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A catchment-scale comparison of field observations of a constructed landform with erosion predictions from a landscape evolution model

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Abstract

Rehabilitation has commenced at the Ranger uranium mine in the Northern Territory of Australia. The Ranger rehabilitated landform is required to contain tailings material for a period of at least 10,000 years, and to produce erosion rates that eventually correspond with those of the surrounding undisturbed landscape. Landscape evolution models (LEMs) provide a means of predicting how a rehabilitated landform may evolve over extended periods of time. In this study, we utilised optical imagery acquired from remotely piloted aircraft (RPA), and ground-based observations to identify gully/drainage line development on the newly constructed Pit 1 landform over the period from 2020 to 2021. The Pit 1 landform encompasses an area of approximately 40 hectares and is the first part of the Ranger landform to be rehabilitated. We compare these observations with predictions from the CAESAR-Lisflood LEM of gully development over the same 12-month period. This work builds on earlier work undertaken to calibrate the CAESAR-Lisflood model at an erosion plot scale on the Ranger mine and applies it at a larger spatial scale. Over the one-year period, the model was able to predict the development of drainage lines in similar places to those observed via imagery and on-ground observations on the constructed Pit 1 landform. While acknowledging the limitations of a study of only 12 months duration, the results here provide confidence that the parameters used in the model are appropriate for predicting gully erosion at the larger catchment scale of this study, and that the results are relevant for extended time periods.

Keywords: *erosion, landform, modelling, drones*

1 Introduction

Processing and milling of stockpiled ore at the Energy Resources of Australia (ERA) Ranger uranium mine in the Northern Territory of Australia ceased in 2021. Rehabilitation of the mine site has commenced and is currently due to be complete by 2026. The unique location of the mine site – 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) – has meant that special consideration has been required for the development of closure criteria and rehabilitation plans for the mine. The Australian Government, through the Supervising Scientist Branch (SSB) of the Commonwealth Department of Climate Change, Energy, the Environment and Water, has recently developed a series of Rehabilitation Standards (http://www.environment.gov.au/science/supervising-scientist/publications/ss-rehabilitation-standards) to ensure a high level of environmental protection to the post-mining environment. Specifically, the standards quantify, based on the best available science, the values that will ensure a high level of environmental protection. These values can in turn be used to assess the achievement of, or progress towards, the rehabilitation objectives.

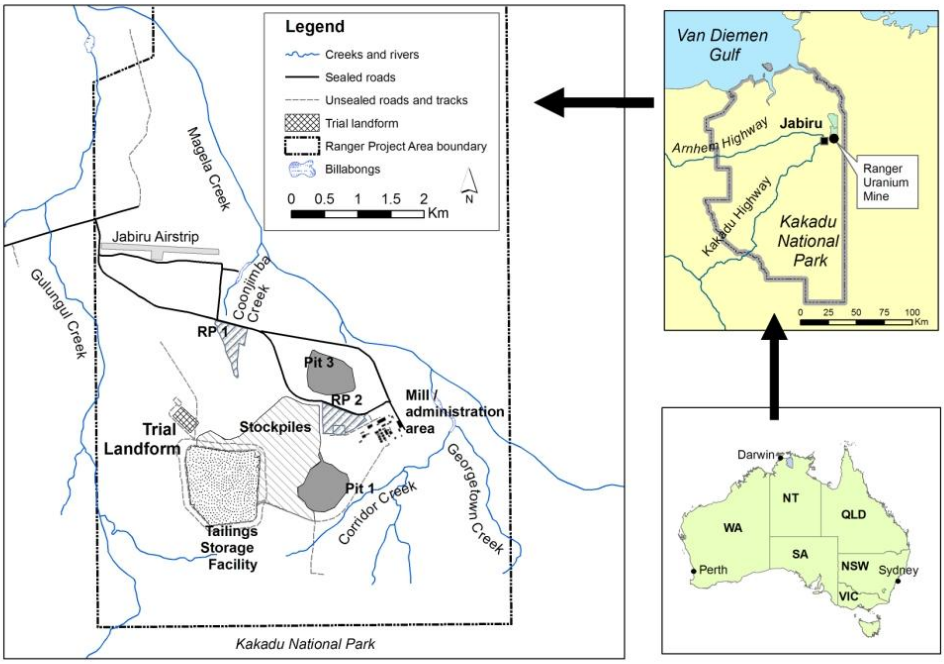


Figure 1 Location of the Ranger mine

The environmental requirements for the closure of the Ranger mine (Supervising Scientist Division 1999) have two key requirements relating to erosion and landform stability: (1) the ability to ensure the isolation of mine tailings for a period of up to 10,000 years, and (2) ensuring the erosion characteristics are similar to surrounding comparable landforms, thereby ensuring landform stability.

Landscape evolution models (LEMs) provide a means of predicting how a rehabilitated landform may evolve over extended periods of time. Here, we apply the CAESAR-Lisflood LEM to a 40-hectare area centred on Pit 1, which is the first part of the Ranger landform to be rehabilitated.

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 modified to study the evolution of proposed rehabilitated mine landforms in northern Australia (Hancock et al. 2010; Lowry et al. 2011, 2013; Saynor et al. 2012). A key attribute of the CAESAR-Lisflood model, in terms of assessing landform stability, is the ability to utilise rainfall data to model the effects of specific rainfall events. Event modelling is particularly relevant to this study, as the climatic region in which the Ranger mine occurs is dominated by seasonal, high-intensity rainfall events (McQuade et al. 1996) and it is recognised that most erosion in the study area typically occurs during a limited number of high-intensity events (Moliere et al. 2002). Consequently, the ability to model specific rainfall events meant that the CAESAR-Lisflood model was the model of choice for this project.

The CAESAR-Lisflood model has been extensively tested and calibrated using data collected from erosion plots (900 m^2) on the Ranger trial landform for multiple years (Lowry et al. 2014, 2020; Saynor et al. 2019). However, it has not been possible to compare model predictions with field observations for areas greater than the erosion plots. Here, we compare model predictions of gully development and landform evolution with field observations from the newly rehabilitated 40-hectare surface of Pit 1. Uranium ore was formerly extracted from Pit 1, and since then the pit has been backfilled, and prior to the 2020–2021 wet season, covered with waste rock and scarified to a depth of 10 cm.

2 Methods

Here we assess the ability of CAESAR-Lisflood to provide predictions of landform evolution and erosion that are realistic for the recently rehabilitated Pit 1 landform (Figure 2). This was achieved by comparing model predictions of erosion and gully development over a simulated 12-month period with observations and measurements for the same period from ground-based surveys and remotely piloted aircraft (RPA) equipped with high-resolution cameras.

Figure 2 Aerial mosaic from 2020 of Ranger mine. Rehabilitated Pit 1 landform highlighted in red

2.1 Application of the CAESAR-Lisflood model

In this study, CAESAR-Lisflood (Version 1.9j) was used to simulate the evolution of the Pit 1 landform. CAESAR-Lisflood allows users to select between one of three different sediment transport equations for use in each simulation. In this study, we used the Wilcock & Crowe (2003) sediment transport equation.

CAESAR-Lisflood requires three key data inputs:

- A digital elevation model (DEM).
- Rainfall data.
- Surface particle size distribution data.

The DEM of the Pit 1 surface that was used as the input for model simulations was produced from aerial photography captured by a DJI Phantom on the 26 October 2020, and generated to a horizontal resolution of 1 m. The date of DEM capture was closest to the start of the rainfall record used in model simulations. The DEMs were processed using ArcGIS software to ensure that the DEMs were pit-filled and hydrologically corrected. Pit filling is an important part of the process in order to remove data artefacts, such as temporary construction infrastructure (peaks) as well as artificial depressions, or sinks. We recognise that pit filling itself may have a prejudicial influence on the modelled sediment yields, as discussed by Temme et al. (2006).

Rainfall data has been intermittently recorded on Pit 1. However, this study utilised rainfall data collated at 10-minute intervals on the Ranger trial landform, some 200 m west of Pit 1, as it provided a continuous rainfall record for the period of study. Specifically, rainfall for the 2020–2021 rainfall year was utilised, with the rainfall year defined as the period between 1 September through to 31 August of the following year.

Using the process described in Hancock et al. (2020), the grain size data for CAESAR-Lisflood were obtained through the application of a grid-by-number method of the waste rock on the trial landform, which was intended to be representative of the surface of Pit 1. Grain size analysis was completed on these samples and the results averaged into nine grain size classes (Figure 3), which were used for input into CAESAR-Lisflood. The sub 0.00063 m (i.e. 63 µm) fraction is treated as suspended sediment within CAESAR-Lisflood.

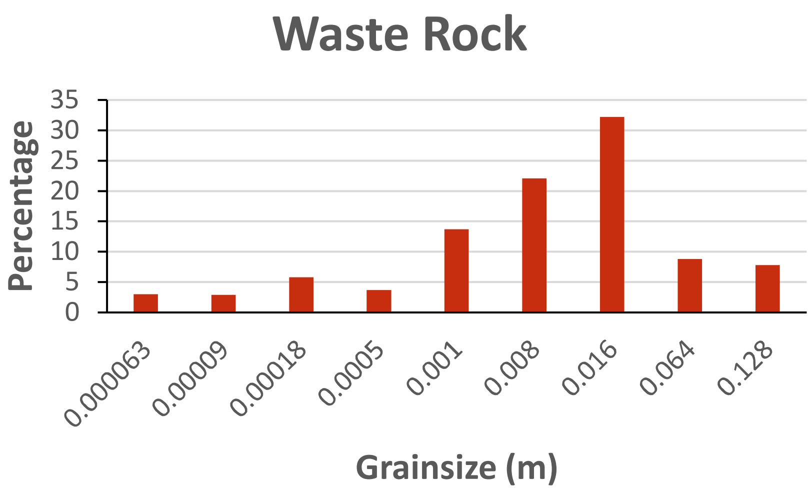


Figure 3 Grain size distribution of the waste rock on the surface of the trial landform

2.2 Field observation

Monthly site inspections of the Pit 1 landform were conducted by staff from SSB, commencing from October 2020. As part of the inspection, staff recorded the position of gully erosion features with photographs and noted any visible changes that had occurred to the surface of the Pit 1 landform since the previous visit.

2.3 Aerial surveys from RPA

Aerial surveys were undertaken at regular intervals with camera-equipped DJI Phantom 4 Pro V2.0 RPA (Figure 4). Flights were flown at an altitude of 80 m and speed of 5 m/s as a series of predetermined latitudinal flight lines above the pit surface. These were used to generate high-resolution (20 cm) orthomosaic images and DEMs of the pit surface.

Figure 4 DJI Phantom on Pit 1 surface

In the study, imagery captured by DJI Phantom flights on the 26 October 2020 were used as the initial DEM for input to the CAESAR model and as a reference of the pre-gully landform. Imagery captured by DJI Phantom flights on 10 February 2021 was used for comparison purposes of the post-gully landform. Image mosaics were processed using Pix4d software, while DEMs were generated from photogrammetric point clouds using CloudCompare software.

For the purposes of this study, the DEMs were resampled to a horizontal resolution of 1 m, to ensure they were of the same resolution used in the application of the CAESAR-Lisflood model. In addition, the DEMs were referenced against the Geocentric Datum of Australia 1994 and rectified to the same geoid and height datum (in this case, the Australian Height Datum) to ensure that the two DEMs could be compared.

3 Results

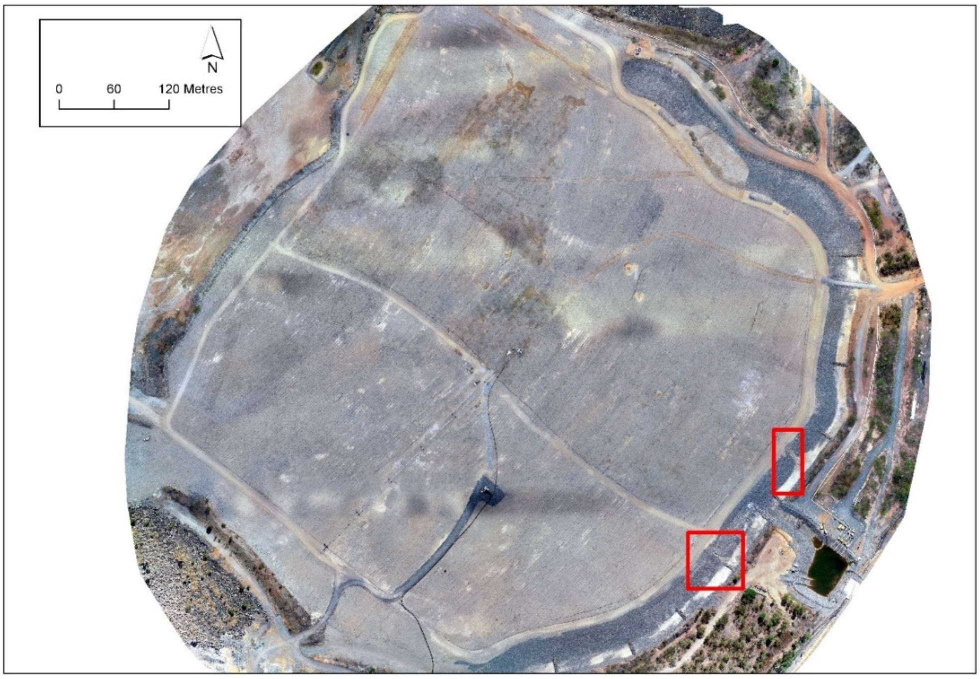
Gullying on the edge of the newly constructed rehabilitated surface of Pit 1 was first observed through routine ground-based site inspection in February 2021 after a series of rainfall events, in which 95 mm fell over the period from 4 to 6 February (Figure 5). Specifically, gullies were observed to have formed in two locations on the edge of the landform on 8 February. Prior to this rainfall event, gullies had not been detected on the landform.

(a)

(b)

Figure 5 (a) Gully 1 observed during field visit 10 February 2021; (b) Gully 2

An aerial survey of Pit 1 was conducted on 10 February using a Phantom 4 Pro V2.0. Analysis of the aerial imagery confirmed the presence and location of the two gullies on the edge of the Pit 1 landform (Figure 6). No additional gullies were identified from the imagery.



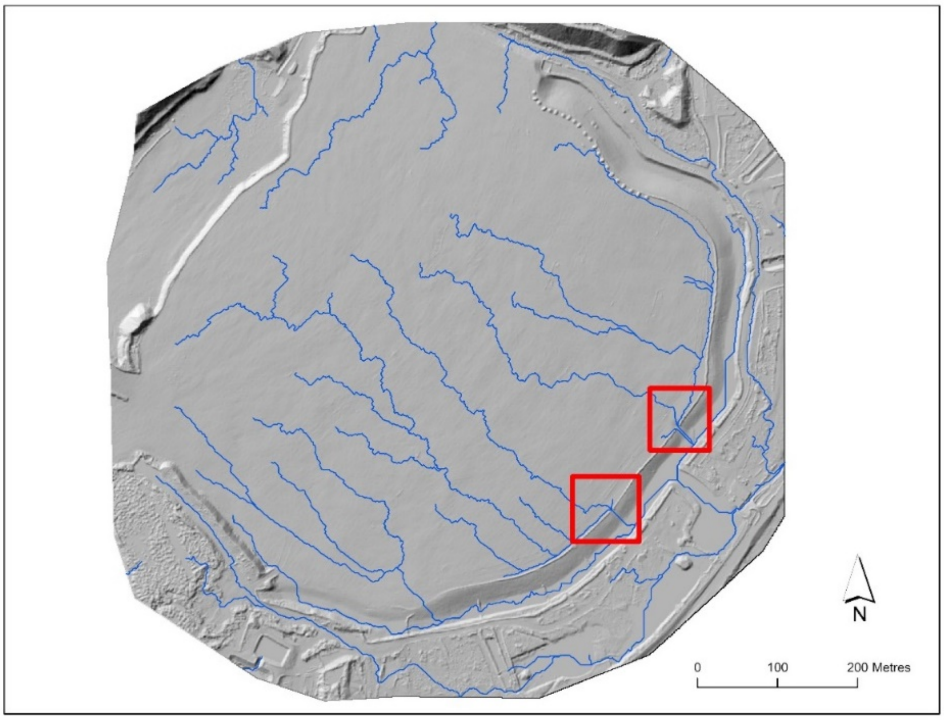
(a)

(b)

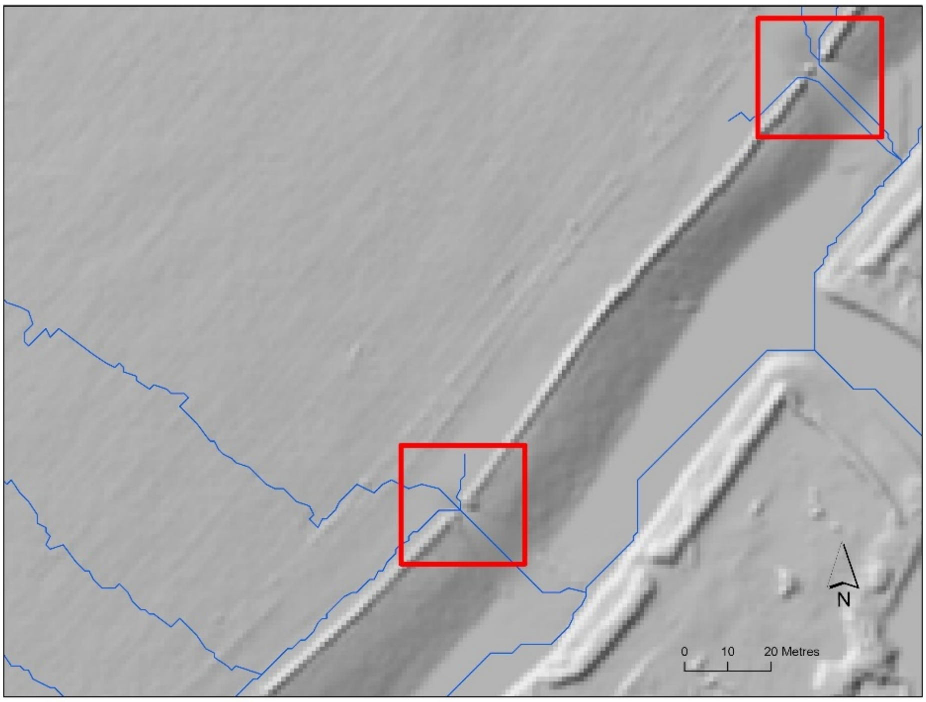
Figure 6 (a) Location of two gullies (in red boxes) observed from 10 February 2021 flight: Gully 1 in box on right and Gully 2 in box on the left; (b) Enlargement of area

Ongoing aerial and ground-based monitoring of Pit 1 identified that no additional gullies were formed in the remainder of the rainfall year up to 31 August 2021. It is important to note that in July 2021 ERA undertook maintenance works on the landform, which resulted in the gullies being filled in.

Model simulations using the CAESAR-Lisflood LEM were run for a simulated period of 12 months utilising rainfall data collected for the 2020–2021 rainfall year. The simulations predicted two gullies to occur on the surface of Pit 1 in the same time period and in the same area on the landform (Figure 7), as observed from the drone flights (Figure 6).



(a)



(b)

Figure 7 (a) Model predictions of gullies (red boxes) and drainage network (blue lines): Gully 1 in box on the right and Gully 2 in box on the left; (b) Enlargement of gully area

A cross-section through the predicted gullies shows them to be in a similar location and of a similar depth as those detected and measured from the drone flights (Figure 8).

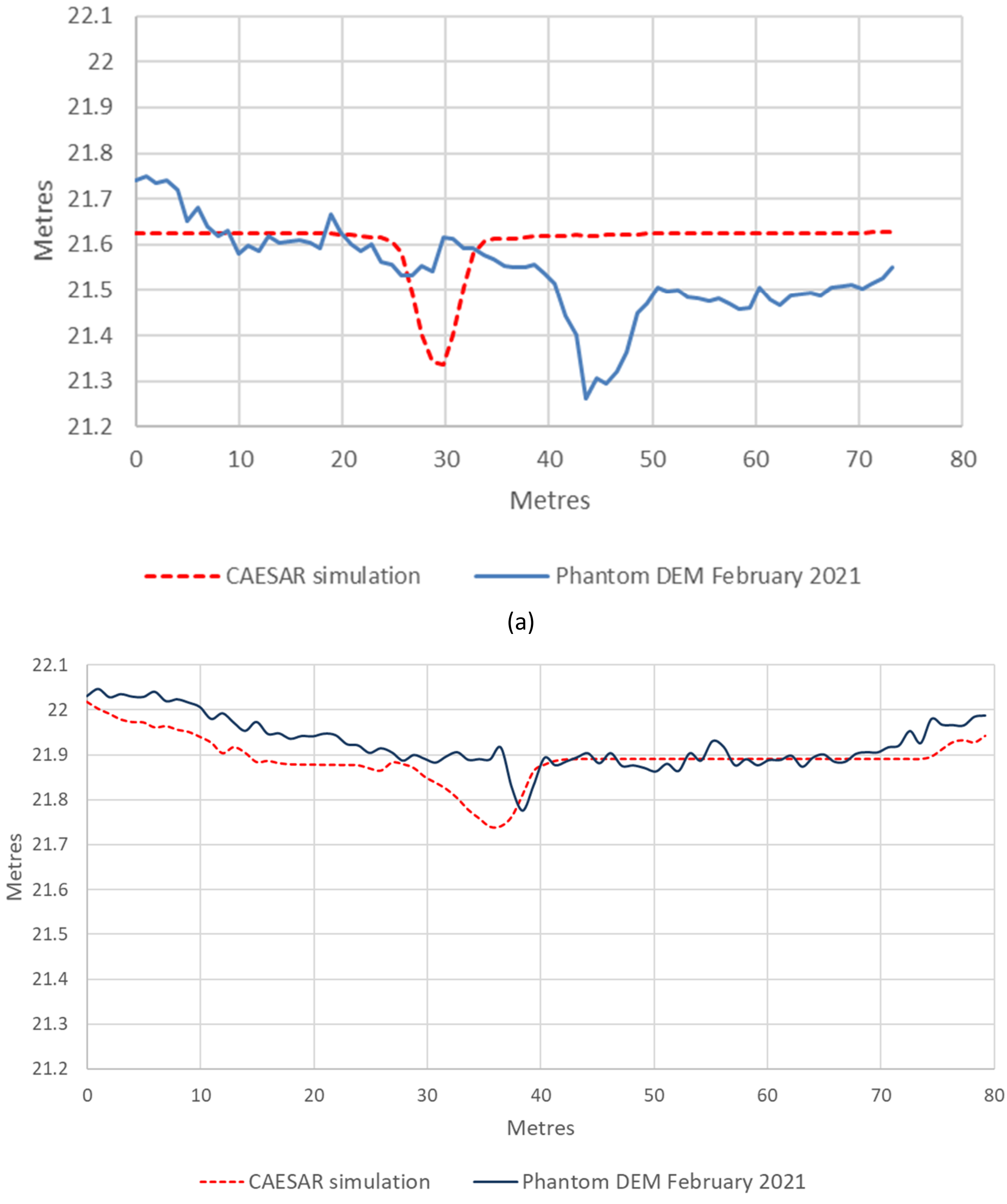


Figure 8 Comparison of cross-sections of gullies of DEM from model and RPA. (a) Gully 1; (b) Gully 2

Model simulations by CAESAR-Lisflood predict that a total sediment load of 83 m^3 would be eroded/moved from the surface of the Pit 1 landform (which includes the two gullies detected here) in a 12-month period. This equates to a surface denudation rate of 0.12 mm yr^{-1}.

4 Discussion and conclusion

The objective of this study was to assess the ability of the CAESAR-Lisflood LEM model to predict gully development and landform evolution from a rehabilitated landform when compared to observed erosion locations.

The results here demonstrate that the model can successfully predict the development of gullies on the surface of a rehabilitated surface (in this case, Pit 1) over the space of one year. Importantly, the model correctly predicts:

- That gullies ***will*** occur on the pit surface as it was constructed in 2020.
- The area ***where*** gullies are likely to occur.
- ***When*** gully initiation (development) is likely to occur.

Specifically, in this study, the CAESAR-Lisflood LEM predicted the development of two gullies that occurred at the same simulated time of year and in the same location as two gullies that were observed to have actually physically formed on the surface of Pit 1. This demonstrates that the model and the key inputs used – the DEM representing the surface of the landform, the rainfall, and the soil particle size distribution – were able to successfully predict erosion on the landform.

However, we acknowledge there are several limitations and caveats with this study. First, we recognise that a 12-month period does not represent the full range of climatic or environmental factors that will be present in the longer term that may influence landform development over 10,000 years. While model results match observations from an unvegetated surface, as vegetation communities had not been established in the first year of rehabilitation, we acknowledge vegetation parameters will need to be incorporated into longer term simulations to reflect the effect of revegetation on the landform. We believe the slight differences in the location between the predicted and observed gullies may be due to:

- The use of different ground control point locations to register the aerial photography that was used to generate the mosaics and DEMs used in this study in 2020 and 2021.
- The time of day that the drones were flown, with shadows impacting slightly on DEM interpolation.

We acknowledge that the requirements of the CAESAR-Lisflood model meant that the input DEM used at the commencement of modelling was a simplified representation of the pit surface. This needs to be accounted for in any comparison between model outputs, and DEMs of the pit surface derived from RPA over time and is an important factor as the surface condition or roughness can have a significant impact on model outcomes (Hancock et al. 2016). We also recognise that over the period of this study, maintenance and other construction activities on the landform was undertaken that resulted in change to the pit surface that the model could not be expected to simulate, such as the infilling of the gullies within 12 months. The model results therefore represent how an idealised landform may be expected to evolve over 12 months. Importantly, a first-order drainage network was observed to form across the pit surface, culminating in the formations of gullies on the pit edge, that the model was able to replicate.

As identified in the sensitivity analysis of the CAESAR-Lisflood model by Coulthard (2019), the choice of sediment transport equation and the particles size classes applied were essential in ensuring that model outputs best represented the actual erosion and gully features that occurred on the landform.

It was not possible to quantify the amount of sediment that was predicted to be eroded by the model against measured observations of sediment loss, as the landform was not equipped with instruments or monitoring points to measure sediment load or hydrology. Based on predicted sediment loads, a surface denudation rate of 0.12 mm yr^{-1} was derived. This is higher than the regional background denudation rate of 0.07 mm yr^{-1} (Wasson et al. 2021). However, this is not surprising, as it is expected that in the first years after rehabilitation, rates of denudation and erosion will be higher than those of the background.

Further data will need to be collected to determine if the denudation rate will decline to meet the environmental requirements.

Importantly, this is the first time model predictions have been assessed at this scale over a period of 12 months. Earlier work undertaken to test and calibrate the CAESAR-Lisflood model at the trial landform scale has enabled the model to be successfully applied to predict the movement of sediment and the development of gully features over a larger geographic scale on the surface of Pit 1. Further work, including monitoring and longer-term simulations of the Pit 1 surface is continuing. This will provide confidence that the model will be able to successfully simulate the long-term evolution of the whole rehabilitated landform.

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