameters needed for SIBERIA are related to both runoff and soil erodibility (Willgoose *et al.* 1989) and must be derived for each particular material at each particular site. Use of parameters generated for similar materials but for a different rainfall regime is not acceptable.

CAESAR

The CAESAR (Cellular Automaton Evolutionary Slope and River) model is a landscape and river channel evolution model (Coulthard *et al*. 2000, 2002, 2005, 2006; Van de Wiel et al. 2007). Like SIBERIA, CAESAR represents the landscape as a mesh of cells and a range of information is known for each cell, including hydrological parameters, particle size of materials, water discharge parameters, and vegetation levels. The model is driven by hillslope and fluvial processes which determine the spatial pattern of erosion and deposition, and, therefore, changes to the land surface. The hillslope and fluvial processes respond to rainfall inputs, and these inputs can range in time step from minutes to hours to days. The smaller the timestep, the more computing (and time) required to evolve the surface. Model iterations are governed by three broad sets of rules:

- Slope processes,
- Hydraulic routing, and
- Fluvial erosion and deposition.

Slope processes that deliver sediment to channels are controlled by a soil creep factor and a slope failure threshold. Hydraulic routing is achieved by taking discharge from the neighbouring cell, calculating the flow depth, and delivering the flow to receiving cells. Because a flow depth is calculated, the CAESAR model is able to route flows both over and around obstacles where they are encountered. The fluvial erosion and deposition rules calculate entrainment and deposition of suspended and bed load sediment by a nine class particle size distribution (or 'grain') file. The catchment can be partitioned into different grain file regions to reflect different materials such as hillslope soil or cobble stream bed.

The CAESAR model is able to route flows and sediment across the landscape in response to short term single storm events or long-term time scales. The model data inputs are few and comprise a catchment surface (DEM), rainfall data, and grain sizes of surface materials.

As erosion and deposition occurs in response to surface flows from rainfall, the model alters the land surface by calculating a new DEM for each iteration. As a consequence, the model requires enormous computer processing capability and model runs are quite slow. The process is further slowed if the resolution of the elevation model (i.e., smaller cell sizes) and rainfall resolution (e.g., daily to hourly rainfall record) increase.

Comparison of the two LEMs

SIBERIA has been extensively used by the Supervising Scientist division of the Commonwealth Department of Environment, Water, Heritage and the Arts, and subjected to extensive validation. In general, the tests indicate that, provided the model is adequately calibrated, SIBERIA predictions appear to be reasonable (Hancock *et al.* 2000, Hancock *et al.* 2002, Hancock *et a*l. 2003, Willgoose *et al.* 2003). In addition, Hancock (2004a) notes that rates of erosion predicted by SIBERIA for a catchment in the Northern Territory compared very favourably with estimates of erosion derived using the caesium-137 method for soil erosion assessment. As the two methods used completely independent input information, the agreement is particularly significant.

The SIBERIA model has been widely used for assessment of the evolution of constructed landforms on a range of mine sites across Australia and overseas (Willgoose and Riley 1993, Boggs *et al*. 2000, Hancock *et al*. 2003, Hancock and Willgoose 2004, Hancock 2004b, Mengler *et al.* 2004, Hancock and Turley 2006). The model is equally applicable to any climatic regime as its input parameters are derived by calibration to runoff and erosion data.

Because SIBERIA was originally written for academic purposes, it model has idiosyncrasies that mean that considerable knowledge is needed to setup, parameterise, and run the model. As with all models, care is required in derivation of its input parameters. SIBERIA requires the DEM to be in a specific format, and the number of cells that can be considered is limited. SIBERIA considers long-term changes in landscapes, and is not designed to consider changes on an event basis. The graphic output of SIBERIA is limited and often requires post processing for reporting purposes. Computing power demands are low and most runs of SIBERIA are sub-hourly.

CAESAR has not been as widely applied as SIBERIA, but more recently the model has been applied to the rehabilitation planning at the Ranger Uranium mine in the Northern Territory (Hancock et al., 2010; Lowry et al., 2011; Saynor et al., 2012; Lowry et al. 2013). The CAESAR model has a climate file component and simulations can be made over long time periods (like SIBERIA) or applied to single storm events. The input requirements for CAESAR are minimal, and all that is required for simulations are a DEM of the study area, a climate file, and particle size distribution (PSD) information on the materials. The graphic output of CAESAR is of higher quality than that of SIBERIA and has a component that interfaces with Google Earth so that images can be directly overlayed and animations of the simulation can be readily created. CAESAR has a high computing demand as after each rainfall event, a new DEM is written before the next evolution. Depending on the resolution of the DEM and rainfall data, simulation can take over a week of constant computing time to run.

Comparison methods

To compare the two models, a simulation of a mining landscape in the Goldfields region was completed using SIBERIA and CAESAR. The surface materials were characterised to derive the necessary SIBERIA input parameters and CAESAR PSD parameters. The study location has low relief and is covered by deep yellow aeolian sand consisting of 3% clay, 3% silt, and 94% sand (Figure 1). Low gradient dumps included in the DEM were <7m high with 3° batters. The dumps were approximately 100m wide, 650m long, and were protected by a 2m high flood bund (Figure 2). Model simulations assumed that the dumps and contributing catchment were capped with the same sandy soil.

Figure 1. The study area low relief landscape (left), and detail of the sandy soil material (right).

Derivation of SIBERIA input parameters

Input parameters for SIBERIA are typically derived by fitting the various model equations to time series data of runoff and erosion. However, in all but a few instances, sufficiently long series of these data are not available for landforms of interest. This is obviously a considerable limitation to the parameterisation of SIBERIA for waste landforms yet to be constructed. Therefore, Landloch has developed an alternative approach to the estimation of SIBERIA model parameters by deriving the necessary parameters using output from the WEPP erosion model. The material of interest is subjected to simulated rainfall and overland flows either in the field or in the laboratory. From this, relationships between erosional stresses, runoff and detachment are derived and these are used in defining the necessary SIBERIA parameters. Importantly, the quality of the WEPP input parameters has been shown to significantly influence the accuracy of erosion predictions. Data presented by Howard and Roddy (2012) not only support previous validation studies showing that the model can be used to predict erosion trends satisfactorily, but also show that Landloch's methods for deriving parameters produce erosion predictions that correspond well with erosion rates measured in the field.

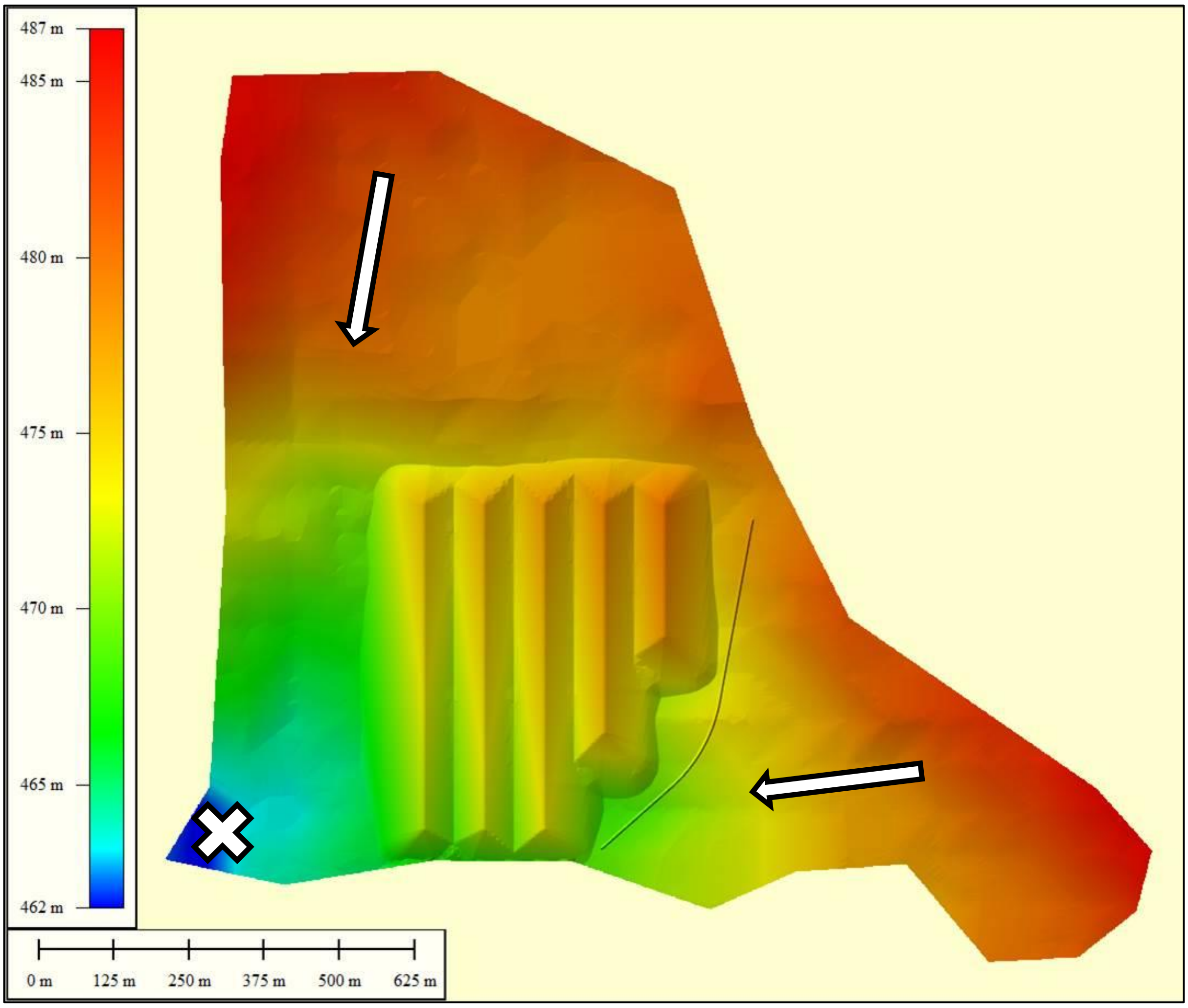

Figure 2. The study area catchment with low relief dumps and flood bund. Approximate flows indicated by arrows and the catchment outlet with a cross.

These parameters were used to produce output that was compared to CAESAR output for the same catchment and the same material.

Derivation of CAESAR model input parameters

The only material-based input parameter that is input to CAESAR is the particle size distribution (grain) data and this was derived from a NATA accredited laboratory for the surface material considered.

In Australia, the CAESAR model has been modified to examine rehabilitated mine landforms in the Northern Territory (Hancock et al. 2010; Lowry et al. 2011; Saynor et al. 2012). In these examples, the model output was calibrated by tuning the CAESAR model parameters such that it matched as closely as possible the measured slope erosion from several long-term instrumented erosion plots at the Ranger Uranium mine. The tuned model parameters were sediment transport law; maximum erode limit (m); active layer thickness (m); lateral erosion rate; 'm' value; input/output difference (m3/sec); courant number; and Mannings n.

Such high quality long-term erosion plot data were not available for this comparison, and indeed, are rarely available for most mine sites. So, for this paper, the above input parameters (apart from grain size and the climate file) were set based on the CAESAR user's manual and information available in peer reviewed published journals.

Model input parameters

Using the process described above for the SIBERIA model, the β_1 and m_1 input parameters used are shown in Table 1. These were derived using runoff and erosion date generated for the material using a Kalgoorlie climate file. The CAESAR grain file was created from PSD data derived during the study. The remaining parameters used are shown in Table 2.

Table 1. SIBERIA input parameters.

SIBERIA input parameter	Value
β_1	0.9821
m_1	0.00155

Table 2: CAESAR model parameters used in the catchment simulation.

Parameter	Unit	Value
Grain size (sand, silt, clay)	%	94 / 3 / 3
Water depth erosion threshold	m	0.002
Minimum discharge for depth calculation Min Q	-	0.00002
Maximum erode limit	m	0.001
Active layer thickness	m	0.05
Method for calculating shear stress	-	Velocity
Sediment transport rule	-	Einstein
'm' value	-	0.01
Soil creep exponent	-	0.0025

Results

The 100 year simulation results for SIBERIA are shown in Figure 3. The results show that the maximum erosion was predicted to occur at the flood bund (shown in red in Figure 3). There is minor erosion at the top of the dump crests and minor channel lines are evident in the wider catchment. Deposition up to 0.2m has been predicted at the toe of slope (shown in blue in Figure 3) around the edges of the dumps and between each individual dump cell. In general the rate of erosion as predicted by SIBERIA is low.

The CAESAR result for only a 5 year simulation period is shown in Figure 4 (5 years shown as the 100 year simulation was not completed at time of paper submission). In contrast, over this short simulation period, the model has predicted development of a deeply incised channel network over 1m deep towards the north and east of the dumps, and near the catchment outlet. The channel network has a high degree of sinuosity and extends across a large proportion of the catchment.

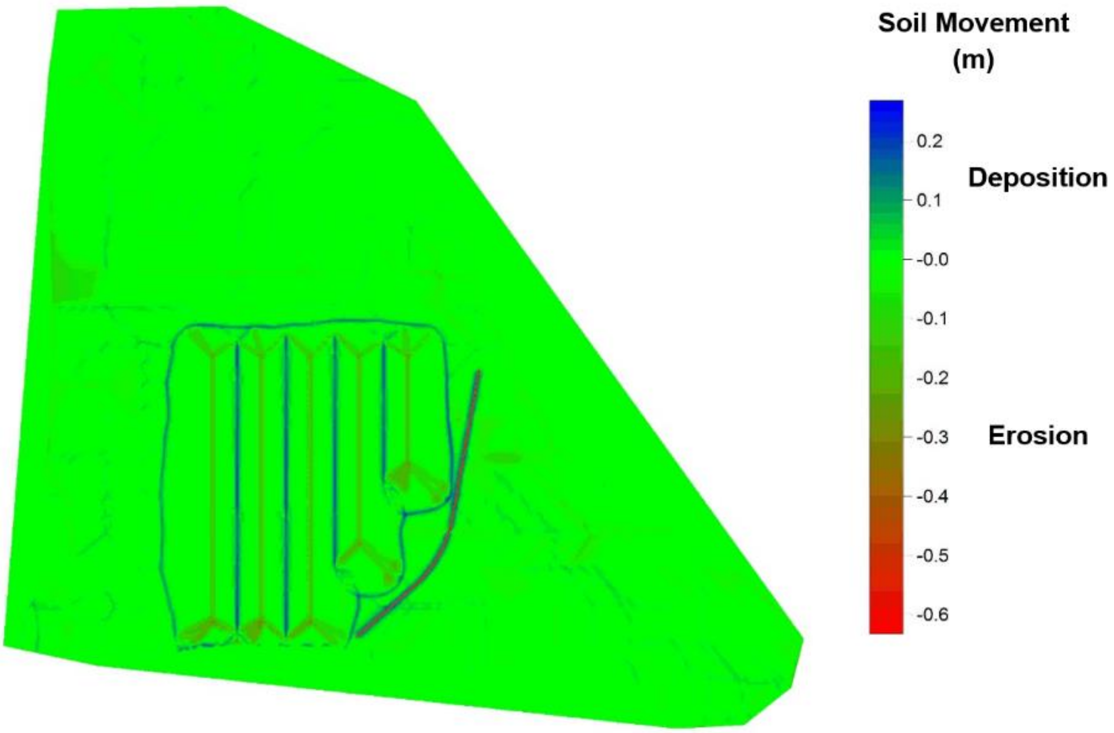

Figure 3. SIBERIA results for 100 year simulation period using a 1m grid size.

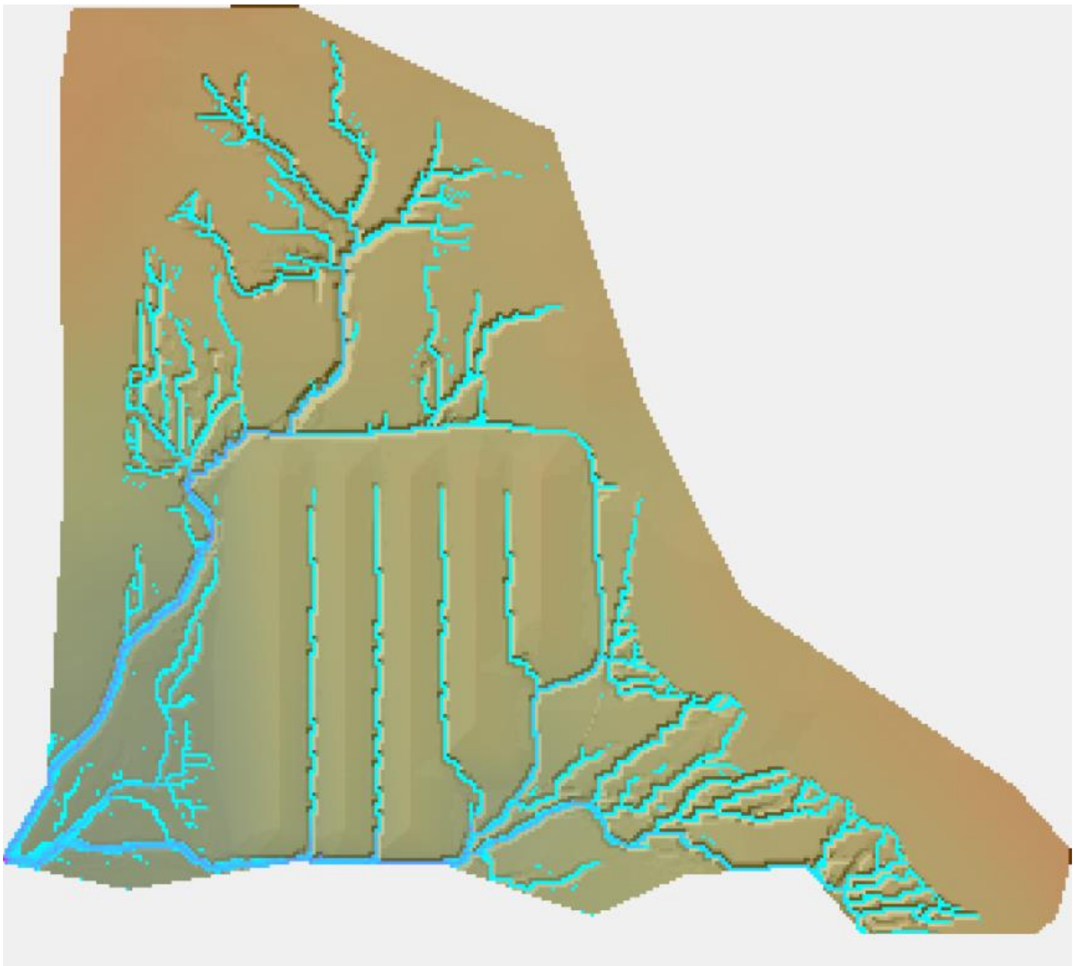

Figure 4. CAESAR results for 5 year simulation period using a 5m grid size.

Discussion

The first point to note is that the comparison of the two models was done on a different grid size. The 100 years simulation for a 1m grid size for SIBERIA was completed in less than 10 minutes. Using the same grid size, CAESAR had taken 48 hours to run 81 days of the 36,500 days of the climate file. The DEM was re-gridded to 5m so that a faster processing time could be achieved but even at this scale the model took over 300 hours of computing time.

Calibration of the CAESAR model in a similar fashion to the way WEPP is used to calibrate SIBERIA and derive its input parameters was also attempted. A small generic batter section was created 100m wide, 7m high, 3° gradient, 1m grid spacing and a defined catchment outlet (which CAESAR requires to run). Using the same climate file, grain size, and input parameters shown in Table 2 the CAESAR model was run for this calibration batter configuration. The model after 100 years did not show any erosion or surface changes. The model was re-run with input parameters obtained from other practitioners who have simulated plot scale erosion, and again no surface change was predicted. Finally the grid scale was adjusted to smaller scales to see if some surface changes could be initiated but this approach was also unsuccessful.

Although this paper makes no claim to the accuracy of either model's output in terms of the rates of erosion predicted, observations of the catchment geomorphology itself show that it is a broad sheet wash area and that there are no well-defined, deeply cut channels (Figure 5), even in lower elevations in the catchment where other sub-catchments converge (bottom left of the model output). This leads to the conclusion that the SIBERIA output is much more closely aligned with the field situation.

This lack of observed deep incision is also supported by observations of the sandy topsoil material in the laboratory when undergoing full characterisation. Its infiltration capacity was measured to be high. When combined with the arid Kalgoorlie climate with a high evaporation rate, there are very few rain events that generate overland flows. Hence, there are very few runoff events that would cause incision into the material in a very low gradient catchment.

The successful use of CAESAR in the N.T. mining environment has in part been due to the availability of long-term instrumented erosion plots providing high quality (sub hourly) data to calibrate the model. As the model only has input requirements for PSD, climate, and DEM, model calibration is limited to adjusting the parameters shown in Table 2 (PSD exempted). Only the soil creep rate is located within CAESAR's slope process input options and the remainder are within the hydrology and sediment input options. For example, the model is very sensitive to changes in the 'm' value that controls the peak and duration of the flood hydrograph generated by a rainfall event. Adjustment of this value (and other parameters not directly related to the material) may calibrate the model predictions to actual plot data, but there is no way to practically derive this value from small-scale or laboratory experimentation.

The limitation of only having two variables within the soil erosion (or hillslope input options) of the model was demonstrated when trying to obtain meaningful output from the generic small scale batter. Solutions often put forward by other users to generate sufficient erosion from hillslopes include modification of the grain size file to a finer PSD to generate increased erosion to match real world data. However, changing the only inputted data that actually describes materials within the catchment is difficult to justify.

Figure 5. Surface sheet flow conditions in the study catchment.

Conclusion

The output of the SIBERIA and CAESAR LEMs were compared by applying them to the same catchment with the same climate and surface materials. The SIBERIA model predicted low erosion rates and minimal development of well-defined flow networks after 100 years, consistent with observed field conditions. In comparison, the CAESAR model predicted deep channel incision after only 5 years. It is therefore concluded that CAESAR greatly over-predicted erosion and incorrectly predicted the development of flow networks that were not observed in the undisturbed catchment.

The CAESAR model is an attractive alternative to SIBERIA, mainly because of its low parameter input requirements, and its ability to simulate and visualise single storm events as well as long-term landscape evolution. However, having are limited parameters to describe the hillslope processes that strongly influence the predicted rate of erosion - whilst convenient when data are difficult to obtain - is also a significant failing. The model was primarily developed for use in fluvial studies and has a strong fluvial and flow routing component, but the hillslope inputs appear to not adequately account for the main drivers of erosion. Algorithms in the model to describe these processes are difficult to objectively parameterise, and model "tuning" so that it predicts realistic erosion rates depends on modification of parameters indirectly related to erosion but to which the model output is highly sensitive. The CAESAR model is perhaps better applied to larger catchments where there are defined stream networks. SIBERIA, on the other hand, appears to be better suited to examine waste dump erosion design issues as, although not without limitations, its key input parameters are directly concerned with hillslope runoff and erosion processes and can be derived from measureable data for the given materials.

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