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# An approach to simulate long-term erosion equilibrium of a rehabilitated mine landform

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## Abstract

*A major focus for evaluating mine site rehabilitation in the tropics of Australia is determining when excessive erosion of above-grade waste rock landforms is no longer occurring and that they are in equilibrium with the surrounding catchment. The Ranger uranium open cut mine in the Northern Territory, Australia, lies between Magela Creek and Gulungul Creek. These creeks are sand-bed, ephemeral streams draining into the East Alligator River and wetlands of international significance. Landform evolution modelling (LEM) and assessments of streamflow fine suspended sediment (FSS) discharge are being used to evaluate erosion and determine whether FSS exported to Magela and Gulungul creeks during rainfall-runoff events is in excess of natural background levels.*

*LEM provides an avenue for simulating how a landscape may evolve over extended time periods of thousands of years. The CAESAR-Lisflood LEM is being used to assess the proposed final landform morphology by simulating how the mine landform and the landscape in the Magela Creek catchment and Gulungul Creek catchment would evolve over a 1,000-year period. The model assesses gully formation and bulk sediment export to the creek systems. The challenge is how to assess when a landform has reached equilibrium with the surrounding catchment and therefore whether the site can be considered rehabilitated with respect to landform stability.*

*FSS-stream loads following a rainfall event can be used as an indicator of landform stability, as the studies in Gulungul and Magela Creeks have shown. The aim of this project is to validate a new approach using an event-based stream FSS discharge relationship in combination with a LEM to determine when erosion of a rehabilitated landform is at equilibrium with the surrounding catchment.*

*An event-based FSS/stream discharge relationship was previously developed using stream monitoring data. When disturbance occurred in the catchment, this FSS/stream discharge relationship changed to reflect a system change. For a small disturbance, monitoring has shown that the relationship returned to the pre-disturbance condition after one or two years. The CAESAR-Lisflood model is being used to predict FSS values for a given discharge for a large disturbance across the whole catchment. The hydrology and FSS discharge for the whole Gulungul Creek catchment is being calibrated and validated using the available data. Future rainfall events will be input into the model. The FSS values from the current observed relationship (expected FSS loads for a given discharge) will be compared with that obtained from the CAESAR-Lisflood modelled landscape (predicted FSS loads for a given discharge) to find out when and why the system moves in and out of equilibrium during the 1,000 year period. A variation in event FSS loads beyond the confidence intervals of the best-fit line in FSS (expected from current relationship) versus FSS (predicted from CAESAR-Lisflood model) indicates future landform instability. Such a study will throw light on how a disrupted landform can move in and out of equilibrium until it reaches a steady state with the surrounding environment, which is considered stable.*

**Keywords:** *mine rehabilitation, landform stability, erosion equilibrium*

# 1 Introduction

Geomorphology is the interdisciplinary and systematic study of landforms and their landscapes as well as the Earth surface processes that create and change them. Biological influences and especially human actions directly affect landscape forming processes and steer landscape change. More than 50% of Earth's ice-free land area has been directly modified by human action. Many of these activities have indirect consequences well beyond the area directly affected (Hooke et al. 2012).

The environmental effects resulting from changed landscapes are significant and have to be managed and rehabilitated to the extent possible. Humankind has moved and is moving huge amounts of the Earth, thus creating new landforms, a process that often leads to accelerated erosion and landscape evolution. Some sediment derived from the latter process ends up as colluvium on the hillslopes and as alluvium on the floodplains, thus subtly altering the shape of the land. The rest is carried away by streams and rivers. Following major earth movement activities, runoff from these areas is commonly contaminated and has a high sediment load, with an associated risk potential involving mass movements like flooding, loss of human life, and economic catastrophes.

Minescapes are landscapes generated by mining activity, and most of the research and literature on the subject has focused on geomorphologically based assessments of mining-affected catchments. Mining operations cause a significant environmental disturbance, and if not managed appropriately, may have detrimental impacts in the future. Thus, rehabilitation of mine landforms is of paramount importance.

Mine landforms should be rehabilitated in such a way that post-mining landforms behave similarly as the surrounding stable, undisturbed areas. A challenge for government regulators and mine operators is setting closure criteria for assessment of the stability of the elevated post-mining landforms. Stability of a landform is often measured by the number and incision depth of gullies. This can assess mass stability and bulk movement of coarse material. However, there is a need for a more sensitive approach to assess catchment disturbances using the concept of waves of fine suspended sediment (FSS) and thus determine the dynamics of recovery of a post-mining landform. A more environmentally meaningful approach would be to assess the FSS (silt + clay [0.45 µm <diameter <63 µm]) leaving the system and entering downstream waterways.

# 2 Mine closure plan and rehabilitation objectives

Rehabilitation of disturbed sites is the process of returning the land to an acceptable state depending on the agreed values and end land use. It typically occurs in multiple stages and can take many years to complete. The agreed values for rehabilitation success are detailed by the authority administering the mining operations. Ranger is an open cut mine and has been producing uranium oxide (U3O8) via acid leach extraction since 1981. By current regulatory approvals, mining at Ranger ceased in 2012 and stockpiled ore processed until 2021. All rehabilitation works onsite must be complete by 2026 (Australian Government 2020). The closure of the mine and subsequent rehabilitation works are carried out by the stakeholders, based on certain laid-out objectives.

The authority to mine uranium at Ranger mine, Northern Territory, Australia was issued under s41 of the *Atomic Energy Act 1953* (Australian Government 1953), which was administered by the Commonwealth Minister for Resources and Northern Australia. The authority also provides the Commonwealth's environmental protection conditions, which are set out in the Environmental Requirements (ERs) of the Commonwealth of Australia for the Operation of Ranger Uranium Mine (the ERs) (Australian Government 1999). The ERs outline key objectives and environmental standards for mining operations and rehabilitation. These rehabilitation-related projects are underpinned by the Ranger Rehabilitation Key Knowledge Needs developed by Supervising Scientist Branch in consultation with Energy Resources Australia (ERA) and the Alligator Rivers Region Technical Committee. The Supervising Scientist provides independent advice to the regulators, both the Commonwealth Minister for Resources and Northern Australia, and the Northern Territory Minister for Primary Industry and Resources.

The ERs of the Commonwealth of Australia for the Operations of the Ranger Uranium Mine (Australian Government 1999) stipulates the environmental objectives for the Ranger mine, aiming to ensure that the activities of ERA on the Ranger Project Area (RPA) do not impact the values, attributes and ecosystem health of World Heritage–listed Kakadu National Park, nor the health of the regional community. These stringent environmental protection objectives were set prior to the commencement of mining at Ranger. Rehabilitation planning for Ranger has been underway for several years. In June 2018, ERA publicly released its Ranger Mine Closure Plan detailing the approach to the progressive rehabilitation of the Ranger mine over the next decade. The closure plan will be updated each year. Following the release of the Ranger Mine Closure Plan, the Supervising Scientist has released its Ranger Mine Closure Plan Assessment Report. This assessment report constitutes advice to the Australian and Northern Territory Government ministers to inform decisions regarding approval of the closure plan as to whether the implementation of the plan will result in achievement of the major rehabilitation objectives set out in the ERs. It makes a number of recommendations to ensure the best possible environmental outcomes that can be achieved (Australian Government 2020).

The environmental objectives stipulated by the Australian Government require the site to reach a state that is similar to the adjacent area such that it could be incorporated into Kakadu National Park should that be decided in the future. In the years after 2026, an ongoing effort will be required to ensure that the rehabilitation is successful. A closure requirement for the Ranger mine as per the ERs of the Commonwealth of Australia for the Operations of the Ranger Uranium Mine is that the final rehabilitated landform should possess “erosion characteristics which, as far as can be reasonably achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas” (Australian Government 1999). It is expected that the erosion rates will be initially high then tend slowly towards the natural rates. These time frames are expected to be quite long, so the outcome is to use the best available modelling to demonstrate that the erosion characteristics of the final landform will eventually be comparable to natural landscapes (Energy Resources of Australia Ltd 2018).

# 3 The equilibrium concept to assess the success of mine site rehabilitation

To be considered successfully rehabilitated, an above-grade landform needs to be in equilibrium with the surrounding catchment. The Rate Law developed by Graf (1977) explains the response of a landform to a disturbance that disrupts it from equilibrium. As per the Rate Law (Figure 1), an undisturbed geomorphic system (A) responds to disruption in such a way that the system parameter Y (some dimensional or spatial characteristic of the system such as length or width) is in a steady state B after disruption where new conditions are internalised by the system. This is followed by a relaxation time C when the system adjusts to new conditions. A new steady state is established in the next phase during D, resulting in new dimensional characteristics. However, in mine rehabilitation, the aim is for the steady state D to return to state A or similar.

In the case of RPA, as per ERs, it is recommended that the erosion characteristics reach a state of equilibrium with the surrounding catchment. An important parameter for assessment of site-wide erosion is FSS event load draining into Magela Creek and Gulungul Creek in whose catchment the Ranger mine resides. FSS is the fraction of the eroded sediment that is generally characterised as having a diameter less than 63 µm, which is highly mobile and easily transported. Also, Magela and Gulungul creeks are the first to receive sediments eroded from Ranger mine (Figure 4). The Supervising Scientist has demonstrated turbidity can be used as an indicator for FSS (Moliere et al. 2004). Event-based FSS loads should be measured and assessed using the methodology in Moliere & Evans (2010).

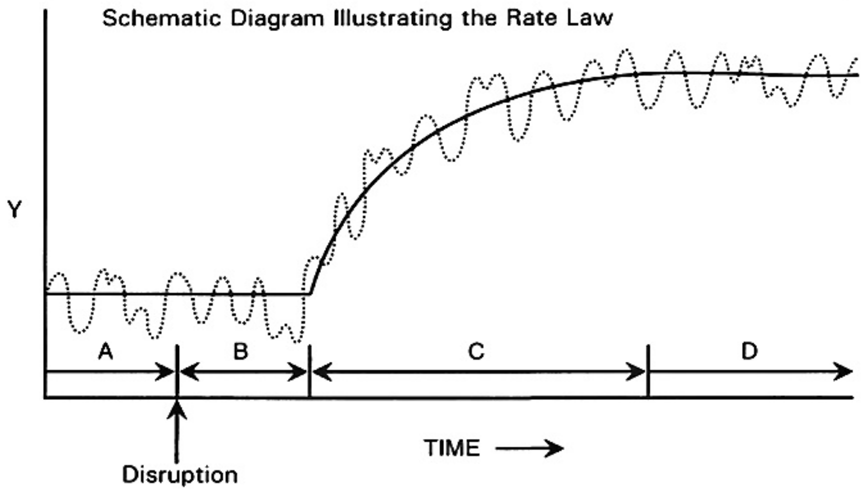

**Figure 1 Representation of Rate Law (Graf 1977)**

Moliere & Evans (2010) considered that the FSS transport in a stream system relative to hydrology wave characteristics is an indicator of landform equilibrium/disequilibrium. They identified significant regression relationships between the FSS load transported during runoff events and the stream discharge during the respective events in Magela and Gulungul creeks in the Alligator Rivers Region. The relationship was expressed as:

$$\text{Total mud load} = K'(Q_T)^a R_i^b \tag{1}$$

where:

$Q_T$ = total discharge during the rising stage of the hydrograph.

$Ri$ = maximum periodic rise in discharge.

$a$, $b$ and $K'$ = fitted parameters (Figure 2).

The FSS transport model should be periodically validated against observed FSS concentrations. Turbidity monitoring up- and downstream of the RPA will be applied as a measure of FSS loads leaving the landform and entering Magela Creek or Gulungul Creek. Sediment loads are expected to decrease over time and achievement of the outcome criterion will be based on trending towards background loads.

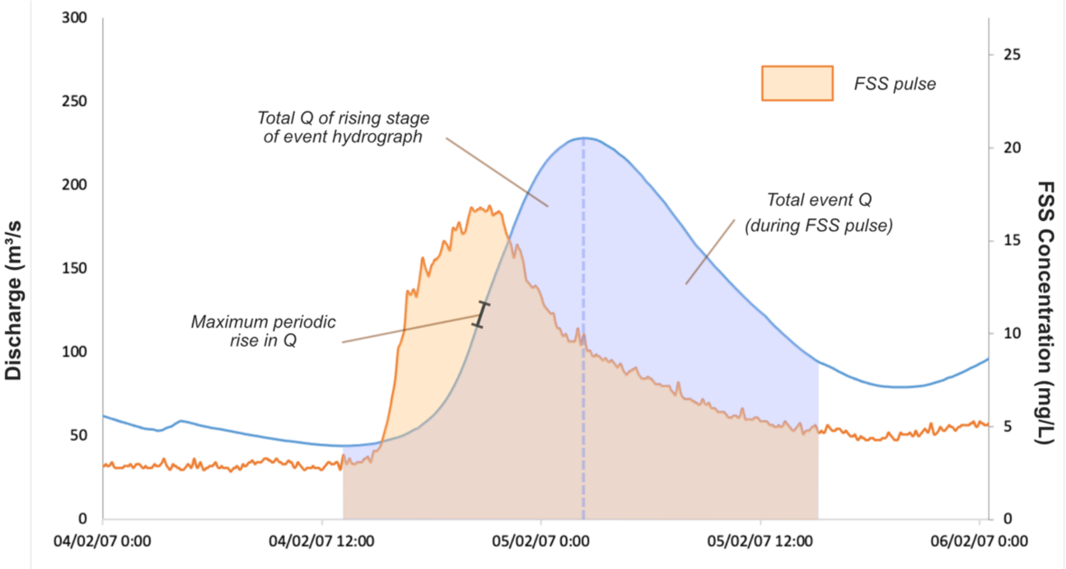

**Figure 2 Schematic diagram showing hydrological characteristics determined for fine suspended sediment pulse (data for Magela Creek in Northern Territory, Australia)**

A more reliable graphical representation to assess the equilibrium condition of the landform is to plot the observed FSS ($FSS_{obs}$) at the site using turbidity as a surrogate measure to predict FSS from the regression relationship ($FSS_{pred}$). The $FSS_{obs}$ versus $FSS_{pred}$ graph should give a best-fit line (1:1 line) when the system is in equilibrium. An FSS spike that varies significantly from the 1:1 relationship is considered to indicate a system in disequilibrium. For example, Figure 3 shows the event mud loads at a gauging station for the monitoring period (2003–2007) for the fitted relationship from Moliere et al. (2007a). Observed loads are normally distributed around the best-fit line (predicted loads). Thus, +1 *SD* (standard deviation), +2 *SD* and +3 *SD* from the 1:1 line were used to derive trigger levels. The events of 'interest' are those that lie above the +2 *SD* line, as these are events that have a relatively high mud load compared to the corresponding runoff characteristics. Thus, in this case, the event on 31 December 2004 records an elevated mud load and indicates that the system has moved to disequilibrium.

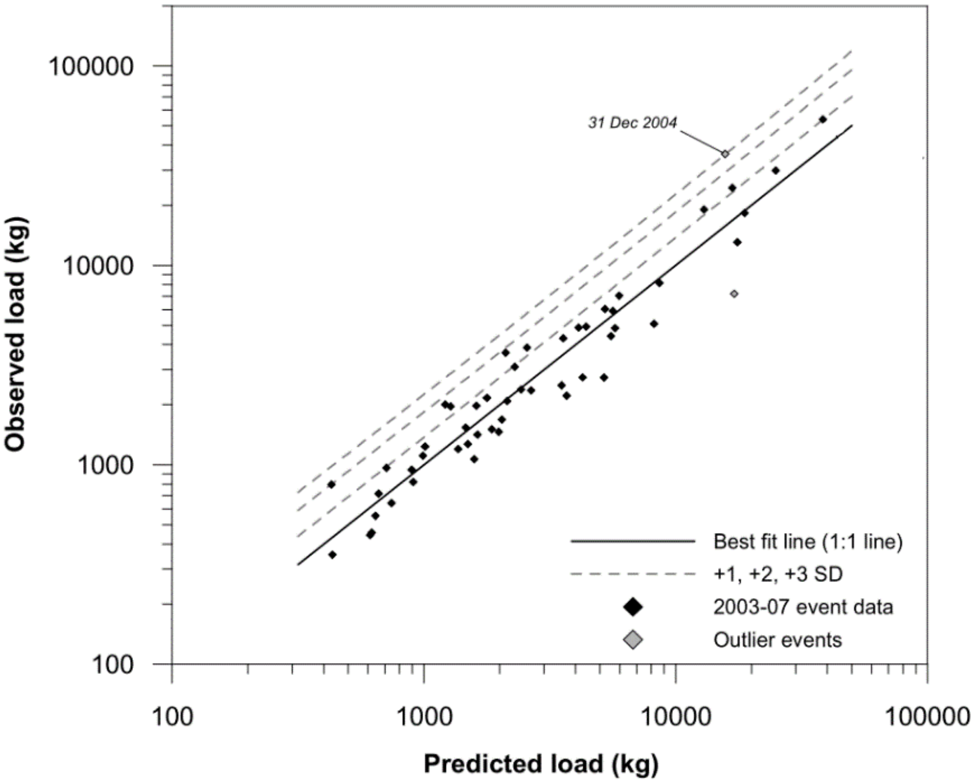

**Figure 3 Event-based mud load relationships (data for Gulungul Creek upstream from Moliere et al. 2007a)**

Thus, a comparison of observed FSS and that obtained from the modelled regression relationship can help assess landform stability. Research to date has not determined when and how the landform will return to equilibrium. A recent study assesses the landform change without mining and compares it to the modelled development of the landform following rehabilitation in terms of denudation rates, gully erosion and sediment loads (Lowry et al. 2019). The approach in this paper assesses how long before the landform achieves erosion equilibrium during the process of rehabilitation. Landform evolution models (LEM) are used to determine FSS predicted in future scenarios, which can be then compared to the FSS expected by the modelled FSS-stream discharge relationship.

# 4 Landform evolution model to assess landform stability

To determine how long before the landform achieves equilibrium following rehabilitation requires a LEM (CAESAR-Lisflood) that includes a hydrologic model (TOPMODEL) and a hydraulic model (Lisflood). Equilibrium can be determined by assessing the FSS produced by the model outputs.

The LEM to be used in this project is CAESAR-Lisflood (Coulthard et al. 2013), which simulates landscape development by routing water over a regular grid of cells and altering elevations of individual cells according to numerically calculated erosion and deposition rates from fluvial and slope processes. Runoff over the landform is generated through the input of rainfall data using an adaptation of TOPMODEL (Beven & Kirkby 1979). Surface flow is routed using Lisflood-FP (Bates et al. 2010), a two dimensional hydrodynamic flow model. Morphological changes to the landform result from transport and deposition of sediments. Einstein (1950) and Wilcock & Crowe (2003) sediment transport equations are the two options for calculating sediment transport in this version of CAESAR-Lisflood model.

A key attribute of the CAESAR-Lisflood model is the ability to use variable time-interval rainfall data from the study area, which is beneficial to the project site under consideration. This enables the modelling of the effects of specific rainfall events. As the climatic region in which the Ranger mine occurs is dominated by seasonal, high-intensity rainfall events, the ability to model specific rainfall events means that the CAESAR-Lisflood model is the most suitable model for this study. The CAESAR-Lisflood LEM requires three key data inputs: a digital elevation model of the landform, rainfall data, and particle size distribution data of the landform surface. The presence or absence of a vegetation cover may also be incorporated into model simulations (Lowry et al. 2013).

CAESAR can also be used to simulate the impact of extreme rainfall events, since time series data for actual or simulated rainfall events can be used as input. This ability is a critical attribute given the long times that radioactive material is required to be contained, and the probability that one or more very extreme rainfall events will occur. Extreme event testing of the proposed design parameters for the constructed landform has assumed greater importance given the possibility of an increase in frequency of intense rainfall periods as a consequence of climate change.

Thus, using the studies referred to above, FSS predicted can be obtained by simulating long-term FSS eroded from Ranger mine in CAESAR-Lisflood. FSS expected is obtained from the updated FSS-stream discharge regression relationship for Magela and Gulungul creeks based on current data. A comparison of both will decide if the catchment has achieved a return to equilibrium. An approach to discover the journey of erosion equilibrium of a rehabilitated mine site in the long run and assessment of landform stability has been discussed in the methodology detailed below.

# 5 Methodology

Here, we describe the project site and the updating of the FSS-stream discharge regression relationship at Gulungul and Magela Creek to determine FSS expected. FSS expected values will later be compared with FSS predicted values to evaluate landform stability with respect to erosion in the years to come. The methodology for determining FSS predicted values through CAESAR-Lisflood LEM is described. This requires calibration and validation of the model using present data and then simulating it for the future years, taking climate change and other variables into account.

## 5.1 Site background study: Ranger mine

The Ranger open cut uranium mine (12°41′ S, 132°55′ E) is in the Alligator Rivers Region of the Northern Territory, Australia, 8 km east of the township of Jabiru. The mine is surrounded by, but separate from, the World Heritage–listed Kakadu National Park (Figure 4). The Ranger mine is adjacent to Magela Creek, a tributary of the East Alligator River. Gulungul Creek is a small tributary of Magela Creek that is adjacent to the tailings dam.

The regional geology around the Ranger mine is dominated by the mineralised metasediments and igneous rocks of the Pine Creek geosyncline and the younger sandstones of the Mamadawerre Formation. The Ranger site is characterised geomorphically as part of the deeply weathered Koolpinyah surface. This consists of plains, broad valleys, and low gradient slopes, with isolated hills and ridges of resistant rock (East 1996). Located in the monsoon tropics climatic zone, the Alligator Rivers Region experiences a distinct wet season from October to April and a dry season for the remainder of the year. Consequently, streamflow is highly seasonal. The average annual rainfall is 1,557 mm (Bureau of Meteorology 2020).

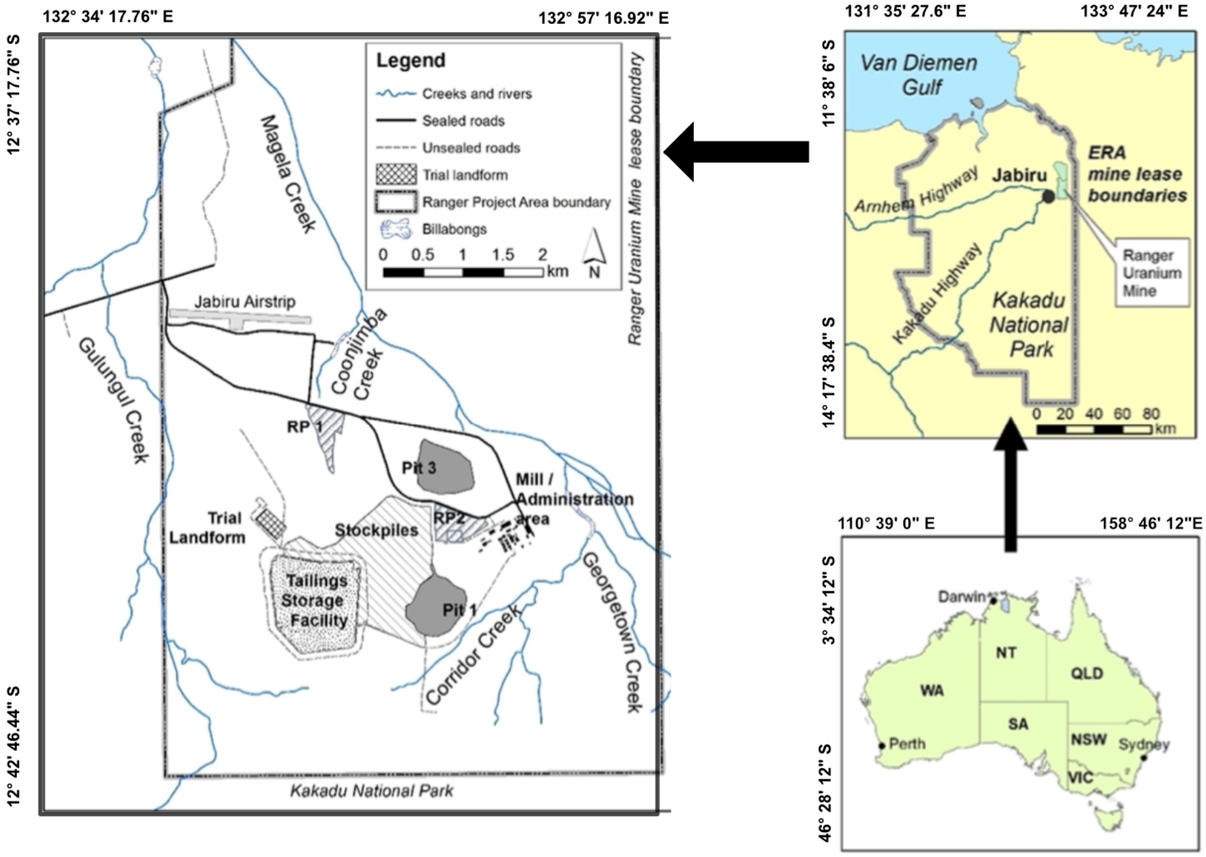

**Figure 4 Location of Ranger Uranium Mine. Adapted from (Lowry et al. 2020) and reproduced under Creative Commons CC by attribution**

## 5.2 Updating the FSS-stream discharge relationship for Magela and Gulungul Creek

To assess equilibrium relationships, increased mud or FSS (silt + clay, <63 µm, >0.45 µm) concentrations and loads in receiving streams is a useful indicator of catchment disturbance (Nair et al. 2021). The Ranger mine is adjacent to Magela Creek (Australian Government 2020) and Gulungul Creek, which is a small tributary of Magela Creek. Gulungul Creek is one of the tributaries that would be the first to receive sediment generated from the mine site during and after rehabilitation (Erskine & Saynor 2000). Detailed stream mud monitoring over a period of 22 years at Magela Creek and Gulungul Creek in the Magela Creek catchment (Evans et al. 2016; Moliere et al. 2000, 2003, 2005b, 2005c, 2005d, 2007a, 2007b) has been conducted to assess mining impact on receiving streams downstream of the Ranger mine.

Moliere & Evans (2010) used a relationship between the observed total event FFS load (OTL) and predicted total event FSS load (PTL) to assess catchment disturbance. In the undisturbed state, the best-fit line between OTL and PTL is the 1:1 line. If the relationship for the downstream site moves away from the 1:1 line, but stays the same at the upstream site, then an event introducing greater FSS total loads at the downstream site has occurred between the upstream and downstream sites.

Moliere & Evans (2010) assessed FSS and turbidity, in nephelometric turbidity units (NTU), from 2004 to 2008 at four locations to calculate OTL and the equations for PTL. The four locations were monitoring sites in Gulungul Creek downstream (GCDS), Gulungul Creek upstream (GCUS), Magela Creek downstream (MCDS), and Magela Creek Upstream (MCUS) of the mine (Figure 5). During the 2008 dry season, a 50-ha trial landform was constructed on the Ranger site within the Gulungul Creek catchment. The trial landform is on the right bank of Gulungul Creek between GCUS and GCDS and is several hundred metres from the creek.

Runoff from the trial landform drains through savanna woodland and heavily vegetated black soil swamps near the stream channel. The only significant disturbance in the catchment is the Ranger mine. FSS, NTU, rainfall and discharge data were collected at all monitoring sites from 2004 to 2015, enabling assessment of how a landform will return to its pre-disturbance sediment flows after mining and rehabilitation.

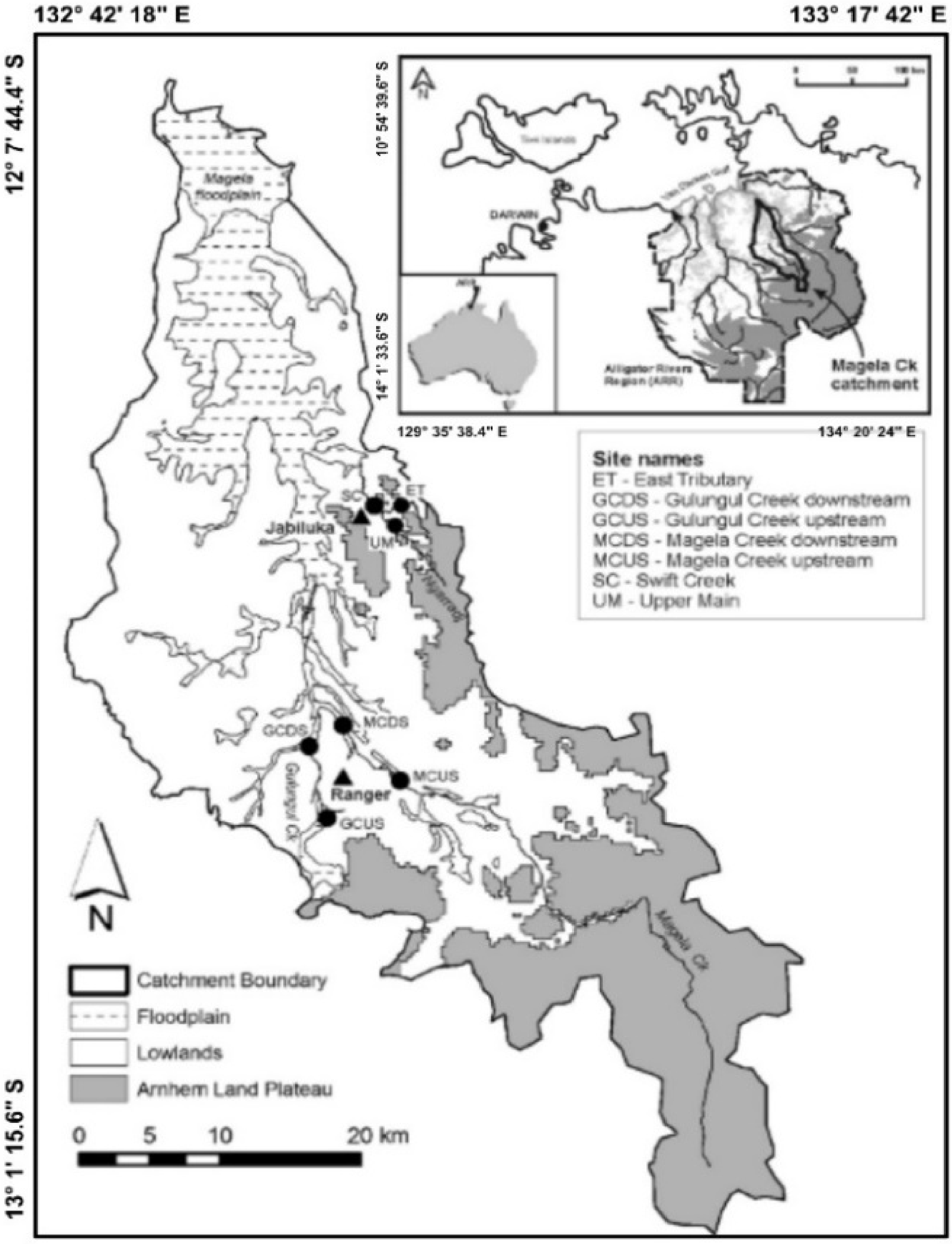

**Figure 5** **Location of gauging stations at Ranger. Adapted from Moliere & Evans 2010; copyright Commonwealth of Australia**

FSS data could not be collected for each rainfall event, but NTU data can be used as a surrogate for FSS (Moliere et al. 2005a). The FSS–NTU relationships at each site in Gulungul and Magela Creeks can be used to accurately estimate FSS and create a continuous FSS record. The relationship can vary between sites and with different instruments and it is important that the FSS data be collected regularly to update and confirm the FSS–NTU relationship. The FSS–NTU relationship was plotted with available data (2009–2013) for each gauging station, and the equation of the best-fit line was calculated using the trendline function in Excel for GCUS, GCDS, MCUS, and MCDS (Nair et al. 2021).

In order to calculate the event FSS load and event discharge characteristics, it is necessary to segregate a rainfall-runoff event from the annual stream discharge data by analysing the rise and fall of FSS concentration in the stream pertaining to a rainfall event. Discharge and FSS data were plotted on the *y*-axis and the timeline on *x*-axis (as shown in Figure 3) for each water year (31 August to 31 August) from 2005 to 2015. An FSS concentration of 2–5 mg/L was considered as the base flow level. Each event resulting in an FSS pulse where the sedigraph rises and reaches a peak concentration >5 mg/L was identified. The start of the FSS pulse was taken as a point where the sedigraph started to rise with a steep slope up to a peak value. The end of the FSS pulse was taken as a point on the sedigraph, where the slope of the receding part of the sedigraph was first parallel with the *x*-axis. Here, the event FSS loads and event discharge for corresponding rainfall-runoff events are thus determined by adding instantaneous discharge and FSS loads corresponding to the time intervals from the start to the end of an identified rainfall-runoff event.

The relationship between event FSS load and the runoff characteristics total event discharge ($Q_T$) and maximum periodic rise in discharge ($R_i$) were determined using a multivariate regression analysis. A total of 110 events were analysed for GCUS, 100 events for GCDS, and 60 events for MCDS. Equation 1 is updated for each gauging station (Nair et al. 2021):

$$\text{For GCUS: } T_{GCUS} = 0.265 Q_T^{0.75} R_i^{0.43} \text{ (R2 = 0.92, } n \text{ = 106)} \tag{2}$$

$$\text{For GCDS: } T_{GCDS} = 0.004 Q_T^{1.02} R_i^{0.05} \text{ (R2 = 0.96, } n \text{ = 83)} \tag{3}$$

$$\text{For MCUS: } T_{MCUS} = 0.018 Q_T^{0.94} R_i^{0.16} \text{ (R2 = 0.93, } n \text{ = 41)} \tag{4}$$

$$\text{For MCDS: } T_{MCDS} = 0.012 Q_T^{0.97} R_i^{0.19} \text{ (R2 = 0.94, } n \text{ = 60)} \tag{5}$$

The PTL for FSS pulse events for each station were determined from these equations.

For each event data analysed, OTL was calculated using the FSS–NTU relationship and PTL was calculated for the updated equation for each site. The OTL versus PTL graph for Magela and Gulungul was produced for each year from 2004 to 2015 to assess the effect of the trial landform construction and rehabilitation on FSS event loads in Gulungul Creek and Magela Creek.

This analysis supports the hypothesis that a system change in FSS mass can be observed downstream as a result of catchment disturbance – in this case, trial landform construction – and that this system change will return to baseline as the disturbance ‘heals itself’ (Nair et al. 2021). For the years till 2008, prior to the construction of trial landform and the potential impact on Gulungul Creek, the original fitted line using the events analysed is in congruence with the 1:1 line. This relationship represents the functioning of the catchment system with respect to total FSS mass transported during rainfall-runoff events for GCUS, GCDS, and MCDS. The only likely source of disturbance in the catchment is the Ranger mine, as there has been very little disturbance elsewhere in the catchment. Immediately after construction of the trial landform, there was a system change in GCDS in 2008–2009 and 2009–2010, but not in GCUS and MCDS. Thus, the lack of broader disturbance across the catchment confirmed that it was the trial landform construction in Gulungul catchment that caused the system change. During the following years there was recovery in the catchment. There was a reduction in total FSS load relative to event discharge, with the fitted line moving downward toward the 1:1 line. This corresponded to some settling of the trial landform. By 2010–2011, the catchment was functioning at pre-trial landform conditions, as even very large FSS load events, due to high rainfall events, fell on the 1:1 line. Thus, the method is proved to be a sensitive approach that can be applied as a mine landform rehabilitation assessment tool.

Thus, the FSS expected is evaluated from the updated equations 2, 3, 4, 5. To determine FSS predicted, CAESAR-Lisflood is calibrated and validated to simulate the same FSS data.

## 5.3 Calibration and validation of hydrological and FSS components of CAESAR-Lisflood

This section focuses on calibrating the Gulungul Creek catchment using measured rainfall and discharge data and fitting the hydrograph exponent m and Manning’s n. A distributed Manning’s n file based on vegetation and soil types will be mapped using remote sensing. Using the geographic information system, the shape file of the catchments and Manning's polygon will be overlapped and is to be imported to the CAESAR-Lisflood model. In the CAESAR-Lisflood model, using different Manning's coefficient 'n' (level of surface roughness affecting flow velocity and flow path), the hydrograph exponent 'm' (determines the peakiness and duration of the hydrograph) will be adjusted so that the predicted discharge is similar to the observed one. Calibration will then be done by iteratively fitting FSS in the CAESAR-Lisflood to measured FSS load data by using variable Manning's n values and adjusting the shear stress. The predicted peak sediment concentration will be fitted to the observed peak FSS concentration. The calibration of the model for hydrological and FSS components is done initially for a single rainfall event, followed by validation.

Validation of the model will be done by running the calibrated model for another rainfall event and checking that the simulated output of the model is similar to the observed hydrological and FSS components of the catchment, which proves the calibration of the model as successful. It will also be also run for a whole of wet season for a further check of the model by considering the initial loss and continuous loss in the wet season rainfall. Downstream of Gulungul catchment will be calibrated by the above method due to wide availability of data. In the case of Gulungul upstream catchment, calibration and validation can be done using two different models and then adjusting the parameters in both models so that the models give similar outputs. This calibrated and validated model can then be run for simulations to determine predicted event FSS in future rainfall events over time. To do this for simulations into the future requires the input of predicted rainfall, which needs to take potential climate changes into account.

## 5.4 Deriving future climate change rainfall scenarios and discharge inputs

Extreme wet and dry rainfall scenarios will be derived using a weather generator and previous rainfall records for the region. Initially, the existing rainfall data from an established weather station can be assessed and, secondly, used to stochastically generate rainfall time series based on the longest and most reliable rainfall data. In northern Australia, rainfall variability is markedly higher than most comparable climates in other continents (Dewar & Wallis 1999) and rainfall records are both sparse and short. One important data requirement of these LEMs is long-term, high-quality, high-temporal resolution rainfall data, including reliable high-resolution rainfall data that captures the extent of variability that can be expected for the region since each rainfall scenario produces a unique pattern of erosion (i.e. the location and extent of the gullies is variable). Jabiru airport is the closest rainfall station to the Ranger site with the pluviograph data. Sub-daily (6 min) rainfall data can be obtained from the Australian Bureau of Meteorology. Complete year data may be used to correctly capture the annual rainfall patterns, including the extreme rainfall events and dry periods.

A stochastic rainfall generator (also known as a weather generator) is a model that is designed to generate synthetic rainfall time series with the same statistical properties as observed data (Thyer & Kuczera 2000). CAESAR-Lisflood requires sub-daily (hourly) rainfall data. There are two main approaches to generating rainfall data at sub-daily level. The first method is to stochastically generate daily rainfall using either the Bartlett-Lewis Rectangular Pulse stochastic rainfall model or an Autoregressive 1 (AR1) model and then disaggregate to hourly rainfall. The second method is to directly generate sub-daily (6 min/hourly) rainfall data using such models as the Disaggregated Rectangular Intensity Pulse (DRIP) model (Heneker et al. 2001) or the Neyman-Scott Rectangular Pulse (NSRP) process model (Frost et al. 2004).

The complete historical rainfall data for Jabiru can be added end to end to produce a continuous 1,000-year record that could be used as input into the CAESAR-Lisflood model (Hancock et al. 2017). Rainfall data generated by DRIP has been shown to reproduce short timescale statistics better than the alternative NSRP model, and it has been tested in Australia in terms of its ability to reproduce certain 'standard' and extreme rainfall model statistics derived from the pluviograph record over a range of timescales (Frost et al. 2004). Thus, the DRIP model will be used to generate 1,000-year 6-min stochastic replicates based on the Jabiru airport rainfall data, which will be aggregated to 1-hourly replicates for use in CAESAR-Lisflood. The replicates will be validated by inspecting if they satisfactorily represent the types of storm events that are common to the site under consideration (Hancock et al. 2017).

### 5.5 Running long-term simulations of landform and assessing FSS spike disequilibrium

The Ranger mine site will be modelled and run across a 1,000-year rainfall period to assess long-term stability post-closure. Impacts of climate change on rainfall in the Top End of the Northern Territory are currently unclear. Long-term effects of potential future climatic change on landscape morphology will be considered by evaluating both a wetter rainfall and drier rainfall future climate scenario. Since the vegetation cover is introduced in the model using Manning's 'n' values, it will be changed in stipulated intervals during long-term simulations to account for change in vegetation cover. Also, when future climate change scenarios are reproduced, 'n' can be changed accordingly to include the effect of vegetation cover change during extreme wet or dry conditions. FSS expected will be derived from the fitted FSS-stream discharge relationship. FSS predicted will be simulated by CAESAR-Lisflood LEM. In a graph representing $FSS_{predicted}$ versus $FSS_{expected}$, if the best-fit line is in congruence with the 1:1 line, it indicates that the system is in equilibrium. At any point in time, if the best-fit line shifts from the 1:1 line, it indicates that the system has shifted to disequilibrium (Nair et al. 2021), thus the dynamics of the relationship can be investigated. Potentially, the landform could start in a state of disequilibrium, based on FSS discharge, for a period immediately after rehabilitation and then stay in a state of equilibrium. Alternatively, the landform may revert from equilibrium to disequilibrium at various time intervals after rehabilitation.

## 6 Conclusion

Mining can cause environmental disturbances, and thus mined lands must be managed properly to avoid detrimental impacts in the future. They should be rehabilitated in such a way that post-mining landforms behave similarly as the surrounding stable undisturbed areas. The methodology discussed in the paper can be used to assess landform stability and thus helps to understand the dynamics of landform equilibrium. FSS spikes above the background relationship occurring in the creeks with catchments where the mine resides acts as an indicator of the catchment disturbance. This method is sensitive and can be applied as a mine landform rehabilitation assessment tool. Beneficiaries from this research include government regulators, mining environmental staff, and, in the case of the Ranger mine, the traditional owners of the land.

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