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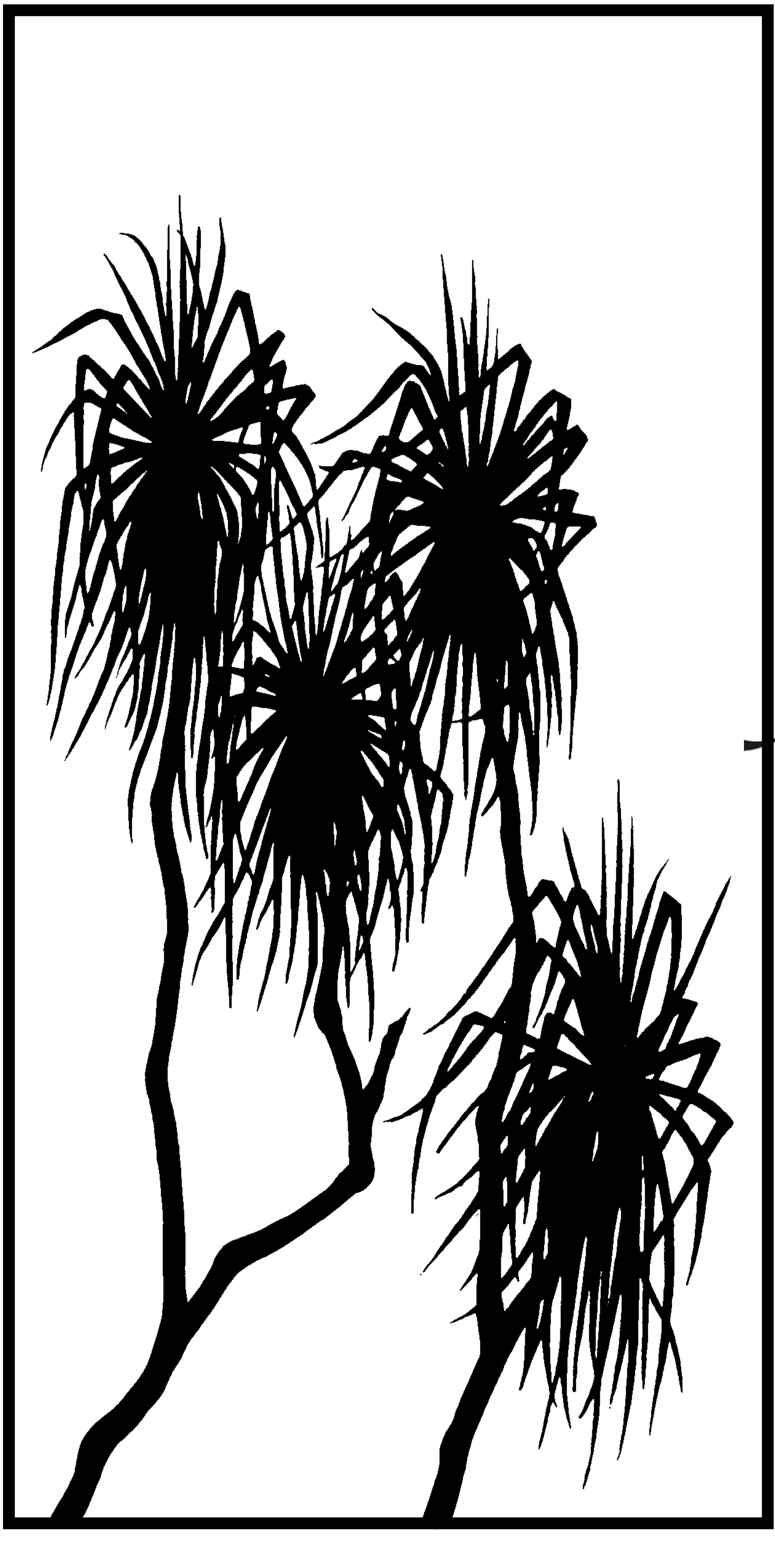

The impact of rip lines on erosion at the Ranger minesite

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December 2017

Release status –Internal use and key stakeholders

The Department acknowledges the traditional owners of country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures and to their elders both past and present.

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Executive summary

The rehabilitated landform of the Ranger uranium mine will require some form of erosion control, or surface amelioration to reduce the sediment leaving the landform. One method of surface amelioration is the construction of rip lines. Rip lines have been used in both mining and agricultural environments to reduce surface water velocity, trap fine sediment and nutrients and reduce erosion from the landform. However, there is little quantitative information on what impact rip lines have on reducing erosion. In addition, the potential use of rip lines on the rehabilitated Ranger landform has raised a number of economic and cultural concerns. Specifically, these include the potential for rip lines to impede pedestrian access and traversability of the landform; and the cost of implementing rip lines may be prohibitive. Using the CAESAR-Lisflood landform evolution model (LEM) we assessed the effectiveness of rip lines by simulating the evolution of both ripped and non-ripped surfaces on a range of slopes from 2 to 12% for simulated periods of up to 50 years.

We found that rip lines are most effective at controlling erosion on slopes of up to 4%. However, this study also demonstrated that as slope increases, rip lines become less effective over time. For example, when the slope is increased to 12%, ripped surfaces become less effective at reducing erosion compared with non-ripped surfaces and are predicted to produce higher sediment loads than non-ripped surfaces.

These results, in the context of the Ranger rehabilitated landform, which is proposed to have slopes of between 2 and 4%, indicate that rip lines would be an effective way of mitigating soil loss and sediment transport.

Furthermore, simulations of ripped surfaces show that the structure of the rip lines break down over time, with the rip line depressions infilling and the peaks being eroded, lowered or reduced in height. This finding is important because it demonstrates that rip lines will not exist in perpetuity in the landscape. This may address concerns by traditional owners that the presence of rip lines may impede or restrict pedestrian access and activity across a rehabilitated surface in the long term.

Finally, model results reinforced the importance of the presence of vegetation on the landform and its role in reducing erosion on all the slopes and surface conditions modelled. The work also highlighted the need for further work to better understand the erosive shear stresses required to remove vegetation on a rehabilitated landform in northern Australia and refine model parameterisation for future simulations.

1 Introduction

1.1 Introduction

The Ranger uranium mine is located in the wet-dry monsoonal tropics approximately 250 km east of Darwin in the Northern Territory of Australia. The unique location of the mine (Figure 1) –surrounded by the World Heritage–listed Kakadu National Park and upstream of floodplains and wetlands listed as "Wetlands of International Significance" under the Ramsar Convention – has required special consideration be given to both current mine operations and the development of closure criteria and rehabilitation plans for the mine.

Mining of the open-cut ore body at Ranger ceased in 2012, and milling and production are scheduled to cease by 2021. At the conclusion of mining and milling operations, mine tailings will be returned to the mined out pits 1 and 3, which must then be physically isolated from the environment for at least 10,000 years (Australian Government 1999). A stable landform, similar to the surrounding landscape is required to safely encapsulate the tailings and to minimise any eroded sediment transported off-site that could impact on water bodies and aquatic biota downstream. The Environmental Requirements[1] for mine closure specify that the final landform should possess "erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas" (Australian Government 1999). The proposed post-mining rehabilitated landform at Ranger uranium mine will cover approximately 847 hectares (8.5 km^2). This represents an area of disturbed and subsequently rehabilitated land that has the potential to supply sediment to catchments and streams downstream.

The rehabilitated landform will require some form of surface amelioration combined with the establishment of vegetation and other erosion mitigation measures (such as sedimentation basins) to reduce the sediment leaving the landform. One method of surface amelioration is the construction of rip lines (depressions and mounds) along the contour to reduce surface water velocity and to also trap fine sediment and nutrients in the depressions to assist vegetation growth.

Saynor & Evans (2001) reference numerous studies that have been conducted on the effect of vegetation on sediment loss (e.g. Morgan 1986; Rogers & Schumm 1991; Simanton et al., 1991; Greene et al., 1994; Loch, 2000; Stocking, 1994) and it is well known that vegetation generally reduces erosion. But there is little quantified information on the impact of rip lines on erosional characteristics of the landform. The usefulness of rip lines in the rehabilitation of mine sites is also currently being debated amongst various stakeholders. Concerns associated with the installation of rip lines include potential restrictions to pedestrian access to and across the rehabilitated landform; and the potential cost of constructing rip lines on a rehabilitated landform.

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[1] Ranger uranium mine operates under a s41 Authority issued under the Atomic Energy Act. The *Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine* are attached to the s41 Authority.

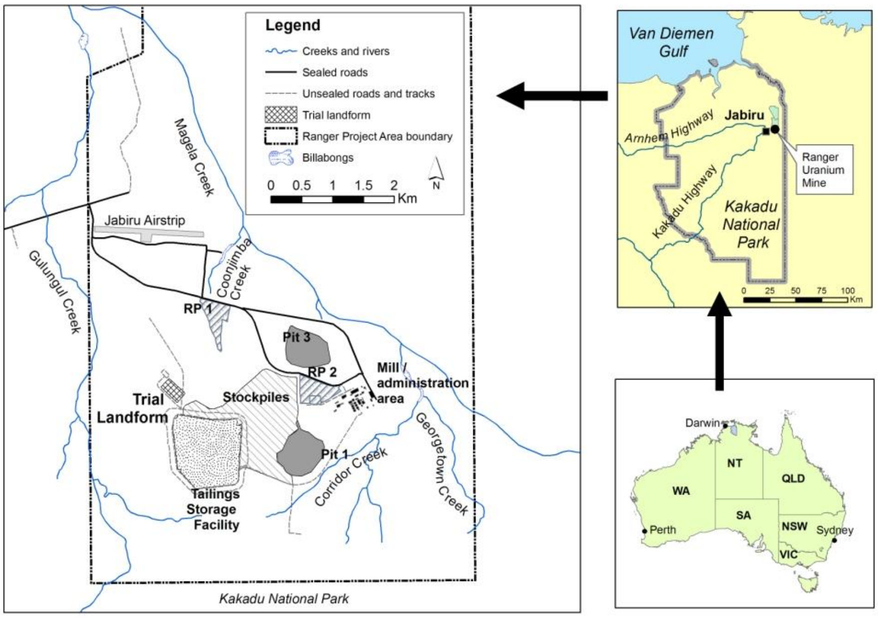


Figure 1 Location diagram of the Ranger uranium mine

The objective of this study was to assess the impact of rip lines on erosion on the trial landform (TLF) at Ranger mine. The TLF was constructed in 2009 for the purpose of informing the rehabilitation of the mine. The following tasks were completed in this study:

- A literature review on the use of rip lines, where they have been used worldwide and more specifically in Australia;
- Using the CAESER-Lisflood landform evolution model (LEM), comparison of the amount and spatial and temporal characteristics of erosion predicted to occur on a ripped versus non-ripped surface over periods of up to 50 years;
  - for different slopes (2, 4, 8 & 12%); and
  - and on either vegetated or non-vegetated surfaces.
- A remote sensing assessment including ground-truthing of an area, of erosion and deposition that has developed on the surface of the TLF since its initial construction.

The study's results will assist with the development and assessment of the final rehabilitated landform at the Ranger mine. It is important to note that while this study used data collected from the Ranger site, it was conducted primarily as a desktop modelling exercise. All modelled scenarios are predictions of erosion rates and loads and are not absolute values.

1.2 Rip lines: an introduction.

A rip line may be defined simply as a linear excavation that breaks up the surface of a landform, for the purpose of controlling (reducing) erosion and runoff from a surface. In this context, the term 'ripping' refers to breaking up the surface. Rip lines may be created and installed for several reasons including:

- Reducing surface water flow and increasing deposition of sediment and nutrients;

- Breaking up the compaction of surfaces caused by repeated passes of heavy machinery; and
- Breaking up the material left in shallow mined out pits and borrow pits along roads.

A rip line may be created by dragging a tyne (or tynes) behind a bulldozer or grader to create a depression with mounds on either side, similar to ploughing (Figure 2). Rip lines are usually constructed along the contour and GPS-controlled graders can be used to ensure that they are spaced uniformly across the slope. The ripping process creates a small valley caused by the passage of the tyne with excavated material being pushed to either side of the valleys into what are termed mounds (Hancock et al 2016). Many mines use ripping to create surface roughness on newly created rehabilitated surfaces to reduce hill slope connectivity and surface water runoff velocity (Hancock et al 2016) and can be useful in assisting with vegetation establishment.

In the context of this study, rip lines (Figure 2) were installed the TLF when it was constructed in 2008-09. These rip lines were selected to form the basis of this study. Specifically, the rip lines within the instrumented erosion plots on the TLF are the source of field measurements for sediment loads and movement from ripped surfaces. An elevation model representing the ripped surface of Erosion Plot 2 (EP2) was modelled in the CAESAR-Lisflood LEM software to simulate the evolution of the landscape surface over time. Detailed information on the TLF, its construction, installation of rip lines and installation of monitoring equipment is described in Chapter 3.

Figure 2 Fresh rip lines on the waste rock mixed with laterite on EP3 on the TLF at Ranger mine site 4/4/09

1.3 Report outline

This report is composed of eight parts:

1. An introduction and background to the research question addressed in this report
2. A review of literature relating to rip lines
3. Background on the construction and use of the trial landform – one of the key sites in this study.
4. Background on the landform evolution model utilised in this study
5. Methods and techniques used for simulating the effect of rip lines on the surface
6. Results of model simulations
7. Discussion and interpretation of model results
8. Appendices providing additional detail on the methodology employed

2 Rip lines: A review of literature

2.1 Overview

Ripping or contour furrowing has been used in agriculture for many decades to improve infiltration, reduce or mitigate erosion and increase crop production. Ripping has also been used for remediation of roads and tracks and on mine sites to assist with vegetation growth, erosion mitigation and to break up compacted surfaces such as at the bottom of shallow pits or surfaces that have been compacted due to constant movement of heavy vehicles. Surface ripping of sites is also used to assist vegetation growth, with nutrients and sediment deposited in the depressions promoting the growth of vegetation. Luce (1997) suggest that ripping and related activities are an important part of reclaiming mined lands, with ripping considered so fundamental that few studies have addressed it directly.

In the United States, various treatments have been applied to rangelands to conserve moisture, prevent erosion and increase grass and crop production, including contour furrowing. Ripping of the surface is one variation of contour furrowing that has been extensively used. Brown and Everson (1952) found that the rip lines and ridges were still evident 10 years after ripping although smoothed by erosion and deposition and on the basis of present crop production believe that the rip lines would probably remain active for another 5 years.

Also in the United States, Branson et al (1966) reported that land treatments such as contour furrowing and ripping have been applied for more than 30 years in efforts to improve grass and crop production and to control erosion. In a study of seven types of mechanical treatment, contour furrowing at distances of between 3 feet (0.91m) to 5 feet (1.52m) to depths of 8 inches (20 cm) to 10 inches(25 cm) and broad base furrowing (pushing of material to form mounds rather than dragging a tyne or ripper) were found to be the most effective. Contour furrowing also increased moisture storage. No slope angles were given for these studies but the photographs in the paper suggest that the ground was relatively low angled and most likely less than 5%.

Surface ripping has also been suggested as a way of increasing infiltration. In the United States many forest roads are being closed as a step in watershed restoration, and the ripping of these roads is a common practice to increase infiltration capacity of the roads (Luce 1997). Results from a study by (Luce 1997), showed that ripping of roads increased hydraulic conductivities from 0 - 4 mm/hr for non-ripped surfaces to 20 - 40 mm/hr for ripped roads. Ecological restoration of forest roads and watershed requires improved vegetation cover and improved infiltration for forest road surfaces (Luce 1997) and the findings of the study suggest that ripping can be a reasonably effective step in the restoration process.

In Australia, Green (1989) reported that contour furrowing has been used to successfully restore overall productivity and stability of production on severely eroded soils in the Cobar and Broken Hill districts. The slopes are usually on sloping ridge county, and rarely exceed 5%.

In the Darwin area, Northern Territory, Australia the recovery of woody vegetation was investigated for sand and gravel pits/mines (Price et al 2005). The authors found that rehabilitation on sand mines was better than for gravel mines but that neither of them had recovered particularly well. There is no mention of the base of the mines being ripped prior to rehabilitation. They mention in the conclusion that miners now submit a mine management plan that details the rehabilitation methods to be used and are encouraged amongst other activities to reshape the pit and rip the surface, although this is not mandatory.

2.2 Ripping - mine site revegetation and rehabilitation

Rip lines have been used on mine sites for several decades, and are usually associated with the establishment and continued development of vegetation and infiltration of surface water. The studies detailed below initially refer to the use of ripping to promote vegetation growth and increase infiltration, and then how rip lines impact on erosion. In shallow open cut mines ripping is used to break up compaction of the floor of the mine site and allow root penetration for shrubs and trees.

2.2.1 Mine sites in the United States

At mine sites in the United States there is a large body of work focussed on investigating the impact of ripping surfaces to benefit vegetation growth. Kost et al (1998) investigated the influence of tree growth at a rehabilitated mine site with no mention of effects of rip lines on erosion, however they found that ripping benefitted the growth of green ash but no other species of trees was influenced.

In the Appalachian mountains of Eastern United States, trees were measured in October of 2008 after 5 years of growth (Fields-Johnson et al 2014). Subsoil ripping increased mixed hardwood survival from 43 to 71 %, hybrid Poplar trees biomass index from 1.51 to 8.97 Mg ha^{-1}, and Eastern white pine biomass index from 0.10 to 0.32 Mg ha^{-1}. When revegetating and planting trees on unused mined sites, subsoil ripping can aid survival and growth to an extent that will result in a valuable forest.

At a rehabilitated mine site in Kentucky (USA), tree survival, height, and diameter were measured in the fall of 2009, (Burger and Evans 2010). Average tree survival was 47% and 58% for the compacted and ripped treatments, respectively. Overall tree volume, which is an index of above-ground biomass, was 0.37 and 0.50 m^3 on the compacted and ripped treatments, respectively. Ripping significantly improved the growth of all species except white pine, but only 12% of the white pines survived in either treatment. Ripping proved to be an overall beneficial practice; however, it did not fully mitigate the adverse effects of compaction. Tree growth potential on these ripped treatment plots was less than half that of pre-mining capability based on average productivity values listed in the county soil survey for the pre-mining soil type.

Burger and Evans (2010) present some first year erosion pin measurements from a rehabilitated mine site in Lovely, Martin County, Kentucky, United States. In this instance the ripping was done to break up compaction created by multiple traverses of heavy machinery. After the first year before full ground cover establishment, average erosion rates on compacted plots was 1.8 cm (with an assumed bulk density of 1.5 g cm^{-3} this amounted to 270 metric tons per hectare). Soil erosion from the ripped plots was much lower at 0.2 cm or about 2 metric tons per hectare. In a subsequent study at different sites, Fields-Johnson et al (2014) found that after five years, subsurface ripping with weed control on rehabilitated mine sites increased plant survival

2.2.2 Mine Sites in Australia

In Western Australia, Alcoa has been undertaking ripping of mine floors and improving these techniques since 1969 (Menlger et al 2004). Ripping is generally conducted in two phases with the first phase ripping in straight lines across mine floors. The ripped mine floors are graded and topsoil and over burden deposited. Stage two involves ripping along the contour with a winged tyne to mix topsoil and overburden with the previously ripped mine floor.

Szota et al (2007) report on a study at Dwellingup, Western Australia, where the topsoil was spread on the mine floor prior to ripping and then seeds were broadcast at rates based on pre-mining surveys. The results from this study found that in places where the ripping had not penetrated the cemented subsoil, it resulted in fewer and smaller trees (Jarrah). Tap roots had not penetrated the cemented subsoil, with the trees relying instead on a number of lateral and sinker roots.

In the humid tropical climate at Gove, Northern Territory, rehabilitation at the Alcan Gove Bauxite Mine is reported by Spain et al (2006). At the completion of mining, stockpiled soil was applied to the site surface, the site was ripped and the surface soil from another site was applied. Seed of approximately 20 species from local provenance tree and shrubs was sown, grass seed and fertilizer are applied after a light surface cultivation. Between 18 kg and 25 kg ha^{-1} of P was applied as a single superphosphate. Of particular note is the deliberate exclusion of fire, however no time frame is given for the length of exclusion. The ripping of the surface was to break up the surface and not for erosion control.

At rehabilitated coal mines in Central Queensland, deep ripping along the contour was carried out to relieve compaction, improve infiltration and reduce runoff (Grigg et al 2000). Ripping is typically quite rough with pronounced ridges and furrows that will persist for many years. Seed is then spread on this surface. No assessment of the effectiveness or impact of the ripping is made or the impact on erosion.

Carroll et al (2000) found that at Oaky Creek (Queensland), ripping of plots to create a rough surface was shown to reduce runoff and erosion during the early stages of rehabilitation when vegetative growth was slow and the risk of erosion was high. The effectiveness of ripping and the degree of surface roughness tended to be greater on steeper gradients.

The Mary Kathleen mine site (Queensland) was rehabilitated in 1985 and thin soil and waste rock covers were placed on some of the waste rock dumps. These thin covers were ripped for seeding and as a result the underlying waste material was exposed on some of the rehabilitated areas (Lottermoser et al 2005). Contamination of soils and stream sediments from the Mary Kathleen mine site is from two sources (1) natural oxidation and chemical leaching in exposed pit floors and (2) from the erosion of steep waste rock dumps and physical dispersion of mine waste particles into the surrounding soils and local stream (Ashley et al 2003; Lottermoser et al 2005). The waste rock dumps have acted as point sources of contamination, and have only affected the immediate area and the fluvial system downstream, however, there is no quantification of this eroded material (Ashley et al 2003).

The Pine Creek gold mine site, (Northern Territory) was rehabilitated in the early 1990's and the rehabilitation areas were scarified (synonymous with the term ripped) to a depth of approximately 200 to 300 mm prior to seed sowing (Fawcett 1995). During a site visit to Pine Creek in 2015, these scarified lines were clearly visible on the ground, due to a recent fire. There were trees present in the scarified rehabilitated areas but no measurements of species density and composition were undertaken. There was limited visible rill and gully erosion on the rehabilitated site with only minor channel erosion in the channel depressions on the valley floor.

Ludwig et al (2003) undertook studies at both Ranger Mine Site (Northern Territory) and Pine Creek mine site (Northern Territory). Ludwig et al (2003) clearly documented that rip lines persisted for at least 12 years at an experimental rehabilitated area on the Ranger mine site, which they identified as an important indicator and say that surface roughness, as indicated by rip-lines, was also a useful indicator of the potential for a landscape to retain resources because these rip-lines persisted until vegetation was well established to assume this role. The authors note that the rip lines rapidly collect litter and, during the wet-season, this litter quickly decomposes.

The effect and importance of rip lines at the Ranger mine site have been investigated intermittently during the life of the mine, and are discussed in detail in the section below. Finnegan (1993) made the following statement

> "As a treatment for mine spoil, there appears to have been little research performed in Australia into the effectiveness of deep ripping. In his handbook on mine rehabilitation Hannan (1984) recommends ripping to a depth of 60 to 90 cm but provides little further detail. Ward et al (1993) mentioned the use of shallow ripping and seeding to accelerate rehabilitation of the Mary Kathleen uranium mine, but again little detail was provided. Burns (1992) noted that ripping is only effective if infiltration and compaction are genuinely limiting factors in the establishment of vegetative cover".

The quantification of the effectiveness of rip lines on mine site rehabilitation has not been well researched or investigated. The Ranger mine site is perhaps the one site in Australia where research has been undertaken on rip lines.

2.3 Rip lines at the Ranger mine site

As noted in section 1.2, rip lines have most recently been installed on the TLF. However, rip lines have been installed elsewhere on the mine site over the active life of the mine. In addition, the impact of rip lines at the Ranger mine site has been periodically investigated over the last 25 years, with initial studies undertaken in the early 1990's.

Rainfall simulation experiments were conducted on ripped plots on the waste rock dump at Ranger mine site during the dry season of 1991 where six experimental plots were established on a section of seven year old waste rock dump (Finnegan 1993). Each of the plots had a different ripping pattern, including some with cross ripping. Rainfall simulation experiments were carried on the ripped plots consisting of a sequence of increasing intensities (increased number of nozzles). Finnegan (1993) concluded that deep ripping (average of 0.75 m) of the spoil dumps at Ranger mine substantially increased the infiltration rates of the mine soil as compared to non-ripped spoil material. The six ripping treatments, which were produced by combining ripping properties such as depth, spacing and rip line orientation did not provide any clear evidence that one particular property of the ripping treatments was more responsible for improved infiltration. No assessment of erosion from these ripped plots was made.

In 1993, rainfall simulation experiments were undertaken on the same waste rock dump plots as in 1991. The data collected during these experiments was investigated by George (1996) and George & Willgoose (1997). The comparisons between the six ripped plots show that there was no significant difference between the different ripping strategies with regard to infiltration.

During the 1993/94 and 1994/95 wet seasons, natural storms were monitored on 3 erosion plots (Cap, Soil, Fire site) constructed on waste rock dumps at the Ranger mine site. The results from some of this monitoring have been published in Saynor and Evans (2001) and are outlined briefly below.

The Cap site was established in 1993, and had an area of 591m^2 with an average slope of 2.8%. It was not surface ripped, had negligible vegetation and low surface roughness. The Soil and Fire sites were established in November 1994. The Soil site as constructed was 600m^2, had an average slope of 1.2%, was surface ripped and topsoiled (approximately eight years prior to the study) and had a vegetation cover of low shrubs and grasses *(Acacia* and *Sarga* spp., respectively). The Fire site plot was 600 m^2 had an average slope of 2.3% and was originally topsoiled and surface ripped as well. At the time of the study, the Fire site was vegetated with low shrubs, grasses and well established trees/shrubs (*Eucalyptus*, *Acacia* and *Grevillea* spp.) approximately 10 years old. On both the Soil and Fire sites there ware high levels of surface roughness due to being ripped and the presence of large competent rock fragments.

The three monitored plots were within 500 m of each other and it is reasonable to assume that the sites experienced the same storm events. For corresponding storms at each site, bedload was highest from the cap site which had negligible vegetation and was not surface ripped. Bedload was higher for the soil site (which had grasses and low shrubs) than for the fire site (which not only had grasses and low shrubs but also tall trees and a thick cover of leaf litter). For erosion on the three plots with similar slopes, these results indicated that a non-ripped surface with negligible vegetation cover had the highest bedload, however it was difficult to separate out the independent effects of rip lines and vegetation.

Following a controlled fire in May 1995 on the Soil site, debris or litter dams were observed to develop through deposition of vegetative matter from runoff under rainfall simulation (Evans et al 1999). The authors suggested that the development of litter dams may temporarily reduce topsoil loss from burnt areas. These temporary storage areas may reduce loss of seedbank resulting from increased erosion rate after fires, and storage behind the dams may enhance regeneration of post-fire vegetation.

Evans and Willgoose (2000) investigated the effects of vegetation and surface ripping for two surfaces at the Ranger mine site. The surface was ripped using a bulldozer dragging a large tyne which creates a single longitudinal furrow in this case to 1 m deep separated by approximately 1 m from the adjacent parallel rip line. The SIBERIA landform evolution model was used to predict temporal and spatial erosion on the designed rehabilitated landform circa year 2000. The SIBERIA simulations showed that for the non-vegetated and non-ripped case the landform at 1000 years was dissected by localized erosion valleys (maximum depth =7.6m) with depositional fans (maximum depth = 14.8 m) at the outlet of the valleys. For the vegetated and ripped case, reduced valley development (maximum 1000 year depth = 2.4m) and depositions (maximum 1000 year depth of 4.8 m) occurred in similar locations as for the non-vegetated and non-ripped case (Evans and Willgoose 2000). These results suggest that the combination of vegetation and rip lines reduced erosion by approximately 68% and deposition by 67%. However, no simulations however were undertaken on ripped and non-ripped surfaces without vegetation, so it is not possible to quantify the impact of rip lines without the vegetation input.

In research addressing water balance of a waste rock cover for barren mine waste at Ranger uranium mine, Hollingsworth et al (2010), stated that surface treatment activities such as deep ripping also need to be combined with effective revegetation, otherwise the stable soil porosity that is associated with biological activity and is essential for ecosystem function, will not develop.

One of the reasons for creating rip lines is to increase surface roughness. Surface roughness can also be increased by natural construction of debris dams. Debris dams were observed to develop on the soil site at Ranger after the site was burnt in May 1995 and the rainfall simulation runs were completed (Evans et al 1999). Following a controlled fire on the TLF at Ranger in 2016 a rainfall event of 17 mm occurred on 12 July 2016. Several debris dams were observed on erosion plots 3 and 4. The occurrence of fire at the Ranger site has led to the development of debris dams on two occasions which increase the surface roughness and potentially reduce erosion from the areas.

3 Trial landform – rip line establishment

The TLF was constructed at Ranger in 2008-09 to monitor erosion, test landform design and revegetation strategies. The TLF as constructed had a total area of 8 hectares and a nominal slope of 2.2%. The landform was designed to test two types of potential final cover material: waste rock; and waste rock blended with approximately 30% of fine-grained weathered horizon material (laterite). In addition to different types of cover materials, two different planting methods were initially assessed (direct seeding and tubestock). However, because of poor germination, those plots which had been direct seeded, were infilled with tubestock in January 2011. Although not directly relevant to the objectives of this study, it was observed that where tubestock was planted at the bottom of the rip lines, some of these died due to drowning because the water did not infiltrate fast enough due to the presence of the laterite (M. Daws Pers. Com. 2011).

Once construction of the TLF was complete with the surface levelled to a 2% slope (essentially running east to west) the surface was ripped along the contour using tynes attached to a D7 bulldozer (Figures 3 & 4). The surface was ripped on 2nd and 3rd of March 2009 and there was a storm on the night of the 2nd March which increased the water content of the surface material. This resulted in less distinct rip lines on the 3rd of March 2009 in the area containing EP2. The variable nature of the laterite in areas 3 & 4 also resulted in collapsed, less distinct rip lines (Daws & Poole 2010). In general, the rip lines were approximately 2 m apart and generally to a depth of 40 - 50 cm, however, there were variations across the surface of the TLF.

Figure 3 D7 Bulldozer ripping areas of the TLF. 3/3/09

Figure 4 D7 Bulldozer ripping

During 2009, the Supervising Scientist Branch constructed four erosion plots (each approximately 30 m x 30 m) on the TLF surface, with two plots in the area of waste rock, and two in the area of mixed waste rock and laterite (Figure 5). The plots were physically isolated from runoff from the rest of the landform area by constructed borders. The erosion plots were specifically constructed to enable:

1. Monitoring of erosion rates through time to assess effects of different surface treatments and vegetation establishment strategies;

2. Generation of input data for long term predictive geomorphic computer modelling of the proposed landform designs; and

3. Determination of sediment loads and key contaminants present in the dissolved and fine suspended-sediment fractions available for export from the TLF via the surface water runoff pathway.

The data collected from the erosion plots in the waste rock have been collated and used to calibrate and validate landform modelling predictions of sediment loads from the plots. In the context of this study, the simulated evolution of the surface of EP2 to represent a ripped surface on a waste rock, forms the basis for the assessment of the effectiveness and impact of ripped surfaces on a rehabilitated landform. As described in a later section, the results of simulations on EP2 were compared with simulations of a representative non-ripped surface to further quantify the effects of ripping.

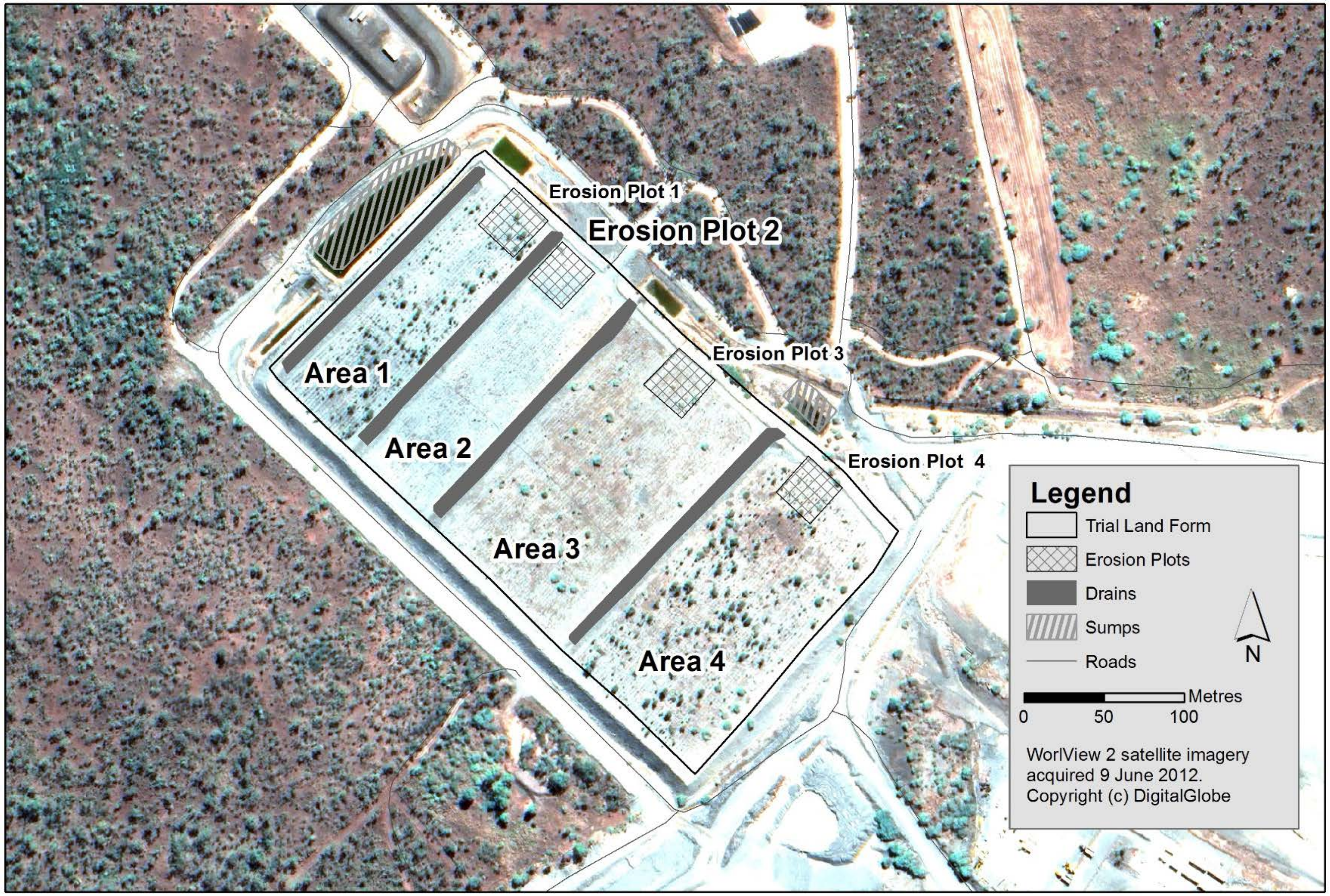


Figure 5 The layout of the Trial Landform

4 Landform Evolution Models

Landform evolution modelling provides a means for assessing the potential performance and effectiveness of rip lines in controlling erosion on a landform. Over the last 40 years a variety of models have been used to evaluate erosion and simulate landscape stability (Evans, 2000; Loch et al., 2000). These models include the water erosion prediction programme (WEPP) (Laflen et al., 1991), universal soil loss equation (USLE), modified universal soil loss equation (MUSLE), revised universal soil loss equation (RUSLE) (Onstad and Foster, 1975; Wischmeier and Smith, 1978; Renard et al., 1994), and SIBERIA (Willgoose et al., 1989).

The CAESAR Landscape Evolution Model (LEM) (Coulthard et al 2000, 2002) was originally developed to examine the effects of environmental change on river evolution, and to study the movement of contaminated river sediments. Recently, it has been modified and applied to study the evolution of proposed rehabilitated mine landforms in northern Australia (Hancock et al, 2010; Lowry et al, 2011; Saynor et al, 2012). Here, CAESAR-Lisflood (Coulthard et al., 2013), an enhanced version of the CAESAR model is used to simulate and assess the geomorphic effectiveness of rip lines on conceptual rehabilitated landform of the Ranger uranium mine in the Northern Territory, Australia.

4.1 CAESAR Lisflood

CAESAR-Lisflood (Coulthard et al., 2013) is the latest iteration of the CAESAR model. In this study, CAESAR-Lisflood version 1.8g was employed. It combines the Lisflood-FP 2d hydrodynamic flow model (Bates et al, 2010) with the CAESAR geomorphic model (Coulthard *et al.*, 2000; 2002; 2006, Van De Wiel et al., 2007)) to simulate erosion and deposition in river catchments and reaches over time scales from hours to 1000's of years. The model does this by routing water over a regular grid of cells and altering elevations according to erosion and deposition from fluvial and slope processes.

CAESAR-Lisflood can be run in two modes: a catchment mode (as used here), with no external in-fluxes other than rainfall; and a reach mode, with one or more points where sediment and water enter the system. Both modes require the specification of several parameters or initial environmental conditions. For each model area, these parameters include surface elevation, grain sizes and rainfall (catchment mode) or a flow input (reach mode). The initial topography of the landscape drives fluvial and hillslope processes that determine the spatial distribution of erosion (loss) and deposition (gain) over a specified time period. This altered topography becomes the starting point for the next time step. Outputs of the model are datasets representing elevation and sediment distributions through space and time, and discharges and sediment fluxes at the outlet(s) through time. There are four main components to CAESAR-Lisflood: a hydrological model; a flow model; fluvial erosion and deposition; and slope processes. When running in catchment mode, runoff over the catchment is generated through the input of rainfall data. The surface runoff generated by the hydrological model is then routed using a flow model.

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

A key attribute of the CAESAR-Lisflood model is the ability to utilise hourly and sub-hourly recorded rainfall data. This enables specific rainfall events to be modelled, which in turn enables the effect to these events (including the amount and extent of erosion and runoff) to be studied. Studies by Erskine & Saynor (1996) and Moliere et al (2002) found that the majority of erosion typically occurs during a limited number of high intensity events, highlighting the strength of the CAESAR-Lisflood model in being able to model individual events. In addition, as the climatic region in which the Ranger mine occurs is dominated by seasonal, high intensity rainfall events (McQuade et al., 1996), the ability to model specific rainfall events meant that the CAESAR-Lisflood model was the model of choice for this project. For the purposes of this study the CAESAR-Lisflood model utilised rainfall data collected at 10 minute intervals. This time interval was selected to reflect the small catchment areas modelled, and the corresponding shorter timeframes for system response to rainfall. Rainfall data collected for the wet seasons between 2009-10 and 2015-16 were used in the simulations reported here.

5 Methods

In order to test the effectiveness of rip lines in reducing erosion, model simulations were undertaken for ripped and non-ripped surfaces on the Ranger mine site. Model simulations were also undertaken for different slope angles for each of the surfaces.

The simulations utilised the CAESAR-Lisflood LEM to assess the effectiveness of rip lines. CAESAR-Lisflood requires the collation and integration of data from a range of different sources. The key data inputs required by the CAESAR-Lisflood model for each simulation are a digital elevation model (DEM) of the landform surface; a rainfall dataset and particle size data for the landform surface.

Specific parameters collected to assess the effectiveness of rip lines included the predicted denudation rate (or rate of surface lowering); the predicted total load yield over a defined period; and temporal changes to the topography of the ripped and non-ripped surfaces.

5.1 CAESAR-Lisflood simulations and analysis

5.1.1 Site selection

Two sites, representing ripped and non-ripped waste rock surfaces were selected at the Ranger mine site. Both surface sites were approximately 30 x 30 m in area and constructed from Ranger waste rock material on relatively even surfaces.

5.1.1.1 Ripped surface – EP2

EP2 of the Ranger TLF was used to represent the ripped surface (Saynor et al, 2016). Importantly, earlier studies (Lowry et al 2011; Saynor et al 2012) have demonstrated that field data collected from EP2 have a high correspondence with CAESAR-Lisflood predictions over the same period. This provides confidence that CAESAR-Lisflood was able to predict sediment load and discharge measurements accurately. This site was distinguished by the presence of rip lines (15 rip lines), regularly spaced along the slope contour at intervals of approximately 2 m. Its measured dimensions are 29.9 m across by 28.8 m down the plot giving an area of 858.3 m^2. The TLF surface was constructed nominally to a 2% slope, however the average slope of EP2 was surveyed at 1.62 %.

5.1.1.2 Non-ripped surface

The non-ripped area (Area 3) was randomly selected from 9 potential sites identified on the mine site using high resolution aerial photographs (Figure 6). Non-ripped sites were selected by visual interpretation of very-high-resolution aerial photography taken by Aerometrex in 2013 of the Ranger mine site in conjunction with 0.5m-interval topographic contours produced photogrammetrically from this imagery. The sites selected had to be relatively flat with a uniform slope and on areas of waste rock. A total of nine possible sites (Figure 6) were identified, and the site called Area 3 was randomly selected as the non-ripped surface for this study.

5.1.1.3 Slope angle determination

The slope angles of 2%, 4%, 8% & 12% were chosen to ensure that the range of possible slopes were included in this study. ERA have suggested that the rehabilitated landform will have slopes ranging up to 4 %, however on the most current version of the rehabilitated DEM (FLV5-2) there are slopes up to 8% on the slopes near the TLF. Therefore slopes of 2%, 4%, 8% and 12% were investigated in this study.

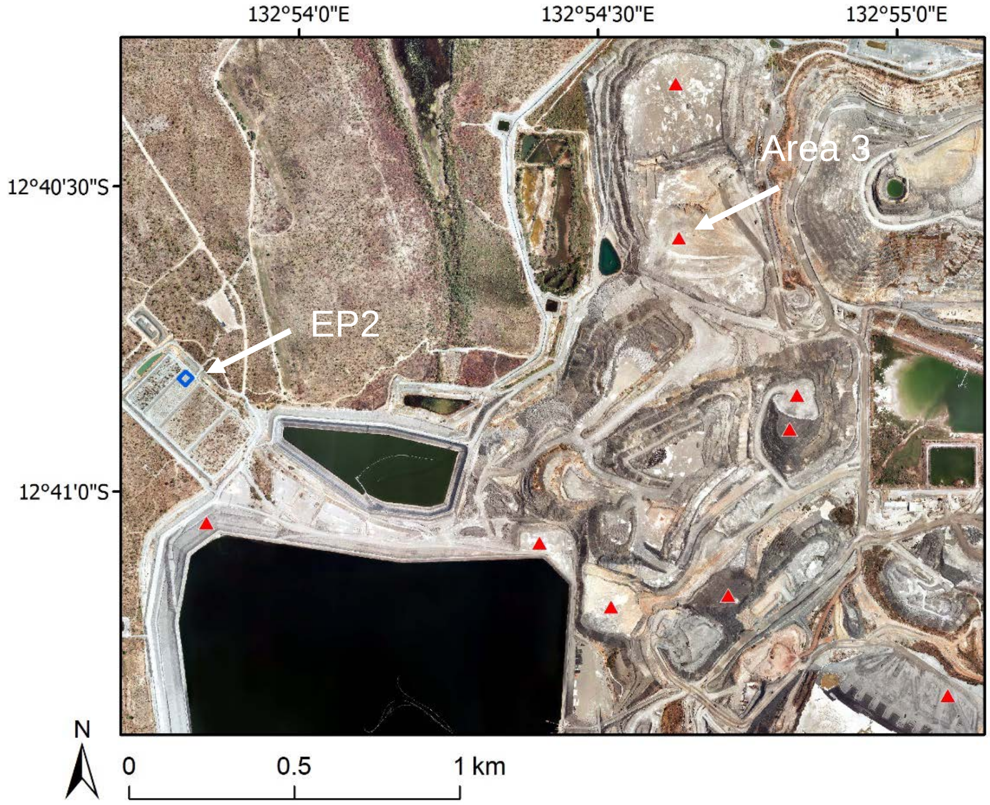


Figure 6 Location of the potential study sites. The non-ripped sites are shown as red triangles and the ripped site is shown as a blue square.

5.2 Preparation of site DEMs

It was important to maintain appropriate scale between the DEMs used to represent the initial surface elevation of the ripped EP2 site and the non-ripped site, for input into CAESAR-Lisflood. A series of steps were undertaken to standardise the spatial resolution, dimensions and outer boundary of the different surface DEMs:

1. DEMs were generated for both EP2 and Area 3 (see 5.2.1 for detail);
2. The DEM of EP2 had a raised bund on three sides (built to isolate the plot) and a collection pipe at the downstream end to channel water off the plot. The bunds served to ensure that no external run-on occurred to the plot. The raised bund on EP2 were replicated and used as a standard frame on the Area 3 site DEM;
3. The DEMs of the ripped EP2 and Area3 had different slopes. The slope of each DEM was set to zero to ensure that each slope had the same level starting point; and
4. Using the zero-slope datasets of ripped and non-ripped surfaces, a series of four DEMs were generated for each surface condition (ripped / non-ripped) with average slopes of 2, 4, 8, and 12 %. Slope functions were calculated by applying a multiplicative linear slope constant.

Details on these slope manipulation methods are provided below with much greater detail in Appendix. 1.

5.2.1 DEM Sources and spatial resolution

Erosion plots of the TLF (including EP2) were surveyed using a Terrestrial Laser Scanner in June 2010 at a spatial resolution of 0.02 m. The data were used to generate a DEM of EP2 with a horizontal grid resolution of 0.2 m, which has been used in earlier modelling studies of the TLF (Lowry et al, 2011; Saynor et al 2012). The DEM of the Area 3 site was originally generated from aerial photography to a grid resolution of 0.5 metres. To maintain consistency with earlier studies on the landform, the DEM of Area 3 was resampled to a resolution of 0.2 m to align it with the DEM of EP2.

Both DEMs were processed to ensure they were pit-filled and hydrologically corrected. This pit filling was important in order to remove data artefacts, which included remnants of vegetation (peaks) as well as artificial depressions, or sinks caused through the process of generating the DEM. Pre-processing of datasets used as DEM inputs for the CAESAR-Lisflood model was initially undertaken using ESRI ArcGIS software and Microsoft Excel spreadsheets.

5.2.2 Applying a standard frame to DEMs

The EP2 site was surrounded by a bund approximately 15 cm in height. This raised boundary was included on three edges of the DEM to prevent any run-on of sediment discharge from external sources. The down-hill slope edge represented the edge of the simulation area, and was the accumulation zone in which all discharge and sediment leaving the plot was recorded in model outputs.

A raised bund was not present on the non-ripped site so the boundary of the EP2 DEM was applied to the non-ripped site to prevent run-on from external sources, and ensure commonality with the ripped site. This 'frame design' ensured that the same area and boundary conditions were used for both the ripped and non-ripped DEMs.

5.2.3 Detrending the slope of site DEMs

There was a difference in initial average slope characteristics between the DEMs of EP2 and Area3. In order to generate DEMs representing a range of different slopes, the slope 'trend' had to first be removed. This process is known as detrending and results in a horizontal surface (slope = zero). Figure 7 shows the original slope as well as the flatter zero slope. A much more detailed method of detrending the slope is given in Appendix 1.

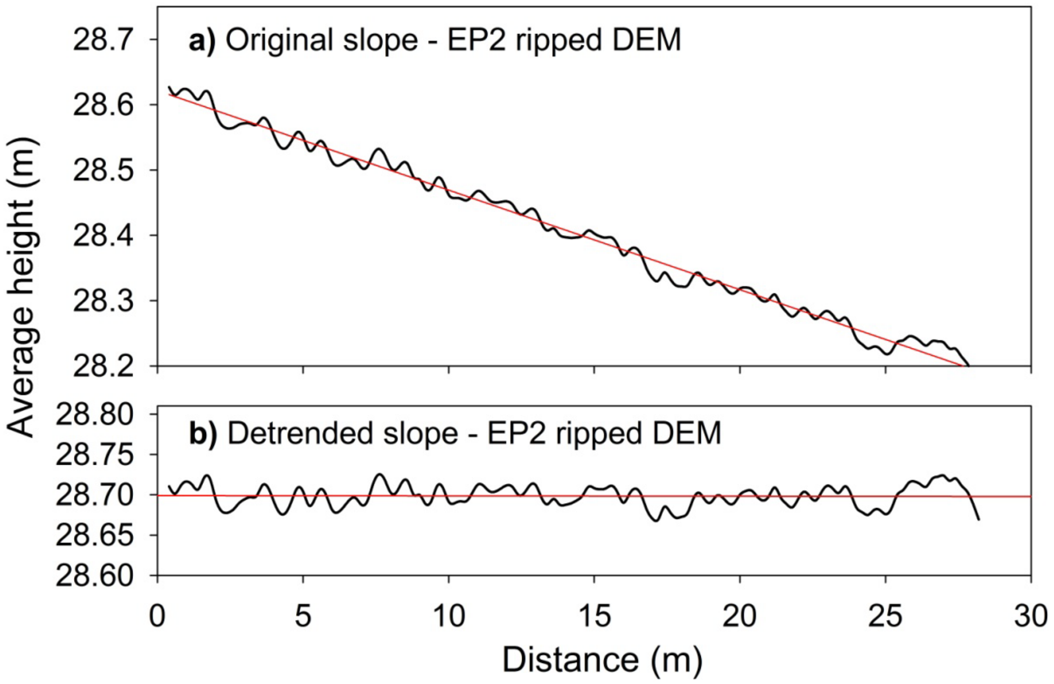


Figure 7 The average height profiles (in black) taken along the major slope of the Erosion Plot 2 (EP2) DEM before **(a)** and after **(b)** the average slope was detrended. Regression trend-lines are represented in red.

5.2.4 Generating a range of slopes from original DEMs

The final step in the preparation of DEM for the model inputs was to produce a series of new slope surfaces (2, 4, 8 and 12 %) from the two zero sloped DEMs representing the ripped / non-ripped surfaces. This was done in Excel using the linear slope functions listed in Table 1. This surface (worksheet) is then subtracted from the actual DEM surface (worksheet) to derive a new surface with the applied slope, with similar 'roughness' characteristics of the original surface. Profiles of average height taken along the length of the new slopes are shown in Figure 8. The x axes in Figure 8 refer to the Australian Height Datum of the original surveyed surface.

Table 1 Linear slope constants applied to ripped and non-ripped DEMs in Excel in order to generate a series of DEMS with different slopes. *Y* is the derived linear slope trend for a specific location (grid cell) and *X* is the distance in metres from the left edge (column A, zero)

Slope (%)	Slope equation
2	Y= 0.02**X*
4	Y= 0.04**X*
8	Y= 0.08**X*
12	*Y*= 0.12**X*

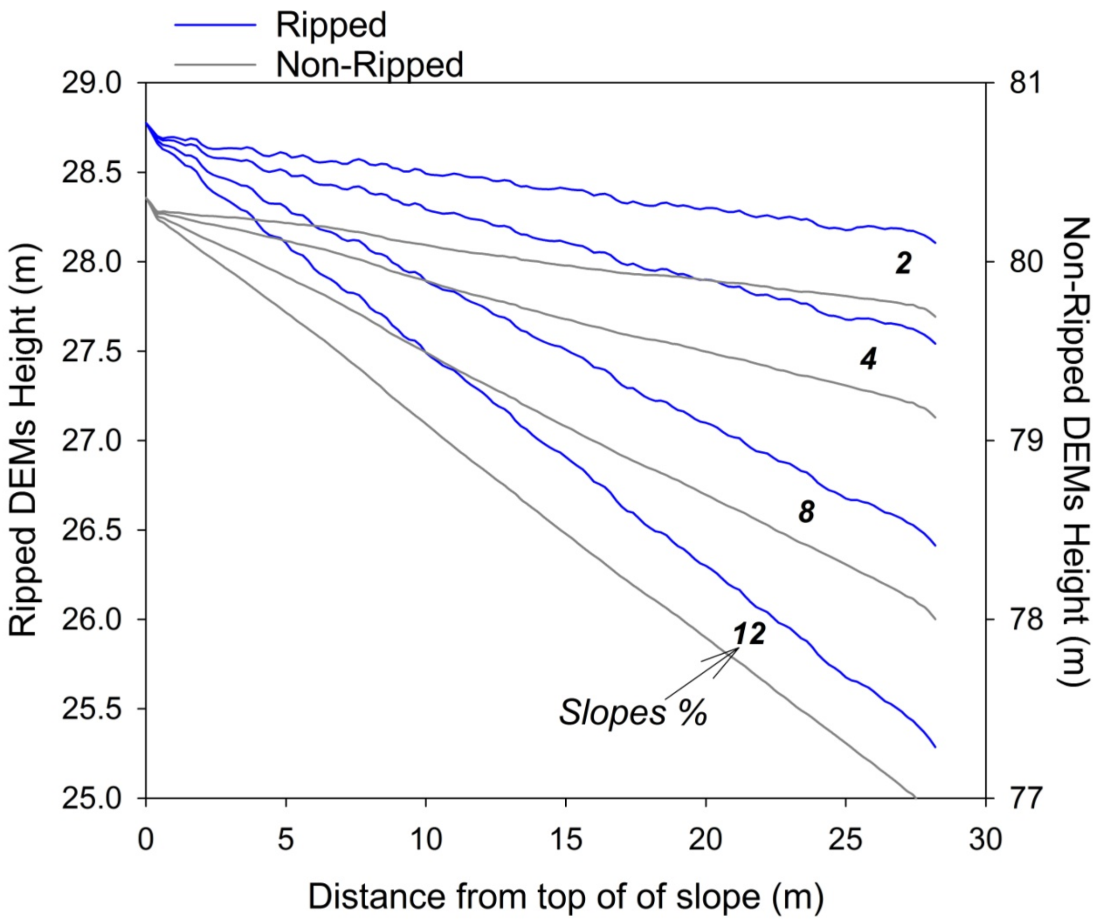


Figure 8 Mean height profiles measured along the length of the resulting slope for ripped (EP2) and non-ripped (Area3).

5.3 CAESER-Lisflood Parameterisation

This section describes parameterisation used for all CAESER-Lisflood ver. 1.8g simulations in this study. All simulations were run in catchment mode (Section 4.1). Screenshots from the model GUI provided in Appendix 2 show additional details on the standardised settings that were used in simulations.

5.3.1 Grain size distribution

One of the key parameters used by CAESAR-lisflood is the grainsize distribution of the surface cover(s) being modelled. For the purposes of this study, the grain size distribution of the waste rock surface of the TLF was used. The methodology for collecting this data and its characteristics have been described in detail by Saynor et al (2012). A schematic representation of the grain size distribution used in this study and in previous studies (Saynor et al 2012, Lowry et al 2014, Hancock et al 2015) is shown in Figure 9.

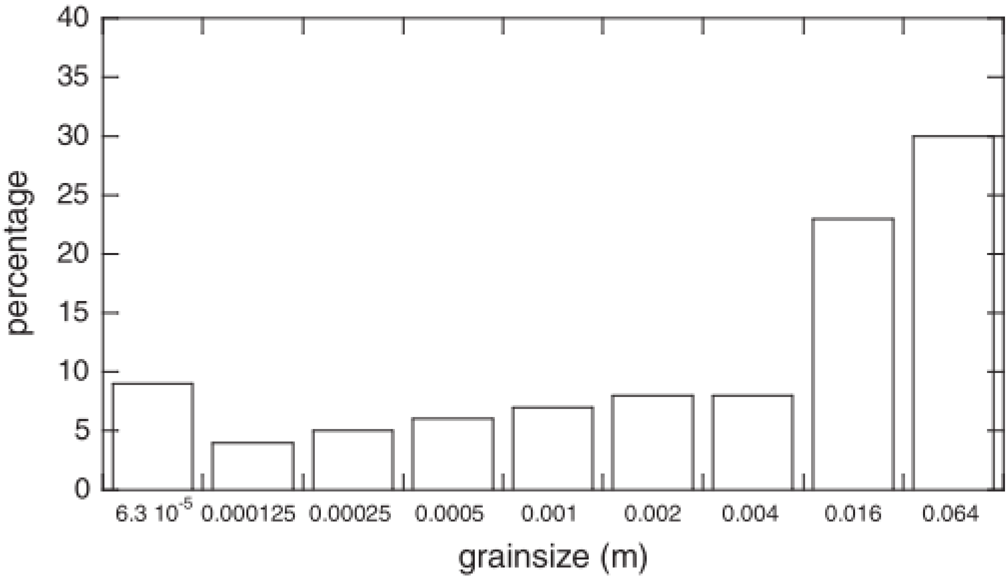


Figure 9 Grain size distribution of waste rock surface conditions (Saynor et al 2012, Lowry et al 2014, and Hancock et al 2015)

5.3.2 Rainfall data

Rainfall measurements were collected by a pluviometer located adjacent to each erosion plot on the TLF. Rainfall measurements were recorded for each rainfall year between 2009 and 2016, with each rainfall year commencing the 1st of September and running through to the 31st August of the following year. For this study, rainfall data from EP2 was output at 10-minute intervals. In order to enable model simulations of 50 years, the 7-year recorded rainfall dataset was looped more than seven times to generate a 50-year rainfall dataset for input into model simulations. The seven year data include a large event where 180 mm fell in 2 hours.

5.3.3 Vegetation data

CAESAR-Lisflood currently has a relatively simple vegetation component, which has the effect of restricting erosion when activated. Two variables are used: "grass maturity" and "vegetation critical shear." Grass maturity relates to the rate at which vegetation reaches full maturity in years. For the purpose of these simulations, a value of two was used for all simulations implying that a mature cover of grass was established across the entire surface in two years. Importantly, this value has been used purely for modelling purposes to simulate the presence of a grass cover and does not represent an expected or observed period for grass maturity on the Ranger site. Vegetation critical shear is the value above which vegetation will be removed by fluvial erosion. The lower the critical shear, the more easily vegetation is swept away; the higher the value, the more resistant the surface. For the purposes of these simulations, a critical shear value of seven was applied. This implies the vegetation is resistant to erosion. In this approach to modelling, a vegetative cover essentially increases the physical resistance of the DEM surface to the erosive force of flowing water by allowing the development through time of a surface cover of grass. Importantly, this is a bulk parameter approach that does not account for specific physical properties of vegetation. To date, the parameters used in model simulations on the Ranger landform are not based on bush, grass or tree communities in the north

Australian environment. Instead, parameters have been determined through an iterative testing program to determine parameter values that best match erosion figures for vegetated environments in the Ranger lease. A vegetation component more relevant to the Ranger mine site is being developed but was ready to be used in this study.

5.3.4 CAESAR-Lisflood scenarios

A number of scenarios were individually modelled for both ripped and non-ripped surfaces, respectively. CAESAR-Lisflood simulations were run for periods of 7 years (matching the period for which field data – specifically rainfall and bedload measurements – have been collected from the TLF); and 50 years. The latter simulations utilised the 7 year rainfall file collected on the landform, looped end-to-end 7 times. Simulations were run for a period of 7 & 50 years on ripped and non-ripped surfaces with slopes of 2, 4, 8 and 12%. The flat surfaces with zero % slope did not have simulations completed due to limitations with the model. Specifically, on slopes of zero %, the model has difficulty predicting the movement of water across the catchment towards the outlet, resulting in excessive simulation times.

The following sets of simulations were applied to each of the ripped and non-ripped surfaces on slopes of 2, 4, 8 and 12 %:

- A 7-year simulation using rainfall data collected on the landform for the period 2009-16 at intervals of 10 minutes, with the vegetation layer turned off. This provides a conservative output scenario;

- A 7-year simulation using rainfall data collected on the landform for the period 2009-16 at intervals of 10 minutes, with the vegetation layer turned on;

- A 50-year simulation using the 2009-16 rainfall data looped 7 times, with the vegetation layer turned off. This provides a conservative output scenario for a medium time-frame; and

- A 50-year simulation using the 2009-16 rainfall data looped 7 times, with the vegetation layer turned on.

5.4 Sediment movement on the TLF

During fieldwork on the TLF in 2016 some deposited material (Figure 10) was noticed on the southern part of Area 2 (Figure 5). A depositional fan (transported and deposited sediment) was observed to have formed amongst the rips in this part of the TLF. The area contributing was observed to be the non-ripped perimeter road around the TLF where shallow eroded channels had been eroded. The perimeter road upslope from the depositional fan was followed/traced upslope and included long sections of the surrounding road that had not been ripped. Runoff from the non-ripped surface area is running down the road, eroding material and depositing the sediment amongst the rip lines. Imagery from a UAV flight in May 2016 was used to map the various areas including:

- depositional areas including depositional fan,
- eroded channel, and
- catchment area.

During a subsequent field trip to the TLF on 14 October 2016 the depth of deposited material was measured in several locations on the depositional fan (Figure 10). Five holes were carefully dug down to the original surface and depths measured using a steel rule. The depth of sediment is taken to approximate the deposition of sediment in the area.

Figure 10 Hole dug in the depositional fan on Area 2 (14 October 2016)

Although this report was mostly a modelling study, this opportunistic observation was used to quantify a non ripped area that had been eroded and the subsequent deposition.

6 Results

CAESAR-Lisflood simulations were run for periods of 7 years and 50 years on the ripped and non-ripped surfaces. The results of the simulations are presented in the subsequent sections.

6.1 Modelling erosion from ripped and non-ripped surface for different slope.

This section provides the results from various simulations, expressed as total loads (m^3) and as denudation rates (mm/yr).

6.1.1 Total load erosion results

CAESAR-Lisflood predicts the load for each grain size class used in the simulation. As noted earlier, nine different grain size classes were incorporated into each model simulation. The total sediment load for each simulation period is obtained by summing the predicted loads of the individual grain size classes.

The results show that in the short term (7 years), the predicted total loads from non-vegetated ripped surfaces are less than from the non-ripped surface, although on the 12% slope the total loads are very similar with the total load from the ripped surface only 6 % higher than from the non-ripped surface (Table 2). It can also be seen in Table 2 that the absence of rip lines on slopes of 2% results in total loads up to 72% greater than a comparable area on a slope of 2% with rip lines.

Table 2 Total load predicted from non-vegetated ripped and non-ripped surfaces of varying slopes after 7 years.

Slope (%)	Ripped surface total load (m^3)	Non-ripped surface total load (m^3)	Percentage change in load
2	0.53	0.91	72
4	0.86	1.00	16
8	0.94	1.07	14
12	1.04	1.10	6

In the longer term (50 years) the simulation results for non-vegetated surfaces show (Table 3) that as slope increases the effectiveness of rip lines in reducing the total sediment loads is vastly reduced. On a 2 % slope, non-ripped surfaces produce 60% more sediment load than ripped surface with a slope of 2%. However, non-ripped surfaces produce at least 11% less sediment load than ripped surfaces on slopes of 12%.

Table 3 Total load predicted from ripped and non-ripped non-vegetated surfaces of varying slopes after 50 years. (Negative value indicates that the load from the non-ripped plot is lower than the ripped plot).

Slope (%)	Ripped surface total load (m^3)	Non-ripped surface total load (m^3)	Percentage change in load
2	1.57	2.51	60
4	3.08	3.20	4
8	3.70	3.57	-4
12	4.08	3.65	-11

The impact that rip lines have on different slopes over time can be seen in Table 4. Total loads on the 2 % slope over the 50 year period gradually reduce, however the total load from the non-ripped surface is still 60 % higher than the ripped surface after 50 years. The total loads for the 4% slope show that the non-ripped surface is still higher than for the ripped surface but only by 4 % after 50 years. For the steeper slopes of 8% and 12% the total load from the non-ripped surface is lower than from the ripped surface after 30 years on the 8% slope and 20 years on the 12% slope.

Table 4 Percentage change (increase / decrease) in total loads of non-ripped plots compared to ripped plots over time on non-vegetated plots of varying slope (Negative value indicates that the load from the non-ripped plot is lower than the ripped plot).

Slope (%)	Year10	Year 20	Year 30	Year 40	Year 50
2	76	70	59.0	60.0	60
4	19	9	9	6	4
8	9	4	-1.0	-3	-3
12	2	-3	-7	-9	-11

6.1.2 Denudation erosion results

Simulation results indicate that over a 7-year period, denudation rates from a non-vegetated surface increase as the slopes increase for both ripped and non-ripped surfaces (Table 5). However, while the denudation rate for ripped surfaces doubles (from 0.08 mm/yr^{-1} to 0.16 mm/yr^{-1}) as the slope increases, the denudation rate for non-ripped surfaces only increases from 0.15 to 0.17 mm/ yr^{-1}.

Table 5 Denudation rates from non-vegetated surfaces after 7 years

Slope (%)	Ripped (Plot 2) Denudation mm/yr-1	No Ripping (Area 3) Denudation mm/yr-1
2	0.08	0.15
4	0.09	0.16
8	0.15	0.17
12	0.16	0.17

Denudation rates from non-vegetated surfaces for 7 years are lower for ripped surfaces although the steeper the slope the less the difference between the rates.

These differ when simulations are extended to 50 years (Table 6). Specifically, while non-vegetated ripped surfaces produce denudation rates half that of non-ripped surfaces on slopes of 2%, non-vegetated ripped surfaces are predicted to produce the same denudation rates as those of non-ripped surfaces on slopes of 4% and 8%. Ripped surfaces on slopes of 12% are predicted to produce greater denudation than non-ripped surfaces on equivalent slopes.

Table 6 Denudation rates from non-vegetated surfaces after 50 years

Slope (%)	Ripped (Plot 2) Denudation mm/yr^{-1}	No Ripping (Area 3) Denudation mm/yr^{-1}
2	0.03	0.06
4	0.07	0.07
8	0.08	0.08
12	0.09	0.08

6.2 Effect of vegetation

Simulations undertaken using CAESAR-Lisflood indicate that the presence or absence or vegetation on the landform has an important effect on the denudation rates recorded from both the ripped and non-ripped surfaces being modelled. While acknowledging the limitations of the vegetation component in the CAESAR-Lisflood model, the simple presence/absence of a vegetation layer in model simulations was shown to have an impact on erosion in all scenarios, across different surfaces and slopes.

6.2.1 Effect of vegetation on total loads

The effect of vegetation on annual total loads and discharge is shown graphically in the figures below. On the 2 % slope for ripped (Figure 11) and non-ripped (Figure 12) surfaces the total load decreases gradually over time with no vegetation but with the vegetation function turned on the total load decreases rapidly in the first 2-3 years and stays low for the remainder of the simulation. This trend is magnified when applied to a 12% slope for ripped (Figure 13) and non-ripped surfaces (Figure 14).

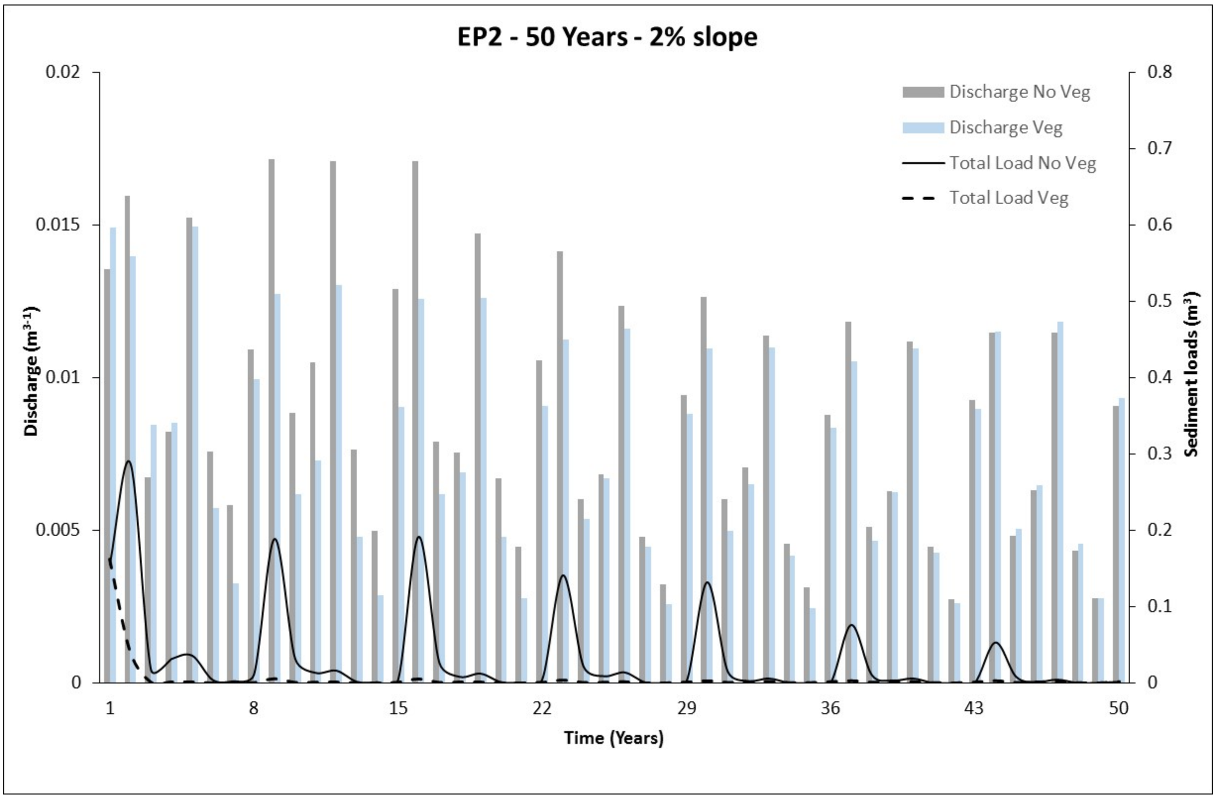


Figure 11 Total annual load and discharge from EP2 for 50 years with a 2% slope

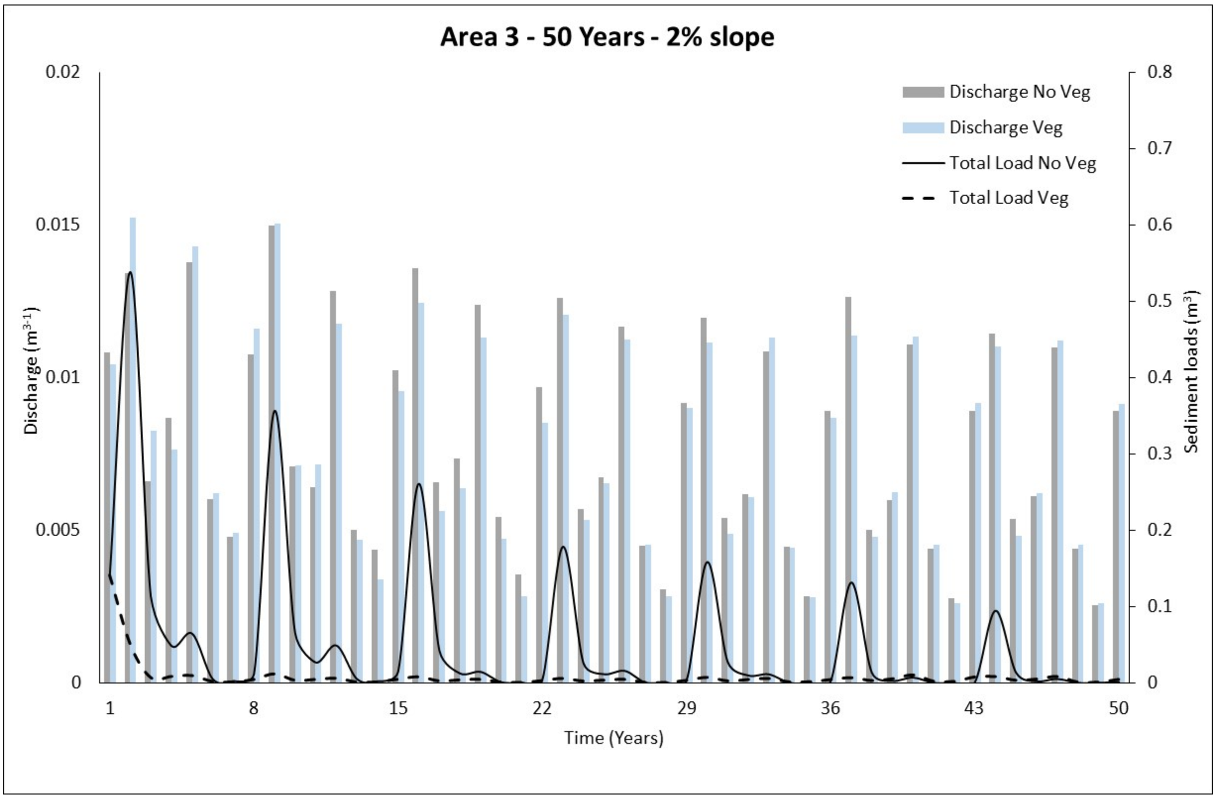


Figure 12 Total annual load and discharge from Area3 for 50 years with a 2% slope

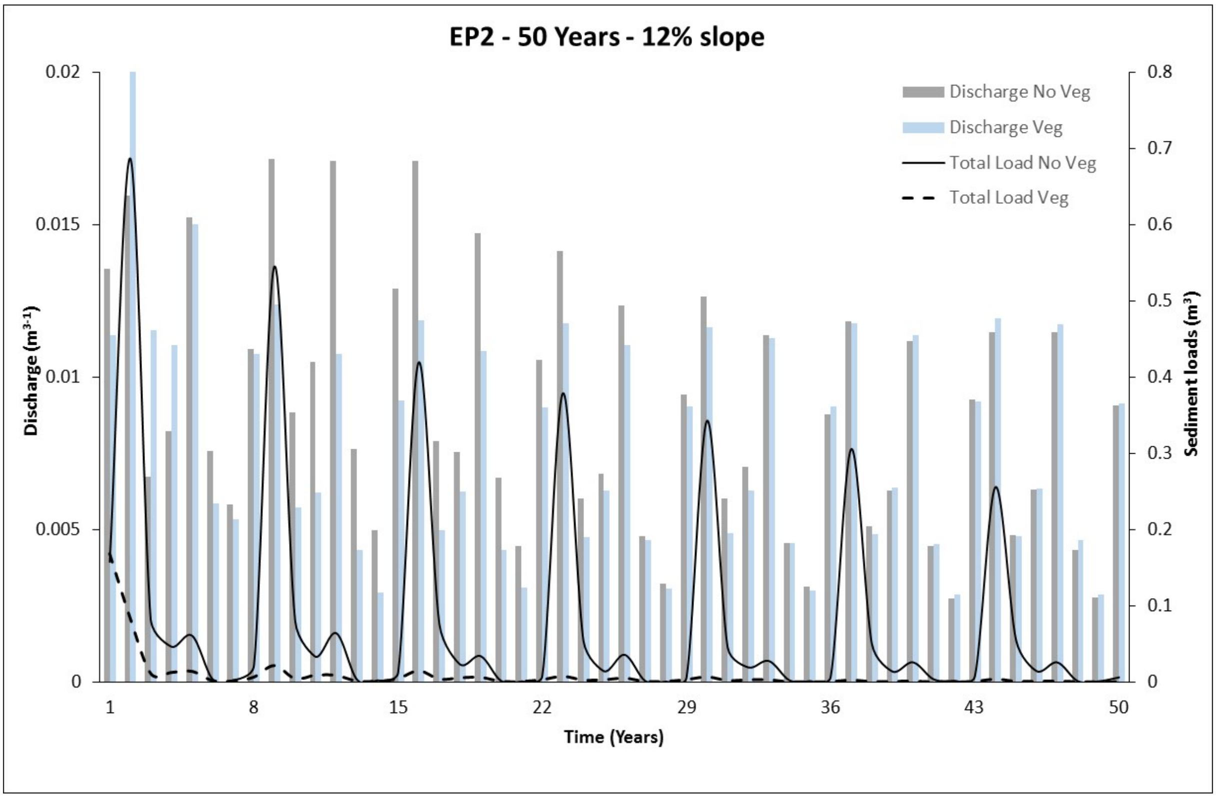


Figure 13 Total annual load and discharge from EP2 for 50 years with a 12% slope

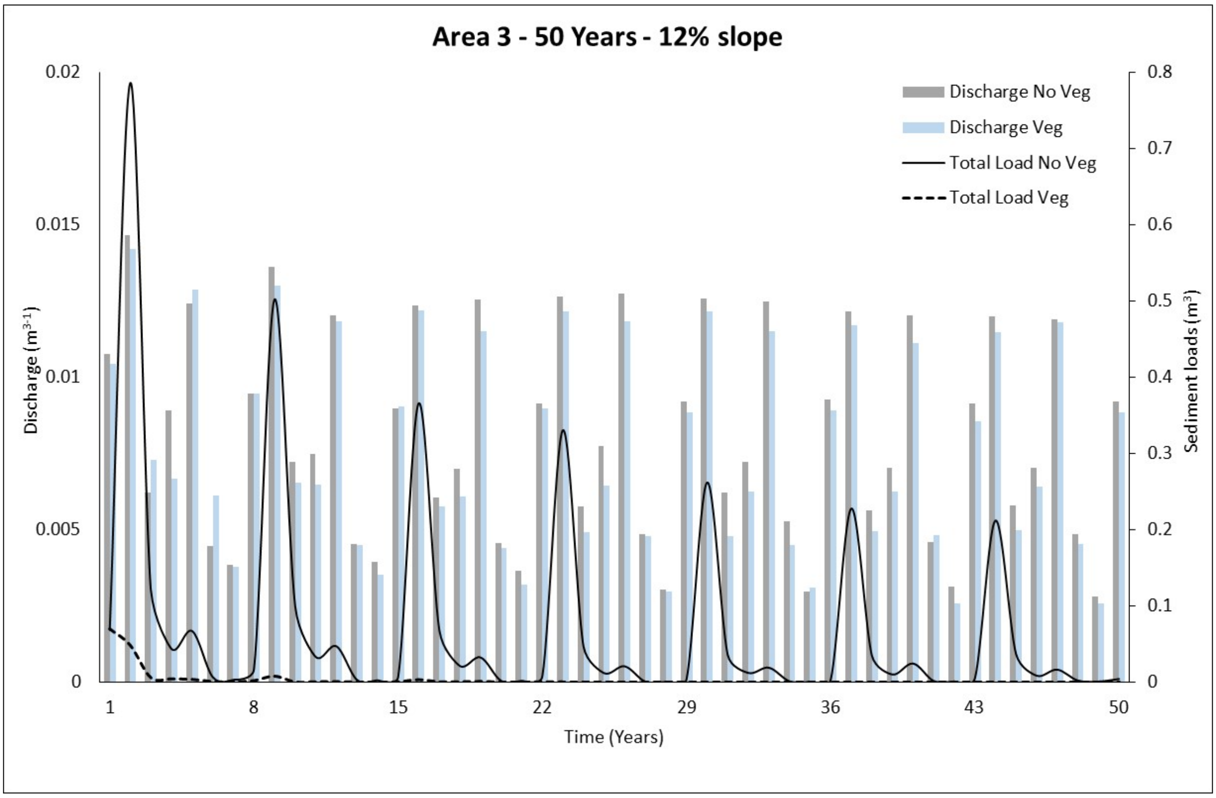


Figure 14 Total annual load and discharge from Area 3 for 50 years with a 12% slope

The sediment load in Figures 11 to 14 shows that the total load is higher for the non-ripped sites than the ripped sites and that the total sediment load is higher on the steeper slopes (results also shown in the section above). These figures illustrate that there is an overall decline in total sediment loads but that there appears to be a response to a very high rainfall (180 mm in 2 hours) from the looped rainfall data. This is noted as occurring but is not discussed further as part of this study. Similarly although the discharge is shown on these figures the results are not discussed as part of this study.

6.2.2 Effect of vegetation on denudation rates

The effect of the presence / absence of a vegetation layer from model simulations can be further seen in the predicted denudations rates. As with predicted loads, the presence of vegetation was found to produce denudation rates that were initially 4-8 times lower on a 2% slope (Figure 15) than those simulations without vegetation. Similar trends were observed with model outputs on a 12% slope (Figure 16).

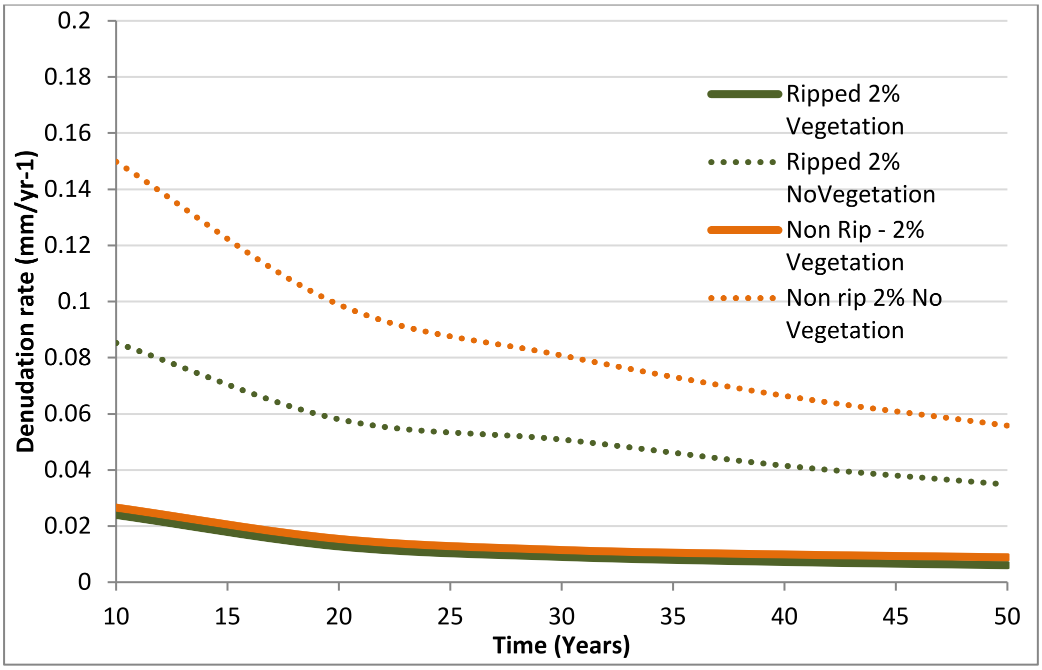


Figure 15 Predicted rates of denudation over time from the ripped and non-ripped areas with and without vegetation cover on a 2% slope

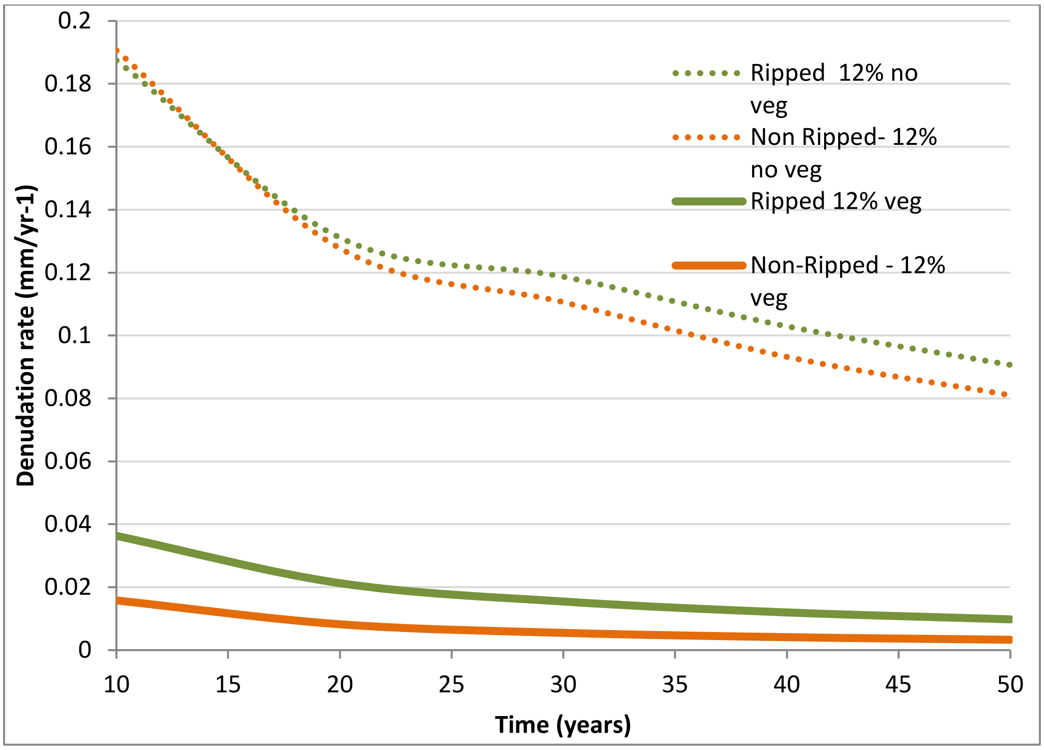


Figure 16 Predicted rates of denudation over time from the ripped and non-ripped areas with and without vegetation cover on a 12% slope.

6.3 Changes in DEM over time

In this section, changes in the surfaces of ripped surfaces and non-ripped surface are shown over a 50 year period. The non-vegetated scenario has been used for these simulations. There are some limitations with these results as the particle size values used are possibly too fine (allowing for sediment to be more easily moved). Investigation of the most appropriate particle size value to use is currently being undertaken. Also the default weathering value was used in the model simulations.

Surface DEMs of the 2% slope of EP2 are illustrated using hill shaded surface images produced at 0 and 50 years intervals (Figure 17). The rip lines appear to have mostly disappeared after the first 10 years and have completely disappeared after 40 years. There does not appear to be any gully formation on these surface areas.

An alternate perspective of changes in the landform surface over a simulated period of 50 years can be seen in Figures 18-21. Cross-sectional graphs representing surface elevation over the different simulation periods (time = 0, 1, 10, 20, 30, 40 and 50 years) have been produced for simulations on 2 and 12% slopes. A series of cross sections through EP2 with a slope of 2% shows how over time, the rip lines are progressively reduced, and the surface smoothed over time with no rip lines are recognisable after 50 years in the cross section of the surface (Figure 18). In contrast, cross sections through a non-ripped surface on a 2% slope showed comparatively little change in the surface topography of the plot over a simulated period of 50 years (Figure 19).

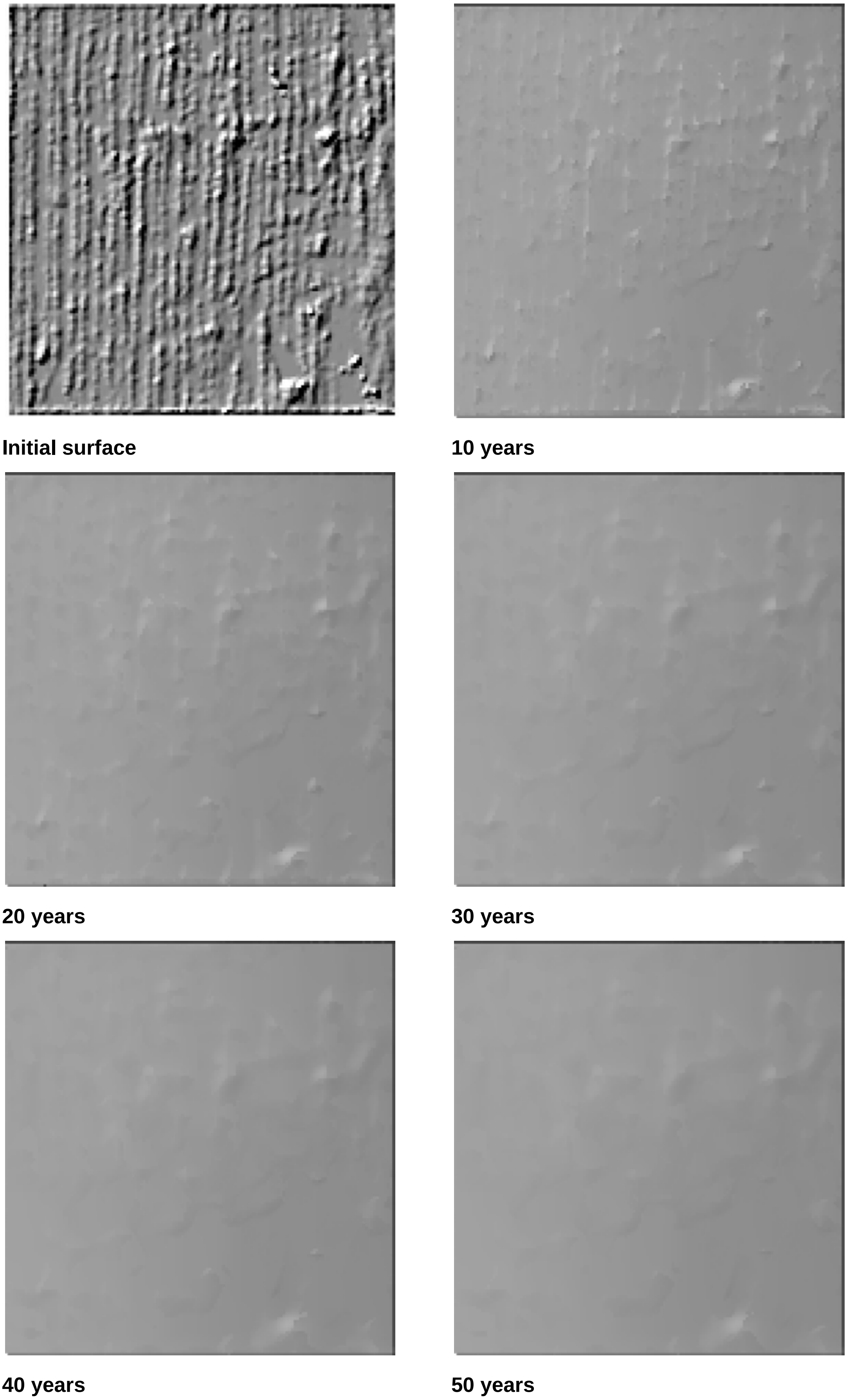


Figure 17 Surface of EP2 (2% slope) at 10 year intervals

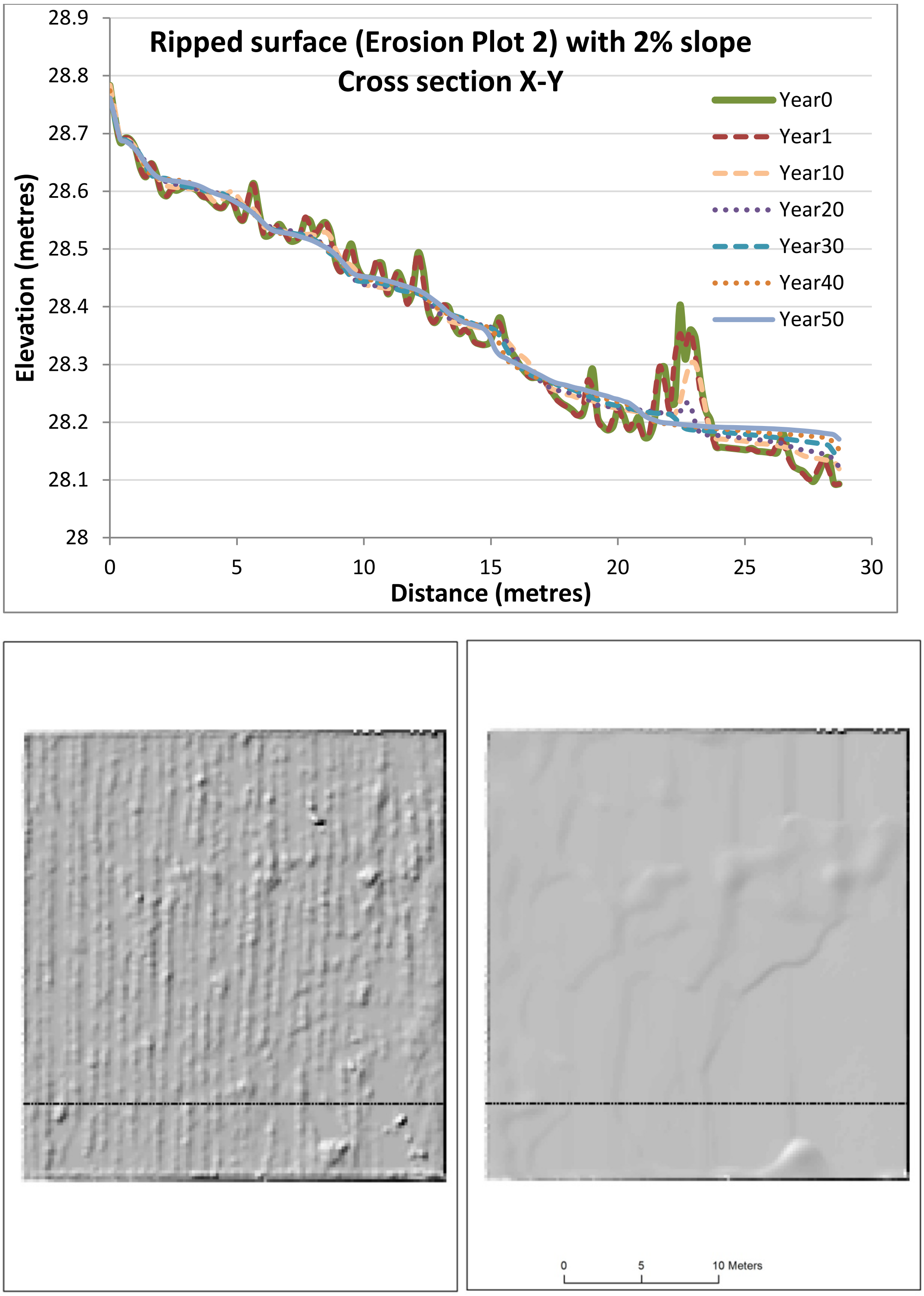
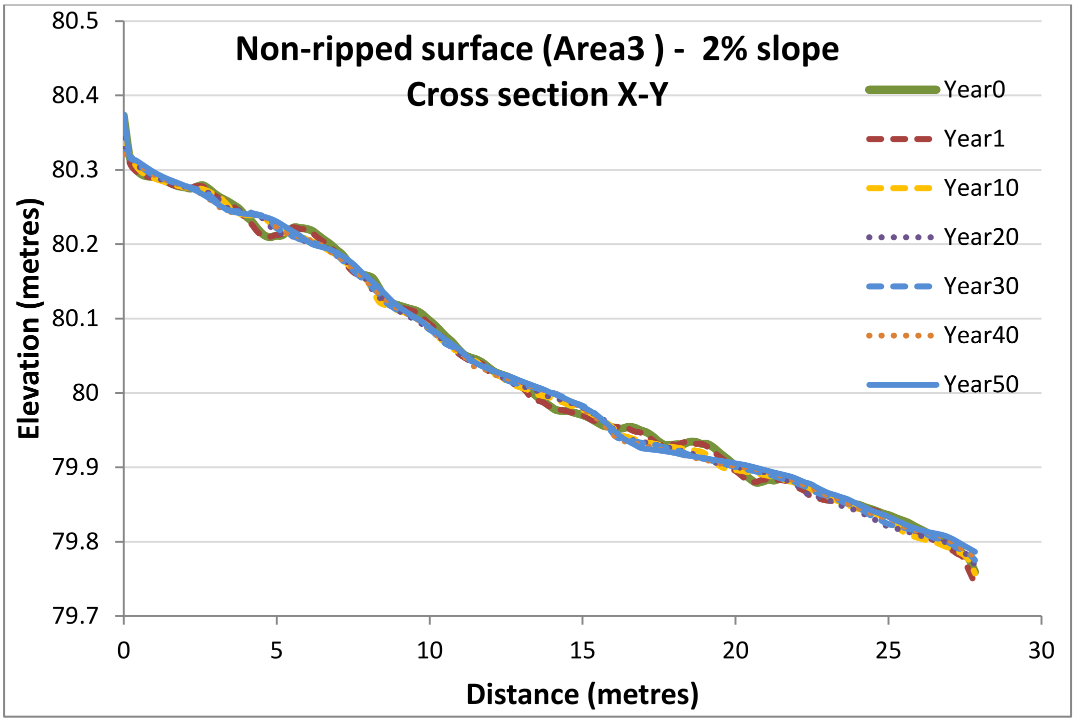
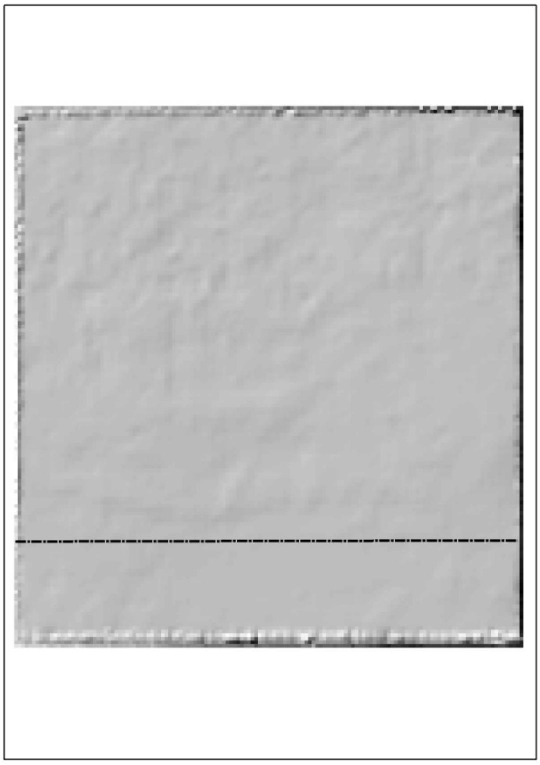


Figure 18 Changes in characteristics of the ripped surface on a 2 % slope, as illustrated by: **a)** Cross sections of surface heights from the surface as taken along transect X-Y; and **b)** Hill shaded images produced for the surface at year 0 (left) and 50 (right) respectively. Dashed line indicates location of transect X-Y.





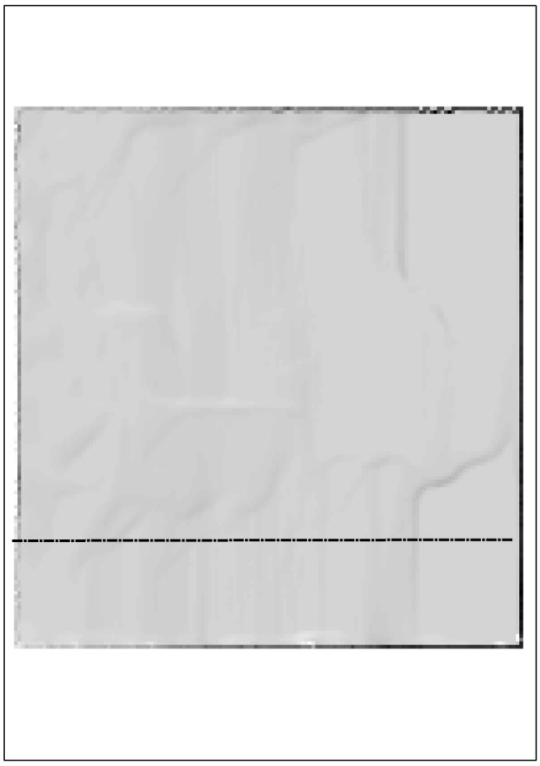


Figure 19 Change in characteristics of the non-ripped surface on a 2 % slope, as illustrated by: **a)** Cross sections of surface heights from the surface as taken along transect X-Y; and **b)** Hill shaded images produced for the surface at year 0 (left) and 50 (right) respectively. Dashed line indicates location of transect X-Y

Similar illustrations of the 12 % slope ripped surface (Figure 20) indicate that rip lines were also progressively reduced at a greater rate compared to the 2 % slope, with no evidence of the rip line profile after 10 years. The non-ripped surface shows very little change with only minor deposition at the base of the slope (Figure 21).

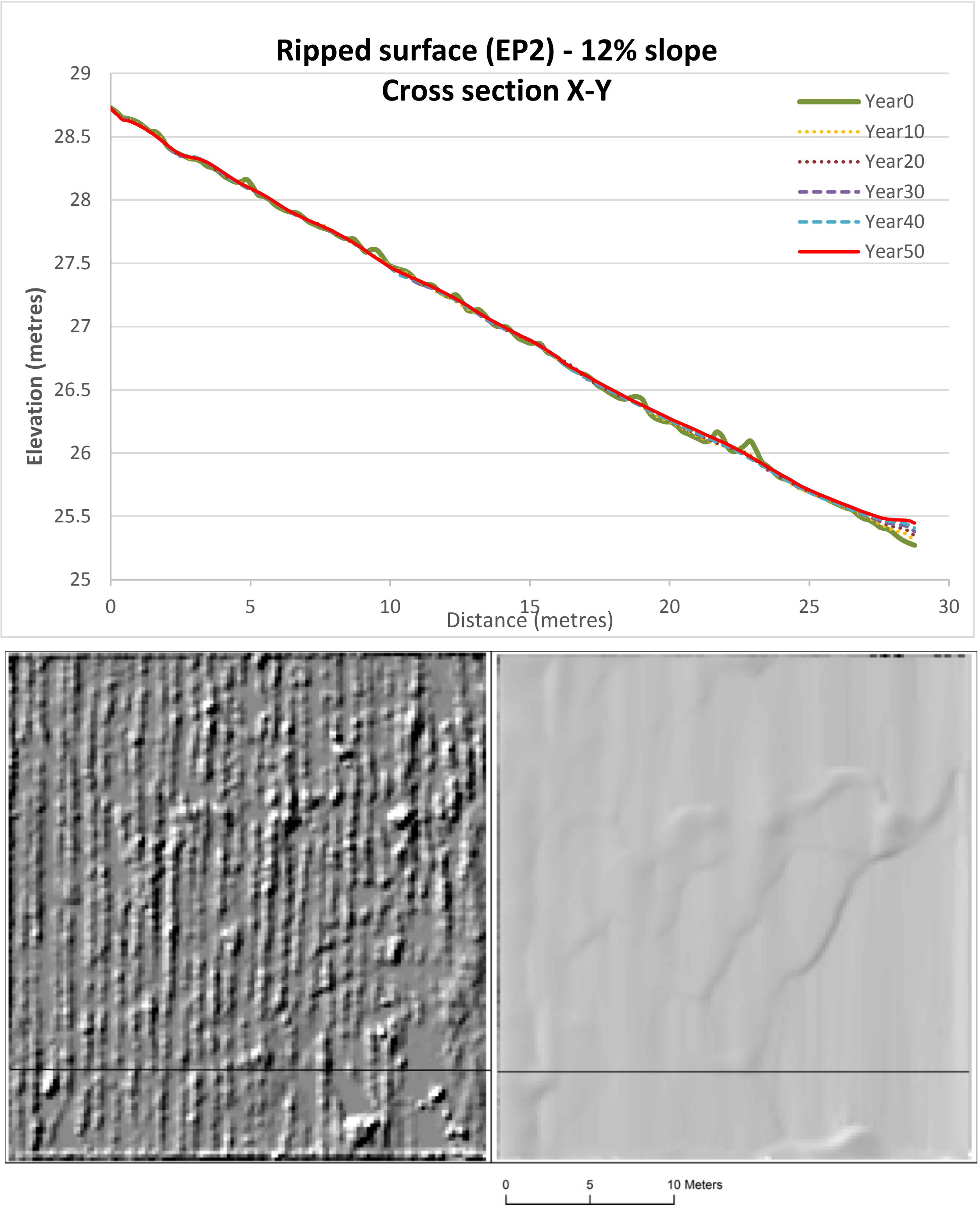


Figure 20 Changes in characteristics of the ripped surface on a 12 % slope, as illustrated by: **a)** Cross sections of surface heights from the surface as taken along transect X-Y; and **b)** Hill shaded images produced for the surface at year 0 (left) and 50 (right) respectively. Dashed line indicates location of transect X-Y

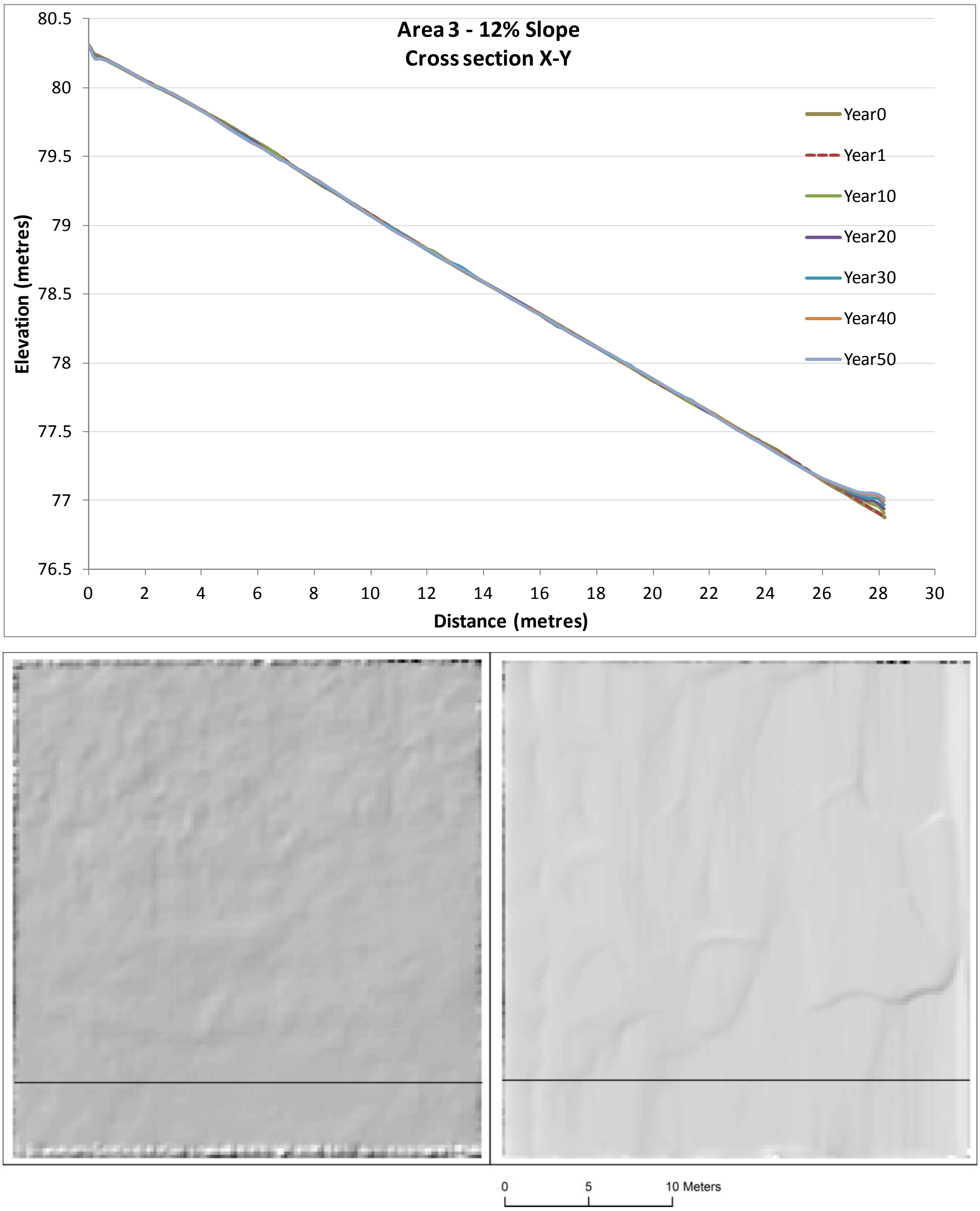


Figure 21 Changes in characteristics of the non-ripped surface on a 12 % slope, as illustrated by: **a)** Cross sections of surface heights from the surface as taken along transect X-Y; and **b)** Hill shaded images produced for the surface at year 0 (left) and 50 (right) respectively. Dashed line indicates location of transect X-Y

Overall, the results demonstrated in Figures 17 to 21 clearly show that using the current parameters in CAESER-Lisflood, the ripped surfaces are smoothed considerably over the 50 year simulation period. There do not appear to be any gullies on either of the surfaces by year 50.

6.4 Sediment movement on the TLF results

There has been sediment movement down the perimeter road on the southern side of TLF. The sediment that has been moved has not come from the ripped areas of the TLF but rather the non-ripped areas along the perimeter road. Catchment area, channels and areas of deposition have been mapped and are shown in Figure 22.

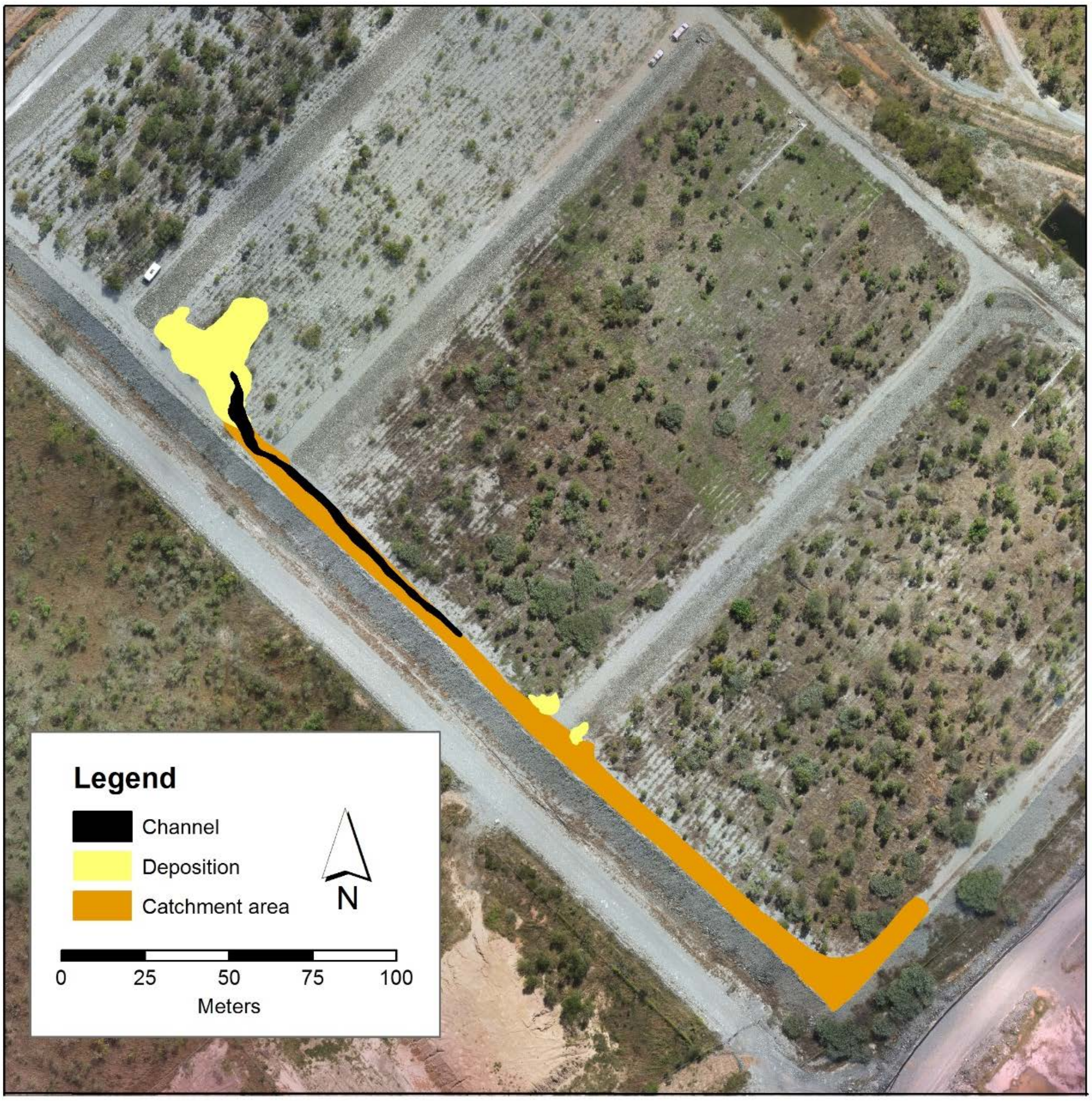


Figure 22 Areas of sediment movement mapped on the trial landform.

Values of area (m^2 and hectares) and perimeter (m) were calculated from ARC-GIS (Table 7). The depths of the 5 holes dug in the deposited sediment were 70 mm, 95 mm, 70 mm, 65 mm and 80 mm, which equals an average depth of 76 ± 12 mm. There are 3 areas of deposition (Figure 22) with the total deposition given in Table 6. The larger deposition fan in Area 2 is 698.9 m^2.

Table 7 Total areas for the 3 different erosion characteristics mapped in Figure 22

	Perimeter (m)	Area (m^2)	Hectares
Catchment Area	582.5	1896.7	0.19
Channel	219.4	211.3	0.02
Deposition	183.1	755.2	0.08

The total volume of sediment deposited in the Area 2 depositional fan assuming an even depth of 76 mm (0.076 m) is given by the following;

Total Volume = 698.9 (area of deposition) x 0.076 (average depth) = 53.1 m^3.

Using a bulk density of 1.22 (Hancock et al 2016) the amount of sediment in the depositional fan is 64.8 tonnes. These equates to 34,166 tonnes per km^2 from the seven years of data collection on the TLF.

7 Discussion

Using the CAESER-Lisflood modelling results of the different scenarios, rip lines have different impacts on erosion depending on slope and time being modelled. These impacts are discussed further in the following sub-sections.

7.1 Modelling erosion from the different ripped and non-ripped slopes

Simulations undertaken for this study show that, as slopes increase, ripped surfaces become progressively less effective at reducing soil movement and erosion than non-ripped surfaces. This is demonstrated both in the short term (7-years), for which field measurements exist that support the results and in the longer term (50-years). The discussion in this section focusses on the results of those model simulations which were run with the vegetation component turned off, as this represents a more conservative scenario.

The total loads for the 7 year period for the two surfaces were shown in Table 2, where it can be seen that the absence of rip lines on slopes of 2% results in greater sediment loss than a comparable area on a slope of 2% with rip lines. However, this sediment loss is reduced as the slopes increases, with the non-ripped surfaced producing similar sediment loads to a ripped surface for a 12% slope. This pattern extends to the longer term scenarios (modelled of 50 years) as shown in Table 3

This demonstrates that rip lines on steeper slopes have less of an impact on the reduction of erosion. Table 4 shows for the 50 year scenario, in the first 10 years the presence of rip lines reduces erosion on all slopes for both plots. The impact of rip lines after 20 years suggests that more erosion will be present on non-ripped areas that are at 12%. After 50 years there is more erosion on non-ripped slopes for both 8% and 12%. The ripped 4 % slope is still showing less erosion than the non-ripped slope 4% by a numerical value of 4 %.

Denudation rates refer to lowering of the surface and show similar results to the total loads. Simulation results indicate that over a seven-year period, denudation rates from a non-vegetated surface increase as the slopes increase for both ripped and non-ripped surfaces (Table 5). However, while the denudation rate for ripped surfaces doubles (from 0.08 mm/yr^{-1} to 0.16 mm/yr^{-1}) as the slope increases, the denudation rate for non-ripped surfaces only increases from 0.14 to 0.17 mm/ yr^{-1}.

When the simulations were extended to 50 years (Table 6), the denudation rates from ripped surfaces on slopes of 12% were predicted to exceed those of non-ripped surfaces on 12 %. These results support results for the 7 years predictions that ripped surfaces are less effective on steeper slopes over time.

The results of this study show that in the longer term rip lines actually increase total loads and denudation rates. Landloch (2003), suggest that surface roughness (in the form of furrows) on steep slopes can actually increase erosion rather than controlling it. Landloch (2003) describe the process as follows. Generally, the furrows will fill with sediment and the ridges will be worn down by erosion, faunal activity and weathering. After some time, ranging from months to several years (depending on the stability of the surface material), water ponded in depressions begins to break through and flow downslope. That flow will add to water in the next depression downslope, and overtop it as well. Thus once one depression "fails", there will be a general failure down the slope and a flow line is created.

Although Landloch (2003) does not specifically state what slope angles this increased erosion due to rip line occurs on, rather that mine sites typically have batter slopes with gradients ranging from 15-35%. These slopes are steeper than the slopes (maximum of 12%) that have been modelled as part of this study. Vegetation is referred to by Landloch (2003) in the context of establishment on the different slopes of the rip lines themselves. It is assumed that the slopes described by Landloch (2003) are newly formed with no initial vegetation establishment.

The Mine Rehabilitation Hand Book (Commonwealth of Australia 2016), states the following

"that surface roughness is an important consideration in rehabilitation of mine-site landforms. Roughness tends to trap water and seed, and it is generally accepted that a rough surface will provide better vegetation establishment than a smooth one. However, while the creation of large surface roughness through rip-lines or moonscaping may give benefits in the short term, in the longer term it may lead to increased erosion and instability of the landform, as large roughness elements tend to concentrate flows over greater widths of slope and those large flows then cause higher rates of erosion. Although some surface roughness is generally good, it does not naturally follow that large roughness elements are therefore better. The value of surface roughness is closely linked to its persistence through time, which is largely controlled by the particle size distribution (rock content) of the material in which the roughness is created and the degree to which overtopping may or may not develop new flow paths."

In this hand book, there is no reference to the slopes that the rip lines have been established on. Our results for slopes greater than 8% agree with the statement that in the longer term rip line may contribute to higher rates of erosion.

Although not specifically on a mine site, Macdonald and Melville (1999) investigated the impact of contour furrowing on chenopod ground at Fowlers Gap, New South Wales. One of their findings was that contour furrowing tended to promote increased erosion because of the inherently dispersive characteristics of the soil used to construct the contour banks, and an increase in the erosive potential of water after impounding. As a result, the banks suffered from breakthroughs and the subsequent release of the erosive potential on the downslope land surface. The furrowed areas tended to have increased erosion features, such as rill and minor gully erosion, due to exposure of more erodible subsurface soils to flowing water and the poor strength of the furrow bank. Whilst the sediment on the TLF is not of dispersive nature (as presumably neither will the sediment used on the rehabilitated landform), the impoundment of water behind the rip lines, in some instances can increase erosion (Macdonald and Melville 1999).

The results from our study concur with LandLoch (2003) in that that there may be a threshold slope, above which rip lines contribute to and promote increased erosion. In the case of the Ranger mine site the modelled scenarios suggest that that the threshold slope of rip lines after 50 years is somewhere between 4% and 8% slope to promote increased erosion.

7.2 Effects of Vegetation on erosion

The establishment of a vegetation and surface cover are generally accepted as a way to reduce erosion. The early establishment of a vegetation community is seen as one way of stabilising a landform. In this respect, the presence of rip lines may assist with the early establishment of a vegetation community as erosion from ripped areas is less than from non-ripped and rip lines may trap /collect sediment and vegetative material which will contribute to the growth of vegetation.

As stated earlier, the presence of vegetation in some model scenarios was simulated through the applications of the relatively simple vegetation component that is incorporated into the CAESER-Lisflood 1.8g model. Figures 11 to 14 showed that while total loads decreased gradually over time with no vegetation, there was a sharp and dramatic decline with the vegetation component turned on.

Although this report is primarily focussed on ripped and non-ripped surface, the key points with respect to vegetation are:

(1) Vegetation is understood to have an effect on reducing erosion;

(2) Model results to date show that the presence of vegetation does reduce erosion/stabilise the landscape, across all slopes and surface types (ripped or non-ripped);

(3) The CAESAR-Lisflood model currently has a limited capacity to show vegetation cover but cannot accurately quantify how effective vegetation is at reducing erosion;

(4) Further work could/should be done, including looking at the role of fire in community establishment; and

(5) Consequently, recognise that vegetation is important, but most of the focus of this study is on non-vegetated scenarios. Non vegetated scenarios provide a more conservative output to use for planning purposes.

7.3 Surface morphology and rip line longevity

Model results show that rip lines are effective in controlling erosion – particularly in their early years (7- 10 years) and that their effectiveness decreases with slope and time. However, the modelling shows that the rip lines themselves are predicted to disappear within the 50 year model period, indicating that they are not a permanent presence (Figure 17). The simulations of ripped surfaces indicate that rip lines progressively weather and infill over time. This is significant from a rehabilitated landform design perspective. This may in turn address some of the stakeholder concerns about the presence of rip lines on a rehabilitated landform, specifically that they may impede access across country. Simulations to date indicate that within a period of 50 years, constructed rip lines will cease to be a visible feature in the landscape.

The cross sections in Figures 18 – 21, all show that after 50 years the surface of the areas represented have become reasonably level with minimal hills or depressions. This is true for the 2 and 12% slopes so it is reasonable to assume that the same could be said for the other slopes between these. Deposition is shown at the base of the areas on both the 12% slopes (Figures 20 & 21) as well as ripped 2 % slope (Figure 18). The non-ripped

2% slope does not have the sediment deposition due to the low slope angle and the lack of rip lines that could provide sediment.

In all of the figures 18 – 21, the surface becomes much smoother and, significantly, there do not appear to be any gullies. This may be due to the small size of the area ($900m^2$) that is being modelled, and there may not be sufficient catchment area to initiate gully development. Modelling of larger areas representing a rehabilitated landform predicted the formation of gullies within a model period of 50 years (Lowry et al 2013, 2015).

The modelled results show that the removal of the rip lines over time may be influenced by the parameters that have been used in the modelling, particularly the weathering and particle size components. In this study, the weathering component utilised the default values. Further investigation of weathering of the rocks at the Ranger mine site and subsequent refinement of the weathering parameter may improve these results.

We propose that an appropriate method to quantify the longevity of the rip lines is to re-survey the surface. The rip lines on the TLF were originally scanned with a terrestrial laser scanner in 2010 to generate DEMs at a variety of spatial resolutions. While the rip lines are visually present after 7 wet seasons, we would recommend that a further high resolution DEM of the ripped surface be generated after the 2019-20 wet season to determine what changes have occurred and to compare with the surfaces generated by the model for the same time period. The rip lines on erosion plot 3 were clearly visible after a fire in 2006, seven years after they were constructed (Figure 23).

Figure 23 Erosion Plot3 with rip lines clearly visible after the fire on 18 May 2016. This image was taken on 6 June 2016

7.4 Sediment from the roadways

An observation was made of sediment has been actively eroding on the perimeter road around the TLF. Opportunistic field measurements were made and areas calculated from UAV imagery flown over the TLF. A large area of deposited material (depositional fan) was observed in the Area 2 in the dry season of 2016, with a small eroded channel having developed on the road upstream of the depositional fan. Various features were mapped in ARCGIS including contributing areas, length of road and area of deposition. The total amount of sediment deposited was calculated as 34166 t/km^2. The contributing catchment area is 1897 m^2 and the maximum length of run down the perimeter road is approximately 250 m.

Sediment that is eroded from the four erosion plots on the TLF has been collected, weighed and tabulated for each wet season (Saynor and Erskine 2016). Table 8 reproduced from Saynor & Erskine (2016) has had an additional year of bedload data added so that the sediment data is comparable to the 7 years of erosion and deposition down the road. The annual loads have been summed to give the total sediment transported from each of the erosion plots ranging from 236 t/km^2 (EP3) to 462 t/km^2 (EP2). These total load values are from a ripped area approximately 30m in length. In comparison, the total load of sediment in the deposition fan (34166 t/km^2) is two orders of magnitude larger than the total loads from the erosion plots. The length of contributing road surface is 250 m and there are no rip lines or roll overs on the perimeter road. These values show that rip lines can substantially reduce the amount of sediment being moved. The presence of rip lines slows down water velocity reducing the potential for sediment to become entrained and transported downslope.

Table 8 Average bed load yields for each plot for each year (adapted from Saynor & Erskine 2016).

Wet season	Mean annual rainfall ± standard error (mm)	Plot 1 t/km^2.yr	Plot 2 t/km^2.yr	Plot 3 t/km^2.yr	Plot 4 t/km^2.yr
2009–10	1518 ± 13	106	147	111	143
2010–11	2255 ± 23	59	113	54	56
2011–12	1496 ± 16	34	48	38	15
2012–13	1274 ± 5	28	50	14	14
2013–14	1966 ± 5	24	53	11	13
2014–15	1085 ± 23	11	29	6	6
2015–16	931 ± 29	7	21	4	3
Total		**270**	**462**	**236**	**250**

7 Conclusions

This study has three key findings. First, the simulations showed that, rip lines are effective at reducing the sediment load from a landform under certain conditions. Specifically, our results indicated that, over a simulated period of 50 years, rip lines are very effective on slopes of 2%. However as slope increases, rip lines become less effective over time. For example, surfaces with rip lines on slopes of up to 4% are predicted to produce smaller sediment loads than non-ripped surfaces over the same 50-year period, although by a smaller margin. When the slope is increased to 8% and 12%, ripped surfaces become less effective than non-ripped surfaces at minimising sediment loads and are predicted to produce higher sediment loads then non-ripped surfaces. However, in the context of the Ranger rehabilitated landform, as most of the rehabilitated landform is proposed to have slopes of between 2 and 4%, this would indicate that rip lines would be an effective way of mitigating soil loss and sediment transport. In areas where slopes may exceed 4%, rip line installation would not be recommended as erosion may be exacerbated.

Second, while recognising the limitations of the vegetation component of the CAESAR-Lisflood model used in this study, model results show the importance of the presence of understory vegetation and its role in reducing erosion from all slopes. The establishment of vegetation is an important part of reducing erosion from a recently rehabilitated mine site. The dampening effect of vegetation occurs on all slopes regardless of whether it is ripped or not ripped. These modelled vegetation results further support the impact that vegetation has on reducing erosion as noted in Saynor and Evans (2001). Further work is required to better understand the erosive shear stresses required to remove vegetation on a rehabilitated landform in northern Australia, and to refine model parameterisation for future simulations. Future enhancements to the vegetation component of the CAESAR-Lisflood model, including the ability to incorporate the role of fire into vegetation development, and an improved seasonal and spatial growth function will further enhance the capacity to model and predict the effect of vegetation on landform stability and evolution.

Third, simulations of ripped surfaces show that the geotechnical structure of the rip lines break down over time, with the rip line depressions infilling and the peaks being eroded, lowered or reduced in height. This finding is important because it demonstrates that rip lines will not exist in perpetuity in the landscape.

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Appendix 1 Detrending the slope and a standard frame

Detrending the slope of site DEMs

There was a difference in initial average slope characteristics between the DEMs produced from the ripped and non-ripped sites. In order to generate input DEMs representing a range of different slopes, the slope 'trend' had to first be removed. This process is known as 'detrending' and results in a , on average, horizontal surface (i.e. with a slope = zero). To achieve this the following steps had to be undertaken:

1. To simplify the trend surface calculation, the axis of the ripped site DEM was to rotated so the change in height associated with the slope was orientated with the columns of the spreadsheet, left to right. The rotation was undertaken using the bilinear re-sampling technique of the raster Rotate Tool (under the ArcMap Projections and Transformations Toolbox).
2. A 'trend' surface was calculated in Excel for each DEM. For example, consider spreadsheets named Trend (the trend surface) and DEM (the original DEM surface), with column "A" of DEM representing height values at the top of the slope, and other columns representing height values at various distances to the bottom of the slope (last column). At 1 meter down the slope (e.g. at F7) the change in height from the top of the slope is represented by the calculation: Trend!F7 =DEM$A7-DEM!F7. Hence, the trend surface was calculated by copying this formulae across the Trend spreadsheet
3. An algebraic function was then derived by linear regression between distance along the slope (*X*) and the trend surface (Figure A). Column averages of the trend surface worksheet (step 2) were used in the regression to determine this function (i.e. average change in height at position *X* down the slope).
4. The regression equation, above, was then applied to a spreadhseet to derive correction factors to detrend the average slope trend at any one location (gridcell) on the DEM spreadsheet.
5. new spreadsheet representing the detrended DEM surface was calculated by adding the correction-factor spreadsheet, above, to the original DEM spreadsheet. To demonstrate the effect of applying the correction factor, (in main text) shows a transferse profile of the average height of the ripped surface DEM before and after the slope was detrended.

The variation in the relative height for ripped and non-ripped sites respectively, as calculated on a zero slope the DEMs at this resolution, was ± 0.06 and ± 0.03 m SD (n = 19305 grid cells each).

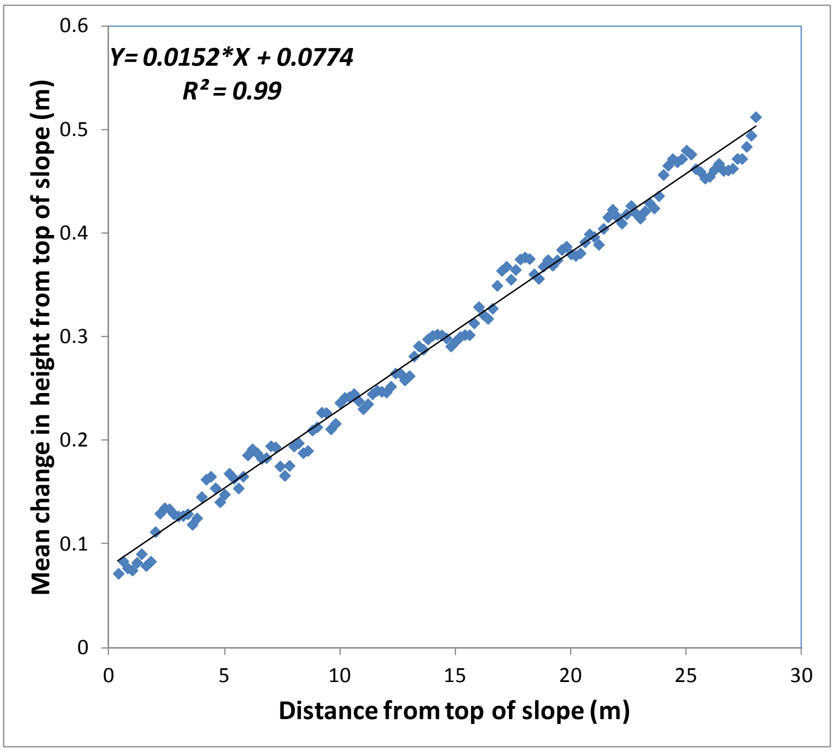


Figure A1 Example of the regression relationship and equation derived between the between of the EP2 slope trend surface (spreadsheet column averages) and the distance from top of the slope.

Applying a standard frame to DEMs

The EP2 site was surrounded by a bund of approximately 30 cm in height. This raised boundary was included on three edges of the DEM for the ripped-site: the up-hill edge and edges running downhill with the slope. During simulations, the presence of the bund had an effect of preventing runoff and erosion from exiting along these edges. The down-hill slope edge was clipped from the DEM, leaving an 'open' edge from which runoff and erosion might escape. In addition, height values of the lower-most corner of the DEM were changed to a minimum height (for 4 x 4 grid cells). The position of the minimum values corresponded to the location of the outlet basin from which runoff and bedload have been monitored in the field. The 'open' lowermost edge and 'basin' ensured that rainfall, runoff and erosion could leave the sites when CL was run in catchment mode. This 'frame design' prevented slow processing time and was applied to both the ripped and non-ripped DEMs using the detrended surfaces described in the previous section.

A raised bund was not present at the non-ripped site. For consistency, the boundary of the ripped DEM (including bund walls of three sides plus the downslope, 'runoff', boundary) was used to frame the inner boundary of the non-ripped site area. This ensured that erosion differences calculated by CAESAR-Lisflood between both sites were measured from the same designated area within a similar frame. In order to replicate the bund-frame on the non-ripped DEM, height values of the bund frame were standardised, relative to adjacent values from the inner boundary of the non-ripped DEM (A2).

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	a) Correction factors calculated for Un-Ripped DEM from the EP2 (Ripped) DEM boundary												
2													
3	28.75	= original height values of Ripped DEM boundary (F column, transverse profile of Y-axis, north boundary)											
4	28.86	= "											
5	28.83	= "											
6	28.74	= Reference height value of inner frame											
7			0.02	-0.02	-0.04	0.00	0.01	0.00	-0.04	-0.04	-0.04	0.01	-0.01
8			0.02	-0.08	0.06	0.11	0.04	=H11-H$13		0.02	0.00	0.06	0.04
9			0.31	0.20	-0.03	0.04	0.01	0.09	0.04	0.00	-0.03	0.06	0.01
10	0.06	0.08	28.83	28.85	28.77	28.74	28.75	28.75	28.76	28.75	28.75	28.78	28.79
11	-0.04	-0.07	28.83	28.79	28.86	28.85	28.78	28.86	28.86	28.81	28.79	28.82	28.84
12	0.34	0.30	29.11	29.07	28.77	28.78	28.75	28.83	28.83	28.79	28.76	28.82	28.81
13	0.00	0.07	28.81	28.87	28.80	28.74	28.74	28.74	28.79	28.79	28.79	28.76	28.80
14	0.09	0.09	28.90	28.90	28.81	28.74	28.74	28.74	28.78	28.77	28.73	28.74	28.86
15	0.13	0.18	28.88	28.93	28.75	28.75	28.74	28.78	28.78	28.78	28.73	28.80	28.80
16	0.04	0.13	28.80	28.89	28.76	28.74	28.74	28.76	28.78	28.82	28.73	28.75	28.76
17	-0.01	0.04	28.80	28.85	28.81	28.73	28.74	28.75	28.83	28.76	28.73	28.73	28.74
18	-0.06	0.04	28.74	28.85	28.81	28.73	28.74	28.79	28.81	28.82	28.73	28.75	28.75

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	b) Frame correction applied to 'Non-Ripped' DEM												
2	80.24	= Frame value corrections (Bund /boundary height values common to the transverse profile of the Y-axis, north boundary											
3	80.35	= "											
4	80.32	= "											
5	80.23	= Reference height value of inner frame											
6													
7													
8	80.31	80.31	80.17	80.22	80.24	80.24	80.20	80.20	80.20	80.25	80.23	80.19	80.28
9	80.31	80.31	80.27	80.33	80.28	=F$11+'EP2_local frame correction'!H8				80.30	80.28	80.29	80.36
10	80.31	80.31	80.18	80.26	80.25	80.32	80.28	80.24	80.21	80.30	80.25	80.22	80.34
11	80.27	80.30	80.21	80.22	80.23	80.23	80.24	80.24	80.24	80.24	80.24	80.24	80.25
12	80.18	80.14	80.21	80.23	80.23	80.24	80.24	80.24	80.24	80.24	80.24	80.24	80.24
13	80.57	80.53	80.23	80.24	80.24	80.24	80.24	80.24	80.24	80.23	80.23	80.23	80.24
14	80.25	80.31	80.24	80.25	80.25	80.25	80.25	80.25	80.24	80.23	80.23	80.23	80.23
15	80.33	80.34	80.25	80.25	80.25	80.25	80.25	80.25	80.24	80.24	80.24	80.24	80.24
16	80.38	80.43	80.26	80.25	80.25	80.25	80.25	80.25	80.25	80.25	80.26	80.26	80.26
17	80.30	80.39	80.26	80.25	80.25	80.25	80.26	80.26	80.26	80.26	80.26	80.27	80.27
18	80.24	80.29	80.25	80.25	80.25	80.26	80.27	80.27	80.27	80.27	80.27	80.28	80.28

Figure A2 Excerpt from site DEM spreadsheets showing how correction factors (**a**) were calculated from each edge of the Ripped DEM boundary and used to apply a standardised frame to the Un-Ripped DEM (**b**).

To demonstrate this method, **Figure** A2 shows the high similarity between the height differences of the bunds on both DEM surfaces, relative to the inner edge (to which the bund was artificially stitched in the case of the Non-Ripped DEM).

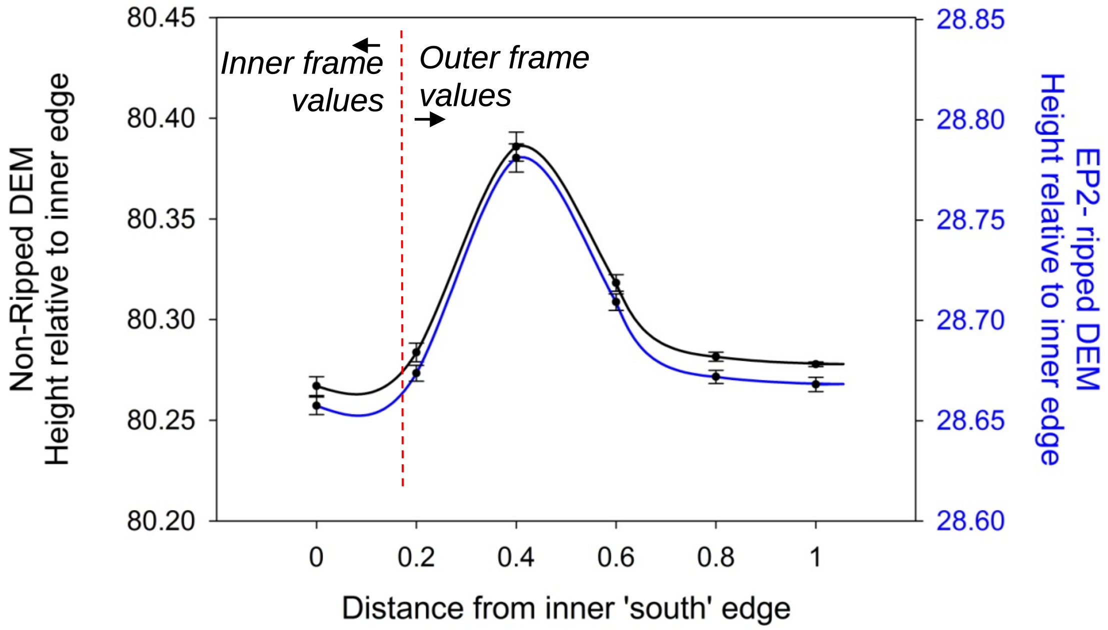
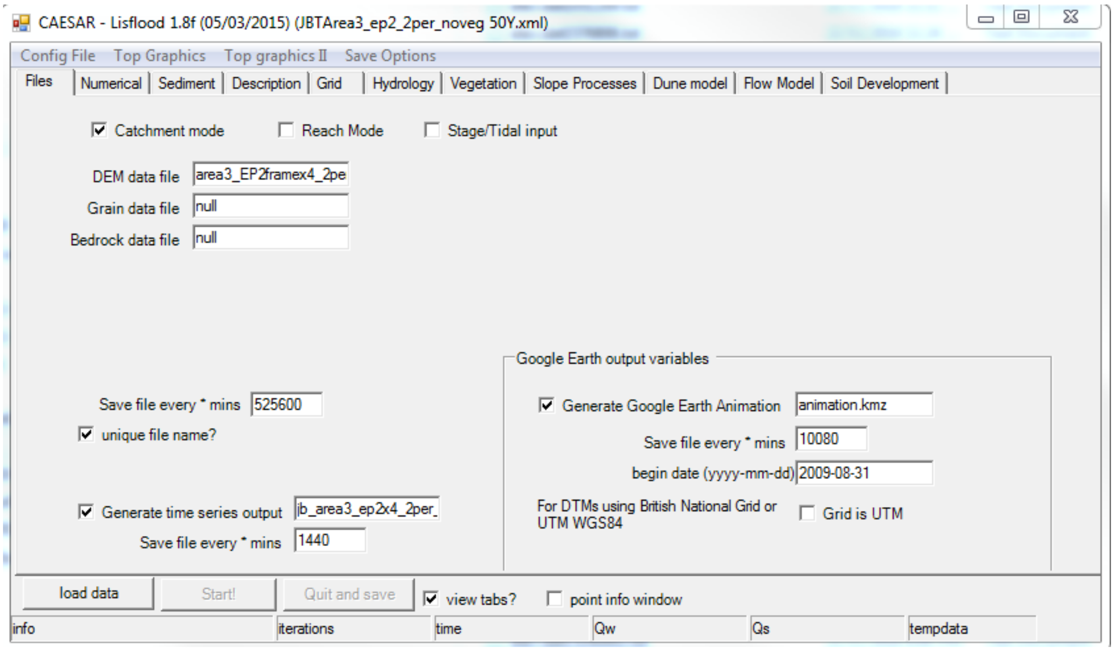
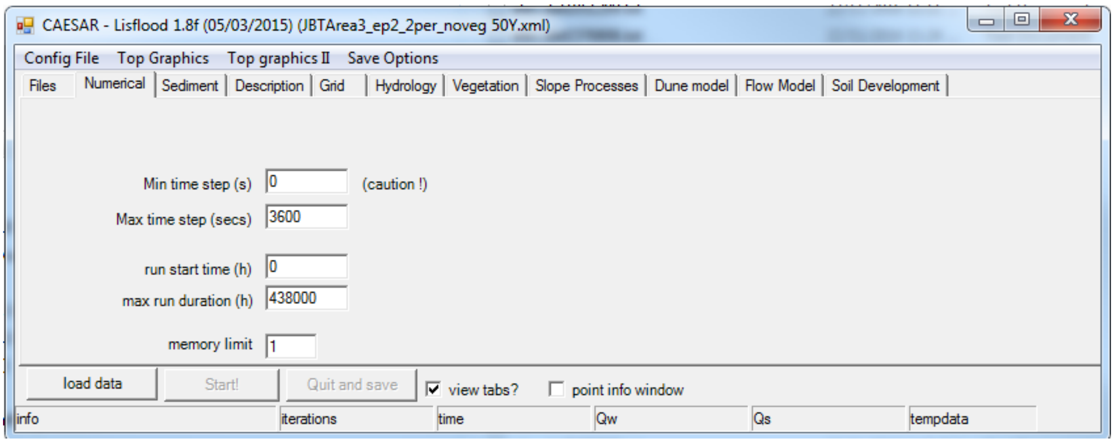
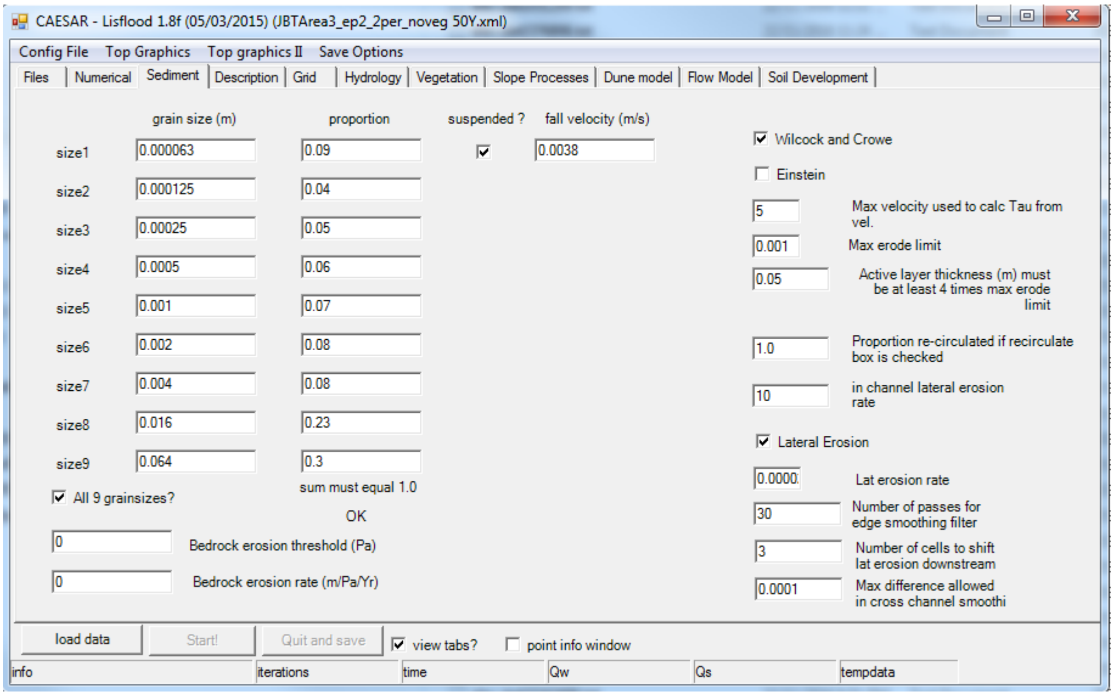


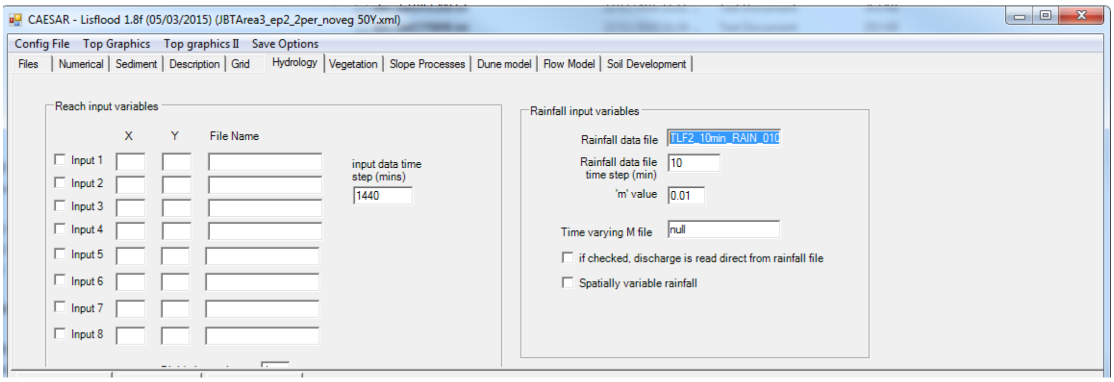
Figure A3 Transverse height profiles of the mean 'bund' heights along the south boundary of the non-ripped DEM surface relative to its inner-frame edge (i.e. distance = 0 m). The bund represented by the original EP2 DEM is in blue. The y-axes have been offset slightly and bars are standard error.

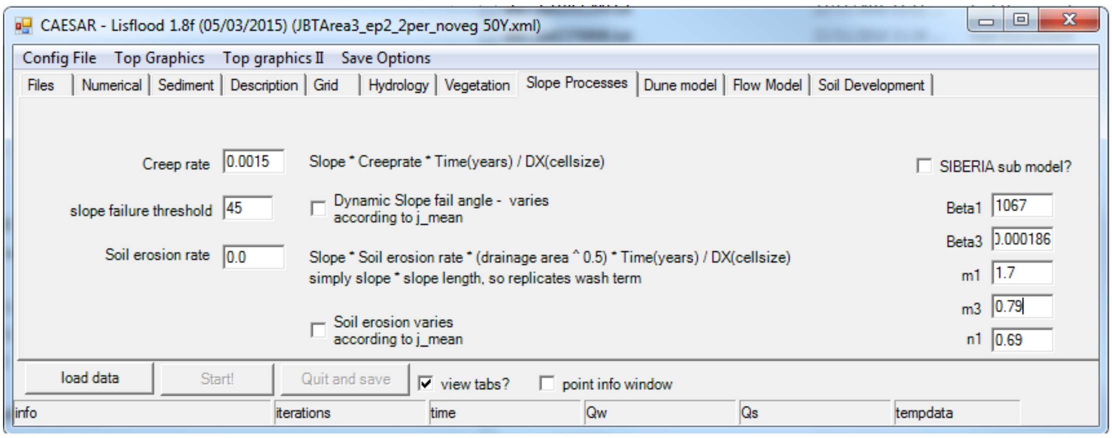
Appendix 2 CAESAR-Lisflood 1.8 Parameter settings (screenshots)

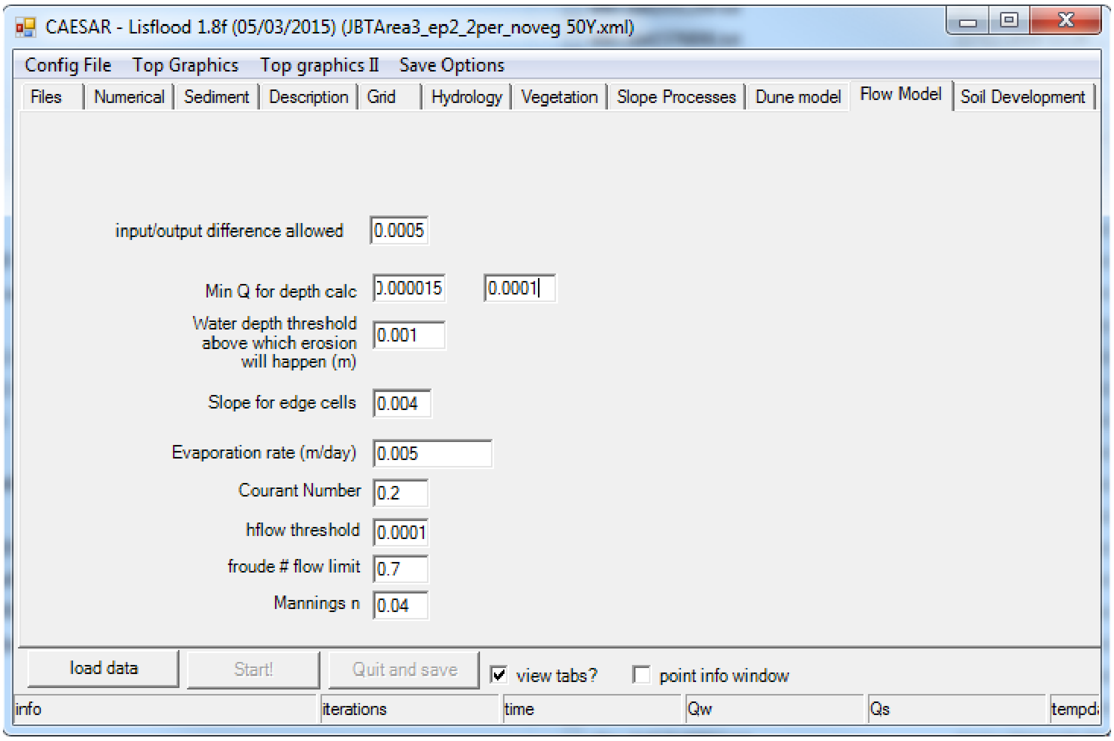





CAESAR - Lisflood 1.8f (05/03/2015) (JBTArea3_ep2_2per_noveg 50Y.xml)
Config File Top Graphics Top graphics II Save Options
Files Numerical Sediment Description Grid Hydrology Vegetation Slope Processes Dune model Flow Model Soil Development
grain size (m) proportion suspended ? fall velocity (m/s)
size1 0.000063 0.09 0.0038
size2 0.000125 0.04
size3 0.00025 0.05
size4 0.0005 0.06
size5 0.001 0.07
size6 0.002 0.08
size7 0.004 0.08
size8 0.016 0.23
size9 0.064 0.3
All 9 grainsizes?
sum must equal 1.0
OK
0 Bedrock erosion threshold (Pa)
0 Bedrock erosion rate (m/Pa/Yr)
Wilcock and Crowe
Einstein
5 Max velocity used to calc Tau from vel.
0.001 Max erode limit
0.05 Active layer thickness (m) must be at least 4 times max erode limit
1.0 Proportion re-circulated if recirculate box is checked
10 in channel lateral erosion rate
Lateral Erosion
0.0000 Lat erosion rate
30 Number of passes for edge smoothing filter
3 Number of cells to shift lat erosion downstream
0.0001 Max difference allowed in cross channel smoothi
load data Start! Quit and save view tabs? point info window
info iterations time Qw Qs tempdata


CAESAR - Lisflood 1.8f (05/03/2015) (JBTArea3_ep2_2per_noveg 50Y.xml)
Config File Top Graphics Top graphics II Save Options
Files Numerical Sediment Description Grid Hydrology Vegetation Slope Processes Dune model Flow Model Soil Development
Reach input variables
X Y File Name
Input 1
Input 2
Input 3
Input 4
Input 5
Input 6
Input 7
Input 8
input data time step (mins)
1440
Rainfall input variables
Rainfall data file TLF2_10min_RAIN_010
Rainfall data file time step (min) 10
'm' value 0.01
Time varying M file null
if checked, discharge is read direct from rainfall file
Spatially variable rainfall


CAESAR - Lisflood 1.8f (05/03/2015) (JBTArea3_ep2_2per_noveg 50Y.xml)
Config File Top Graphics Top graphics II Save Options
Files Numerical Sediment Description Grid Hydrology Vegetation Slope Processes Dune model Flow Model Soil Development
Creep rate 0.0015 Slope * Creeprate * Time(years) / DX(cellsize)
slope failure threshold 45
Dynamic Slope fail angle - varies according to j_mean
Soil erosion rate 0.0 Slope * Soil erosion rate * (drainage area ^ 0.5) * Time(years) / DX(cellsize)
simply slope * slope length, so replicates wash term
Soil erosion varies according to j_mean
SIBERIA sub model?
Beta1 1067
Beta3 0.000186
m1 1.7
m3 0.79
n1 0.69
load data Start! Quit and save view tabs? point info window
info iterations time Qw Qs tempdata


CAESAR - Lisflood 1.8f (05/03/2015) (JBTArea3_ep2_2per_noveg 50Y.xml)
Config File
Top Graphics
Top graphics II
Save Options
Files
Numerical
Sediment
Description
Grid
Hydrology
Vegetation
Slope Processes
Dune model
Flow Model
Soil Development
input/output difference allowed
0.0005
Min Q for depth calc
0.000015
0.0001
Water depth threshold above which erosion will happen (m)
0.001
Slope for edge cells
0.004
Evaporation rate (m/day)
0.005
Courant Number
0.2
hflow threshold
0.0001
froude # flow limit
0.7
Mannings n
0.04
load data
Start!
Quit and save
view tabs?
point info window
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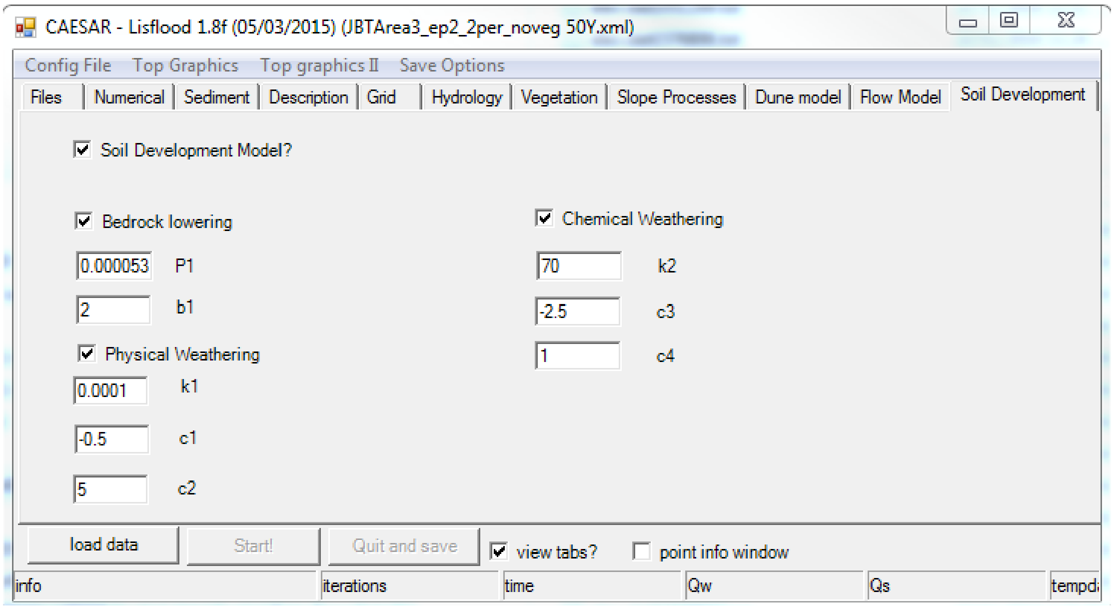
Qw
Qs

CAESAR - Lisflood 1.8f (05/03/2015) (JBTArea3_ep2_2per_noveg 50Y.xml)
Config File
Top Graphics
Top graphics II
Save Options
Files
Numerical
Sediment
Description
Grid
Hydrology
Vegetation
Slope Processes
Dune model
Flow Model
Soil Development
Soil Development Model?
Bedrock lowering
0.000053
P1
2
b1
Physical Weathering
0.0001
k1
-0.5
c1
5
c2
Chemical Weathering
70
k2
-2.5
c3
1
c4
load data
Start!
Quit and save
view tabs?
point info window
info
iterations
time
Qw
Qs