

Climate change impact on the closure design for the rehabilitation of the former Rum Jungle uranium mine

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Abstract

The former Rum Jungle uranium mine, located approximately 100 km south of Darwin, operated between 1954 and 1971 and underwent rehabilitation from 1983 to 1986. The rehabilitation addressed significant environmental impacts caused by acid metalliferous drainage and achieved objectives related to reducing public health hazards. However, recent studies documented that the original rehabilitation works do not meet modern environmental standards, meaning further rehabilitation work would be required for site closure and relinquishment.

An improved rehabilitation strategy, consistent with the views and interests of stakeholders and that meets contemporary environmental and mined-land rehabilitation standards, was developed in 2020. The strategy involves relocation of potentially acid forming waste rock to new surface waste storage facilities (WSFs) and a water and tailings filled pit, treatment of contaminated pit and groundwater, and the realignment of the East Branch Finniss River (EBFR) to follow its original course back through the pit.

There is now widespread acceptance that human activities are contributing to observed climate change. Continued emissions of greenhouse gases are highly likely to cause changes in all components of the climate system. The Northern Territory Government requested that the effects of long-term climate change on specific aspects of the proposed rehabilitation design be assessed.

Based on the UN's Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5; IPCC 2014), and Australia's CSIRO and Bureau of Meteorology (CSIRO & BOM 2015) climate change projections, regional highlights relevant to the project site include warming between 0.5°C and 5.1°C, dry season changes projected to range from 45% drier to 44% wetter, and, for the wet season, 23% drier to 19% wetter. Additionally, fire weather will become more frequent and harsher.

Key climate change indicators likely to influence the rehabilitation design are considered to be climate change-induced rainfall, especially peak intensity rainfall events, and climate change impacts on fire weather, considering both the potential for a catastrophic fire decimating the vegetation throughout the project site catchment, and how the intense heat from an extreme bush fire might change the structure of the soil, resulting in hydrophobic conditions.

The effect of the above potential climate change-related factors has been studied to ascertain the robustness of the specific rehabilitation design elements, including backfilling of the pit, realignment of the EBFR and the erosion of the WSFs.

The key findings of the study have shown that the primary impacts of climate change on the success of the rehabilitation are changes to flow regime and flood levels within the EBFR, with an increase in peak flood levels of between 50 mm and 600 mm. However, the flood level increase would not exceed the defined channel and therefore would not inundate the proposed WSF footprints; hence, no specific mitigation will be required. Increased creek flow velocities would require enhanced erosion and scour protection immediately

upstream and downstream of the Main pit. Other drainage structure design upgrades would also be required to mitigate the effects of increased flows.

Modelling of the WSFs to account for climate change effects has shown the maximum gully erosion after 500 years is less than 1.3 m, providing contingency compared to the 2.5 m cover design thickness. Spatially, less than 1% of the erosion will be of a depth greater than 1 m.

Under both base case and climate change scenarios, the type and rate of revegetation is critical to controlling erosion. The final revegetation plan should carefully consider how climate change influences can impact the type and extent of vegetation used.

Keywords: *climate change, rehabilitation design, erosion modelling*

1 Introduction

Since 2009, the Northern Territory and Australian governments have undertaken investigative works to develop an improved rehabilitation strategy that is consistent with the views and interests of stakeholders and meets contemporary environmental and mined-land rehabilitation standards. The rehabilitation design involves relocation of potentially acid forming (PAF) waste rock to new waste storage facilities (WSFs) and a water and tailings filled pit, treatment of contaminated pit and groundwater, and the realignment of the East Branch Finniss River (EBFR) to follow its original course back through the pit.

An improved rehabilitation design for the former Rum Jungle mine site was completed in 2020 and involved the design of new WSFs and a backfill strategy for the Main pit to accommodate the PAF waste rock that is currently impacting the groundwater and downstream reaches of the EBFR.

The former open cut Main pit was 105 m deep and is partially filled with tailings, resulting in a permanent pit lake depth of ~46 m. The pit is to be backfilled over the tailings with the highest potential PAF waste rock and then capped with inert material, to a maximum of 2 m below the currently predicted lowest pit water level.

The EBFR is currently diverted to the south of the Main pit and the adjacent Intermediate pit. Once the Main pit is backfilled and capped, the EBFR is to be realigned to follow its original course through the Main pit and Intermediate pit, which is to remain as a pit lake.

Two new WSFs are to be formed from the remaining PAF waste rock. The WSFs have been shaped to minimise erosion and blend as much as possible with the surrounding topography. The PAF will be encapsulated within low permeability material and non-acid forming (NAF) waste rock and capped with inert borrow material. The proposed rehabilitated site layout is shown in Figure 1.

Following the completion of the 2020 rehabilitation design, the Northern Territory Government requested that the effects of long-term climate change on specific aspects of the proposed rehabilitation design be assessed. There is now widespread acceptance that human activities are contributing to observed climate change. Continued emissions of greenhouse gases are highly likely to cause further warming and changes in all components of the climate system. Mean, minimum and maximum temperatures are predicted to keep increasing with very high confidence, along with the frequency of hot spells and droughts. While overall rainfall is predicted to result in both wetter and drier periods, depending upon regional geographical influences, climate modelling predicts with high confidence that heavy rainfall events will become more intense. Rising temperatures and prolonged hot spells are predicted to lead to an increase in the frequency and intensity of bush fires. The impacts of long-term climate change are considered relevant to the Rum Jungle mine's location, and may alter evapotranspiration, soil moisture and runoff.

To understand the robustness of the design of the EBFR realignment, pit capping layer and WSF cover design, a climate change sensitivity assessment has been undertaken. This has included identification of the relevant climate change influences and comparison of hydrological, hydraulic and erosion modelling results for the base case against under the climate change influences.

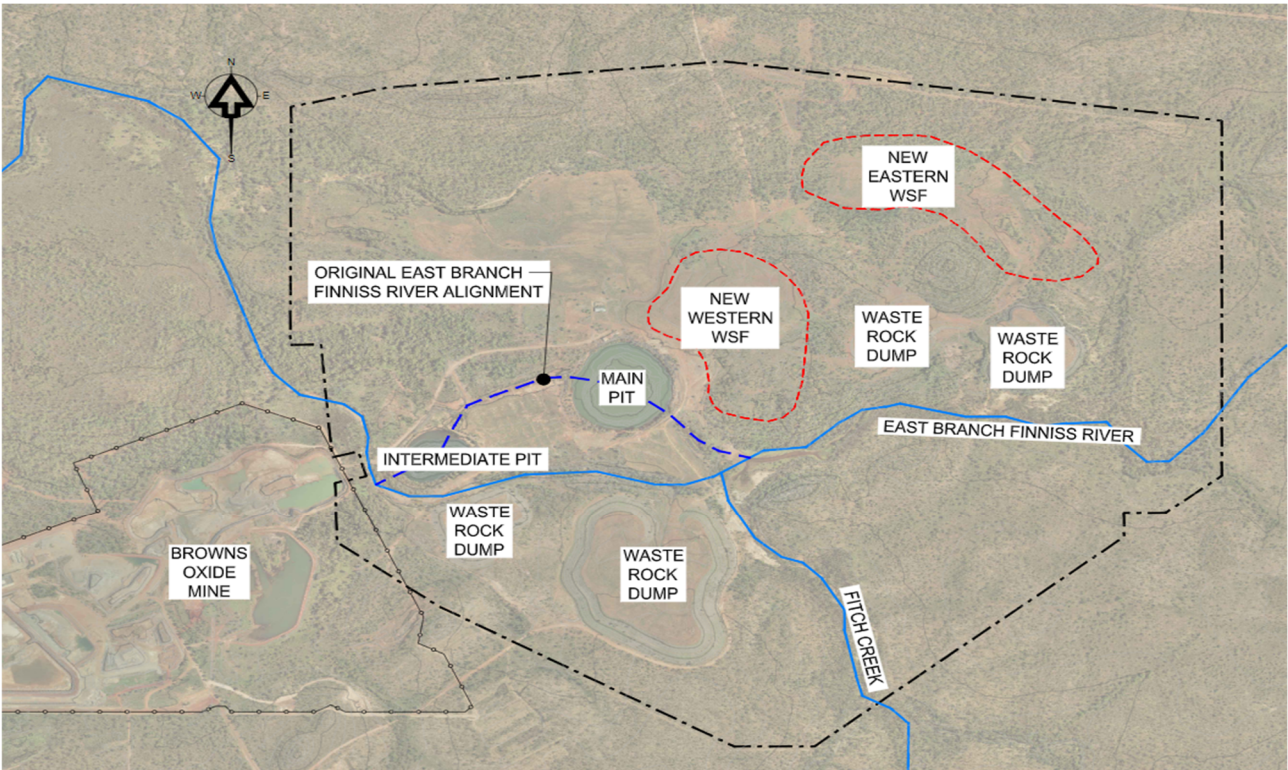


Figure 1 Site layout with proposed WSFs and EBFR realignment

2 Climate change influences

2.1 Australia’s NRM clusters and subclusters

The Australian Government developed the Regional Natural Resource Management (NRM) Planning for Climate Change Fund to provide projections of the likely impact of climate change on Australia’s natural resources. Australia has 54 NRM regions (clusters and subclusters), defined by catchments and bioregions, which are broadly consistent in terms of history, population, resource base, geography and climate. The location of the project site is within the Monsoonal North (West) subcluster, as shown in Figure 2. The site experiences a hot, humid wet season from November to April and a cooler dry season from May to October.

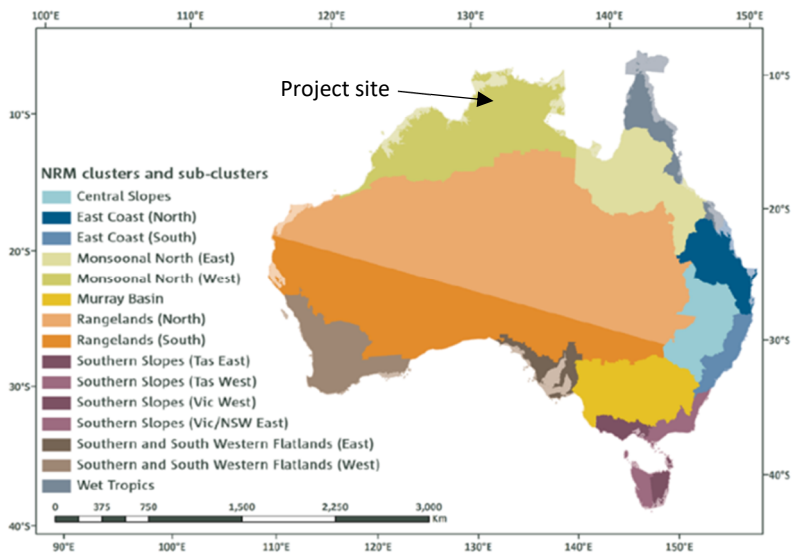


Figure 2 Australia’s Natural Resource Management (NRM) clusters and subclusters

2.2 IPCC AR5 climate change projections

The UN's Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5; IPCC 2014) (note, the more recent AR6 Synthesis Report is due to be released in September 2022) provides climate change projections based on a series of future climate change scenarios encompassing a plausible range of likely outcomes. These climate change scenarios have been developed into 'Representative Concentration Pathways' (RCPs) able to explore credible future options, expressed in terms of future carbon emissions and associated radiative forcing. The standard RCPs are as follows:

- RCP8.5 – chosen to represent a future with little curbing of emissions, with CO₂ concentrations continuing to rapidly rise, reaching 940 ppm by 2100.
- RCP6.0 – represents lower emissions, achieved by the application of some mitigation strategies and technologies. CO₂ concentrations rise less rapidly than RCP8.5, but still reach 660 ppm by 2100, with total radiative forcing stabilising shortly after 2100.
- RCP4.5 – concentrations are set slightly above those of RCP6.0 until after mid-century, but emissions peak earlier (around 2040). CO₂ concentrations reach 540 ppm by 2100.
- RCP2.6 – represents the most ambitious mitigation scenario, with emissions peaking rapidly (around 2020), then rapidly declining.

In response to the AR5 report, Australia's CSIRO and Bureau of Meteorology (BOM) (CSIRO & BOM 2015) prepared tailored climate change projections for each of Australia's NRM clusters. Regional highlights relevant to the project site include:

- By 2030, warming will range from 0.5°C to 1.2°C (low emissions RCP) to 0.7°C to 1.3°C (high emissions RCP).
- By 2090, warming will range from 0.9°C to 1.6°C (low emissions RCP) to 2.8°C to 5.1°C (high emissions RCP).
- Near-future projections for the dry season range from 35% drier to 29% wetter, depending on RCP scenario. For the wet season, projected changes range from 8% wetter to 7% drier.
- By 2090, the projected dry season changes range from 45% drier to 44% wetter, depending on RCP scenario. For the wet season, the projected range is 23% drier to 19% wetter.
- Under all future RCP scenarios, fire weather will become more frequent and harsher.

3 Climate change influences on rehabilitation design

Key climate change indicators likely to influence the Rum Jungle rehabilitation design are:

- Climate change-induced rainfall: especially peak intensity rainfall events.
- Climate change impacts on fire weather I: considering the potential for a catastrophic fire decimating the vegetation throughout the project site catchment.
- Climate change impacts on fire weather II: considering how the intense heat from an extreme bush fire might change the structure of the soil, resulting in hydrophobic conditions.

The above influences will impact the hydrological, hydraulic and erosive behaviour by changing the following inputs to the modelling:

- Rainfall intensity.
- Surface water infiltration parameters, including initial and continuing losses.
- Surface roughness (Manning's 'n').
- Vegetation cover and soil sterilisation.

4 Estimating climate change impacts on rainfall

The Australian Rainfall and Runoff Guideline (Ball et al. 2019) identifies two alternative methods to estimate the impact of climate change on rainfall depths.

4.1 Simplified method

This allows for the incorporation of the effects of climate change in the design rainfall used in flood estimation by modelling of the 0.5% (1 in 200) annual exceedance probability (AEP) as a proxy for future estimates of the 1% (1 in 100) AEP event. For the critical duration 30-hour rainfall event, this would represent an increase in rainfall depth and intensity of 15%.

4.2 Detailed assessment

The detailed assessment is based on predictive modelling of temperature increases sourced from the Climate Change in Australia website and applying a change in design rainfall from global warming as follows:

$$I_p = I_{ARR} \cdot 1.05^{Tm} \quad \text{Eq.1.6.1 (Ball et al. 2019)}$$

where:

- I_p = projected rainfall intensity (or depth).
- I_{ARR} = design rainfall intensity (or depth).
- Tm = temperature at the midpoint of the selected class interval.

Based on AR5 climate change scenarios for the year 2070 (the minimum period for analysis for long-standing projects; Ball et al. 2019), a conservative temperature increase for the project site of 2.25°C has been adopted and is considered adequate for estimating future rainfall intensity increases. Using Eq.1.6.1 in (Ball et al. 2019), this would equate to an 11.6% increase in rainfall intensity.

Table 1 provides a comparison of the resulting rainfall depths. The conservative approach is therefore to adopt the 0.5% AEP rainfalls.

Table 1 Comparison of climate change rainfall increases

Duration	Rainfall depth, 30-hour duration	Comment
2019 rainfall – 1% AEP	318 mm	Baseline
Simplified method	366 mm (+15.0%)	Adopted for sensitivity analysis
Detailed method	355 mm (+11.6%)	Is of similar magnitude

5 Climate change and effect on infiltration of soils

5.1 Physical impact

Catastrophic fire has the potential to destroy the entire contributing catchment relevant to Rum Jungle. The result is exposure of erodible soils via burning of the vegetation on the soil surface. Under intense heat, the predominant sandy clay soil in the upper catchments can crystallise, similar to the firing of clay in a kiln, and intensely burning organic material can release a waxy substance that penetrates the soil as a gas and solidifies after cooling, bonding the soil particles together. The nature of the open pores of a sandy clay soil will allow the penetration of heat and gas deep into the soil profile. These processes can result in the top layer of soil becoming hydrophobic, which will result in impacts on hydrological and hydraulic processes, including reduction of surface water infiltration rate, runoff rates and velocities increasing and increased downstream flood depths.

5.2 Impact on modelling parameters

With regards to the surface water modelling undertaken, the current-day calibrated infiltration parameters were reassessed to emulate the behaviour of the soils in the immediate aftermath of an intense catastrophic fire engulfing the catchment. The results are summarised in Table 2.

Table 2 Climate change impact on infiltration for hydrologic and hydraulic modelling

Parameter	Base case	Climate change influence
Initial loss	38 mm	10 mm
Continuing loss	0.6 mm/hour	0 mm/hour

6 Climate change and effect on erosion characteristics of soils

6.1 Physical impact

The impact of the catastrophic fire on the erosion characteristics of the WSF covers will be dependent on the type and establishment of the rehabilitation vegetation. Under intense heat the surface layer of soil is virtually sterilised. All surface plant material and seed are destroyed, and soil organic carbon may be reduced and soil organisms killed or reduced in the top 10–15 mm.

The ability to survive a hot burn varies between species: grasses with growing points below the soil surface survive best. The proposed cover for the WSFs is a mix of native annual and perennial grasses with low biomass, ground cover shrubs, and possibly shallow-rooted trees. The impact on the erosion parameters would be:

- Reduction in vegetation cover, which is represented by an increase in the C-factor, which measures the effect of interrelated cover and management variables, as per E3.5 C-factor of Book 2, Volume E of the International Erosion Control Association guidelines (IECA 2008). The results are summarised in Table 3.
- No impact on the K-factor, which represents the erosivity of the soil without cover. The hydrophobic phenomenon immediately after bushfires on the first centimetres of the soil will produce a change on the bonding on particles that can increase the erosion resistance. However, it is transitory and with time will revert, so has not been modelled.
- Factors m_1 and n_1 define the type of erosion that can occur (i.e. gullying or sheet), which is a factor of soil type, landform shape and rainfall intensity. These factors were established using laboratory flume testing for the base case; however, no additional testing has been done for the climate change impact on the rainfall intensity that is simulated during the laboratory testing. These factors were therefore not altered for the erosion modelling. This is discussed further in the section on WSF cover erosion modelling.

Table 3 Climate change impact on C-factor for erosion modelling

Season	Base case	Climate change influence
Dry	0.04	0.45
Wet	0.005	0.24

7 Climate change and effect on catchment roughness

7.1 Physical impact

The contributing catchments are heavily wooded with dense undergrowth and tuft grasses. The effect of a fire denuding the surface would be akin to the urbanisation of a forested catchment.

7.2 Effect to modelling parameters

The modelling takes into account the vegetation characteristics in the contributing catchment of Rum Jungle. For calibration purposes, a Manning's 'n' between 0.06 and 0.1 was considered appropriate. In the event of a catastrophic fire and resulting changes in surface roughness characteristics, where the whole catchment could comprise charred stumps and branches with no undergrowth, a Manning's 'n' of 0.04 has been adopted.

The effects on the runoff calculations comprised increased runoff rate, increased volume of runoff and increased flooding.

8 Impact of the influences on hydrological effects

8.1 Rainfall temporal patterns and the adoption of temporal pattern ensembles

The use of an ensemble of 10 temporal patterns for each storm duration (a total of 290 different storms for each magnitude) is now required by ARR (Ball et al. 2019). The temporal patterns have been chosen to represent the variability in observed patterns. The required approach is to select the storm that represents the mean of the ensemble maxima (Ball et al. 2019).

8.2 The baseline 1% AEP discharge

The hydraulic infrastructure has been designed to safely pass the 1% AEP event. Modelling shows the 30-hour duration 1% AEP storm with temporal pattern no. 6 is the mean of the maximum ensembles and produces a peak flow of 195 m³/s. This storm is to be used for design purposes and is considered the baseline for climate change influence effects. The critical duration is the 18-hour rainfall event, which produces a maximum flow of 231 m³/s.

Modelling for the climate change influences has been simulated for the following scenarios:

- Increased rainfall intensity impact.
- Fire weather impact – that is, change of surface roughness (Manning's 'n').
- Soil structure impact – hydrophobic conditions leading to reduced initial and continuing losses.
- A combination of all three influences.

The results are shown in Figure 3 and comparison of the base case results to the results from modelling for the climate change influences is given in Table 4.

Table 4 Hydrological modelling results

Parameter	Base case	Climate change influence			
		Increased rainfall	Fire weather	Soil structure	Combined
Mean storm duration	30-hour	30-hour	4.5-hour	6-hour	24-hour
Mean flow peak	195 m ³ /s	230 m ³ /s	259 m ³ /s	217 m ³ /s	340 m ³ /s
Critical storm duration	18-hour	18-hour	18-hour	18-hour	6-hour
Critical flow peak	231 m ³ /s	276 m ³ /s	311 m ³ /s	257 m ³ /s	428 m ³ /s

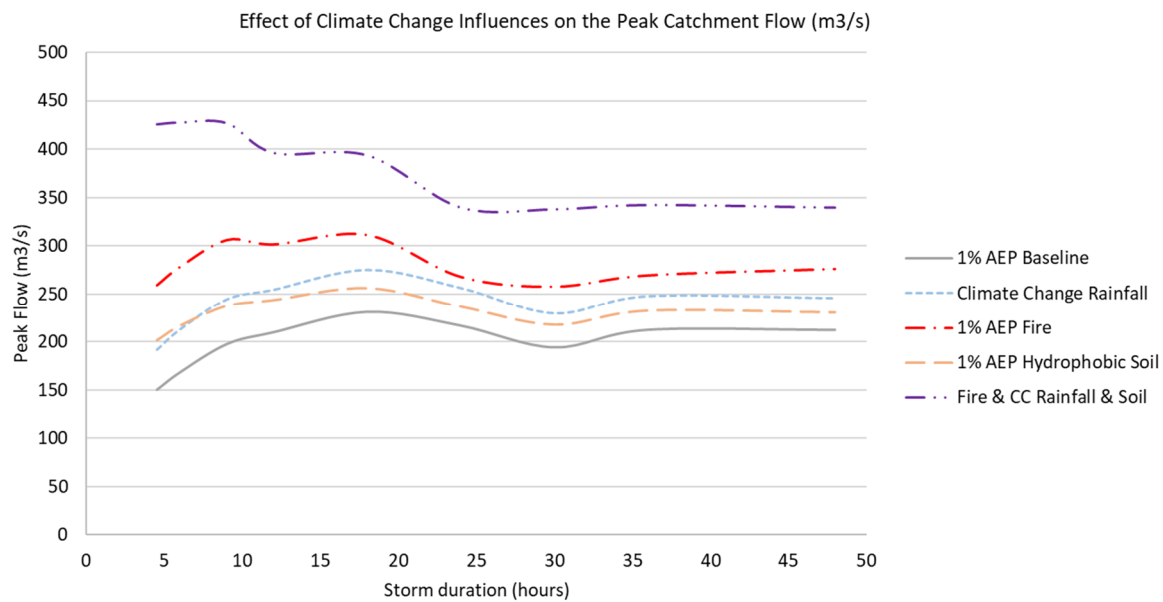


Figure 3 Summary of peak catchment flows for climate change influences

The results indicate that:

- Catastrophic fire that denudes the catchment of vegetation will have the greatest influence on runoff increases at the site.
- The predicted rainfall increases will have a slightly greater influence than the hydrophobic soil conditions.
- Overall, the peak runoff could increase by approximately 78% should all influences occur simultaneously.

9 Impact of influences on the Main pit, EBFR design and WSF footprints

9.1 The proposed remediated landform

The proposed final landform was to address the following minimum requirements:

- The diversion channel is to remain to convey surcharge of the EBFR upstream of the Main pit during extreme floods to relieve the hydraulic load of the Main pit.
- The existing culverts at the entry and exit of the Main pit and the entry of the Intermediate pit will be removed to provide a continuous flow path.
- The channel surface would be heavily lined with rip rap to prevent erosion. The interstices of the rip rap would be covered with a seeded soil mix to promote vegetation and mitigate the engineering appearance. Large boulders and logs placed in a meandering arrangement would provide refuges for migratory fish during the wet season. The riverbed would have riffles and depressions to retain pools after flows.
- During the dry season, the capping of the Main pit would be covered by 2 m of water. The permanent groundwater table will ensure the capping remains covered in the dry season. During the wet season, the level increases by approximately 2 m, providing a 3 m to 4 m submergence over the capping.

- The Main pit has been modelled with the top of the capping surface as level, which is the worst-case condition, only likely to occur immediately after rehabilitation or should sediment drop out, levelling out the surface over time.
- The WSFs comprise a relatively flat top surface and concave (dual) slopes of 9° at the base and 14° in the upper portion, and will be capped with a 2.5 m (vertical) cover comprising layers (measured parallel to the slope) of 1.0 m of compacted NAF waste rock, 0.65 m of low permeability clay and 2.0 m of growth medium.

9.2 Hydraulic impact

Hydraulic modelling using SWMM-XP 2D software was undertaken for the proposed final rehabilitated topographical surface to understand flow and velocity distribution, water surface elevation, backwater, velocity magnitude and direction, flow depth, and surface shear stress. Comparison has been made between the base case and the combined climate change influences.

9.2.1 Modelling results

Figure 4 shows the flood extent in the rehabilitated channel for the 1% AEP event with the combination of all three influences. Figure 5 shows the incremental differences between the base case and the worst-case scenario (with vegetation).

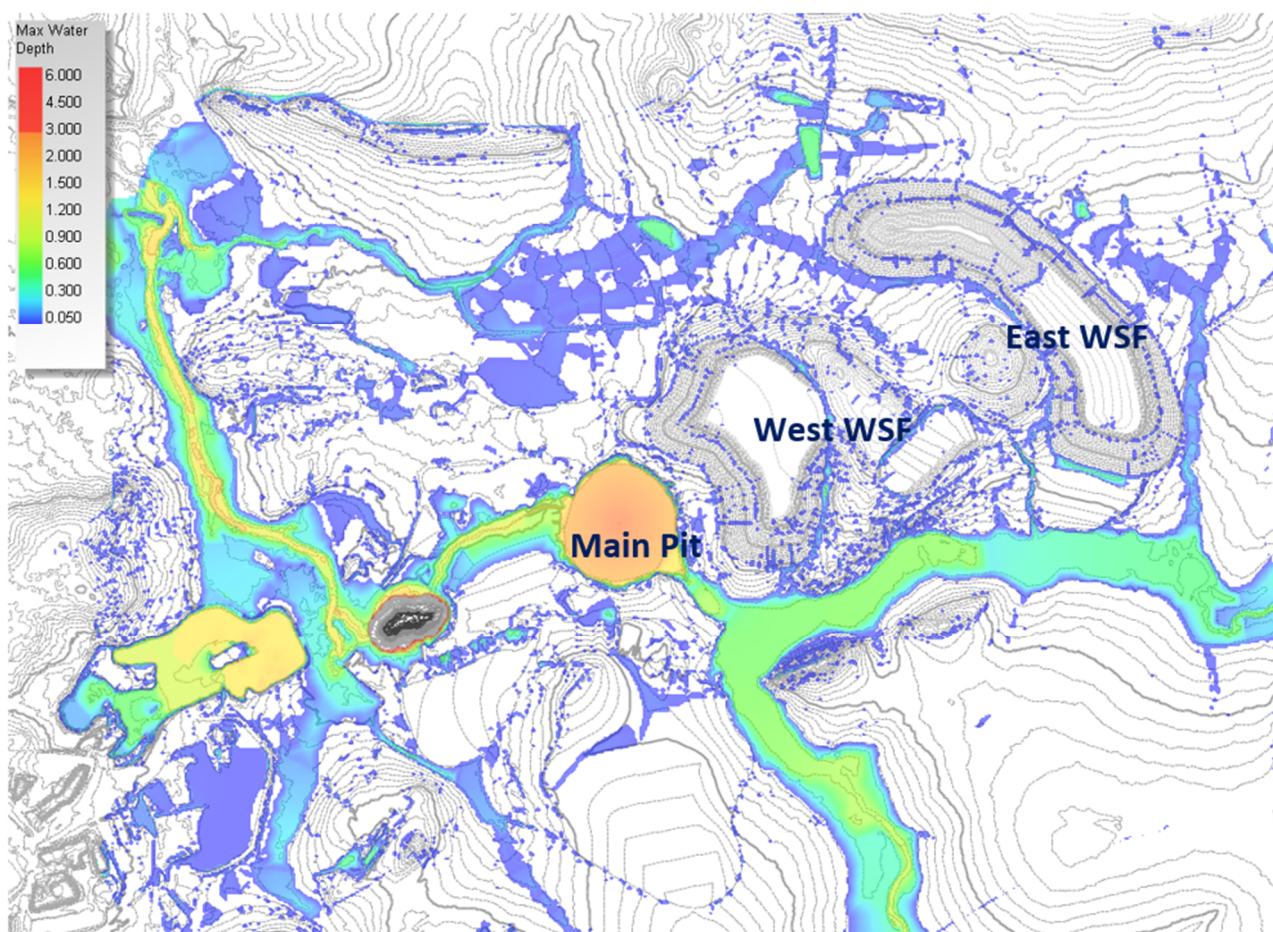


Figure 4 1% AEP flood depth as a consequence of the climate change influences

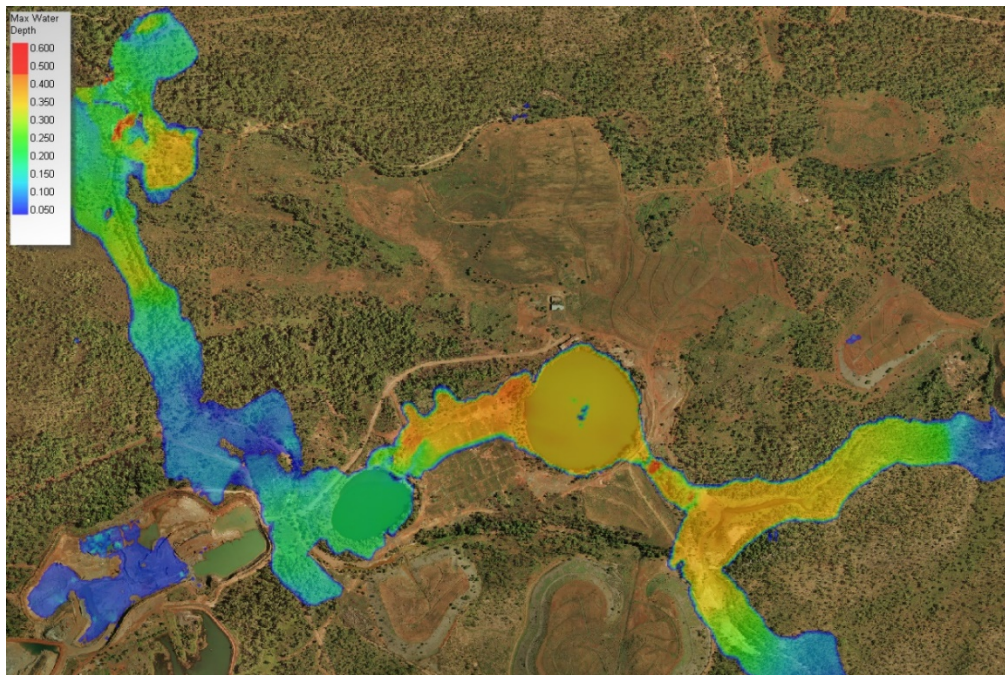


Figure 5 Increase in flood depth as a consequence of the climate change influences (1% AEP)

The results indicate:

- Climate influences could increase flood levels within the EBFR between 50 mm and 600 mm, with the average increase of approximately 350 mm.
- The flood level increase would not exceed the defined channel and hence would not inundate the proposed WSFs.
- The modified diversion channel will not be activated.

9.2.2 *Influence of climate change on velocities*

Figure 6 shows the maximum velocity and direction averaged over the depth. Two-dimensional hydraulic modelling cannot stratify the velocity across the full depth; however, the research by Chow (1959) showed that an approximation of the channel bed velocities can be made by halving of the average cross-sectional velocity. Modelling indicated that the climate change influences could:

- Increase channel bed velocities by up to 0.6 m/s, which is within the design safety factor of the rip rap.
- Increase velocities over the Main pit floor by up to 0.2 m/s, which could cause mobilisation of the sandy bottom.
- Change the flow pattern from a dissipated behaviour to a short circuit between the inlet and outlet of the Main pit.

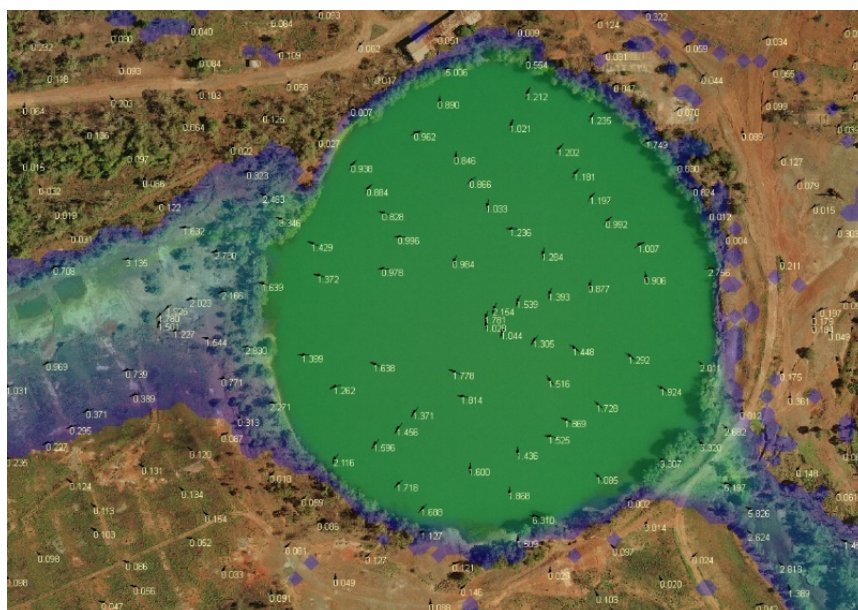


Figure 6 Climate change influences causing higher velocities and short-circuiting behaviour

9.2.3 Addressing the hydraulic conclusions

The results indicated potential changes in hydraulic behaviour over some areas of the Rum Jungle site due to the influence of the climate change variables assessed. These changes suggest a need for minor enhancements to the erosion protection in strategic locations, including immediately upstream and downstream of the Main pit.

The larger flows are resulting in values within the 'line-of-site' between the inlet and outlet of the Main pit, which exceed the mobilisation velocity. This can be alleviated by minor modifications (i.e. widening) to the inlet design to ensure flow dissipates as it enters or is directed north to increase the flow path area and reduce the velocity.

9.3 Impact on the WSF capping erosion

Erosion modelling using SIBERIA was undertaken to establish the type and extent of erosion under long-term (up to 500 years) conditions. Comparison has been made between the base case and under climate change influences for both gully erosion and sheet erosion.

9.3.1 Modelling results

Figure 7 presents the comparison of the maximum gully depth, and Figure 8 compares the average erosion rates.

Key results are:

- Gully erosion is 0.22 m greater under the climate change scenario.
- Sheet erosion is up to nine times higher under the climate change scenario.

Spatial results for the erosion are shown in Figures 9 and 10 for the base case and climate change scenario after 500 years.

Key results are:

- For the base case, 73% of erosion is less than 0.25 m. Only 1% of the erosion is greater than 1 m.
- For the climate change scenario, 61% of erosion is less than 0.25 m, 10% is between 0.25 m and 0.5 m, and again only 1% of the erosion is greater than 1 m.
- Both experience the same areas of spatial erosion.

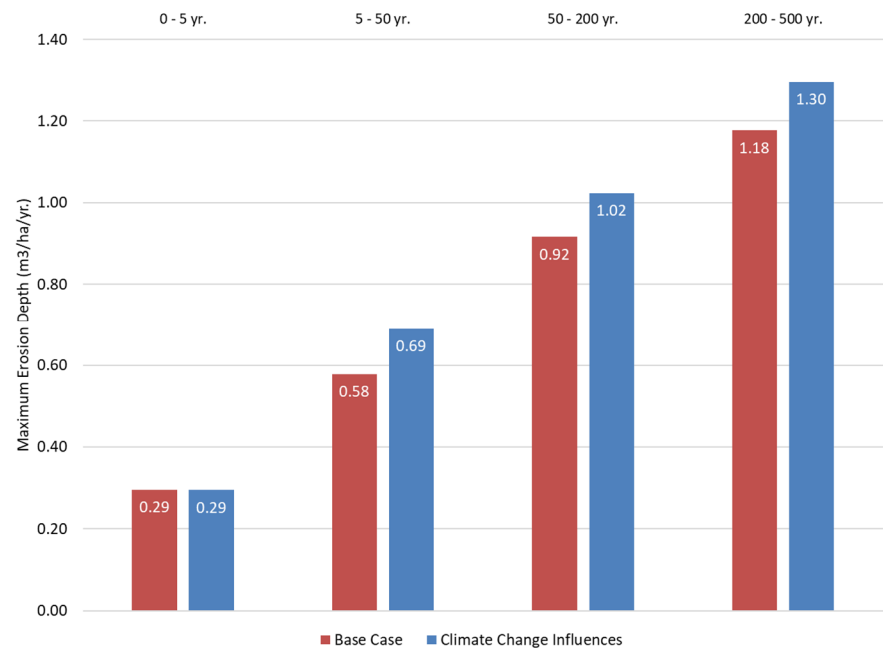


Figure 7 Comparison of maximum gully erosion depth

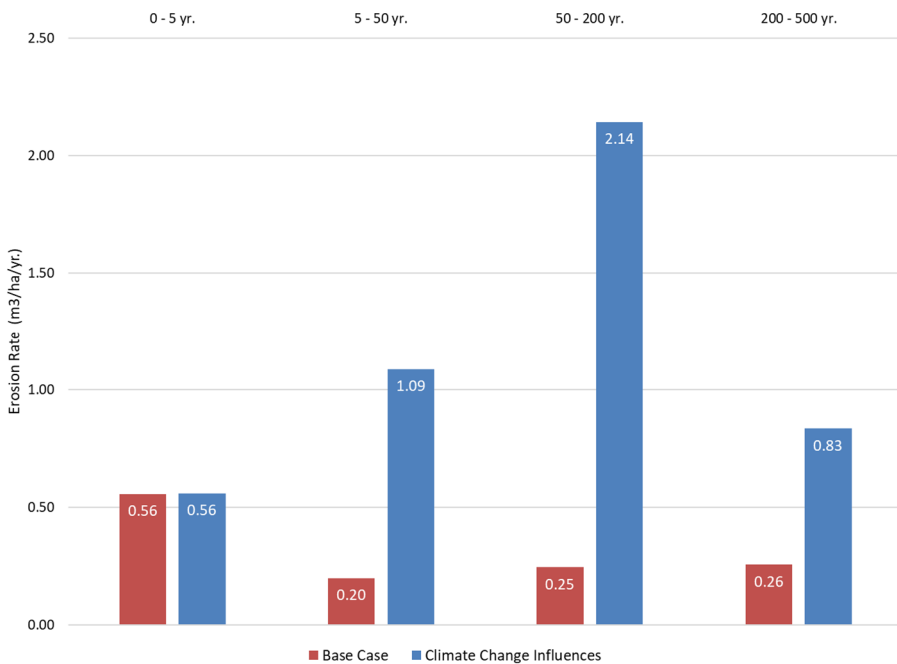


Figure 8 Comparison of average erosion rates

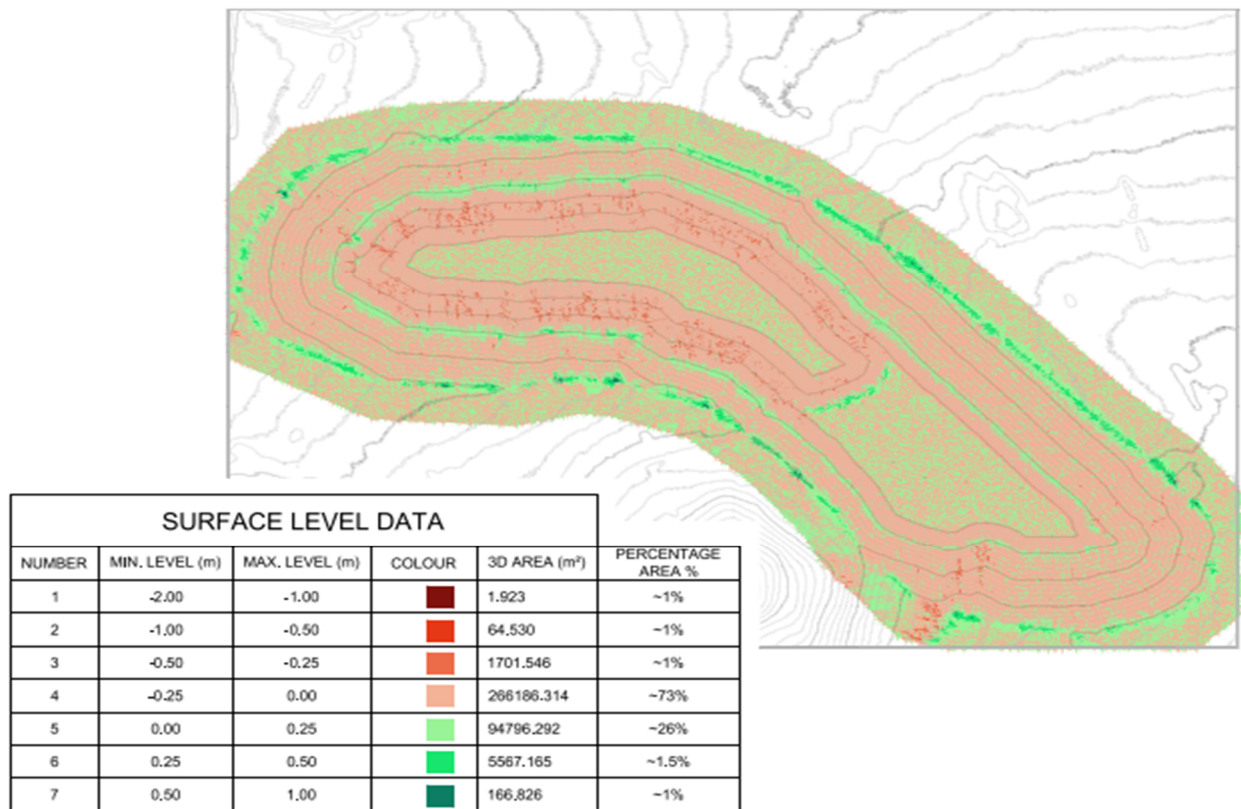


Figure 9 Spatial extent of erosion after 500 years for the base case

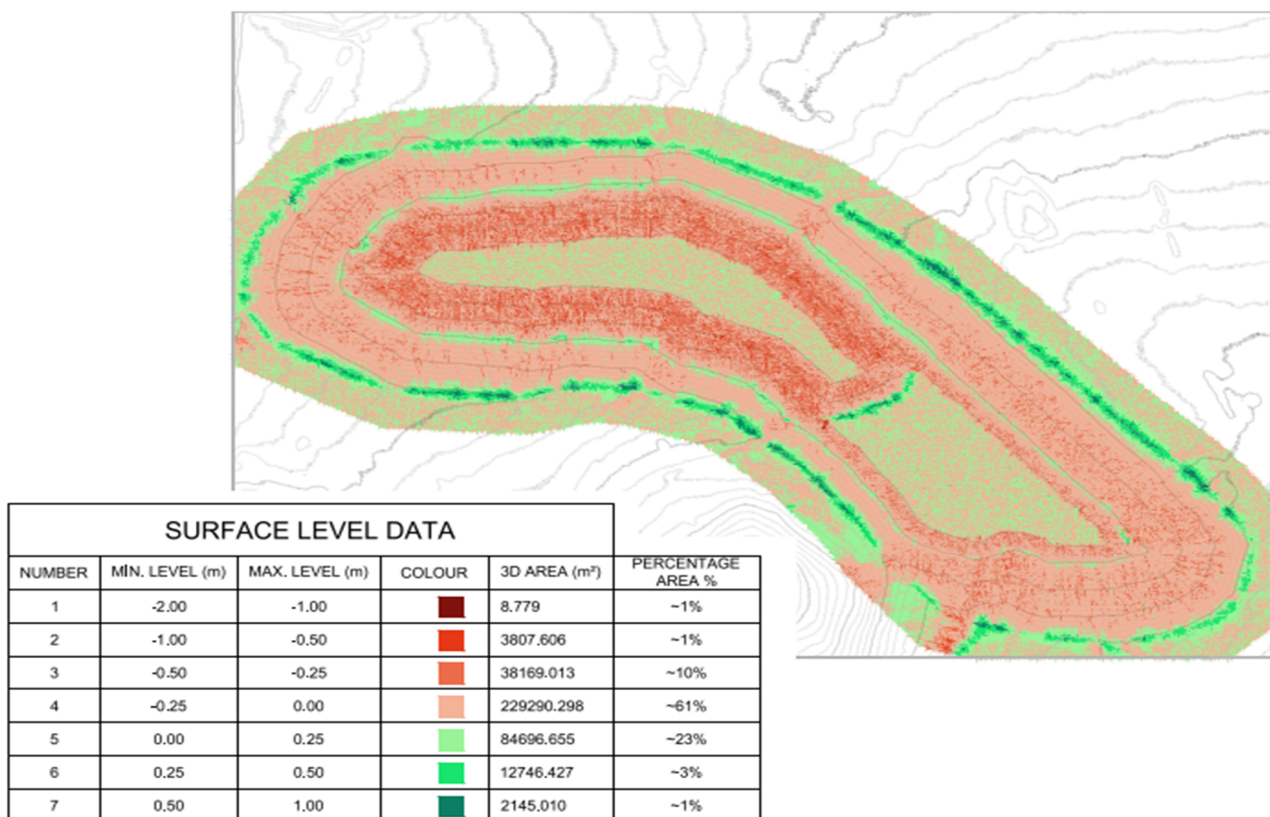


Figure 10 Spatial extent of erosion after 500 years under climate change influences

9.3.2 *Note on climate change rainfall impact on erosion modelling*

As referenced earlier, laboratory flume testing has only been carried out for the base case. No laboratory testing has been undertaken as yet to assess the impact of the increased rainfall intensity on the SIBERIA input parameters ' m_1 ' and ' n_1 '. SIBERIA operates using the ~1:2 AEP event as the most geomorphologically active rainfall event, as this is the storm that on average does the most geomorphic work (Willgoose 2005). It is therefore likely that the climate change erosion modelling is under-representing the erosion rates. For the purposes of the paper, this is not considered a significant factor. The final WSF landform is likely to change during construction, as final waste rock volumes, compaction and bulking factors become better understood. Further flume testing will be undertaken closer to the end of the WSF construction that can take into account the increased rainfall impact.

9.3.3 *Summary and conclusions from the erosion modelling*

For both the base case and climate change scenario, the maximum gully erosion depth is less than 2 m. It is acknowledged that the climate change scenario is under-predicting the erosion; however, there is significant contingency between the predicted maximum 1.8 m gully erosion compared to the 2.5 m cover thickness. Spatially, only 1% of the erosion will be of a depth greater than 1 m.

Based on a literature search of relevant guidelines, it is surmised that there is currently no broad agreement on what can be considered as an 'acceptable' rate of erosion on a mine site. However, the Queensland Department of Minerals and Energy's 'target erosion rate' for rehabilitated spoil is 12 to 40 t/ha/yr (Hustralid et al. 2000). Under the climate change scenario, modelling shows that the maximum average erosion rate is around 2.14 m³/ha/yr. Considering a material bulk density of 1.25 t/m³, the erosion rate can be expressed as 2.7 t/ha/yr, which is still within acceptable limits.

9.3.4 *Addressing the erosion conditions*

The recommended changes to the landform design modelled do not vary from the base case to the climate change scenario. For both scenarios, the type and rate of revegetation is critical to controlling erosion. The revegetation plan should carefully consider how climate change influences can impact the type and extent of vegetation used. Further sharp edges at crests, change of batter slope and the toe should be avoided as these act as seeds for localised gully erosion.

10 Conclusion

The effects of climate change in the long term have the potential to impact the success of the proposed rehabilitation of the site. Climate change has the potential to alter evapotranspiration, soil moisture and runoff characteristics across the Rum Jungle catchment. This, in turn, could have adverse impacts on the key design inputs of rainfall intensity, surface roughness and vegetation cover.

The study has shown that climate change influences will likely lead to increased flood depths across the site. However, the modelling has shown that the increased flood levels will not impact the footprint of the WSFs. For the EBFR realignment and Main pit capping, additional erosion protection at the Main pit inlet and outlet will be required, and a slight realignment and widening of the inlet will also be required to dissipate higher velocity flows resulting from climate change. These design changes can easily be implemented in later stages of the scheme design.

Climate change is not expected to significantly influence the cover design for the WSFs. While the climate change modelling done to date may be under-predicting the long-term erosion, there is significant contingency between the predicted maximum 1.3 m gully erosion compared to the 2.5 m cover thickness. Spatially, only 1% of the erosion will be of a depth greater than 1 m.

The maximum average sheet erosion rates over 500 years is ~2.7 t/ha/yr, which is within acceptable industry standard limits.

The revegetation plan should carefully consider how climate change influences can impact the type and extent of vegetation used in the rehabilitation.

References

- Ball, J, Babister, M, Nathan, R, Weeks, W, Weinmann, E, Retallick, M & Testoni, I 2019, *Australian Rainfall and Runoff: A Guide to Flood Estimation*, Commonwealth of Australia (Geoscience Australia).
- Chow, VT 1959, *Open Channel Hydraulics*, International Student Edition, The Blackburn Press, Caldwell.
- CSIRO & BOM 2015, *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report*.
- Hustralid, WA, McCarter, MK & Van Zyl, DJA 2000, *Slope Stability in Surface Mining*, Society for Mining, Metallurgy & Exploration, Englewood.
- IECA 2008, *Best Practice Erosion and Sediment Control*, Book 2, Picton.
- IPCC 2014, *Fifth Assessment Report (AR5)*.
- Willgoose, G 2005, 'Mathematical modeling of whole-landscape evolution', *Annual Review of Earth and Planetary Sciences*, vol. 33, pp. 443–459.

