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Assessing soil erosion on a rehabilitated landform using the CAESAR landscape evolution model ©

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Abstract

The ability to predict the stability of post-mining landscapes through time scales ranging from decades to thousands of years is a critical element in the assessment of closure designs for uranium mines. Landscape Evolution Models (LEMs) can provide information on soil erosion rates at decadal or centennial temporal scales, over large spatial scales and evaluate the sensitivity of these processes to environmental changes. In this paper, the CAESAR LEM is tested for its ability to predict soil erosion from a series of 30 x 30 m experimental plots constructed on a trial rehabilitated landform at the Ranger Uranium Mine in the Northern Territory, Australia. Data inputs required by the model (particle size distribution and rainfall time series) were obtained from field measurements made during the 2009–10 wet season. A very high resolution (20cm) digital elevation model of each erosion plot was produced from a laser scan of the surface.

The erosion rates predicted by the model were compared with time series field measurements of suspended sediment and bedload. This is the first time that predictions from an LEM have been assessed against field measurements at such high spatial and temporal resolution scales. Once the model had been calibrated for the specific site hydrological conditions, the predicted loads for both bedload and suspended sediment demonstrated excellent agreement with the field data.

Erosion data collected through subsequent wet seasons will provide the opportunity to assess how well the model predicts the evolution of the surface erosion properties through time as the surface weathers and vegetation develops.

1 Introduction

The Ranger Uranium Mine operated by Energy Resources of Australia Ltd (ERA) currently accounts for about 10% of the world’s annual production of uranium oxide. It is located in the catchment of Magela Creek in the wet-dry tropics of the Northern Territory of Australia (Figure 1). The region in which the mine is located experiences an annual average rainfall of 1568 mm (Bureau of Meteorology, 2011), with most of this rain falling in the wet season between October and April.

Downstream of the mine, Magela Creek debouches into the East Alligator River through a broad expanse of floodplain and wetlands listed as ‘Wetlands of International Importance’ under the Ramsar Convention. In addition, the mine is surrounded by the World-Heritage listed Kakadu National Park.

Reflecting the environmental and cultural sensitivities of the area, the Supervising Scientist Division of the Commonwealth Department of Sustainability, Environment, Water, Population and Communities undertakes an independent physical, chemical and biological monitoring programme in the river catchments around the mine to ensure that the environment outside of the mine project area remains protected (Jones et al., 2009; www.environment.gov.au/ssd).

The mine currently plans to continue production through to 2020 after which the site will be rehabilitated. Given the environmental and cultural sensitivity of the area surrounding the mine, it is important to determine the likely erosional stability of the proposed rehabilitated landform through time, to ensure that post closure environmental protection objectives are met. These state, with respect to mine closure, that:

"… the operator of the mine shall rehabilitate the Ranger Project Area to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park."

The environmental requirements further 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".

It is therefore crucial that rehabilitation planning and landform design incorporate landform shape 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.

Numerical 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 (Riley, 1994; Evans and Loch, 1996; Evans, 2000; Loch et al., 2000). These models include the water erosion prediction programme (WEPP) (Laflen et al., 1991; Flanagan and Livingston, 1995), universal soil loss equation (USLE), modified universal soil loss equation (MUSLE), revised universal soil loss equation (RUSLE) (Onstad and Foster, 1975; Wischmeier and Smith, 1978; Renard et al., 1994), and Siberia (Willgoose et al., 1989).

The CAESAR model (Coulthard 2000, 2002) was originally developed to examine the effects of environmental change on river evolution, and to study the movement of contaminated river sediments. Recently, it has been modified and applied to study the evolution of proposed rehabilitated mine landforms in northern Australia (Hancock et al., 2010; Lowry et al., 2009). In this paper, the CAESAR model has been used to assess potential erosion from purpose-built erosion plots located on a trial rehabilitated landform on the Ranger mine area.

2 The CAESAR model

The CAESAR landscape evolution model (Coulthard et al., 2000, 2002, 2005; Van de Wiel et al., 2007) simulates landscape development by routing water over a regular grid of cells and altering elevations according to erosion and deposition from fluvial and slope processes. CAESAR can be run in two modes: a catchment mode (as used here), with no external in-fluxes 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: 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 and Kirkby, 1979) that contains a lumped soil moisture store which when it exceeds a threshold value creates surface runoff. The surface runoff generated by the hydrological model is then routed using a flow model.

For the purposes of this study the CAESAR model was modified to run data recorded at 10 minute intervals, to reflect the much smaller catchment areas modelled, and the corresponding shorter timeframes for system response to rainfall. Rainfall data collected during the 2009–10 wet season from the trial landform surface was used for the simulations reported here.

Flow is the main driver for the geomorphological processes in alluvial environments and CAESAR uses a "flow-sweeping" algorithm, which calculates a steady-state, uniform flow approximation to the flow field. Discharge is distributed to all cells within the a 2–5 cell range in front of a cell according to differences in water elevation of the donor cell and bed elevations in the receiving cell. If no eligible receiving cells can be identified in the sweep direction, i.e. if there is a topographic obstruction, then the discharge remains in the donor cells to be distributed in subsequent sweeps (in different directions) during the same scan.

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

At each time step iteration of the model, all transported bed load material is deposited in the receiving cells where it can be re-entrained in the next iteration. The extent of deposition of suspended sediments at each step is derived from fall velocities and concentrations in suspension for each suspended sediment fraction.

3 Study area – Ranger trial landform

The soil erosion plots providing the input data for this study are located on a much larger trial landform constructed to study rates of soil erosion at the Ranger mine. The trial landform was constructed by ERA between late 2008 and early 2009. It is located to the north-west of the tailings storage facility at Ranger mine (Figure 1).

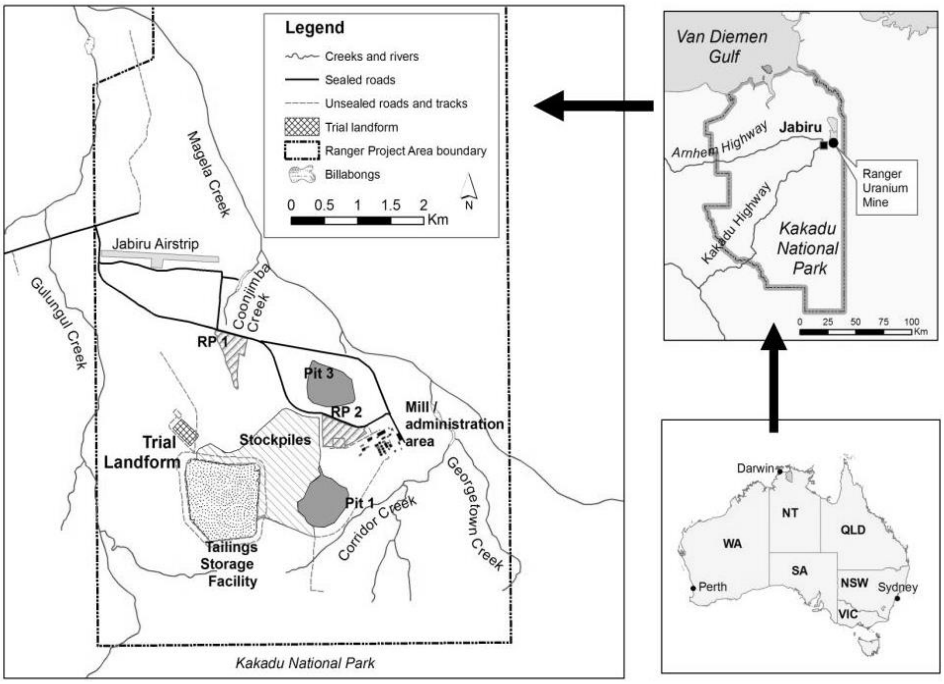

Figure 1 Location of the Ranger Mine and the trial landform

The trial landform covers a total footprint area of 8 ha. Excluding boundary batter slopes and perimeter access roads the effective top surface area is 6 ha with a mean slope of 3.3%. The landform was designed to test two types of potential final cover layers: waste rock alone; and waste rock blended with approximately 30% v/v of fine-grained weathered horizon material (laterite). ERA intends to use the trial landform to test landform design and revegetation strategies to assist in the development of a robust rehabilitation strategy once mining and milling have finished. In the longer term, the trial landform will be incorporated into the final rehabilitated landform.

During 2009, the Supervising Scientist Division constructed four erosion plots (30 x 30 m) on the trial landform surface, with two plots in the area of waste rock, and two in the area of mixed waste rock and laterite (Figure 2). The plots were physically isolated from runoff from the rest of the landform area by constructed borders. The erosion plots were constructed to enable the following:

- Measurement of erosion rates through time to assess effects of different surface treatments and vegetation establishment strategies.
- Generation of input data for long term predictive geomorphic computer modelling of the proposed landform designs.
- Determine loads of key contaminants present in the dissolved and fine suspended-sediment fractions available for export from the trial landform via the surface water runoff pathway.

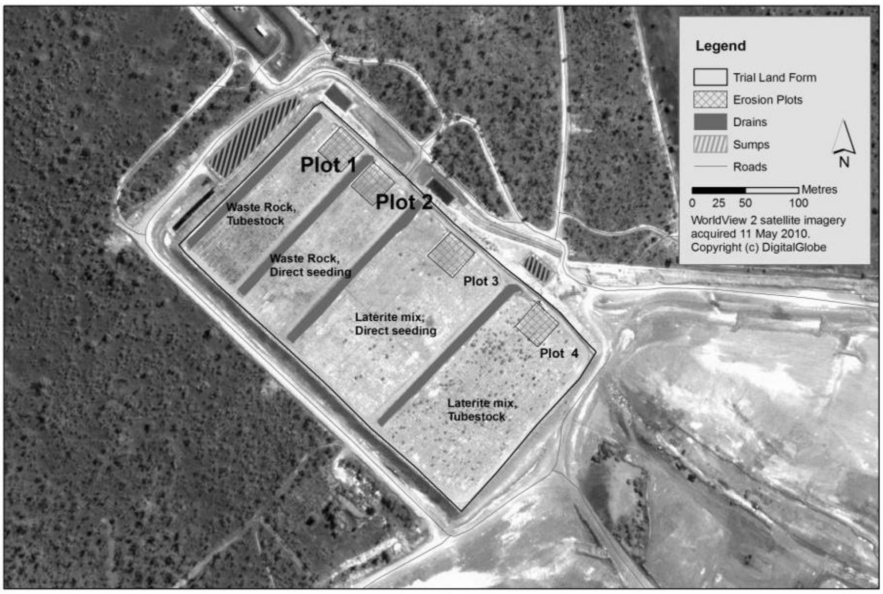

Figure 2 Satellite image and schematic of the trial landform at Ranger mine detailing the size and location of Plots 1 and 2

4 Methodology

The application of the CAESAR model to the trial landform required the collation and integration of data from a range of different sources. The key data inputs used by the model were a digital elevation model (DEM); rainfall data and surface particle size data.

The model outputs were compared with field data collected from the outlet of each erosion plot, which was instrumented with a range of sensors. These included a pressure transducer and shaft encoder to measure stage height; a turbidity probe; electrical conductivity probes located at the inlet to the stilling well and in the entry to the flume to provide a measure of the concentrations of dissolved salts in the runoff; an automatic water sampler to collect event based samples; and a data logger with mobile phone telemetry connection. Data acquired during the 2009–10 wet season were stored in the hydrological database Hydstra.

A DEM of the trial landform was produced from data collected by a Terrestrial Laser Scanner in June 2010. Each of the four erosion plots was scanned at a resolution of 2 cm at a distance of 100 m. For the purposes of this study, the data for the erosion plots were interpolated to produce a surface grid with a horizontal resolution of 20 cm. The DEMs were rotated by 137° to ensure that drainage flowed from west to east (a CAESAR pre-requisite), and then processed using ArcGIS software to ensure that the DEMs were pit-filled and hydrologically corrected. Pit filling is an important and necessary pre-processing step when analysing or modelling a DEM. It involves the removal of imperfections or artefacts in the surface of a DEM. In this study, peaks in the surface representing remnants of vegetation, and artificial depressions or sinks incorporated in the survey data were removed. Only Plots 1 and 2, on a waste rock surface were used for this current study, as the hydrological and suspended sediment data for Plots 3 and 4 were not yet available. It is envisaged that field data will be collected for all 4 plots for at least 5 years. The collection of additional data will enhance the ability to model a range of environmental scenarios.

Rainfall data were collected individually for each erosion plot using a rain gauge installed at the downstream end of each of the plots.

Grain size data for CAESAR were obtained by collecting bulk samples of surface material at eight points within each of the two plots, and size fractionating them. Mean values for all eight sites were taken and these means were then re-sampled into nine grain size classes (Figure 3) to be used for input into CAESAR. The sub 0.00063m fraction was treated as suspended sediment within CAESAR.

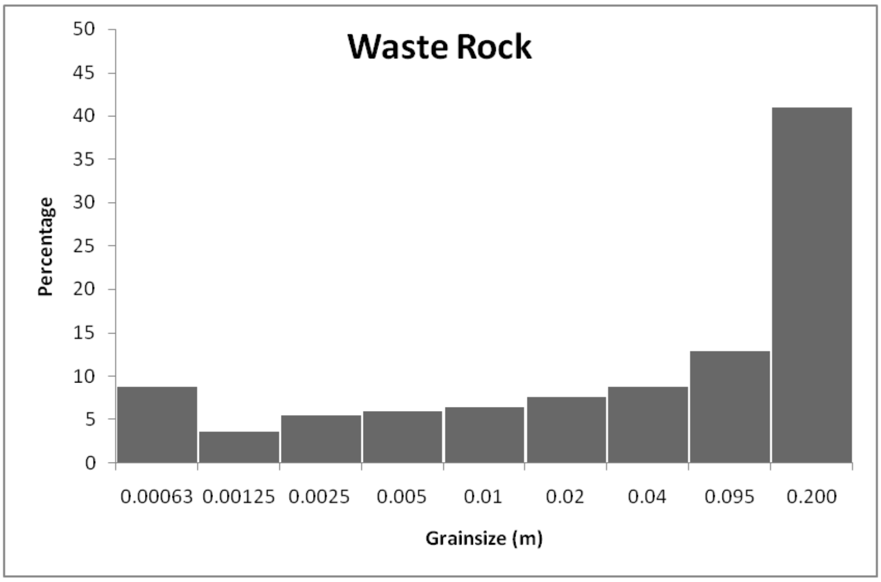

Figure 3 Grainsize distribution for Plot 2

Three sets of simulations were carried out. The first simulation involved the application of the 2009–2010 wet season data to Plot 2, whilst the second simulation involved the application of the 2009–2010 wet season data to Plot 1. Finally, the 2009–2010 wet season was repeated 20 times to simulate how the plots may evolve over longer time scales on Plot 2. Sediment totals for each of the nine grain size classes were recorded from the model every 10 minutes of simulated time along with runoff values. Surface elevations and the distribution of grain sizes for material remaining on the landform surface were recorded every simulated month.

5 Results

Figure 4 shows the results for Plot 2 of both modelled and field data for both suspended sediment and bedload results, and the field hydrograph. The modelled and measured bedload and suspended sediment data shows a close correspondence in both volume and timing of increases. The increases in field data are asynchronous with the modelled data as bedload samples were taken sporadically with a typical 2 week frequency compared to the 10 minute output resolution of the model data. Figure 4 also demonstrates a very close similarity between field (solid line) and modelled suspended sediment yields from Plot 2. Here, unlike the bedload, the measured suspended sediment data is at the same 10 minute resolution as the modelled data and an excellent correspondence in terms of timing and magnitude can be seen. Increases in sediment yield correspond to the larger runoff events in the plot.

Due to instrumentation problems there was less processed data available for runoff or suspended sediment from Plot 1. As the Plots 1 and 2 are 60 m apart, it was assumed there would be little difference in the rainfall for Plot 1. Consequently, the rainfall data for Plot 2 was used in the simulations for Plot 1. While less processed field data was available, the simulations for Plot 1 indicated a very good correspondence between the modelled and observed bedload yields. Also, like Plot 2 the field and model data responds mostly to the larger runoff events.

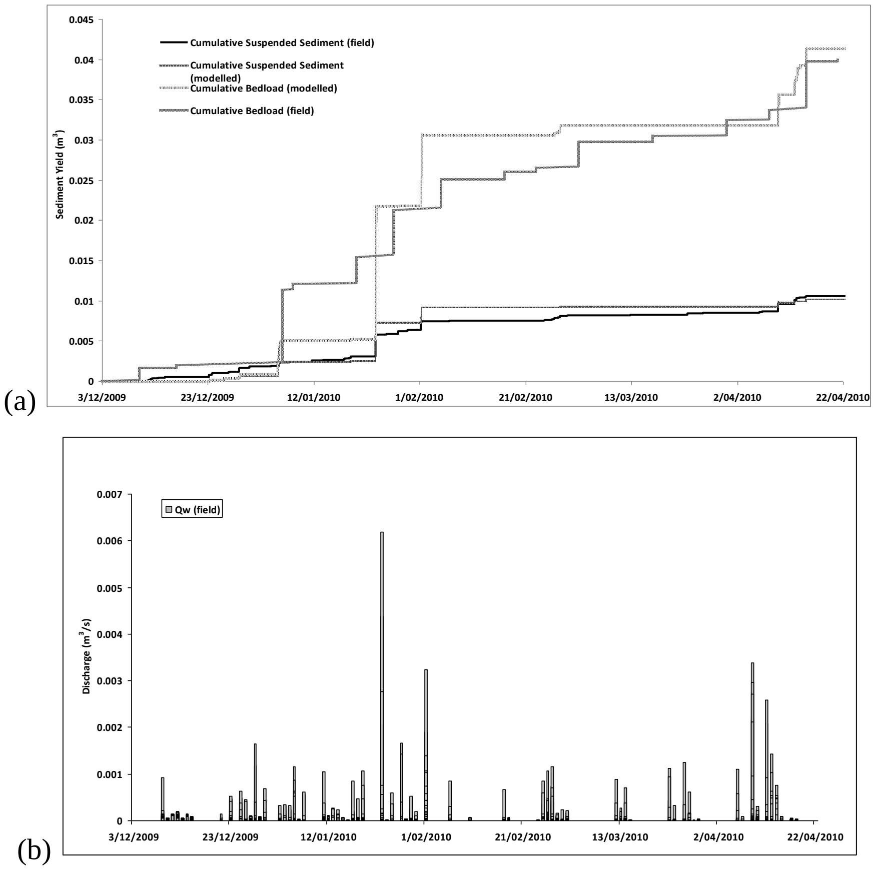

Figure 4 **Plot 2 (a) modelled and field measured bed and suspended sediment yields and (b) measured surface runoff**

The rainfall sequence from the 2009–2010 wet season was repeated twenty times to produce a hypothetical 20 years simulation of the evolution of Plot 2 (Figure 5). This enabled a preliminary assessment to be made of how the rates of sediment loss and the plot morphology may change over this period of time. Figure 5 indicates that there is rapid tail off and decrease in sediment yields after the first five years.

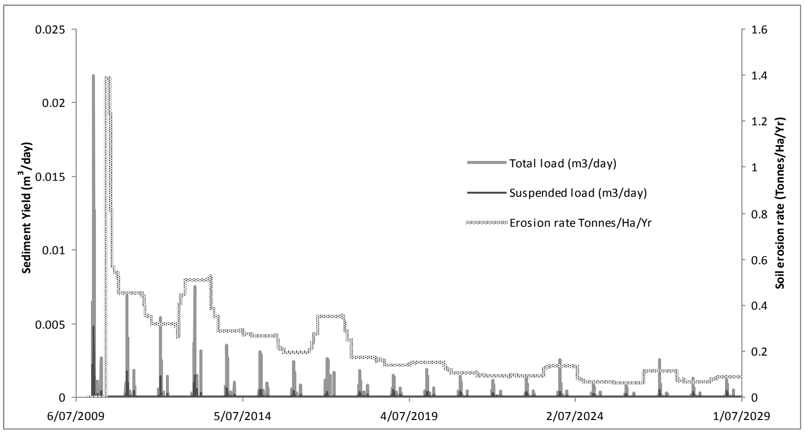

Figure 5 **Sediment yield for Plot 2 over 20 years – with soil erosion rate in tonnes/ha plotted (100 day smoothing)**

The initial high sediment output may be attributed to the underlying DEM being smoothed, and fine material removed in a period of self-adjustment until the model reaches an internal equilibrium. This in turn is attributed to the model starting these simulations with a uniform grainsize distribution representing a homogenous surface of waste rock.

6 Discussion

CAESAR offers several advantages over other soil erosion models especially when compared to empirical models. CAESAR requires a minimum of input data for the model to be run, with only a DEM, rainfall data and soil particle size data required as input parameters. Specifically, the ability to use measured physical characteristics, such as rainfall, is a significant advantage and difference to models such as Siberia or the USLE which require both greater numbers of inputs and relatively complex pre-processing/calibration of the inputs parameters. This makes it considerably simpler to set up and run. A further advantage of CAESAR is its ability to use a soil particle size distribution and allow the surface particle size distribution to evolve. This evolution involves an initial washing through of fines leaving the more coarse material on the surface. While not unique to CAESAR, the ability to input a DEM of the hillslope or catchment into the model is a further advantage. This allows individual drainage networks to develop, unique to each particular DEM that in turn leads to different patterns of erosion and deposition.

It is only recently that the costs of LIDAR, laser scanning and digital photogrammetric techniques have come down to a level such that they can be routinely used to provide detailed representations of land surfaces. Significant loss of hillslope detail, and hence ability to predict erosional properties, can occur if a DEM with insufficient grid resolution is used. For example, Hancock (2005) demonstrated that a 10 m DEM is satisfactory to capture hillslope geomorphology in rolling terrain but at coarser grid sizes considerable detail is lost. Important hillslope detail can be lost at grid sizes greater than a metre in tilled areas as ploughing produces regular meso-scale patterns of high and low areas. On mine sites the final rehabilitated surface is often ripped by a large tine pulled behind a bulldozer to enhance surface infiltration. This 'meso' topography will influence flow paths and thus sediment transport rates. For the work reported here, the use of a terrestrial laser scanner to generate a DEM enabled a very detailed representation of the surface topography to be generated. This in turn influences the flow paths, drainage network distributions and sediment transport rates that are able to be simulated in the model.

The instrumented field plots were specifically constructed to evaluate the hydrology and erosion characteristics of a post-mining landscape. The results to date provide confidence that CAESAR is capable of providing good predictions of initial sediment fluxes (i.e. soil erosion) under these conditions. There is an excellent correspondence between modelled and measured data – both in volumes of bedload, suspended load and water fluxes as well as in the timing of their delivery. The results validate the predictive capacity of the CAESAR model and provide greater confidence in being able to extend its application to steeper slope scenarios not addressed by the design of the current trial landform.

Significantly, this is the first time that a LEM has been evaluated against field data at such high resolution spatial and temporal scales. Implications for the use of LEMs in soil erosion prediction as well as model strengths and limitations are discussed below.

The erosion rate of approximately 0.1–0.2 t ha^{-1} yr^{-1} (equivalent to a denudation rate of approximately 0.01mm yr^{-1}) (Figure 5) predicted for a preliminary 20 year simulation of Plot 2 approximates the long term erosion and denudation rates established for the region using a variety of different methods. An assessment using the fallout environmental radioisotope caesium-137 (137Cs) as an indicator of soil erosion status for two transects in the much steeper Tin Camp Creek catchment produced net soil redistribution rates between (0.013–0.86 mm yr^{-1}) (Hancock et al., 2008). Overall denudation rates for the region range from 0.01–0.04 mm yr^{-1} determined using stream sediment data from a range of catchments of different sizes (Cull et al., 1992; Erskine and Saynor, 2000). Therefore the decadal scale predictions from the CAESAR model, once the initial period of surface acclimation has passed are well within field measured values. This provides confidence in the model as a predictor of decadal scale erosional processes.

It is important to recognise that several critical caveats need to be placed on the results produced to date. These include recognising that these simulations have been done for an 'idealised' environment. The erosion plots have relatively uniform characteristics, and occur on a gently sloping surface that represents a component of the overall mine landform that is likely to be least susceptible to erosion. Crucially, the role of developing vegetation was not considered in the 20-year simulations. The sensitivity of erosion rate to slope angle and vegetation cover needs to be implicitly considered as part of future modelling runs. In addition, a sensitivity analysis will need to be done of the effect of potential extreme rainfall events.

Continued monitoring of the trial landform over successive wet seasons will enable the effects of surface weathering, self armouring and the development of vegetation coverage to be quantified. These field data will be used to further refine the relevant algorithms in the CAESAR model and increase confidence in its ability to make more robust longer term predictions of rates of erosion from rehabilitated mine landforms.

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