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Predicting the long-term erosional stability of valley fill tailings dams using a computer-based landscape evolution model

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Abstract

Tailings are commonly stored in 'tailings dams' where the particulate component can settle out and such dams are a feature of many mine sites. As they impound water and sediment, tailings dams can be at risk from both catastrophic and gradual failure, especially if unmanaged. Therefore, in many post-mining landscapes, tailings dams will be permanent features. A fundamental question for their management is, can tailings dams ever be walk-away structures? Catastrophic failure occurs when there is a large-scale rapid structural failure of the dam wall suddenly releasing large quantities of water and sediment. Further, over time, there will be the increased risk of gradual failure by the slow infilling of the dam and the erosion of the dam wall. This occurs where water overtops the dam wall and then incises through the wall due to a loss of freeboard in the dam, a situation which is more likely in legacy tailings dams where they have been filled, vegetated and abandoned. This work demonstrates how a computer-based landscape evolution model (CAESAR-Lisflood) can be used to assess a hypothetical tailings dam failure risk for the gradual failure situation. Using a conceptual setting, our findings demonstrate that given average climate conditions, a dam can be sufficiently robust to last centuries. CAESAR-Lisflood also can model runoff and here the assessment includes modelling of water quality both during mine operation and post-breach. Tailings can be contained if there is maintenance and/or an increase in the dam wall height over time or a more robust dam wall constructed to manage extreme events. However, erosion and infill will continue to reduce the integrity of a more robust structure over time. Therefore, it is highly likely that tailings dams will require continued monitoring and maintenance.

Keywords: *CAESAR-Lisflood, mine closure, dam closure, environmental risk, water quality*

1 Introduction

Tailings are commonly emplaced in 'tailings dams' and such dams are a feature of many mine sites. Tailings dams exist in many forms and configurations but typically are either 'standalone' structures with a dam wall or bund created around their perimeter, or a 'valley fill' dam (Armstrong et al. 2019; Dibike et al. 2018; Dong et al. 2020; Edraki et al. 2014; Hancock 2021; Kossoff et al. 2014; Mahdi et al. 2020; Oberle et al. 2020; ICOLD 2001; Rana et al. 2021; Slingerland et al. 2022).

Tailings dams are considered to have similar risk to that of water storage dams, with seismic, geotechnical, construction, hydrological (extreme rainfall) and erosional induced failure concerns (www.ancold.org.au). However, a significant additional issue with tailings dams is the potential release of contaminated water and contaminated sediment that can travel downstream large distances (Oberle et al. 2020). Over 350 recorded tailings dam failures have occurred globally since the early 1960s (www.wise-uranium.org/mdaf.html). These failures have major impacts on catchments downstream, causing damage to ecosystems and communities, loss of life, erosion and tailings deposition (Kossoff et al. 2014).

However, in addition to catastrophic failure, mine tailings dams are vulnerable over longer timescales to slower-acting geomorphic processes, including slope erosion and the infilling and re-working by fluvial action. For the majority of post-mining landscapes, tailings dams will become new and permanent features (McKenna & Van Zyl 2020; Schafer et al. 2018; Slingerland et al. 2018) that are geomorphically different (and newer) to that of the surrounding older and undisturbed landscape. They may, for example, have higher slope angles than the surrounding landscape, increasing local erosion rates, or disturb or disrupt pre-existing channel networks and drainage lines (e.g. valley fill tailings dams). Some research suggests that tailings dam may be considered stable, where the risk of failure is equivalent to that of a natural analogue (Canadian Dam Association 2014).

However, every dam has a design life. Some have suggested a design life of 1,000 years (McKenna & Van Zyl 2020; Schafer et al. 2018; Slingerland et al. 2018). Some mines employ scenarios of 10,000 years (i.e. uranium tailings encapsulation) (Supervising Scientist 2021). Others suggest that tailings dams have an indefinite life (i.e. forever) (McKenna & Van Zyl 2020; Rico et al. 2008). Regardless of legislation, following closure, tailings dams will be subject to erosional forces (Schafer et al. 2018) and therefore affected by drivers such as changes in the climate, land use and/or vegetation. Therefore, to account for future environmental change, erosion of dam walls will need to be managed, requiring design assessment procedures of the whole landscape, including erosional stability.

Previous assessments of tailings dams employing computer-based landscape evolution models (LEMs) examined designs using both experimental landscapes and theoretical designs (Hancock 2021; Hancock et al. 2003; Hancock & Willgoose 2003). They can provide guidance on long-term landscape behaviour, allowing designs (such as those of tailings dams) to be evaluated and improved.

Here we examine the long-term (centennial) erosional stability of a hypothetical valley fill tailings dam using numerical modelling. For modelling simplicity, we assume static parameters that do not account for any surface and subsurface change nor any surface cover (however, this can be accounted for in the modelling). We aim to (1) demonstrate the use of LEMs – here, the CAESAR-Lisflood model (Coulthard et al. 2013) – as a tool to better understand centennial timescale erosional stability of tailings dams and (2) provide a means of assessing downstream geomorphic and water quality impacts of tailings dams.

2 Methods

The study site is a hypothetical tailings dam digitally added to an existing small basin located in western Arnhem Land, northern Australia. The region has many operating mines and is highly prospective for a wide range of minerals. The site examined here has an average annual rainfall of approximately 1400 mm. Rainfall occurs in the wet season (November to April). High-intensity, short-duration storms are common, with fluvial erosion the primary erosion process.

The study site is tectonically inactive. The natural surrounding area consists of closely dissected and short, steep slopes (10–100 m long), with slope between 15–50%. Soils are red loamy earths and shallow gravely loam. Vegetation is open dry sclerophyll forest (common to northern Australia) dominated by acacia and eucalypts with an understorey dominated by spear grass (*Heteropogon contortus* and *Sorghum* spp.). Erosion, hydrology and erosion modelling data exists for the site, with reported erosion rates of 0.2 and 1.3 t ha^{-1} yr^{-1} (0.013–0.86 mm yr^{-1}) (Hancock & Lowry 2015; Moliere et al. 2002).

The hypothetical dam was located in a natural catchment suitable for dam construction (Figure 1). Total catchment area was approximately 30 ha. The dam wall was positioned at a site abutting the natural hillslope such that the dam wall length was minimised, while wall height was constructed for maximum storage volume. The dam wall was constructed of a compacted clay with a height of 10 m with an external slope of 25% and clad with natural soil and allowed to revegetate with local grass species. The final surface was assumed similar to the natural surrounds with similar roughness and hydraulic properties. The dam was designed to be filled with tailings to a depth of approximately 8 m at the dam wall, leaving approximately 2 m of freeboard. At this wall height and freeboard, the dam wall could contain a 1:100 probable maximum precipitation event.

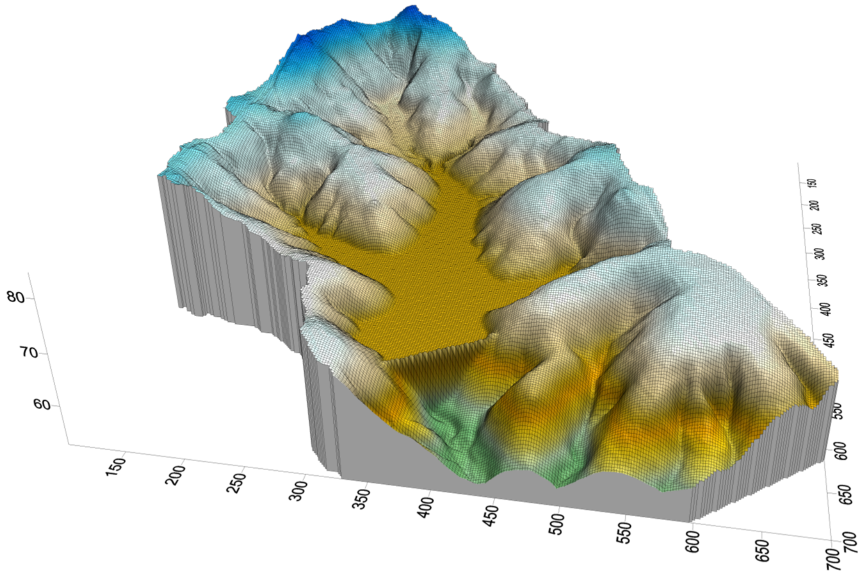


Figure 1 Hypothetical valley fill tailings dam. Dimensions are in metres

2.1 Landscape evolution models

CAESAR-Lisflood is a physically based landscape and river reach evolution model evolving from the CAESAR model developed by Coulthard et al. (2002). CAESAR-Lisflood employs the Lisflood-FP code of Bates et al. (2010), a hydrodynamic two-dimensional flow model. The work reported here uses version 1.9 g, and a full description can be found in Coulthard et al. (2013). The model simulates erosion and deposition at timescales from hours to 1,000s of years. CAESAR-Lisflood enables a user to input a digital elevation model (DEM) of the site of interest and employs hourly rainfall (pluviograph) data to drive hydrology via TOPMODEL (Beven & Kirkby 1979).

An advantage of CAESAR-Lisflood over other models is in its utilisation of rainfall at hourly time intervals. This allows different rainfall time series to be input. Surface runoff generated from rainfall is routed using the Lisflood-FP code. This calculates flow between cells using the slope of the water surface and local inertia, employing one-dimensional flow models in both X and Y directions. This creates a two-dimensional flow field from which shear stress is determined and then calculates sediment entrainment via either Wilcock and Crowe or Einstein sediment transport models (the user can choose). Sediment is then routed based on velocity, with both sediment with water flow directed and deposited based on settling velocity.

Sediment transport can be determined for a range of (up to) nine grain sizes. These are a series of layers and are fixed from the start (Coulthard et al. 2013). This functionality allows development of differential surface particle size distribution (PSD) development of bed armouring and grainsize changes for depositional features, such as alluvial fans and channel bars. CAESAR-Lisflood can also employ a maximum of five individual particle size datasets (representing different surfaces) over the study domain. The PSD can be employed on a pixel-by-pixel basis.

2.2 CAESAR-Lisflood input parameters

CAESAR-Lisflood requires three major inputs: surface topography, as represented by a DEM; rainfall data (mm hr^{-1}); and material PSD data. These are described below.

The catchment topographic data was derived from LiDAR survey with a resolution of 1 m. The dam wall was placed at a position abutting both sides of the catchment, where dam volume could be maximised with a minimal footprint (Figure 1).

Here, we use previously published particle size data and hydrology parameters determined from field and previous model data for the site (Moliere et al. 2002).

A 23-year pluviograph rainfall record from 1972 to 2007 from Jabiru Airport, Northern Territory, Australia was employed. The 23-year record, the longest available for the region, contains a wide range of rainfall events and seasonal (annual) variability. The major event in the dataset was the 2006–2007 rainfall, which had the highest rainfall on record (2528 mm) (Moliere et al. 2008). This record total contains rainfall of 800 mm and 1140 mm, respectively, for February and March 2007. The record also contains low rainfall data, with January 2007 rainfall the lowest monthly total for January ever recorded. This 23-year rainfall record was modified for input into CAESAR, with two rainfall time series created. These were:

1. 22 years of rainfall (1972–2006). This dataset was termed the 'average' rainfall dataset. This represents average whole-year rainfall up until the 2006–2007 wet season (mean of 1431 mm yr^{-1} for the 22-year period). This data represents a typical design rainfall scenario, where average rainfall is assumed to represent long-term patterns.
2. 23-year rainfall record. This dataset was termed the 'complete' rainfall dataset and represents all the currently available whole year rainfall data (mean of 1463 mm yr^{-1} for the 23-year period). This dataset includes the 2006–2007 rainfall data.

To create a long-term rainfall record, the average and complete rainfall data were added end to end individually to produce a continuous 1,000-year rainfall record (i.e. the average and complete rainfall data described above was repeated end on end for 1,000 years).

2.3 Modelling set-up

CAESAR-Lisflood can spatially distribute different material particle sizes over the model domain. The model can distribute nine different particle sizes across the landscape. Here, natural (or undisturbed) particle size is employed on the natural hillslope, while for the tailings dam and material contained within a fine PSD is employed. The PSD for the tailings is a hypothetical distribution based on knowledge of tailings from other mine sites. Here, we define tailings as having a particle size of less than 0.25 mm.

Two model runs were performed using the DEM and PSD, as described:

1. Average rainfall time series.
2. Complete rainfall time series.

CAESAR-Lisflood was run for 1,000 years to assess both short and centennial timescale dam behaviour.

No maintenance of the dam wall or alteration of the DEM was undertaken for the duration of the model run. The tailings are assumed to be fully consolidated (i.e. no settlement) and dewatered.

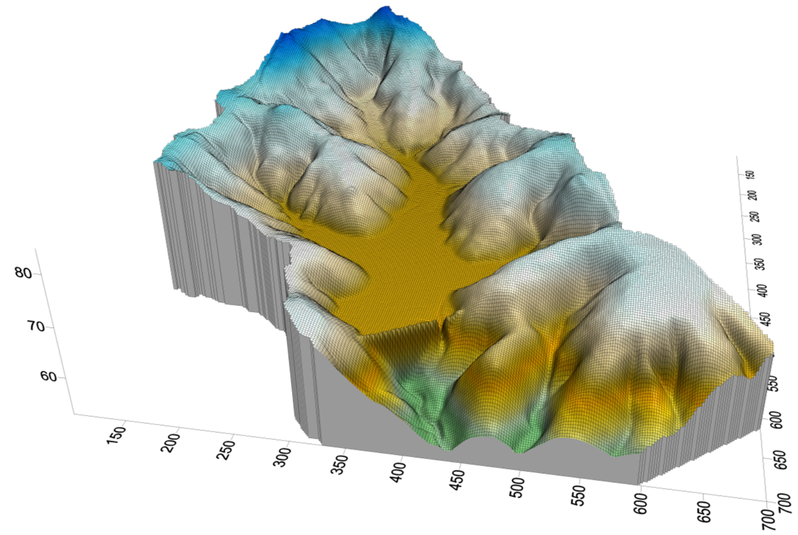
3 Results

3.1 Dam behaviour

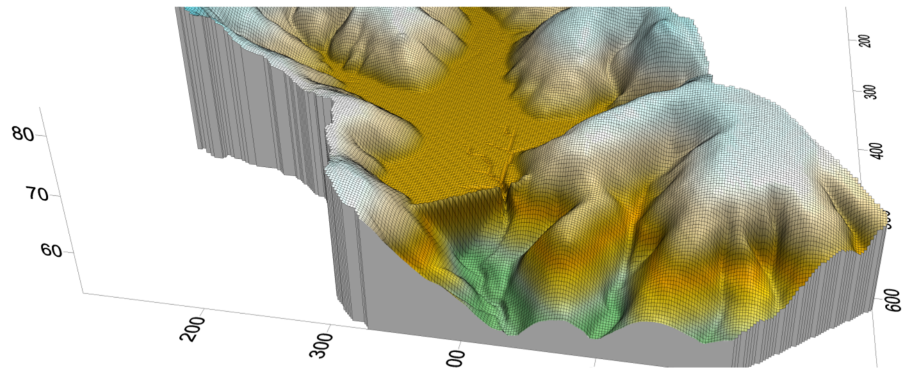
The dam wall remains intact for 247 years, employing average rainfall (Figure 2). Up until this time, the surrounding hillslope is eroding and delivering sediment to the dam on top of the tailings, together with mobilisation of the tailings in the dam itself with channels forming on the surface. At this time, the dam wall crest has lowered (eroded) by approximately 300 mm (200–300 mm along its length). Also, there is a build-up of sediment at the upstream base of the wall of approximately 150 mm (100–200 mm). This results in a loss of dam capacity and insufficient freeboard, and the dam wall overtops at a low point in the dam wall. Concentrated flow at this low point produces an incision that grows into a gully, which then exposes the tailings. The incision in the dam wall widens and the tailings begin to be mobilised and erode (Figure 2). A drainage network then develops in the tailings. The incision on the dam wall continues to increase in size, albeit slowly, in response to the water and sediment flux. A drainage network grows headwards and, over time, expands to fill the tailings area (Figure 3). There were no further failures of the wall as the evolving drainage network ensured that all water and sediment were channelled through the breach. Hydrologically, all runoff is contained within the dam pre-breach, while post-breach runoff is directed by the evolving channel network (Figure 4).

Sediment loads exiting the catchment are low until the dam wall fails (Figure 5). Once breached, annual sediment loads increase by several orders of magnitude and remain high for the duration of the model run.

Average denudation rate pre-dam breach is 0.022 mm yr^{-1} (0.33 t ha^{-1} yr^{-1}), which is within the range measured for the surrounding natural environment (0.013–0.86 mm yr^{-1}). This demonstrates the model is producing an erosion rate commensurate with measured background. While qualitative, this provides confidence in the model and its parameterisation.



(a)



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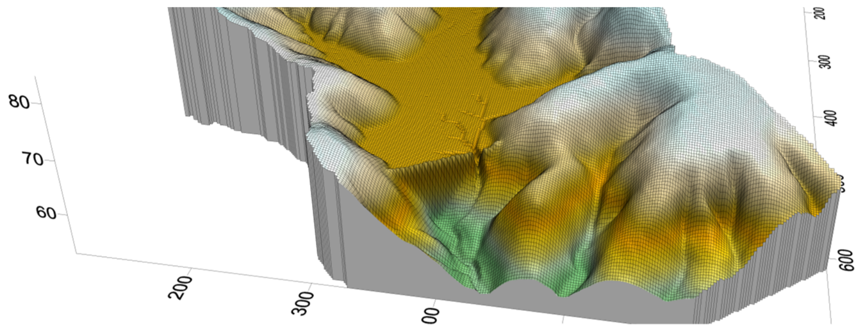


(c)

Figure 2 Hypothetical valley fill tailings dam immediately after dam wall failure at (a) Year 247; (b) Year 248; (c) Year 249. All dimensions are in metres

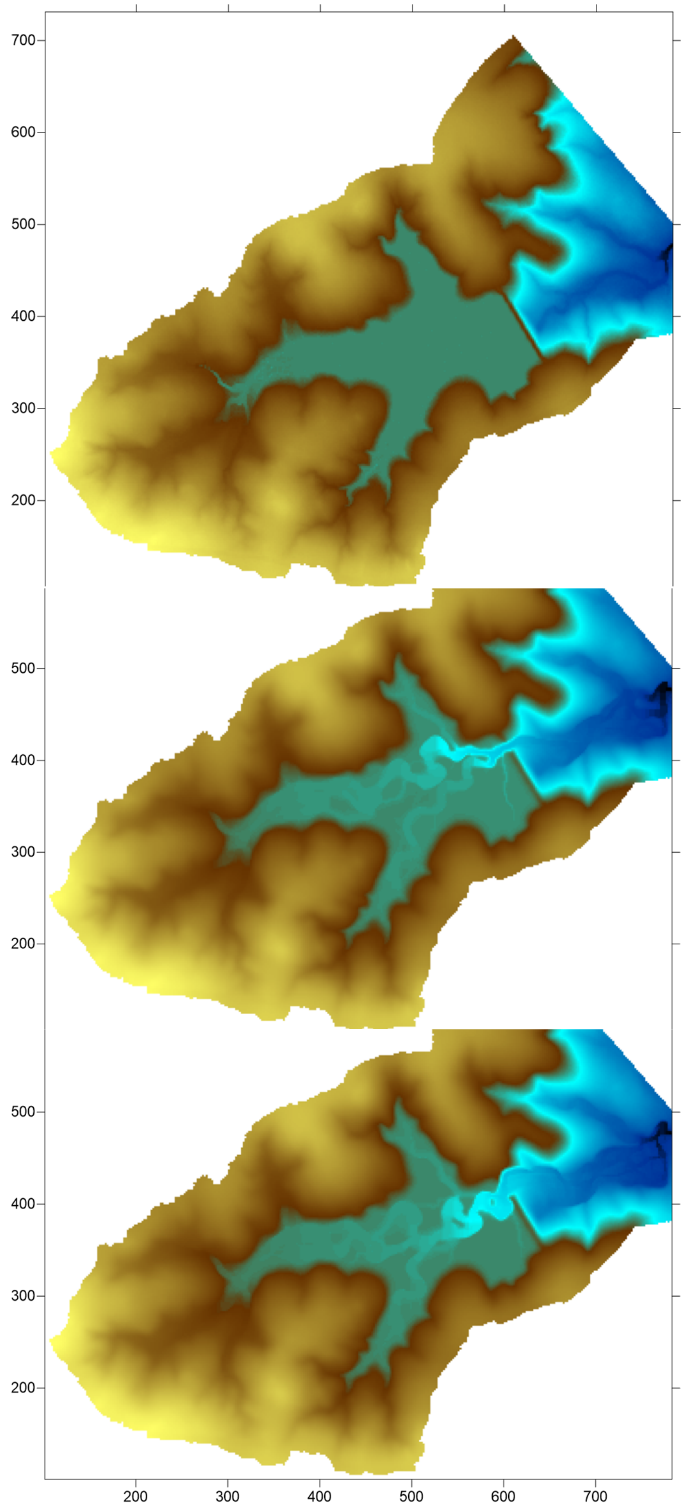
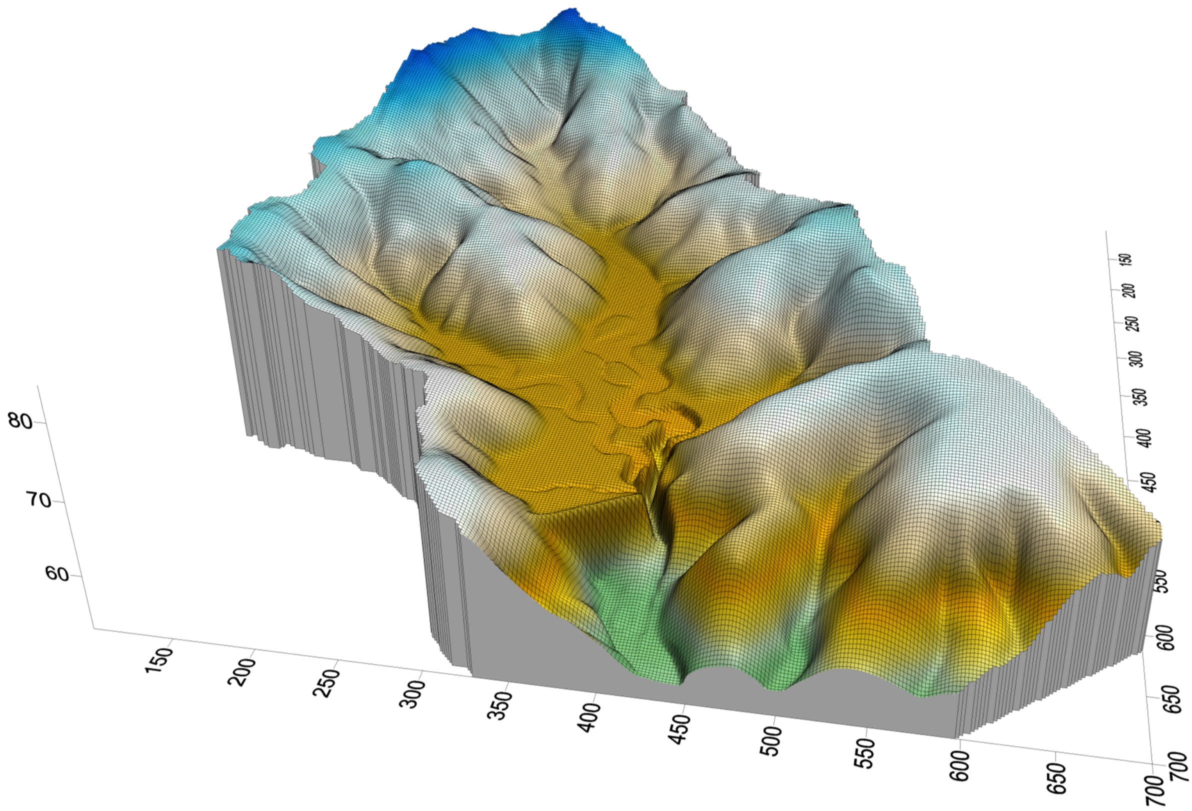
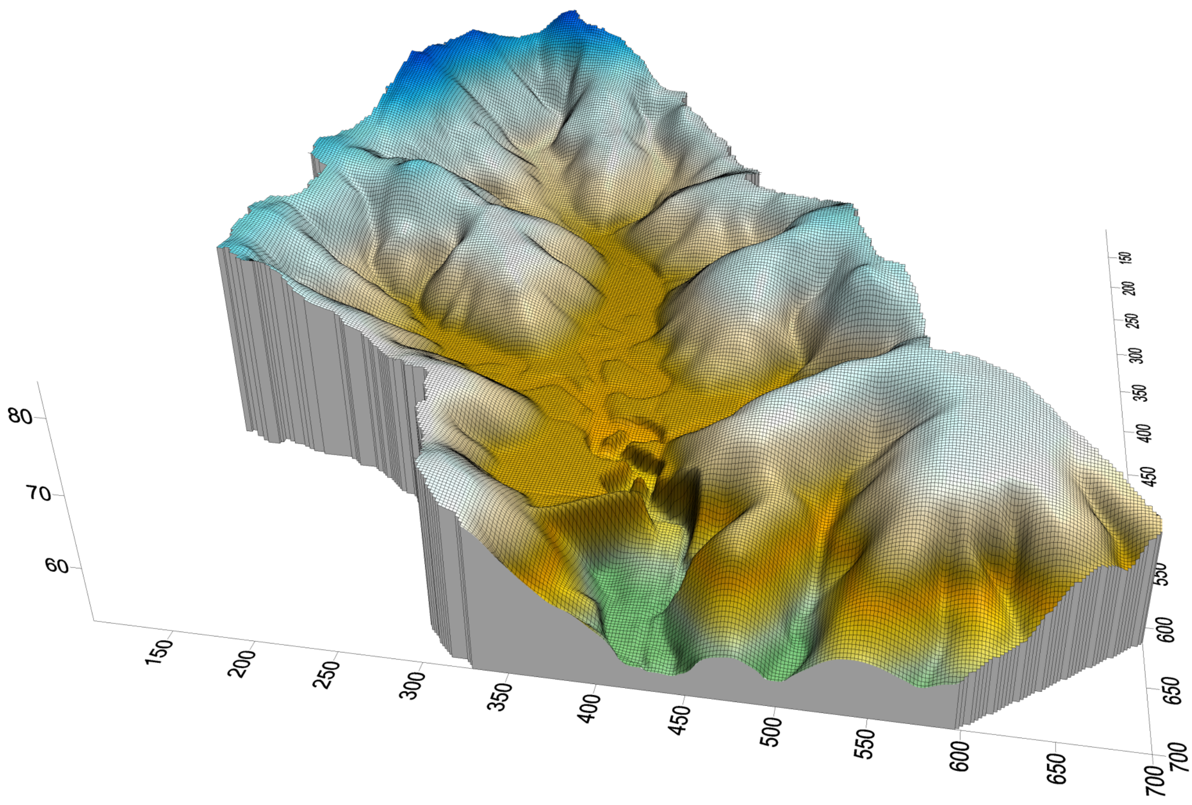


Figure 3 Hypothetical tailings dam at 10 years (pre-dam wall breach), 100 years (with dam breach occurring at 23 years) and 1,000 years using the complete rainfall time series. Runoff is contained within the dam at 10 years, while post-breach the drainage network and its development can be clearly observed. All dimensions are in metres



(a)



(b)

Figure 4 Hypothetical valley fill tailings dam using (a) Average rainfall; (b) Complete rainfall at 1,000 years (dimensions are in metres)

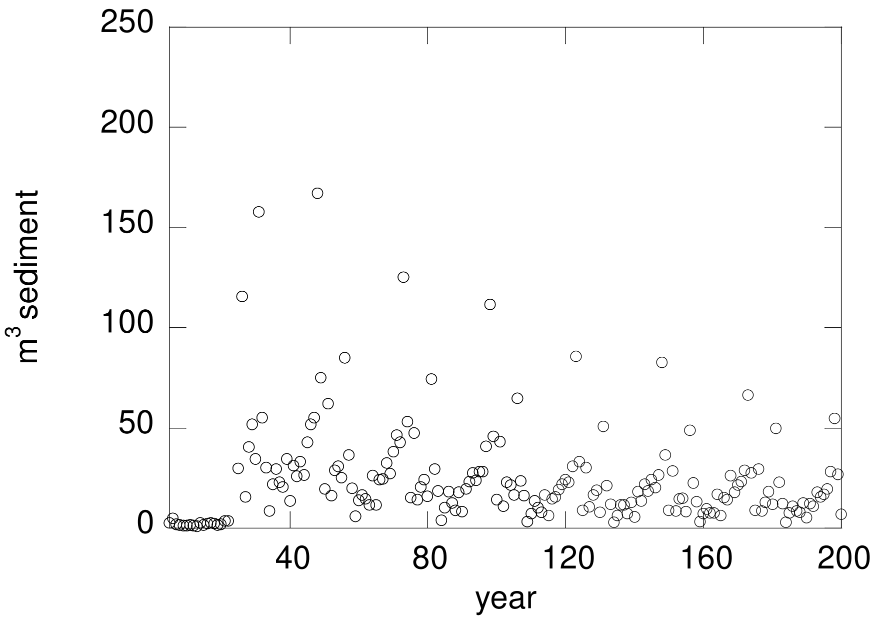


Figure 5 Sediment exiting the catchment for the complete rainfall. Only the first 200 years of the extreme rainfall data is displayed for clarity

Dam wall breach using the complete rainfall data occurs at 23 years. This is when the large storm event occurs and generates runoff that overtops the wall. Prior to this large storm event, there is little erosion of the dam wall and little build-up of sediment in the dam or consequent loss of freeboard. The failure process for the average rainfall scenario is similar in that water overtops the dam wall and concentrated flow incises into the dam wall creating a gully.

Similar to the average rainfall scenario, a gully forms in the wall and exposes the tailings. The incision in the dam wall widens and tailings are mobilised and channelled through the breach. For the complete rainfall, the average denudation rate for the first 22 years post-closure years is 0.022 mm yr^{-1}, which is the same as the average rainfall simulation, as pre-dam wall breach the rainfall time series is the same. Again, the denudation rate is within the range measured for the surrounding natural environment (0.013–0.86 mm yr^{-1}) demonstrating the model is producing an erosion rate commensurate with measured background data over this shorter time period.

3.2 Long-term dam geomorphology

Over time, the tailings are mobilised and transported through the breach and exit the catchment. At 1,000 years, both the average and complete rainfall scenarios have produced landforms with both similarities and differences (Figure 4). The dam wall breach from the average rainfall is not as large as that of the complete rainfall simulation. However, both scenarios have eroded the tailings to dam base level at the wall breach, with both having a well-developed gully network. The gully has steep sides near the breach, similar to what would be expected of field gullies. A gully and channel network has expanded and incised into the tailings to well upstream of the wall. Both rainfall scenarios have channel networks that have expanded to cover the dam surface with meandering form typical of that of fine-grained materials at low slope (Figure 3). At 1,000 years for both rainfall scenarios, a considerable volume of tailings remains within the dam available to be mobilised and exported.

4 Discussion

4.1 Dam stability

The objective of this study was to assess the ability of the CAESAR-Lisflood LEM model to predict sediment transport and landform evolution from a rehabilitated landform when compared to measured erosion and transport rates.

The tailings dam, with the dam wall intact and containing all runoff, has little input into the surrounding creek system with the sediment load within background levels. Therefore, as designed, the dam is effective at containing the mine waste product and has little ecological effect on the environment. Assuming average rainfall and maintenance, the dam wall can last centuries.

For both rainfall scenarios, the dam wall fails due to overtopping, with concentrated flow incising the crest of the dam wall forming a gully. For the average rainfall scenario, the failure is due to slow erosion of the dam wall resulting in a loss of dam wall height by approximately 300 mm that combined with a slow infilling of the dam from sediments upstream. Overall, there is a loss of 0.4–0.5 m of freeboard and failure occurs at the lowest elevation in the dam wall. The dam wall fails for the complete rainfall as a result of the dam not being able to contain the runoff from the storm at 23 years. Runoff is concentrated through the breach, enlarging the incision. In both cases, the tailings erode from the dam wall failure. The tailings erode by gully erosion with a headcut of approximately 6 m deep forming at the dam wall. This headcut migrates upstream. A drainage network can be observed to develop and continue to migrate headwards for the duration of the model run (Figures 3 and 4). The gully deepens and widens, with depth constrained by the natural topography. The gully does not incise any deeper than the natural surface.

At the end of the 1,000-year model run, there is still a considerable volume of tailings remaining in the dam. Interestingly, once breached, the remaining dam wall remains competent for the duration of the model run, effectively retaining the bulk of the tailings. While the breach grows slowly, there is no further catastrophic failure and the majority of tailings remain contained. Erosion and transport of tailings is controlled by the growth of the breach with gully growth, and depth is controlled by both flows from upstream and by deposition at the base of the embankment.

Downstream of the wall, the channel evolves, but there is little storage of sediment. Channel cross-sections downstream of the dam wall demonstrated little change over the 1,000-year model run. All eroded tailings material was transported out of the catchment system, and there was little storage of tailings downstream of the dam wall. As a result, it can be expected that there will be water quality and sedimentation concerns downstream for as long as tailings are available to be eroded.

4.2 Long-term dam geomorphology

Geomorphically, the dam structure is not in equilibrium with its surrounds. The landscape will, over time, erode to the most stable form. Erosion by gullying is the first step in the transition of this landscape to a more geomorphically stable form. The work here demonstrates that if average conditions are assumed, then erosion will be commensurate with risk of failure within expectation. However, above average and also within expectation climate scenarios can produce dam wall failure.

Designing and assessing for climate variability is necessary for post-mining landforms, as it is well understood that extreme events as well as poor design and management lead to failures (www.globaltailingsreview.org; Armstrong et al. 2019; Kossoff et al. 2014; McKenna & Van Zyl 2020).

However, this is not straightforward. Predicting landscape change at periods greater than 100 years, given our limited knowledge of climate, is fraught with difficulty. Climate projections are available at decadal timescales all with considerable uncertainty (CSIRO and Bureau of Meteorology 2015). CAESAR-Lisflood has the capability to easily input different rainfall scenarios; however, methods to extrapolate existing data need to be developed (CSIRO and Bureau of Meteorology 2015; Moise et al. 2015). Therefore, the rainfall scenarios based on recent data and extrapolation to a 1,000-year period are speculation only.

A further simplification is the static parameters that do not account for any surface and subsurface change. Information is required for surface armour development and weathering. The role of vegetation also requires examination.

The geomorphological life of a post-mining landform is an open question (Martín-Marino et al. 2018; McKenna & Van Zyl 2020). Where required, post-mining landforms are assessed using LEMs for hundreds to thousands of years. Once built, they become a component of the local landscape system. Therefore, understanding how these landscapes integrate and perform over geological time is needed. It has been suggested that a design life of 1,000 years be a goal with potentially longer for some sites (McKenna & Van Zyl 2020; Supervising Scientist 2021). Over the modelled period of 1,000 years, it is inevitable that climate and surface properties will have changed. While we used static climate and model parameters, such an assessment provides inference for longer-term landscape trajectory. The results also demonstrate the predictive capacity of the CAESAR-Lisflood model for examining post-mining landforms at short- and longer-term timescales.

5 Conclusion

The findings demonstrate that the dam wall will match design expectations for average rainfall conditions. However, given a possible extreme event, the dam wall falls well short of the design expectation. Post-wall breach water quality will also be greatly reduced. The effect on water quality will last centuries, as at 1,000 years there is a large volume of tailings still to be mobilised.

A question that arises is, can tailings dams ever be walk-away structures? Given average conditions, the dam is sufficiently robust to last centuries. However, the dam eventually fails. This therefore is a long-term legacy issue. The tailings can be contained if (a) maintenance is conducted to maintain and/or increase the dam wall height over time or (b) a more robust dam wall is constructed to manage extreme events. However, erosion and infill will also reduce the integrity of a more robust structure over time. It may be that dams such as this are not walk-away structures and that monitoring and maintenance are conducted as needed in perpetuity.

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