Mine Closure 2024 – AB Fourie, M Tibbett & G Boggs (eds)
© 2024 Australian Centre for Geomechanics, Perth, ISBN 978-1-7636842-0-1
doi:10.36487/ACG_repo/2415_02

Using a landform evolution model to model the effect of extreme rainfall events on the geomorphic stability of a rehabilitated landform

John Lowry [a,*], Mike Saynor [a], Gregory Raymond Hancock [b], Tom Coulthard [c]

[a] *Office of the Supervising Scientist, Australia*

[b] *The University of Newcastle, Australia*

[c] *University of Hull, UK*

Abstract

Ensuring long-term erosional stability is crucial to successful rehabilitation of post-mining landforms. Landform evolution models (LEMs) are being used to assess landform stability in mine closure and relinquishment applications through their ability to predict the extent of erosion and gully development that may occur under a range of climatic and other environmental scenarios. Here we use the CAESAR-Lisflood LEM to assess the potential impact of extreme rainfall events on a conceptual rehabilitated landform design of the Ranger uranium mine in the Northern Territory of Australia. Rehabilitation of the Ranger mine requires the isolation of buried tailings for a period of at least 10,000 years. CAESAR-Lisflood was used in this study as it can model the impact of specific rainfall events over periods of thousands of years. Data from the largest recorded rainfall events at the Ranger mine (~800 mm in 72 hours at Jabiru Airport in February 2007) and in the Northern Territory (600 mm in 24 hours in January 2020 at Dum In Mirrie Island near Darwin) were used to generate different rainfall scenarios for extreme rainfall events at different recurrence intervals and rainfall intensities. Different rainfall scenarios were then modelled for simulated periods of up to 10,000 years to determine whether rainfall-induced gully erosion could expose buried tailings under a hypothetical worst-case scenario. Varying the intensity and frequency of extreme rainfall events in model simulations resulted in different predictions on the extent and depth of gully erosion and sediment transport for each catchment. The results reflect the influence of both the landform design and the impact of extreme rainfall events on the landform itself. This information has been provided to landform designers to assist in optimising the final design of the rehabilitated Ranger landform so that tailings will not be exposed within the 10,000-year period.

Keywords: *landform, erosion, modelling, rainfall, climate change, CAESAR-Lisflood*

1 Introduction

The Ranger uranium mine in the Northern Territory (NT) of Australia ceased the processing of stockpiled ore in 2021. Rehabilitation of the mine site has commenced and is currently due to be completed by 2034 (Energy Resources of Australia [ERA] 2023a). As the mine site is surrounded by the World Heritage-listed Kakadu National Park, and upstream of floodplains and wetlands listed as 'Wetlands of International Importance' under the Ramsar Convention (Figure 1), strict environmental requirements apply (Australian Government 1999). There are two key erosion-related environmental requirements for the rehabilitation of the Ranger mine: the first is to ensure that tailings buried in the mined-out pits are not exposed for at least 10,000 years; and the second is to ensure that the erosion characteristics are, as far as can reasonably be achieved, similar to surrounding comparable landforms. The landform surrounding the mine site is composed primarily of sandstones of the deeply weathered Koolpinyah surface, which consists of plains, broad valleys and low gradient slopes with isolated hills and ridges of resistant rock (East 1996). The regional geology is dominated

---

[*] Corresponding author.

by the mineralised metasediments and igneous rocks of the Pine Creek Geosyncline (Needham 1988). Previous assessments of the geomorphic stability of the Ranger landform against these erosion-related environmental requirements did not consider the impacts of extreme rainfall events, defined as those that represent the highest 5% of rainfall events that have been recorded within the area of interest (Commonwealth Scientific and Industrial Research Organisation 2007). Consideration of such events is important to the Ranger rehabilitation context because: (i) the regional climate is dominated by seasonal, high-intensity rainfall events (McQuade et al. 1996); and (ii) during the early stages of landform evolution the majority of erosion typically occurs during a limited number of high-intensity events (Moliere et al. 2002).

In this study we apply the CAESAR-Lisflood landform evolution model (LEM) (Coulthard et al. 2013) to a conceptual rehabilitated landform design of the Ranger mine to simulate the impact of extreme rainfall events over 10,000 years. The CAESAR-Lisflood LEM was originally developed to examine the effects of environmental change on river evolution and to study the movement of contaminated river sediments. A full description of the formulation and operation of CAESAR-Lisflood can be found in Coulthard et al. (2013). CAESAR-Lisflood has been adapted and applied to assessment of the evolution of proposed rehabilitated mine landforms in northern Australia (Hancock et al. 2010; Lowry et al. 2011, 2013, 2017; Saynor et al. 2012). An important attribute of CAESAR-Lisflood is its ability to utilise high temporal resolution rainfall data to model the effects of specific rainfall events on landform stability, making it highly suitable for studying the potential impact of extreme rainfall events on the Ranger landform.

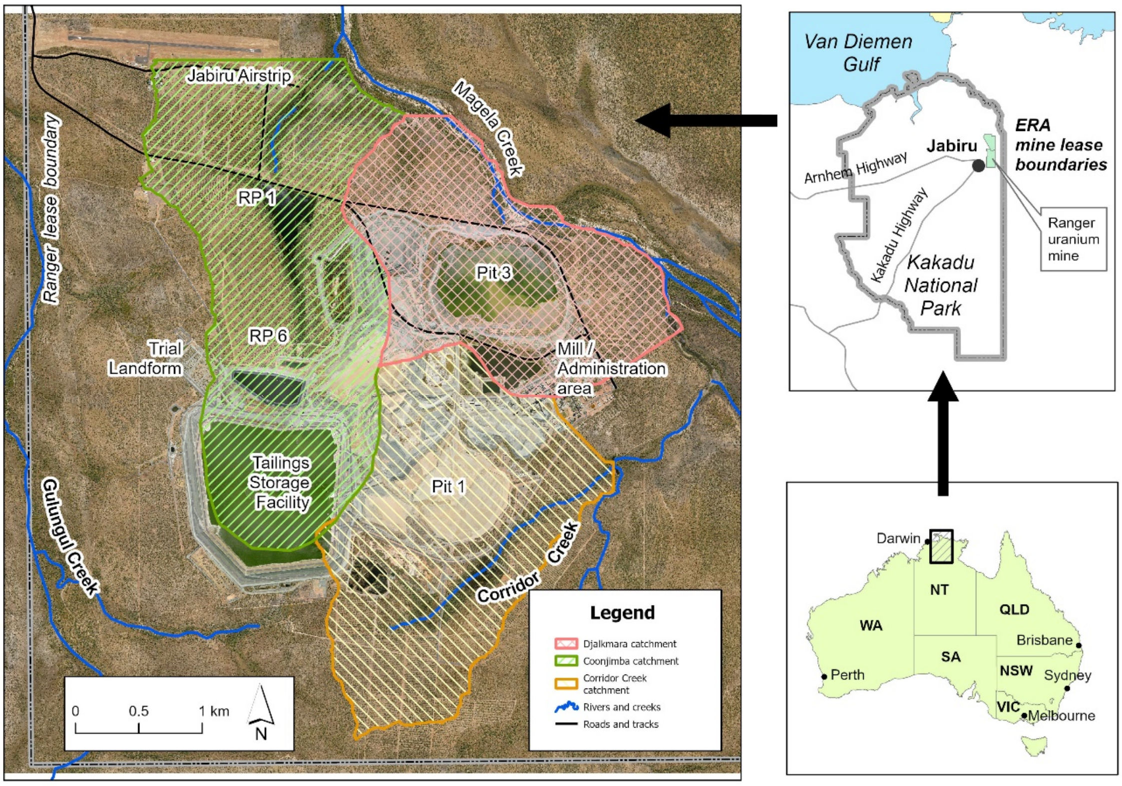


Figure 1 **Location of the Ranger mine**

2 Methods

CAESAR-Lisflood version 1.9j was used to simulate the impact of extreme rainfall events on the evolution of three catchments on the Ranger conceptual landform in which tailings and other contaminated material will be buried: Corridor Creek (420 ha), Coonjimba (541 ha) and Djalkmara (343 ha) (Figure 1).

Three key data inputs required by CAESAR-Lisflood to run model simulations are:

- a digital elevation model (DEM)
- surface particle size distribution data
- rainfall data.

The DEMs of the individual catchments were extracted from a conceptual landform prepared by mine operator Energy Resources of Australia (ERA) and compiled to a horizontal resolution of 10 m.

For the surface particle size distribution the process described in Hancock et al. (2020) was used, where the grain size data for CAESAR-Lisflood were obtained through application of a grid-by-number method of waste rock on the Ranger trial landform (Figure 1). The trial landform was established in 2009 as a test-bed for ecosystem and erosion processes that would inform design and management of the future Ranger landform. Grain size analysis was completed on these samples and the results averaged into nine grain size classes (Figure 2) which were used for input into CAESAR-Lisflood. The sub 0.000063 m (i.e. 63 µm) fraction is treated as suspended sediment within CAESAR-Lisflood; all larger grain sizes are treated as bed load.

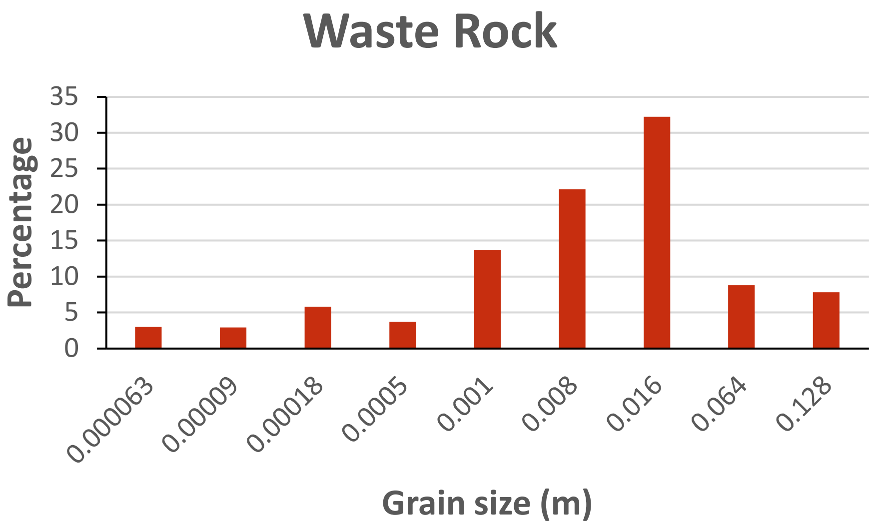


Figure 2 Grain size distribution of the waste rock on the surface of the trial landform

2.1 Development of extreme wet rainfall scenarios

Extreme wet rainfall scenario datasets have previously been developed by Verdon-Kidd & Hancock (2016) for use in long-term LEM simulations of the Ranger landform. These utilised rainfall data from Weipa in Queensland as an analogue for a future climate scenario that was 5% wetter than the current annual rainfall record for the Ranger mine. This dataset represented a period of 100 years, collated at hourly intervals. While this dataset represented a greater overall volume of rainfall, it did not include rainfall events of the magnitude and intensity that have been recorded at the Ranger mine, in the Alligator Rivers Region or in the Top End more broadly.

The assessment here used data from extreme rainfall events recorded in the Darwin-Alligator Rivers Region area of northern Australia. Specifically, data from rainfall events recorded at Dum In Mirrie Island west of Darwin (600 mm in the 24-hour period between 9 and 10 January 2020, highest daily rainfall recorded in the NT) and at Jabiru Airport, adjacent to the Ranger mine, (785 mm in a 72-hour period between 27 February and 2 March 2007, highest rainfall recorded at Jabiru) were incorporated into model simulations at different intervals and used to model periods of up to 10,000 years.

Nine different rainfall scenarios were developed from the original Weipa rainfall dataset of Verdon-Kidd & Hancock (2016) by adding the Dum In Mirrie Island and Jabiru Airport rainfall events at different intervals and frequencies over the 100-year period. Scenarios were developed to assess the impact of extreme rainfall events that were either concentrated at the start of the simulation period or spread over the simulation period. In the former category, up to four extreme events were randomly inserted in the first 30 years of the simulated period; in the latter category, up to five extreme events were randomly inserted over the 100-year period.

For comparative purposes, one scenario was created which utilised the extremely low rainfall data from Mango Farm near Katherine (300 km south of Ranger) that was generated by Verdon-Kidd & Hancock (2016).

Additional model scenarios were created by changing the sediment transport equations used and varying the presence or absence of vegetation. For the purposes of this study, CAESAR-Lisflood simulations were run using either the Einstein (1950) or the Wilcock & Crowe (2003) sediment transport equations. Work by Lowry et al. (2020) found that use of the Einstein equation consistently generated greater erosion rates (and was therefore used to produce ‘worst-case’ outputs) relative to the Wilcock & Crowe (2003) equation which produced similar erosion and sediment transport rates to those recorded on the trial landform.

The vegetation parameter simulates the effect of the presence/absence of a grass layer across the surface of the landform. Input values were derived from flume experiments in Arnhem Land measuring the shear stresses required to remove vegetation and the length of time needed for the grass cover to reach maturity (Coulthard 2019).

Seventeen different scenarios were modelled for 100 years. Table 1 lists the rainfall scenarios and other parameters used in the model simulations. All scenarios were applied to the Corridor Creek catchment, with simulation numbers 1, 9, 14, 15, 16 and 17 also applied to the Coonjimba and Djalkmara catchments for comparative purposes.

Table 1 List of simulations applied to the Corridor Creek catchment. Simulations marked * were also applied to the Coonjimba and Djalkmara catchments

Simulation	Rainfall scenario	Other parameters
1*	100-yr Weipa rainfall with Jabiru Airport 2007 event inserted at year 25, and Dum In Mirrie event at years 10 and 28	Wilcock and Crowe sediment transport equation; vegetation present
2	100-yr Weipa rainfall with Jabiru Airport 2007 event inserted at years 25 and 75	As above
3	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 10, 13 and 40	As above
4	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 10 and 13	As above
5	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 28 and 70	As above
6	100-yr Weipa rainfall with no added extreme events	As above
7	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 7, 9, 40 and 80	As above
8	100-year Mango Farm rainfall – dry rainfall analogue	As above
9*	100-yr Weipa rainfall with Jabiru Airport 2007 event inserted at years 25 and 75, and Dum In Mirrie event at years 10 and 28	As above
10	100-yr Weipa rainfall with Jabiru Airport 2007 event inserted at year 25, and Dum In Mirrie event at years 10 and 28	Einstein sediment transport equation; vegetation present
11	100-yr Weipa rainfall with no added extreme events	As above
12	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 7, 9, 40 and 80	As above
13	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 1, 2,5 and 28	Wilcock and Crowe sediment transport equation; vegetation present
14*	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 1, 2,5, 28 and 80	As above
15*	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 1, 2,5, 28 and 80	Wilcock and Crowe sediment transport equation; vegetation absent
16*	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 1, 2,5, 28 and 80	Einstein sediment transport equation; vegetation absent
17*	100-yr Weipa rainfall with Dum In Mirrie event inserted at years 1, 2,5, 28 and 80	Einstein sediment transport equation; vegetation present
18*	1,000-year simulation composed of 100-yr Weipa rainfall with Dum In Mirrie event inserted at years 1, 2,5, 28 and 80 looped 10 times	Einstein sediment transport equation; vegetation present

In addition, a 1,000-year scenario (simulation 18) was modelled by looping the 100-year rainfall file used in simulation 17, 10 times. Simulation 17 was used as it produced the deepest gullies in Corridor Creek. For comparative purposes, this scenario was also applied to the Coonjimba and Djalkmara catchments.

To simulate the evolution of each catchment over 10,000 years, each was modelled successively nine times as a series of 1,000-year simulations from the final output produced in simulation 18. Importantly, the DEM produced at the end of each 1,000-year simulation for each catchment was used as the starting input for the succeeding 1,000-year simulation.

2.2 Assessment methods

Three spatial analysis tools in ArcGIS Pro were used to assess the surface characteristics of the DEMs produced as outputs by the different scenarios modelled. Each tool was used to perform a specific function:

- The Raster Calculator tool was used to quantify the difference in the surface elevations between the DEMs — specifically, how much higher or lower the simulated surface was after the simulation period (100 or 1,000 years). This identified areas of erosion or deposition.
- The Stack Profile tool was used to generate cross-sectional profiles for each of the DEMs representing the surfaces of the modelled catchments.
- The Zonal Statistics tool was used to calculate the general topographic characteristics — minimum, maximum and mean elevations — of the different surfaces. This quantified the amount of erosion or deposition predicted to occur.

In addition, values for total sediment load exiting the catchment were extracted from the output *.DAT data files produced by each model scenario in Microsoft Excel.

The assessment compared the following model outputs:

1. the distribution, extent and depth of gullying predicted under each scenario
2. the sediment loads and denudation rates produced under each scenario. Denudation rate is the average rate of surface lowering, calculated by dividing the total sediment load by the catchment area over time
3. general topographic characteristics (maximum, minimum and mean surface elevation) of the final surfaces produced under each scenario.

3 Results

For Corridor Creek, the maximum predicted gully depth for each scenario within a simulated period of 100 years is shown in Figure 3. Simulation 17 predicted the deepest gully and was used as the basis for model simulations for periods of up to 10,000 years.

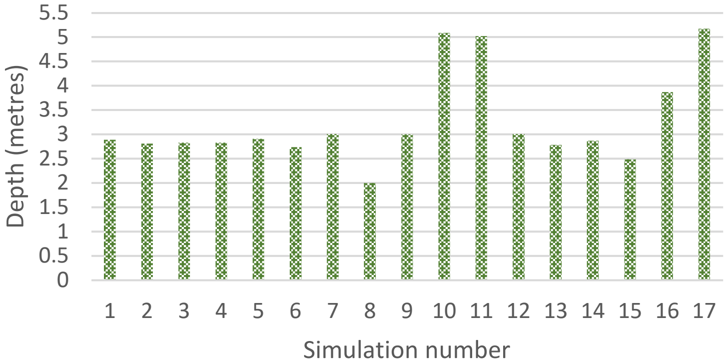


Figure 3 Predicted maximum gully depth after 100 years — Corridor Creek catchment

The extent and distribution of erosion and deposition predicted to occur in each catchment after a simulated period of 10,000 years are shown in Figure 4, along with the location of cross-section profiles through 'areas of concern'. The areas of concern represent areas containing buried tailings or contaminated material in each catchment.

The extent and magnitude of predicted gullying after 10,000 years in the areas of concern is represented as individual cross-sectional profiles in Figure 5. This figure shows (from top to bottom) profiles across Pit 3 in the Djalkmara catchment, across the former tailings storage facility (TSF) in the Coonjimba catchment, and across Pit 1 in the Corridor Creek catchment. Gully depth is predicted to gradually increase over time in each catchment; for comparative purposes, the predicted gully depth after 1,000 years is also shown.

In relative terms, the deepest gullies are predicted to occur in the Coonjimba catchment within the area occupied by the former TSF (Figure 5a — Profile C–D). The prevention of erosion in this area will be critical in ensuring that contaminated soils are not mobilised and moved downstream into Coonjimba Billabong or Magela Creek. In the Djalkmara catchment, the deepest gullies are predicted to form across the surface of Pit 3 (Figure 5 — Profile A–B). The current understanding is that tailings will be buried at a depth greater than this in the Djalkmara catchment (ERA 2023b) and are therefore unlikely to be exposed within the 10,000-year time frame. In the Corridor Creek catchment, relatively large gullies are predicted to form across the surface of Pit 1 (Figure 5 — Profile E–F). The potential for gully development in this area is of concern due to the potential proximity of the gullies to buried tailings in Pit 1, which the Ranger Mine Closure Plan (ERA 2023a) indicates would be at least 9 m below the pit surface.

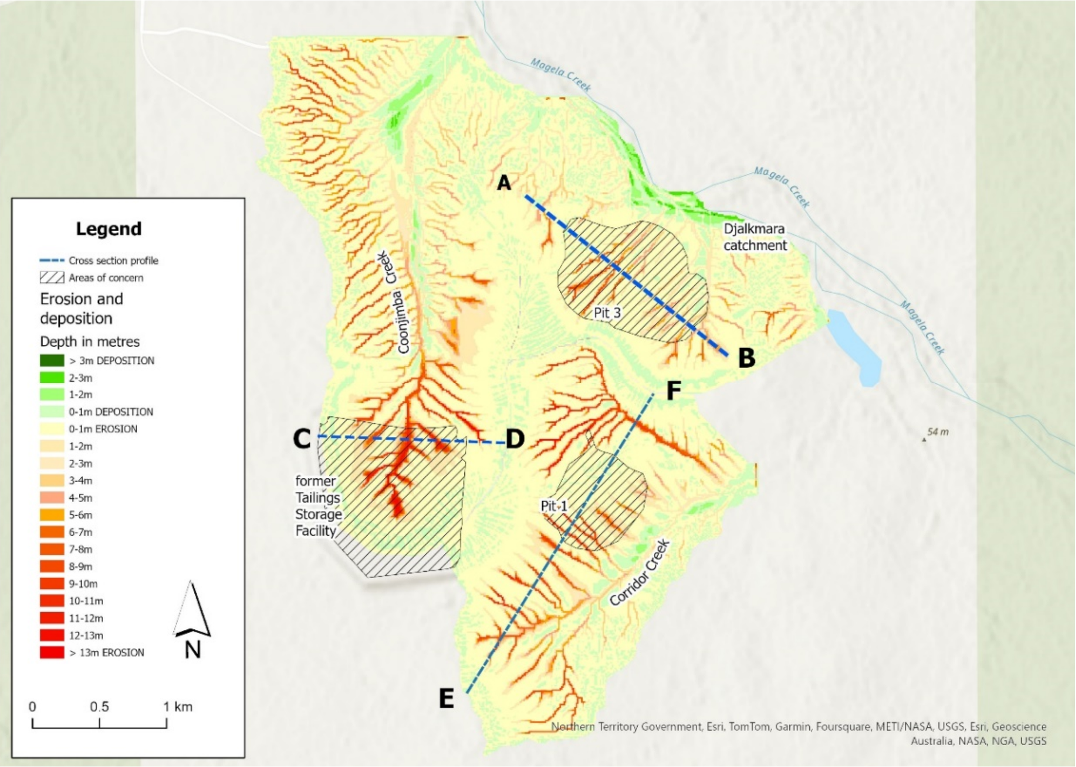
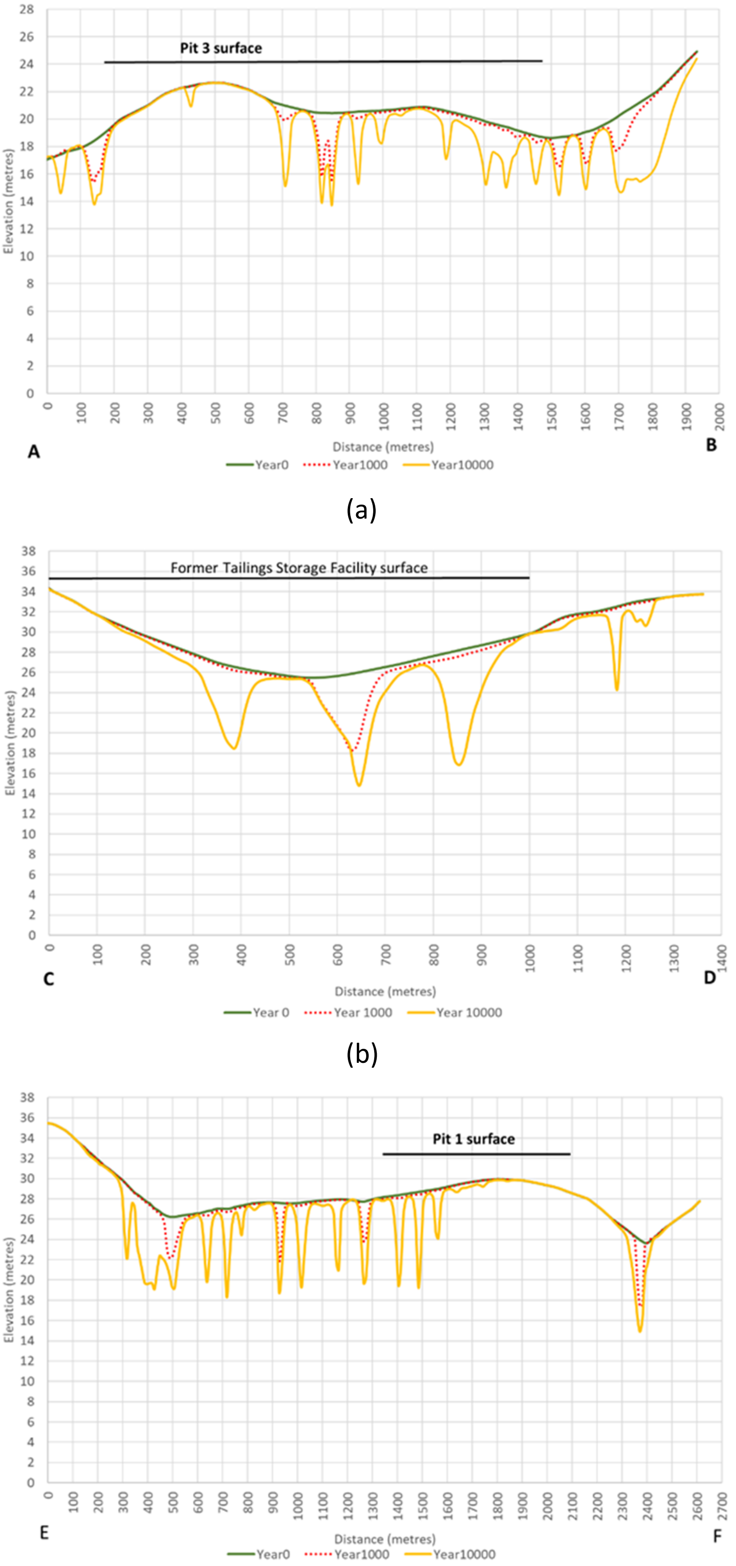


Figure 4 **Extent and magnitude of erosion and deposition after a simulated period of 10,000 years. Profile sections across 'areas of concern' (hatched areas) in the modelled catchments are also shown**

The model predictions for gully formation in this study differ from those in earlier studies for periods of up to 10,000 years (Supervising Scientist 2020); the key differences in model parameterisation in the current study being the inclusion of extreme rainfall events and vegetation cover. A comparison of the predicted gully depths for the Corridor Creek and Djalkmara catchments after simulated periods of 10,000 years shows that the application of the extreme rainfall scenario produces deeper gullies than the scenario without extreme rainfall (Table 2). Specifically, the earlier 10,000-year simulations without the Dum In Mirrie events predicted gully depths which are approximately 20% less than the gully depths predicted from simulations with the extreme rainfall events described here. Earlier simulations for the Coonjimba catchment have only been undertaken for a simulated period of 3,000 years so it is not possible to compare results over 10,000 years in that catchment.



(a)

(b)

(c)

Figure 5 **Profile of predicted gullies after a simulated period of 1,000 years (red dotted line) and 10,000 years (yellow line) in areas of concern in the: (a) Djalkmara; (b) Coonjimba; (c) Corridor Creek catchments**

Table 2 Predicted maximum gully depths with/without extreme rainfall after 10,000 years

Catchment	Predicted depth — local extreme rainfall events included (m)	Predicted depth — no local extreme rainfall events included (m)
Corridor Creek	12.5	9
Djalkmara	9.2	7

Figure 6 shows predicted denudation rates from Year 1, immediately after the completion of rehabilitation activities, in the different catchments. The background denudation rate (0.075 ± 0.013 mm yr^{-1}) (Wasson et al. 2021) is also shown for comparison. Background denudation values were calculated from existing estimates of total denudation (both physical erosion rates and solution losses) for the Alligator Rivers region in which the Ranger mine is situated. Geomorphically, the Ranger mine is situated on the deeply weathered Koolpinyah surface, which consists of plains, broad valleys and low gradient slopes, with isolated hills and ridges of resistant rock (East 1996). When modelled over 10,000 years the denudation rates in all catchments are predicted to decline rapidly in the first 100 years, with a much slower reduction for the remainder of the simulation period.

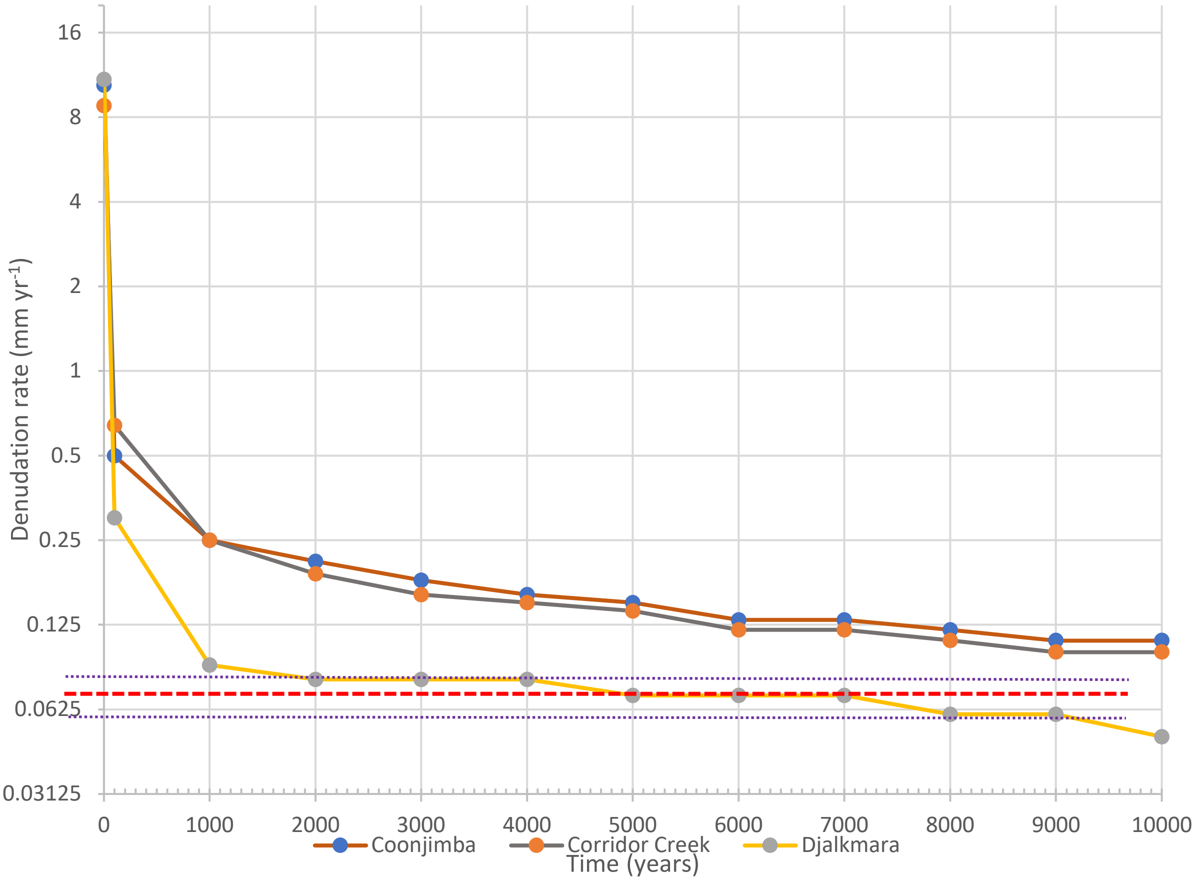


Figure 6 Denudation rates in modelled catchments over 10,000 years. Y-axis is Log 2. Red dashed line represents the background denudation rate; purple dotted line represents the margin of error on the background rate

Importantly, the decrease in the denudation rate in each catchment indicates that the landform is on a trajectory to eventually correspond with the surrounding landscape. Interestingly, Djalkmara is the only catchment in which the denudation rate is predicted to correspond with the background rate in less than 10,000 years, falling within the margin of error of the background denudation rate after 2,000 years (Figure 6). This is attributed to the topographic characteristics of Djalkmara; namely a higher proportion of steeper slopes relative to catchment size, resulting in rapid initial movement of sediment within and from the catchment.

The cumulative total sediment load produced by each catchment over the 10,000-year simulation period is shown in Figure 7. Under the extreme rainfall events modelled in these simulations, the landform is predicted to continue eroding and generating sediment loads for at least 10,000 years. However, the sediment load generated by each catchment is predicted to steadily decrease over time, indicating gradual stabilisation of the landform in each catchment (Figure 4). Importantly, the predicted trend of sediment load decreasing over time corresponds with decreases in measured bed load observed from the Ranger trial landform over a period of six years (Saynor & Erskine 2016).

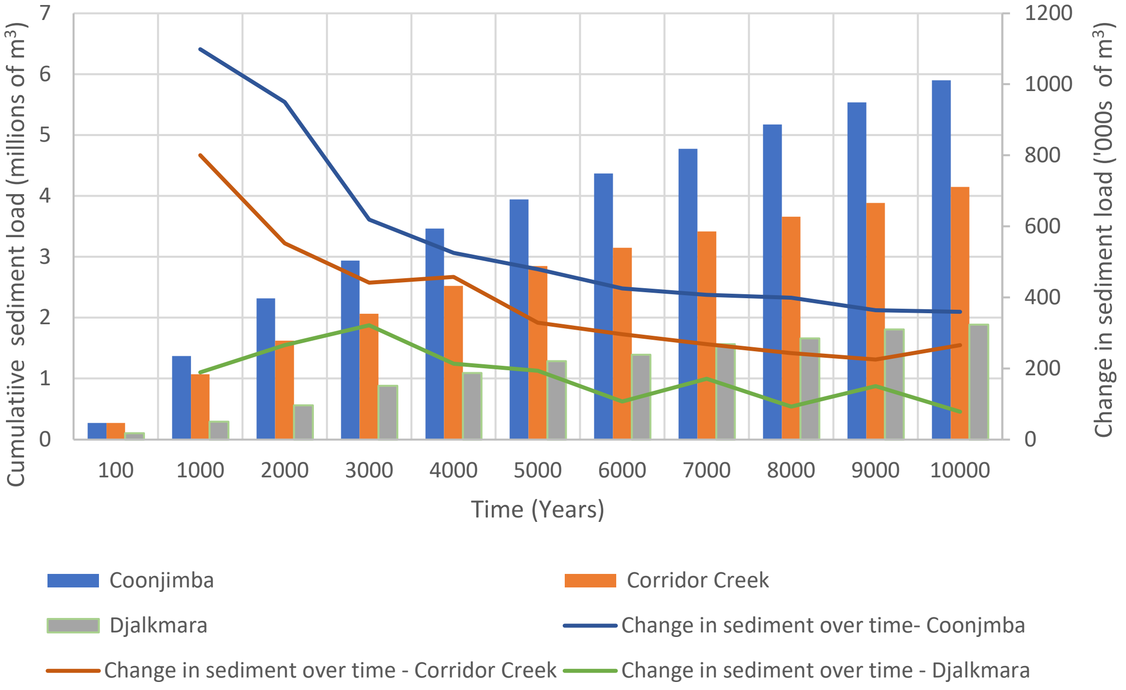


Figure 7 Predicted cumulative total sediment loads for each catchment

4 Discussion

It is important to acknowledge that none of the model scenarios presented here incorporated an erosion-resistant or bedrock layer in the simulation parameters. Recent model simulations incorporating an erosion resistant subsurface layer (Supervising Scientist 2023) found that predicted gully depths across the former mine pit areas were consistently less than those simulations in which such a layer was absent. It is also important to recognise that the absence of an erosion-resistant layer (information for which was not available at the time of publication), combined with the extreme rainfall scenarios modelled here, have resulted in predictions of gully depth that exceed the depths of any gullies known or observed to have occurred in the surrounding landforms that comprise the Koolpinyah surface. The accuracy of the predicted depths is further confounded by the relatively coarse (10 m) resolution of the DEMs used to represent the landforms in the simulations. Consequently, model predictions of gully depth shown in this study are for the relative comparative purposes of hypothetical worst-case scenarios. It is also important to note that the landform modelled here did not include the presence of sediment control structures, which may reduce the amounts of erosion and sediment predicted to be produced by the landform under extreme rainfall scenarios.

The results presented in Figure 3 show that the addition of the extreme rainfall events to the existing wet rainfall scenario dataset result in greater gully depths, and increased sediment loads and denudation rates for each simulation. For example, Simulation 17, which incorporated five extreme rainfall events including three in the first 10 years, is predicted to produce the deepest gully, one of the largest sediment loads and the highest denudation rates. In contrast, Simulation 6, which utilised the original wet rainfall dataset without the addition of local extreme rainfall data, produced the shallowest gully, and lower sediment loads and denudation rates than all other simulations in which the extreme rainfall events were present. Similarly, Simulation 8, the dry rainfall scenario with no extreme wet rainfall events, generated lower gully depths, sediment loads and denudation rates than all other scenarios modelled.

However, the results of all simulations for all catchments were similar in that they all predicted that denudation rates would decline exponentially over the 10,000-year period (Figure 6). Specifically, all simulations initially produced high sediment loads which reduced by at least an order of magnitude within a simulated period of 100 years. The predicted trend of a rapid decrease in denudation corresponds with a steep decrease in measured denudation over a six-year period observed on the Ranger trial landform (Saynor & Erskine 2016). In addition, all of the simulations applied to the three catchments returned a denudation rate that was higher than the regional background denudation rate of 0.075 ± 0.013 mm yr^{-1} (Wasson et al. 2021) within a simulated period of 100 years. However, after a simulated period of 2,000 years, Simulation 18 applied to the Djalkmara catchment produced a denudation rate of 0.09 mm yr^{-1}, which approached the background denudation rate.

While varying parameters such as the sediment transport equation, and the presence or absence of vegetation, had an impact on the sediment load and denudation rate, it was notable that those simulations in which more extreme rainfall events were timed to occur in the first 30 years resulted in greater sediment loads and denudation rates overall in each of the catchments. It is also worth noting that while we have compared our rates of long-term erosion and denudation to those recorded for the region, our values for total sediment load are from simulated extreme rainfall events which were not used in the calculation of the regional background denudation rate by Wasson et al. (2021). Consequently, denudation rates predicted by the scenarios modelled here are presented along with the background rate by Wasson et al. (2021) for indicative/reference purposes only.

5 Conclusion

The application of the CAESAR-Lisflood LEM to 10,000 year simulations of the Ranger landform that incorporate extreme rainfall events has produced results that differ from earlier simulations without the extreme rainfall events. Specifically, the inclusion of the extreme rainfall events is predicted to increase the depth of gullying in all the catchments modelled.

With the caveat that the simulations modelled here did not include an erosion-resistant subsurface layer, or erosion control structures, model predictions for 10,000 years that incorporate the extreme rainfall dataset show:

- Larger gullies are predicted to form across Pit 1 than in earlier 10,000-year simulations run without the extreme rainfall dataset.
- Extensive gullying is predicted to form across the Coonjimba catchment, including the area occupied by the former TSF.
- Tailings are unlikely to be exposed by gully erosion in Pit 3.

Only the Djalkmara catchment is predicted to produce a denudation rate under an extreme rainfall scenario that matches the background denudation rate produced without extreme rainfall within a period of 10,000 years. The Coonjimba and Corridor Creek catchments are on a trajectory to eventually meet background denudation rates.

To provide a realistic assessment of the impact of extreme rainfall events, further modelling incorporating a subsurface layer and erosion-mitigating controls is needed. At the same time, the model results also indicate areas of the landform that are susceptible to erosion, which should be considered in any revisions to enhance future landform designs. Encouragingly, model predictions indicate that one catchment on the landform (Djalkmara) is on track to meet the environmental requirements for closure, even under an extreme rainfall, worst-case scenario.

Acknowledgment

The authors wish to acknowledge ERA for their assistance with access to the study site.

References

Australian Government 1999, *Environmental Requirements of the Commonwealth of Australia for the Operation of the Ranger Uranium Mine, Australian Government Department of the Environment and Heritage*, viewed 12 January 2018, http://www.environment.gov.au/science/supervising-scientist/publications/environmental-requirements-ranger-uranium-mine

Commonwealth Scientific and Industrial Research Organisation 2007, *Climate Change in Australia: Technical Report 2007*.

Coulthard, TJ 2019, *Final Report for the Supervising Scientist Branch, Department of the Environment and Energy*, in fulfilment of Contract 3600001290 "CAESAR sensitivity analysis", unpublished report.

Coulthard, TJ, Neal, JC, Bates, PD, Ramirez, J, de Almeida, GAM & Hancock, GR 2013, 'Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution', *Earth Surface Processes and Landforms*, https://dx.doi.org/10.1002/esp.3478

East, TJ 1996, 'Landform evolution', in CM Finlayson & I von Oertzon (eds), *Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia*, Kluwer Academic Publishers, Dordrect, pp. 37–55.

Einstein, HA 1950, 'The bedload function for sediment transport in open channel flow', *Soil Conservation Technical Bulletin No 1026*, US Department of Agriculture, Washington DC.

ERA 2023a, *Ranger Mine Closure Plan 2023*, report prepared by ERA.

ERA 2023b, *Pit 3 Capping, Waste Disposal and Bulk Material Movement Application,* Volume 1 – Main Report, Reference CDM.03-1321-EY-APP-0003.

Hancock, GR, Saynor, M, Lowry, JBC & Erskine, WD 2020, 'How to account for particle size effects in a landscape evolution model when there is a wide range of particle sizes', *Environmental Modelling and Software*, vol. 124, https://doi.org/10.1016/j.envsoft.2019.104582

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.

Lowry, JBC, Coulthard, T & Hancock, GR 2013, 'Assessing the long-term geomorphic stability of a rehabilitated landform using the CAESAR-Lisflood landscape evolution model', in M Tibbett, AB Fourie & C Digby (eds), *Mine Closure 2013: Proceedings of the Eighth International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 611–624, https://doi.org/10.36487/ACG_rep/1352_51_Lowry

Lowry J, Hancock, G & Verdon-Kidd, D 2017, 'Assessing the geomorphic stability of a rehabilitated landform using climate change analogues', *Proceedings of Enviromine 2017: 5th International Seminar on Environmental Issues in Mining/4th International Conference on Social Responsibility in Mining*.

Lowry, JBC, Coulthard, TJ, Hancock, GR & Jones, DR 2011, 'Assessing soil erosion on a rehabilitated landform using the CAESAR landscape evolution model ©', in AB Fourie, M Tibbett & A Beersing (eds), *Mine Closure 2011: Proceedings of the Sixth International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 613–621, https://doi.org/10.36487/ACG_rep/1152_64_Lowry

Lowry, J, Coulthard, T, Saynor, M & Hancock, G 2020, *A Comparison of Landform Evolution Model Predictions with Multi-Year Observations From a Rehabilitated Landform*, Internal Report 663, Supervising Scientist, Darwin.

McQuade, CV, Arthur, JT & Butterworth, IJ 1996, 'Climate and hydrology', in CM Finlayson & I von Oertzen (eds), *Landscape and Vegetation of the Kakadu Region, Northern Australia*, 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.

Needham, RS 1988, 'Geology of the Alligator Rivers uranium field, Northern Territory', *Bulletin 224*, Australian Government Publishing Service, Canberra.

Saynor, MJ & Erskine, WD 2016, 'Bed load losses from experimental plots on a rehabilitated uranium mine in northern Australia', *Proceedings of Life of Mine Conference 2016*, Australian Institute of Mining and Metallurgy, Melbourne, pp 168–171.

Saynor, MJ, Lowry, J, Erskine, WD, Coulthard, T, Hancock, G, Jones, D & Lu, P, 2012, 'Assessing erosion and run-off performance of a trial rehabilitated mining landform', *Proceedings of Life of Mine Conference 2012*, Australian Institute of Mining and Metallurgy, Melbourne.

Supervising Scientist 2020, *Updated Assessment of the FLV6.2 Landform*, Technical Advice #022.

Supervising Scientist 2023, *An Improved Method for Modelling Erosion and Gully Formation on the Ranger Landform*, Technical Advice #063.

Verdon-Kidd, D & Hancock, G 2016, *Development of Synthetic Rainfall Datasets to Enable Long-Term Landform Modelling for Periods of up to 10,000 Years in the Alligator Rivers Region*, report prepared for the Department of the Environment by the University of Newcastle.

Wasson, RJ, Saynor, MJ & Lowry, JBC 2021, 'The natural denudation rate of the lowlands near the Ranger mine, Australia: a target for mine site rehabilitation', *Geomorphology*, vol. 389, 107823, https://doi.org/10.1016/j.geomorph.2021.107823

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