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Memorandum

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From:	Ben Freidman, Senior Engineer
Cc:	Camilo Cordova, Geotechnical Engineer (Okane) Martine Goldner – Project Manager – MRO Mine Closure (Evolution Mining)
Our ref:	B-1178-224-MEM-005
Date:	10 January 2025
Re:	**MRO NWRD - Landform Evolution Modelling**

Introduction

Mount Rawdon Operations (MRO) is scheduled for closure in July 2025, with mining operations concluding in September 2024 and processing activities ceasing in April 2025. MRO has identified early work activities that can commence prior to the full closure of the site. Among these activities, reshaping and placing cover material on the top tier of the Northern Waste Rock Dump (NWRD) is being considered as part of the early works program.

The scope of Okane Project No. 1178-224 is to support the detailed cover system design for the NWRD. The primary objective is to identify and address any potential failure modes early in the design process.

This memorandum comprises Task 3 (Landform Evolution Modelling (LEM)) under Okane Project No. 1178-224. A series of memoranda will be prepared under Okane Project No. 1178-224 to address the key design and landform stability gaps identified in the concept review study (Okane Project No. 1178-222). These memoranda will be progressively integrated into the detailed cover system design report.

Task 1 – Cover System Modelling

Task 2 – Berm Geotechnical Stability Assessment

Task 3 – Landform Evolution Modelling

Task 4 – Drainage Options Assessment

LEMs are employed to assess potential water runoff, erosion risks, and deposition processes, providing data to inform post-closure planning and long-term performance expectations. LEMs offer insight into soil erosion over extended periods, supporting long-term closure strategies.

Purpose of Assessment

This memorandum outlines the results of erosion assessment for the top tier of the MRO NWRD, covering 25.5 hectares (ha). The document describes the background, methodology, and results of the LEM work conducted using a two-dimensional (2D) hydrodynamic flow CAESAR Lisflood model. CAESAR Lisflood is a morphodynamic/landscape evolution model that simulates erosion and deposition in surface catchments and reaches over time scales from hours to thousands of years. The assessment considers factors such as waste rock properties, NWRD top tier cover system geometry, vegetation cover, climate, and the necessary timeframes to inform future erosion modelling and landform evolution projections.

Scope of Assessment

The primary goal of the NWRD closure is to mitigate the potential for acid and metalliferous drainage (AMD), ensure geotechnical stability, and facilitate long-term environmental rehabilitation (DESI, 2024). This must be achieved while maintaining compliance with regulatory obligations, such as those outlined in the MRO Progressive Rehabilitation and Closure Plan (PRCP). The scope of this LEM assessment includes:

- Estimating erosion rates for the NWRD top tier cover system.
- Identifying potential high-risk erosion areas on the NWRD top tier cover system.

Exclusion of the Rock Batters from the LEM assessment

The rock batters of the NWRD have been excluded from the LEM assessment under the assumption that the average particle size distribution (PSD) of the NAF waste rock selected for these batters is coarse enough to generate runoff only during rare, high-intensity rainfall events. Even when runoff does occur, the flow-induced bed stresses on the batter face are not expected to be sufficient to mobilise the rock particles due to a low hydraulic depth and lack of flow concentrations. Further supporting technical information in provided in Appendix A.

Site Description and Background

Key MRO site features are below and in Figure 1.

1. Residual Void (Main Pit)
2. WRDs, Run-of-Mine (ROM) Pad and Stockpiles

- NWRD
- Long term ore stockpiles
- Western WRD

3. Tailings Storage Facility (TSF), inclusive of cells containing potentially-acid forming (PAF) material.
4. Roads and access tracks
5. Processing plant, workshops, and infrastructure management areas
6. Water management infrastructure and dams (e.g., south dam, west dam, water dams 1-4).

Stockpiles of low-grade ore have been established on the western side of the NWRD, either to be processed or rehabilitated. The NWRD, which covers approximately 105 ha, is used to dispose of both non-acid-forming (NAF) and PAF waste rock. The outer batters of the NWRD have been maintained at their angle of repose for stability. Water from seepage along the northern and eastern boundaries is collected in water dams 1-4.

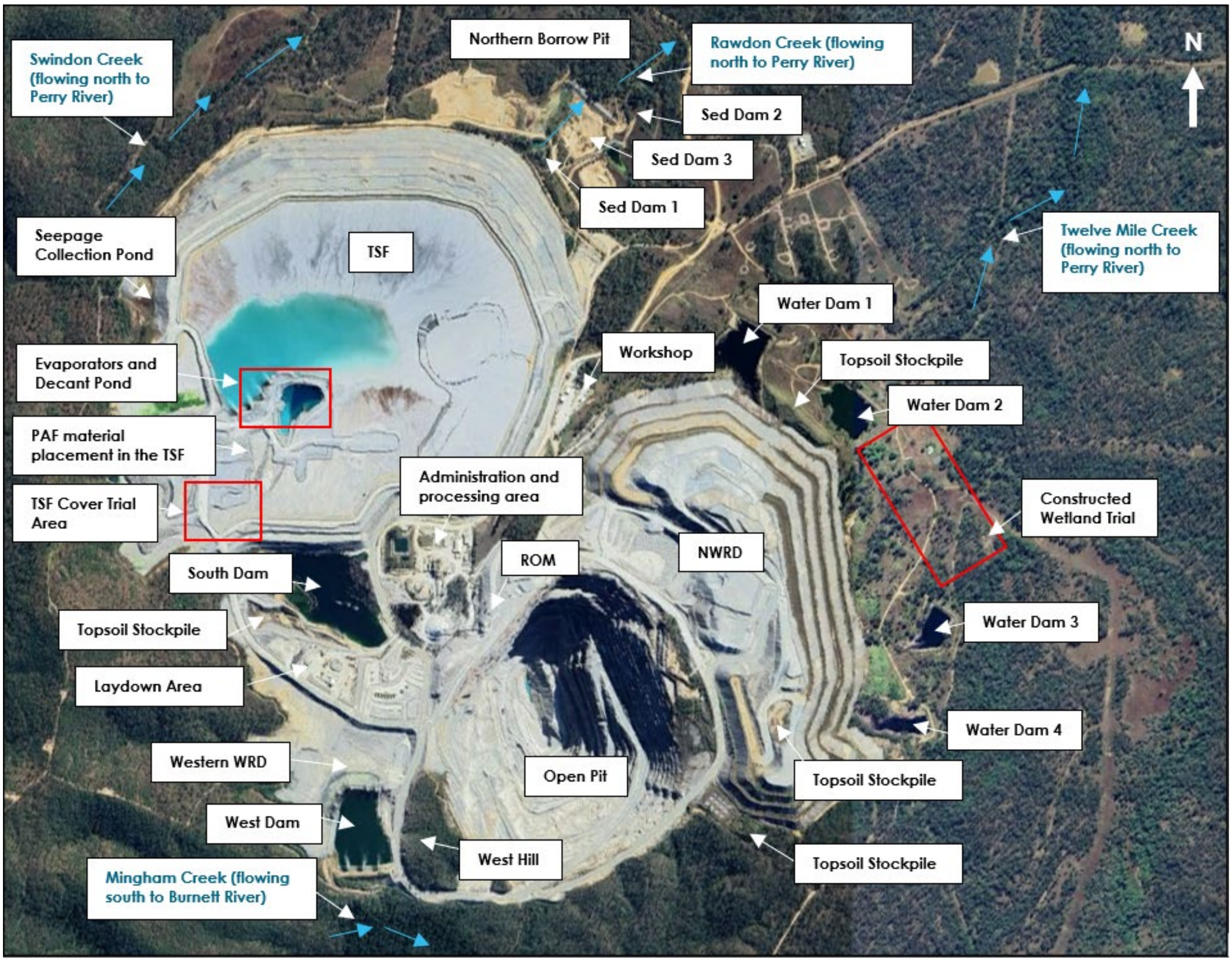
Climate Sequence

The Köppen-Geiger Climate Classification positions the MRO region as Cfa (humid subtropical). This classification is defined by a temperate climate with hot summers and no significant seasonal variation in precipitation:

- C: temperate or mild climate.
- f: no dry season, with significant precipitation in all seasons.

This classification denotes regions with consistently moderate temperatures throughout the year and no dry months during the summer.

SILO (Scientific Information for Land Owners) is an Australian climate database offering daily datasets from 1889 to the present. It provides comprehensive national coverage with interpolated data for gaps, facilitating research and climate applications without extensive data preparation. SILO is hosted by the Science and Technology Division of the Queensland Government's Department of Environment, Tourism, Science and Innovation (DETSI). Table 1 presents monthly mean historical climate statistics (from 1900 to 2024) based on data from the nearest meteorological station (Mount Perry, The Pines, Station #039070), located 14.4 km from MRO, using the SILO Long Paddock data drill system.



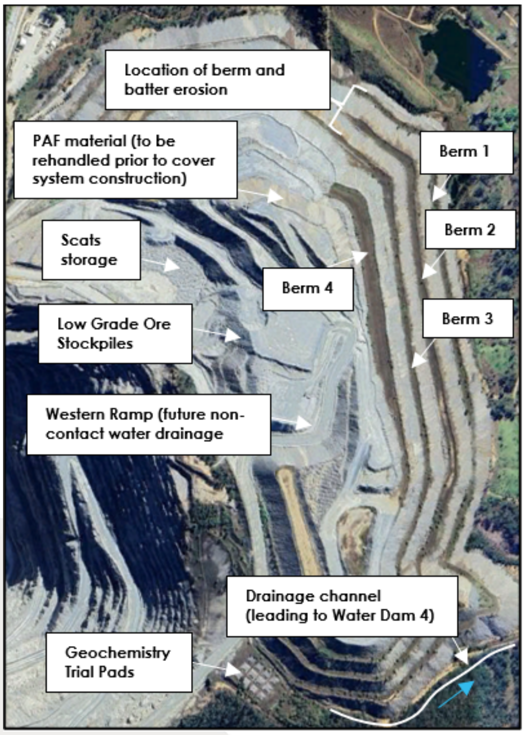


Figure 1: Key site features at MRO (top), and current operational features of the NWRD (bottom).

Table 1: Monthly mean climate parameters at MRO

Month	Air Temperature (°C)		Relative Humidity (%)		Precipitation (mm)	Potential Evapotranspiration (mm)
	Maximum	Minimum	Maximum	Minimum		
Jan	31	20	96	51	1,777	2,021
Feb	31	19	97	53	1,684	1,667
Mar	29	18	98	53	1,355	1,619
Apr	27	15	98	51	668	1,290
May	24	11	98	50	635	1,009
Jun	21	8	98	49	587	817
Jul	21	7	97	46	497	910
Aug	23	8	96	43	356	1,169
Sep	26	11	95	43	375	1,475
Oct	28	14	95	44	832	1,821
Nov	30	17	94	45	958	1,971
Dec	31	19	95	48	1,422	2,094

The mean annual rainfall is 892 mm, however rainfall statistics from Mount Perry 'The Pines' Station since 1889 indicate the high variability of annual rainfall in the region around MRO. Rainfall mainly occurs during the warmer summer months with most of the precipitation (>70 %) falling in the wet season from November to April. The highest daily rainfall recorded via the Bureau of Meteorology (BOM)was 339 mm in January 1890. The highest annual rainfall in the 124-year database was 1,994 mm in 1956 while the lowest annual rainfall was 379 mm in 2019.

Figure 2 illustrates the cumulative deviation from the mean annual rainfall, indicating that rainfall is variable and can deviate year-to-year from the annual average, producing extended wetter and drier sequences.

The average annual maximum and minimum air temperatures at the MRO are shown in Figure 2. Rainfall Intensity Frequency Duration (IFD) relationships are shown in Figure 3 which are also utilised in drainage assessment and design.

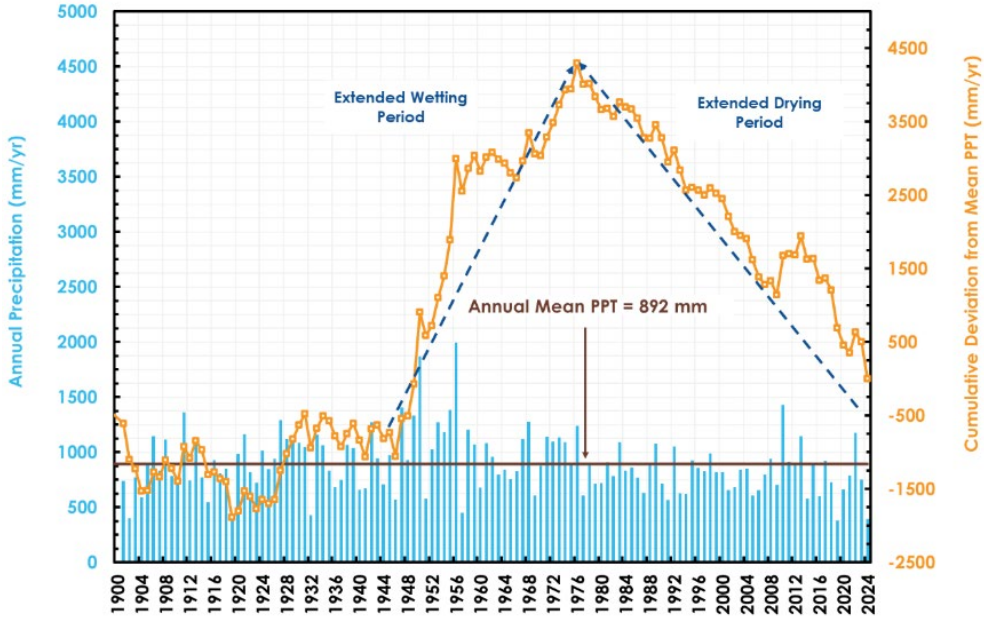


Figure 2: Annual rainfall and cumulative deviations from average annual rainfall at MRO.

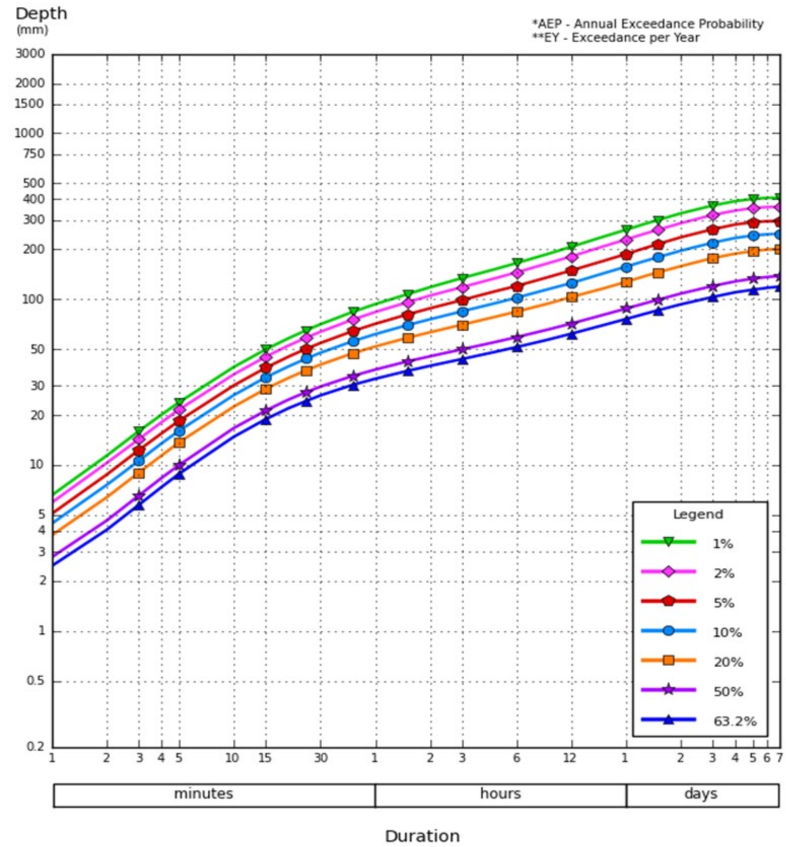


Figure 3: Rainfall IFD relationship at MRO.

Materials

Materials for rehabilitation include topsoil, subsoil, and overburden sourced from designated stockpiles and borrow areas. These materials have been characterised by their geochemical and physical properties to ensure suitability for the cover system. The materials used for the cover system include:

- Topsoil sourced from available topsoil stockpiles and/or borrow areas within the mining lease.
- NAF waste rock from the site's available stockpiles.
- Rocky mulch, which is a mixture of topsoil and NAF waste rock at a 50:50 (bank cubic metres) split.
- NAF oxide regolith from the site's available stockpiles.
- Clayey soil material from the borrow areas to use as a reduced permeability layer (RPL).

Okane (2024) conducted a cover system option assessment using SEEPW modelling (GeoStudio, Version 2024). Option 5 was identified as the preferred solution, balancing material availability, thickness, and constructability. From bottom to top this option includes a 0.5 m interim NAF cover over PAF waste rock, followed by a 0.5 m compacted clayey soil layer (RPL), 1.0 m of NAF oxide regolith (infiltration storage layer (ISL)), and 1.0 m of rocky mulch, as shown in Figure 4.

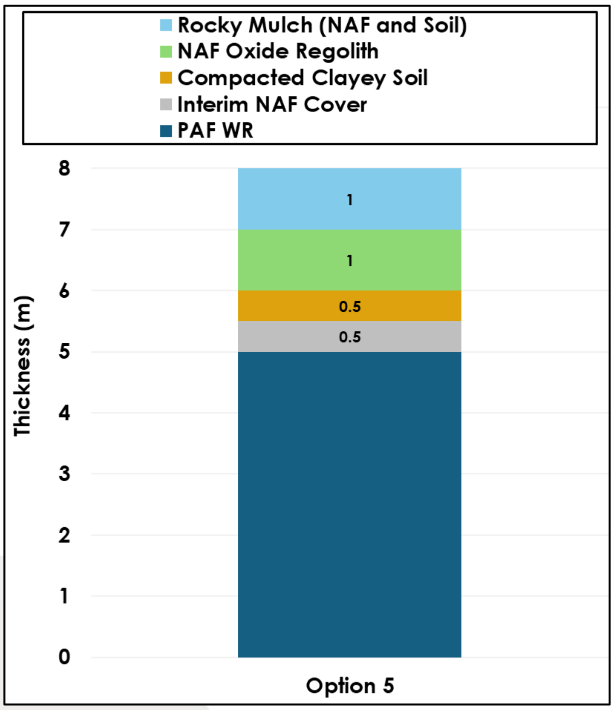


Figure 4: Selected Cover System Design (Option 5).

Five soil samples (pedolith and saprolith samples) from the borrow source have been identified for constructing cover systems on the TSF and NWRD. These samples were analysed for soil quality, geochemical, and physical properties to determine their suitability (RGS, 2022; RGS, 2023).

The rocky mulch material evaluated in the numerical modelling (Okane, 2024) serves as the primary material for the LEM assessment. This material was modelled with properties similar to Sample 4 and Sample 5 from the RGS (2023) erosion measurement investigation. Table 2 presents the physical properties of Sample 4, while Figure 5 compares the PSD curve of the rocky mulch with that of Sample 4.

It is important to note that Sample 5 is described as a mixture of Sample 4 and NAF waste rock, closely resembling the expected rocky mulch material. As a result, the LEM will be calibrated using the erosion results from Sample 5 (RGS, 2023).

Table 2: Sample 4 physical parameters

Soil Properties	Values
Clay (%)	14
Silt (%)	42
Sand (%)	21
Gravel (%)	23
Texture Class	Silt Loam
Particle Density (g/cm^3)	2.4
Bulk Density (g/cm^3) - loose as – placed	1.16
Bulk Density (g/cm^3) – compacted Samples	1.32
Soil Porosity for loose samples (%)	51
Soil Porosity for compacted samples (%)	45

Source: RGS, 2023.

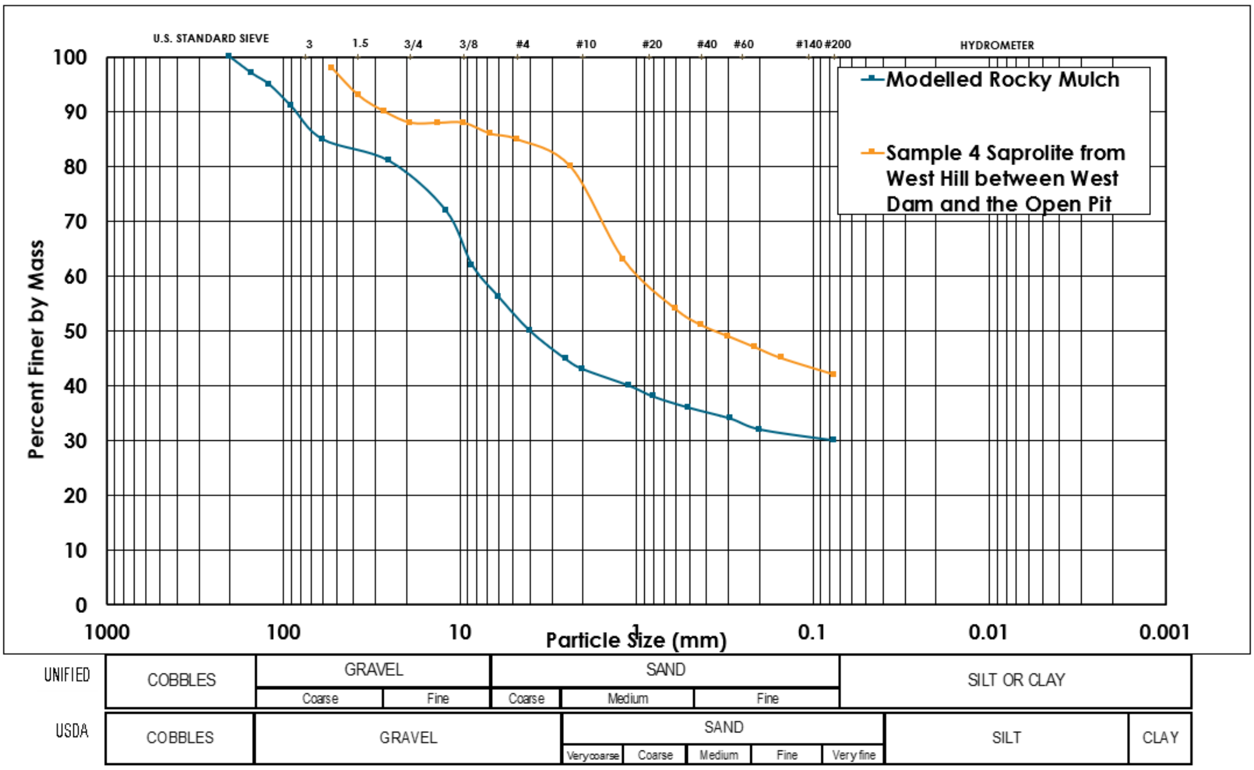


Figure 5: PSD curve for rocky mulch.

Emerson Classification and Sodicity

Emerson Aggregate and column tests were performed on Sample 4. The sample was classified as Class 6, indicating complete flocculation and low tendency to disperse, according to the Emerson classification system. The column test indicated minimal settlement. The sodicity analysis for Sample 4 indicates low electrical conductivity (EC) and an exchangeable sodium percentage of 1.0. Table 3 provides the full sodic soil assessment results for the Sample 4 saprolite material.

Table 3: Sodic soil assessment

Sodic Soil Assessment	Values
Sample Colour (Munsell)	Very dark greyish brown (10YR 3/2)
EC in 1:2 soil:water (µS/cm)	36
Exchangeable sodium percentage	1.0
Column settlement	> 48 hours

Source: RGS, 2023.

Previous Erosion Measurement and Modelling Results

RGS (2023) estimated erosion rates for borrow materials proposed as cover for the NWRD, modelling them on slopes with a 5% gradient and lengths from 10 m to 110 m (Figure 6). Okane's LEM assessment (this memorandum), by contrast, applied a 3% slope for similar lengths in line with the longitudinal flow across the top tier plateau.

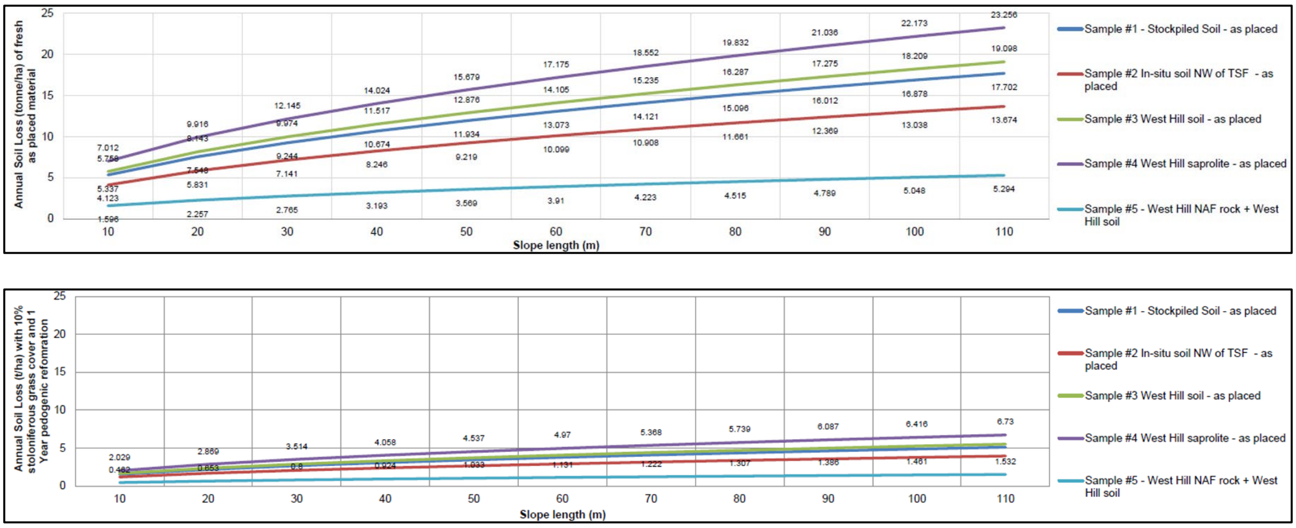


Figure 6: Modelled annual erosion rates for as placed material and 10% vegetation cover.

Source: RGS,2023.

Cover System Drainage Design

The proposed drainage design for the top tier NWRD serves as the base surface for the LEM analysis and was developed using the DRAINS software from Watercom, which takes into account the NWRD's design, cover materials, and local climate. The design adheres to Australian Rainfall and Runoff (ARR) guidelines and incorporates rainfall data from BOM. The drainage system is designed to manage surface runoff from rainfall events, including those with a 1% annual exceedance probability (AEP), by utilising rock-lined channels to accommodate peak flow velocities. Two ramp-style drains are incorporated to align with the NWRD design and to direct water towards the base of the NWRD, with bunding installed to further control water flow and prevent infiltration into PAF material.

The designed channels support the store-and-release cover system by effectively managing excess runoff. With V-shaped grading, these channels create a collection point for surface water at the centre of the landform, facilitating water movement in a conventional open channel drainage network toward the base of the NWRD. As part of its Life of Mine (LOM), MRO has planned that PAF material currently stored on the northern top tier of the NWRD will be rehandled or removed before reshaping to implement the drainage design.

The design features ramp-style drainage on the western side of the NWRD, enabling surface water to flow off the NWRD through previously shaped access ramps. Two ramp-style drains are integrated into the NWRD design, dividing the plateau area into three (3) catchments, as shown in Figure 7:

- Two main catchments (Northern NWRD top tier and Southern NWRD top tier) drain into Channel 1, flowing westward; and

- One centre catchment (Central NWRD top tier) drains into Channel 2 in a north-westerly direction. Okane will optimise this catchment after review by MRO and confirmation of any material rehandling or processing.

Table 4 summarises the drainage specifications for Channel 1 and Channel 2. This is important because the LEM does not assess armoured surfaces. To accommodate this, the total area of the channels was adjusted to reflect only the area that is not covered by the lined channel.

Table 4: Summary of Drainage Specifications for the NWRD top tier

Channel	Length (m)	Average longitudinal gradient (%)	Base width (m)	Channel depth (m)	Channel side slope (1V:H)	Peak flow velocity (m/s)	Minimum freeboard (m)
Channel 1	353	8	6	0.7	2.5	2.7	0.3
Channel 2	403	7	5	0.6	2.5	2	0.3

Methodology

LEMs are employed to simulate potential yield erosion, water runoff, and deposition on landforms over extended periods of time. The CAESAR Lisflood model, specifically designed for such purposes, is used in this assessment. CAESAR Lisflood runs on an hourly timestep using rainfall data, offering detailed analysis of erosion patterns, particularly during significant storm events. These models follow the flow of water on a surface, and then to focus on the higher energy flows that cause erosion.

Model Overview

The CAESAR Lisflood model is a tool used for simulating geomorphic and hydrodynamic processes, including erosion, deposition, and fluvial dynamics over a wide range of timescales. It integrates the CAESAR geomorphic model (Coulthard et al., 2000, 2013; Van De Wiel et al., 2007) with the Lisflood-FP 2D hydrodynamic flow model (Bates et al., 2010). This combination enables the model to simulate changes in landscape morphology across both catchments and river reaches over periods from hours to thousands of years. The model operates by routing water over a grid of cells and adjusting elevations based on erosion and deposition influenced by fluvial and hillslope processes.

CAESAR Lisflood can run in two modes: catchment mode, where the primary input is rainfall, and reach mode, where water and sediment enter the system through specified points. In both cases, the model requires the definition of several initial conditions and parameters, including topography, grain sizes, and either rainfall or flow data. The model calculates the spatial distribution of erosion and deposition over each time step, with outputs including changes in elevation, sediment distributions, and discharge rates.

In catchment mode, the hydrological component of the model is based on an adaptation of the TOPMODEL framework (Beven & Kirkby, 1979), which generates surface runoff when soil moisture exceeds a specified threshold. The resulting surface runoff is then routed through the landscape using the flow model, which drives erosion and sediment transport. CAESAR Lisflood allows for up to nine size fractions of sediment to be transported either as bed load or suspended load, depending on grain size. The model utilises transport equations from Einstein (1950) and Wilcock & Crowe (2003) to determine sediment transport rates.

The model is particularly suited to using recorded rainfall data, which allows for the simulation of the effects of specific rainfall events. This is critical in regions where a significant proportion of erosion occurs during high-intensity rainfall events. The ability to input rainfall data at varying temporal intervals, ranging from 10 minutes to one hour, allows for detailed analysis of the effects of these events on landform evolution. This feature makes CAESAR-Lisflood a practical tool for studying areas with highly variable rainfall patterns.

Advantages of the model include:

- Versatile scalability: operates effectively across a wide range of spatial and temporal scales.
- Comprehensive outputs: generates both graphical and numerical outputs, facilitating diverse analysis needs.
- Material characterisation: uses grain size distribution, a well-established and quantifiable parameter, to accurately characterise materials.
- Rainfall scenario modelling: capable of simulating various rainfall scenarios (long-term trends and individual storm events).

The CAESAR-Lisflood model dynamically balances cover loss and vegetation establishment by simulating interactions between geomorphic processes and vegetation parameters, effectively capturing the relationship between erosion and recovery. Cover loss occurs in areas of high erosion, where sediment detachment and transport expose bare soil, particularly during intense runoff events, while vegetation establishment is simulated in stable or depositional zones where reduced erosion allows regrowth. Vegetation acts as a protective layer, reducing surface runoff and erosion by increasing infiltration and modifying critical shear stress. In areas of high erosion, the model reduces vegetation cover, reflecting its removal, while stable areas promote regrowth, enhancing soil stability. Although the model does not directly simulate organic material build-up from decomposition, vegetation establishment indirectly improves soil quality over time, fostering further growth. Despite its robust simulation of hydrological and geomorphological processes, the model has limitations in representing biological and ecological dynamics, as it does not explicitly simulate vegetation growth, decomposition, or organic matter accumulation. Instead, it relies on user-defined adjustments to parameters like critical shear stress and sediment transport thresholds to approximate vegetation's impact on erosion resistance.

Landform Surface

The modelled landform was assessed using the 2023 NWRD survey in conjunction with the proposed drainage design, which includes the top tier cover system surface, gradients, and channels (Figure 7). The surface resolution is based on a 1.0 m grid. It's important to note the trade-off between survey density and output accuracy: while a 1.0 m grid results in a smoother terrain surface and effectively addresses inter-rill erosion associated with the cover system design, opting for a smaller grid size could enhance detail but would also increase processing time. Given that datasets at this density are already substantial and challenging to manage, the current resolution strikes a balance between detail and feasibility.

As part of the assessment scope, the targeted surface for the LEM included only surfaces covered with rocky mulch as part of the cover system design. Rock-armoured batters were excluded from the erosion assessment due to their high permeability and lack of sediment transport mechanism (see Appendix A). The coarse nature of rock material minimises the potential for sediment detachment and transport.

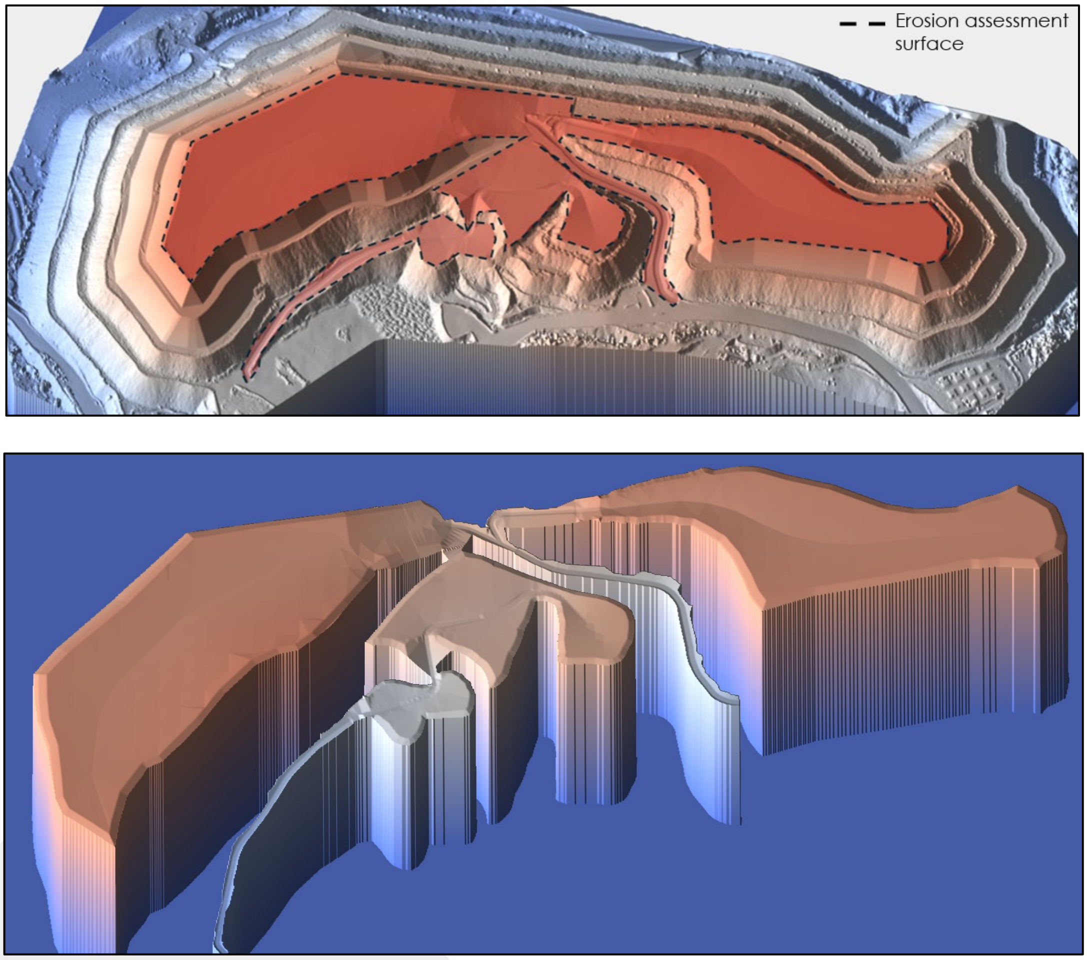


Figure 7: Erosion assessment surface (colour change signals the elevation difference).

Model Calibration

The CAESAR Lisflood model was calibrated using results from flume testing conducted by RGS (2023), which evaluated four different topsoil samples under various rainfall conditions. Sample 5 was selected for comparison with the rocky mulch due to its comparable fine particle content. During the calibration process, parameters such the erodibility factor and critical slope were fine-tuned to achieve erosion yield volumes similar to those reported by RGS (2023) over a one-year period.

Due to the constrained testing conditions in the flume/rainfall simulator (characterised by fixed gradients and slope lengths), a parametrisation was employed to evaluate different slope length that better reflect the variability of the NWRD landform. Based on the specific catchment area of the NWRD top tier cover design (25.5 ha), an estimated erosion rate was calculated for the material as placed and with 10% vegetation cover as listed in Table 5.

This estimation was then compared with a one-year modelling exercise conducted in CAESAR Lisflood to calibrate key parameters, including:

- Maximum erosion limit: the maximum quantity of material that can be eroded or deposited within a cell.
- Active layer thickness: the thickness of the layer of material involved in the erosion and deposition processes.
- Proportion of erosion that can occur with vegetation growth: the reduction of total erosion yield by pixel, based on erosion coverage (Figure 8).

Table 5: Estimated erosion rates from flume testing used for calibration

Catchment	Slope Gradient (%)	Slope length (m)	Catchment area (ha)	Erosion rate as placed material (t/yr)	Erosion rate with 10% vegetation cover (t/yr)
Northern NWRD top tier area	3	654	12.46	97.40	28.19
Southern NWRD top tier area	3	614	8.31	64.10	18.55
Central NWRD top tier area	3	321	4.30	28.77	8.33
Channel 1	8	353	0.13	0.86	0.25
Channel 2	7	403	0.29	2.03	0.59

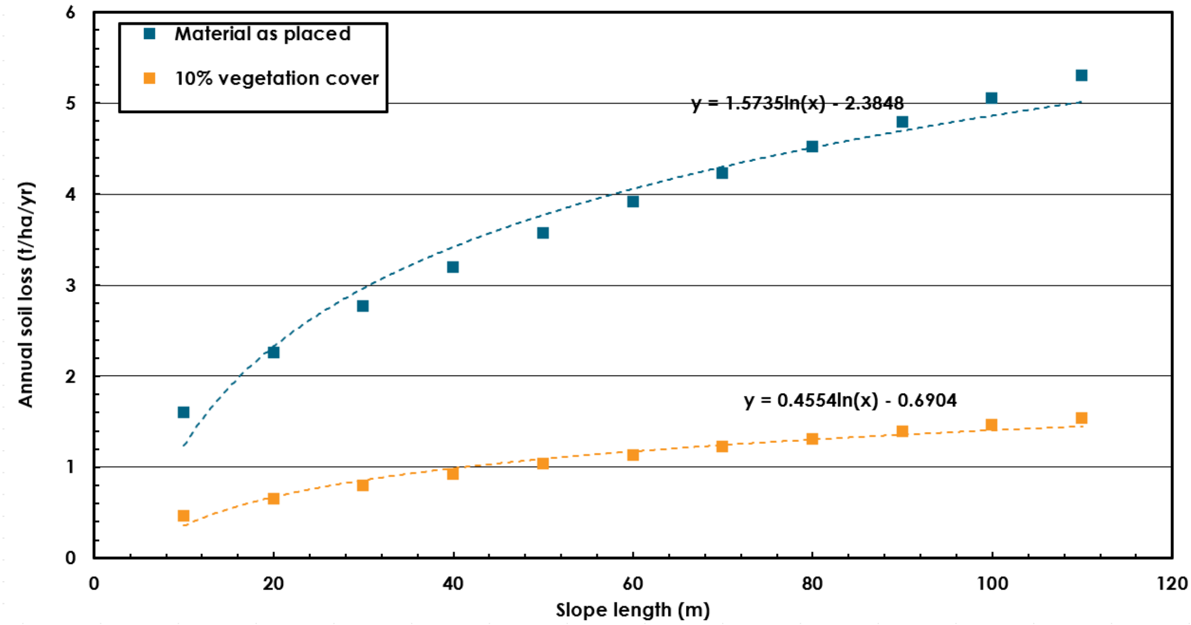


Figure 8: Modelled annual erosion rates for as placed material and 10% vegetation cover for Sample 5.

Source: RGS, 2023.

As CAESAR Lisflood works with material volumes, a density of 1.16 t/m³ was adopted for Sample 5 (Table 6). These annual erosion rates are targeted as calibration values for CAESAR Lisflood.

Table 6. Model calibration sediment volumes

Material condition	From RGS model erosion rates (t/yr)	From CAESAR Lisflood model (t/yr)
Material as placed	193.2	591.7
10% vegetation cover	55.9	77.4

One of the key parameters used by CAESAR Lisflood to account for erosion with vegetation cover is by factoring in erosion by a percentage reduction. This parameter was determined by comparing erosion sediment reduction over time based on the event-based modelling results reported by RGS (2023), specifically for Sample 5, as illustrated in Figure 9. To calibrate the reduction on erosion associated with 60% vegetation coverage, an exponential regression analysis was used, indicating a significant erosion reduction of 99% once vegetation is established.

Modelling input parameters are listed in Table 7.

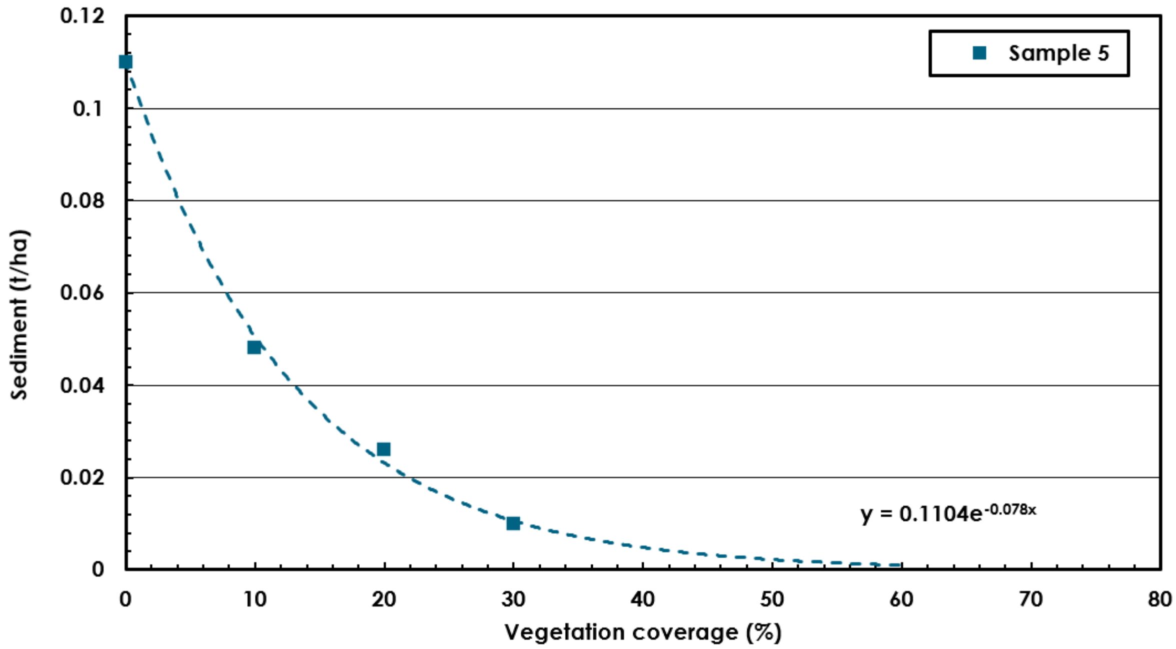


Figure 9: Erosion vs vegetation coverage rate showing a 90% reduction in sediment load with 60% vegetation coverage.

Source: RGS, 2023.

Table 7: Modelling input parameters

Parameter	Value	Unit	Comment
Modelled cover system surface area	25.48	ha	Surface is based on 2023 NWRD survey and hydraulic surface drainage design.
Maximum run time duration	876,000	hours	100 years of rainfall data was used as input accounting for daily rainfall in mm.
Minimum time step	1,440	sec	CAESAR Lisflood accounts for a variable timestep, increasing the time step when the model perceives no rainfall data and reducing the time step when rainfall events occur.
Erosion reduction when vegetation is established	99.6	%	Vegetation is set to achieve 60% of surface cover over 5 years since model initiation. Vegetation helps to stabilise the surface by increasing surface roughness and reducing runoff velocities. Higher vegetation cover can significantly reduce the erosion rate.
Maximum erosion limit	0.001	m³	This specifies the maximum volume of material that can be eroded or deposited within a cell in a single time step. This parameter prevents numerical instability caused by too large amounts of material being moved from cell to cell. It also controls the time step, which is restricted to allow this value (as a maximum) to be moved from one cell to another.
Active layer thickness	0.1	m	The active layer represents surface layers that have the potential to be eroded in a single timestep.
Rocky mulch manning n	0.025		Associated with material roughness, the manning's value is calculated based on D50 = 0.013 m of the proposed rocky mulch PSD, $\boldsymbol{n} = \mathbf{0.0395} * (\boldsymbol{D_{50}})^{1/6}$.

Parameter	Value	Unit	Comment
Courant number	0.2	-	Courant number' is a value that controls the numerical stability and speed of operation of the flow model (Bates et al., 2010).
Froude number limit	1.5	-	This value limits turbulent flow to prevent flows exceeding a Froude number passing between cells.

Erosion Quantification

To quantify inter rill erosion, a 100-yr rainfall sequence was used from the numerical modelling work of the cover system. The model calculates the volume of sediment exiting the surface, as well as indicating areas where sediment is deposited and eroded.

The modelling outputs include sediment tracker and flow velocities, with the visualisation results highlighting visualisation output of the model including:

- Areas with slow water flow: regions such as contour berms experience water flow at low velocities, resulting in minimal erosion. Typically, these areas are considered to have a low risk of erosion.
- High erosion risk areas: these regions exhibit both flow and high velocity, resulting in greater shear stresses. However, they may not be eroding due to the protective rock armouring in place. These features are manually designated for exclusion, though efforts are being made to assess the feasibility of automatic exclusion in future analyses.
- Areas of expected sediment deposition: these areas often include less steep drainage zones. A thorough review of the outputs is conducted to quantify deposition and erosion at key locations.

Classification of Erosion Risk Areas

Upon completion of the modelling, a classification of the identified features is conducted. This involves dividing the model area into main sections and determining the maximum flow velocity, maximum deposition, and maximum erosion for each landform sections. In accordance with the performance criteria established for the NWRD; the model is programmed to achieve 60% vegetation cover after five years.

To determine whether the erosion rates are acceptable, the computed rate is compared to a predetermined target rate:

- For the first year < 20t/ha/year
- By year 3 < 10t/ha/year
- By year 5 <5t/ha/year, that is, at the long-term target.

Erosion rates exceeding the targeted threshold will be flagged as potential risks. Elevated values indicate areas where erosion may surpass the landform's design resilience, posing a threat to vegetation establishment and long-term landform stability.

Model Outcomes

Flow Rates and Erosion Rates

Average sediment yield results from the modelling exercise are presented in Figure 10 and Table 8. The CAESAR Lisflood modelling predicted an overall maximum erosion rate of the NWRD top tier cover system of 25.6 t/ha/y when averaged over the entire surface, which is estimated to be 25.5 ha. The erosion rate is expected to significantly decrease after year 5 when vegetation is set to reach 60% of surface coverage as a conservative approach (Figure 10). These erosion rates are within the acceptable range, meeting the long-term target erosion rate of 5 t/ha/y or less after year 5 since the construction of the cover system. The modelling used the properties of the material specified in the numerical modelling of the cover design, referred to as rocky mulch, and incorporated erosion parameters from the preferred material identified in the previous erosion study (RGS, 2023).

A visualisation of the NWRD after the 100-year assessment period is presented in Figure 11. This visualisation illustrates the predicted spatial distribution of erosion and deposition over the NWRD top tier cover system. This includes measurements of surface vertical deformation developed from erosion and deposition mechanisms after 100 years.

The model domain contains only assessed areas covered by the cover system design. Results show that average yield erosion over the assessed surface is slightly greater than the proposed target in year 1 to year 4. Following year 4, erosion yield stays well below target after vegetation its established.

Features of the model include:

- The model incorporates a 60% vegetation cover after year 5, which significantly mitigates surface erosion. Erosion rates demonstrate high sensitivity to increases in vegetation coverage, with a marked reduction observed after year 4.
- Deposition is also identified in the lower channel areas, indicating that most sediment is retained within the landform as channels tend to reduce flow velocity on flatter surfaces.
- The model identifies high erosion risk areas where flow concentration occur, such as the junction of the northern and southern top tier sections into Channel 1 and the steep surfaces above Channel 2, as shown in Figure 12 and Figure 13.
- The NWRD top tier cover system design includes engineered structures that direct surface water runoff along preferred drainage routes. These features account for areas that do not include channel rock armouring while assessing the adjacent area covered with rocky mulch.

It is important to note that the model flags these areas with concentrated flow, which will be channelled in engineered rock-lined channels.

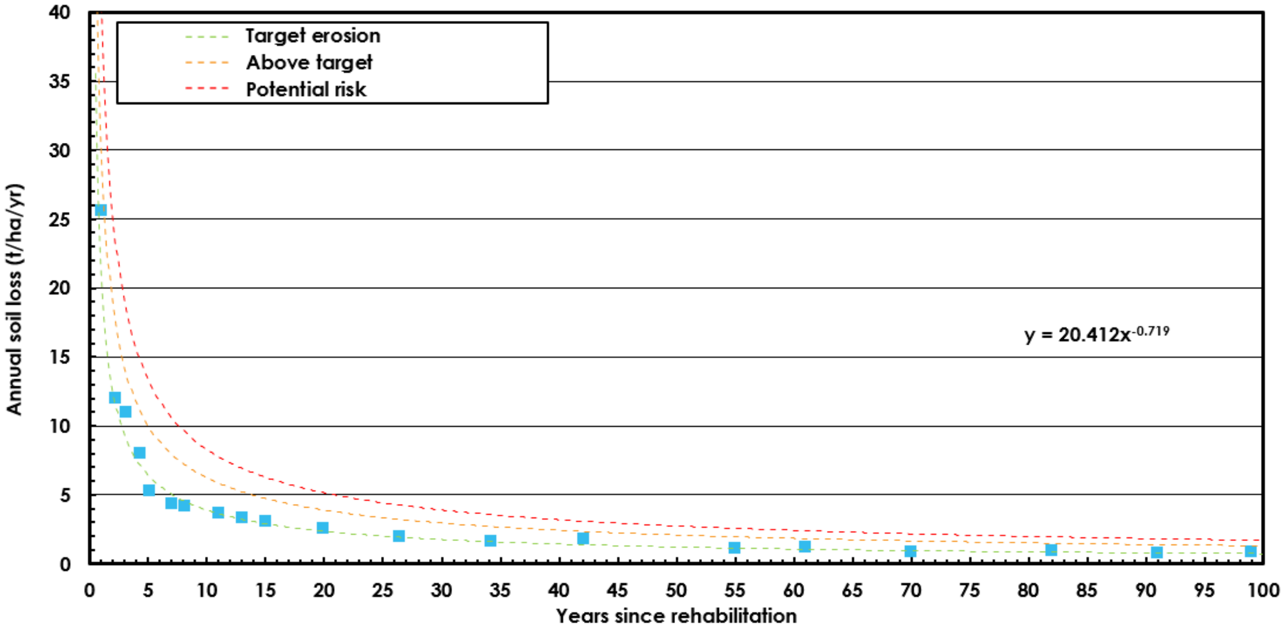


Figure 10: Total annual soil loss rate over complete surface.

Table 8: Average sediment yield exiting the analysed cover surface.

Years since rehabilitation	Average annual soil loss (t/ha/year)	Total sediment yield mass (t/ha)
1.0	25.6	25.6
2.2	12.0	26.5
3.1	11.0	34.1
4.3	8.0	34.4
5.1	5.3	27.0
7.0	4.4	30.8
8.1	4.2	34.0
11.0	3.7	40.7
13.0	3.3	43.0
15.0	3.1	46.3
19.9	2.5	50.6
26.4	2.0	51.7
34.2	1.6	55.4
42.1	1.8	75.6
55.0	1.1	61.0
61.0	1.2	73.3
70.0	0.9	64.0
82.0	1.0	78.6

Years since rehabilitation	Average annual soil loss (t/ha/year)	Total sediment yield mass (t/ha)
91.0	0.8	69.2
99.0	0.9	86.3

Based on the CAESAR Lisflood model's erosion yield results over 100 years of rainfall data, as shown in Figure 10, an exponential regression equation can be derived to accurately represent the modelling results:

$$Erosion\ yield = 20.412 * (years\ since\ rehabilitaiton)^{(-0.719)} \qquad \text{(Equation 1)}$$

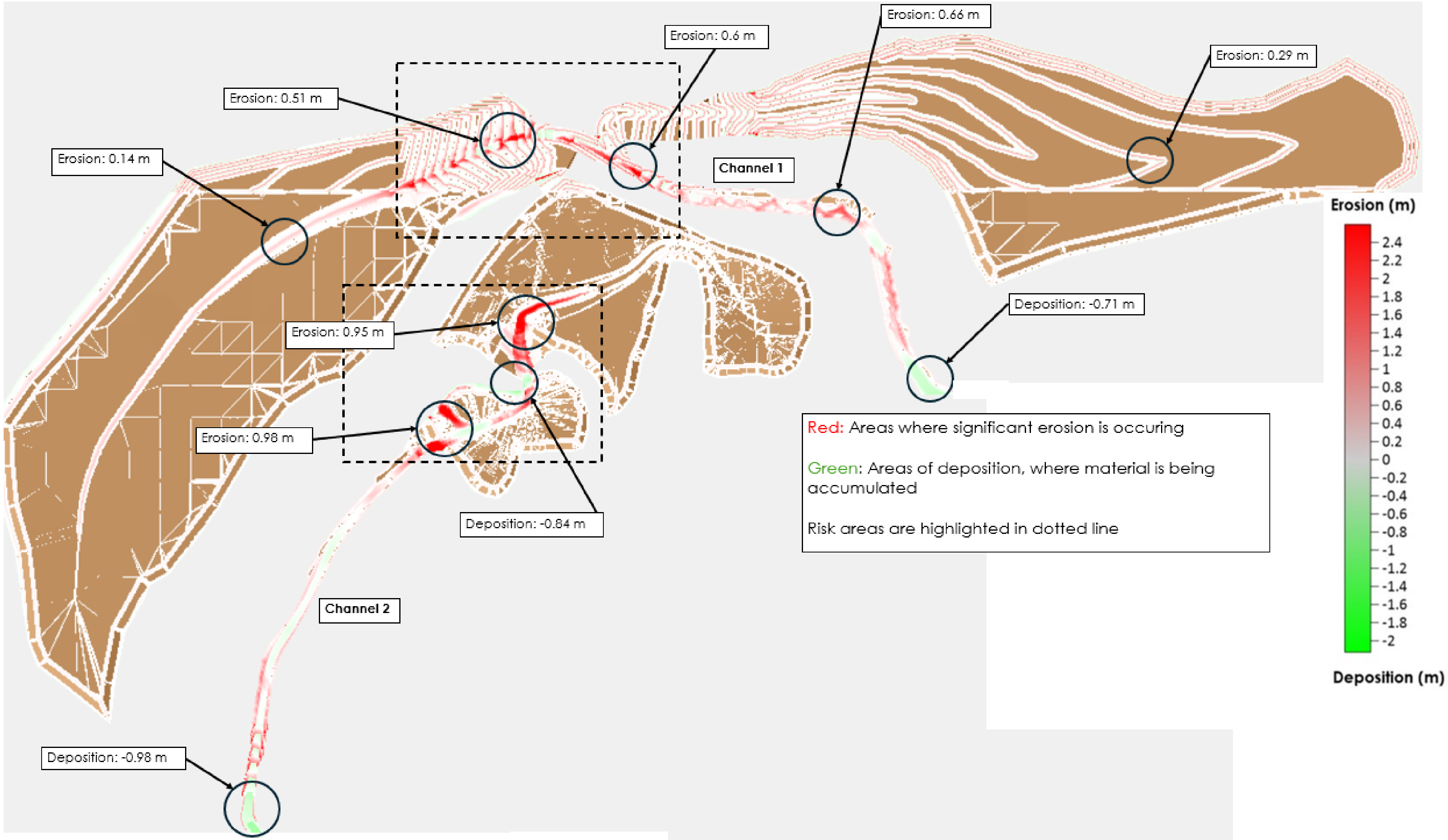


Figure 11: CAESAR Lisflood erosion/deposition output visualisation after the 100-year assessment period.

Event-Based Assessment for 1-in-200 AEP

The sediment yield approximation equation, developed from 100 years of long-term modelling data (Equation 1), was utilised to estimate erosion yield at year 200, providing insights into the extended performance and resilience of the landform design. This analysis resulted in a sediment yield of 0.26 t/ha/year, consistent with the assumption that, over time, as the landform matures, and vegetation becomes established, annual sediment yield decreases to marginal quantities. It also reflects that erosion volumes are primarily driven by high-intensity storm events capable of dislodging established vegetation.

In addition to estimating annual yield erosion based on historical rainfall data, an event-based analysis was performed to evaluate the landform's performance under a high-intensity storm pattern associated with a 1-in-200 AEP. This analysis aimed to assess the landform's ability to manage short-duration, high-intensity runoff events, identifying key risk areas. By combining cumulative erosion modelling with high-intensity event assessments, the approach offers a comprehensive evaluation of both gradual degradation and the risks posed by extreme events over the closure timeframe.

The selection of the storm pattern was guided by the ARR Guidelines, and a 6-hour storm burst was selected based on the 1-in-200 AEP event (Figure 12).

The results of the event-based assessment are presented in Figure 13, which highlights key areas where high peak flow velocities were observed.

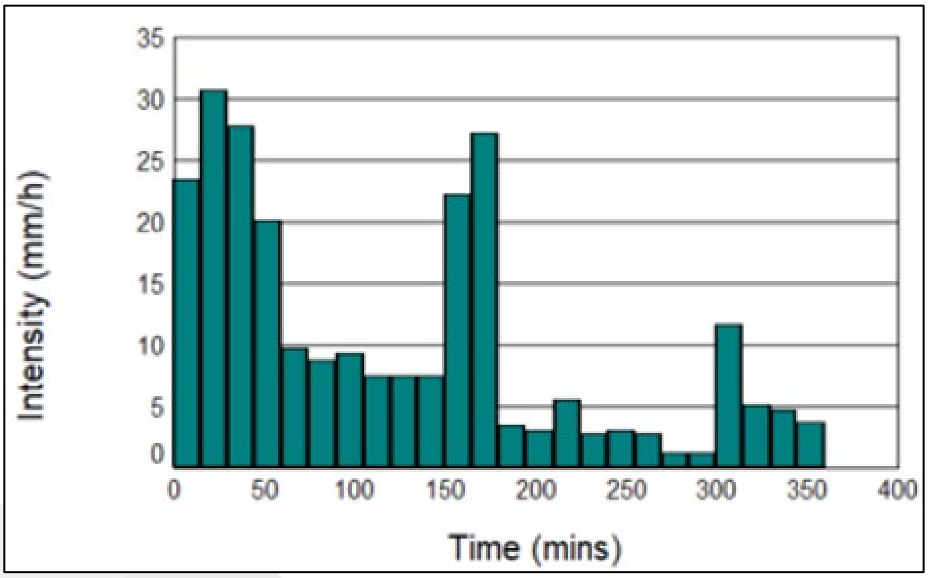


Figure 12: 1-in-200 AEP event pattern and a 6-hour storm burst.

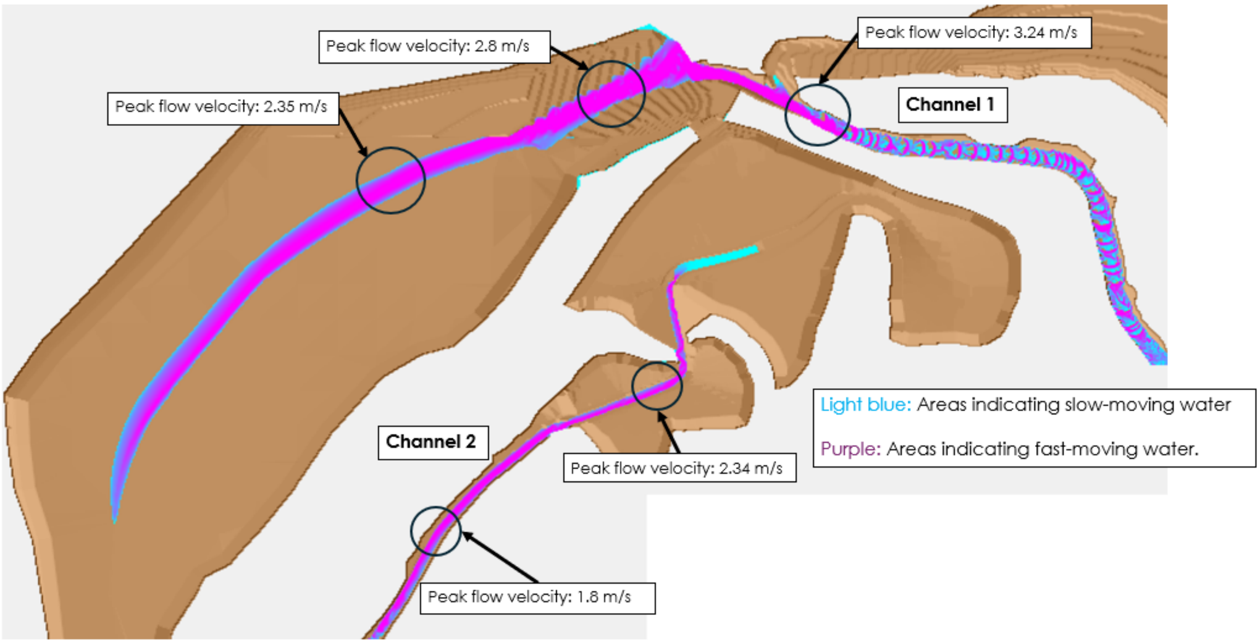


Figure 13: Identified high flow velocity risk areas for 1-in-200 AEP.

Conclusion

Modelling has indicated that total erosion risk of the top tier cover system is deemed acceptable according to the proposed criteria:

- For the first year < 20t/ha/year
- By year 3 < 10t/ha/year
- By year 5 <5t/ha/year, that is, at the long-term target.

Erosion rates generally decrease over time, with the upper areas of the top tier cover system remaining well below the 5t/ha target after a five-year period.

It is important to note that the scope of this work includes identifying potential scour risk areas from surface water flow along the top tier cover system. Generally, these conditions pertain to drainage areas that will be designed with rock armouring to prevent erosion.

Overall, erosion rate trends indicate a downward trajectory, decreasing from 25.6 t/ha/year in the first year, to approximately half that amount within 3 years post-rehabilitation, assumption that 60% vegetation coverage is achieved by year 5. It is also important to note that, in areas where average rates exceed erosion targets, there is a medium to low risk of erosion (areas highlighted by a dotted line in Figure 11). In such cases, rock armouring may be necessary in these specific areas with concentrated flow.

To monitor progressive rehabilitation and rehabilitation outcomes, a technique similar to that used in this assessment should be employed with observation calibrations, for example measuring changes in the cover system surface over time and comparing with model predictions, and ensuring total yield volumes are within the ranges expressed in the proposed criteria. This approach will provide a quantitative assessment of the landform's performance during closure, enabling timely maintenance as needed and demonstrating trends to the regulator at the time of closure.

The use of high-resolution aero photogrammetry or high-density LiDAR to quantify erosion rates through hydrological modelling is a relatively robust and cost-effective method for tracking the closure performance of a landform. Assessing changes in the surface of the top tier cover system over time enhances the potential for achieving long-term “safe and stable” landforms post-closure. However, seasonal variations may occur due to factors such as drought and abnormally high rainfall. A reasonable monitoring cycle is estimated to be around 5 years after closure, although more frequent monitoring could be beneficial for assessing the need for annual maintenance.

Model limitations

While erosion results are presented in this report as quantitative values (predicted erosion rates), it is important to acknowledge that the accuracy of the LEM is qualitative. This is due to several factors, including:

- The inherent predictive nature of LEM.
- Potential variability and heterogeneity in materials.
- The limited number of samples tested, forming the basis of the LEM.
- Potential future environmental extremes. These factors introduce uncertainties that can affect the accuracy of the model's projections.

Therefore, it is important to understand that the predicted erosion rates should not be interpreted as definitive values. LEM should be considered a tool to inform and support the broader engineering process and risk framework, providing insights and informing decision-making processes.

Closing

We trust information provided in this memorandum is satisfactory for your requirements. Please do not hesitate to contact me via bfreidman@okaneconsultants.com should you have any questions or comments.

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Appendix A: Supporting Information – Exclusion of Rock Batters from the LEM Assessment

Hydraulic induced erosion in rocky materials is governed by a critical balance between the forces driving sediment transport, primarily shear stresses from runoff, and the intrinsic resistance of the substrate to particle detachment. In coarse gravel and rocky materials for example, this balance is influenced by high permeability, which promotes infiltration, and the inherent stability of larger massive particles under typical flow conditions. As a result, these terrains rarely experience significant erosion or sediment mobilisation except under extreme hydrological events.

Coarse gravel and rocky materials are characterised by high permeability and large void ratios which increase with the increase in coarse fraction for materials with D50 above gravel size (see Figure A1), which allow them to store significant volumes of water within their pore spaces. From a hydraulic standpoint, this reduces the amount of surface runoff generated during precipitation events. Because water readily infiltrates rather than accumulates on the surface, the overland flow that typically contributes to erosion and the entrainment of particles is minimised. Consequently, in coarse-grained soils or rocky terrains, the threshold for generating continuous runoff is rarely met except under very high-intensity or prolonged rainfall conditions where the infiltration capacity is momentarily exceeded.

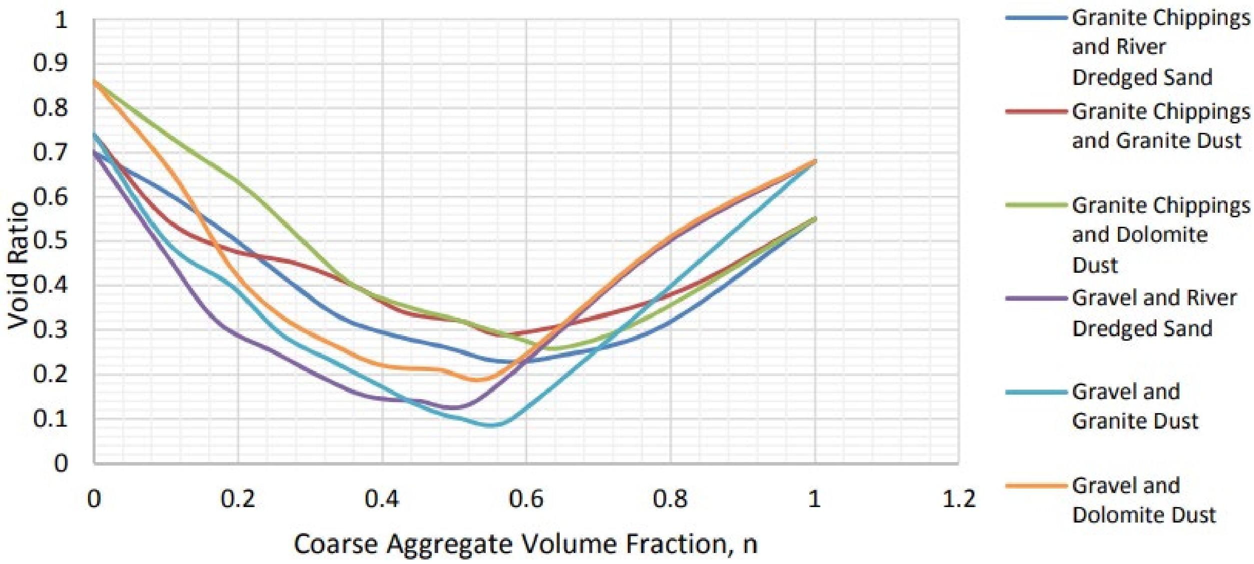

Figure A1: Graph of void ratio against coarse aggregate volume fraction (Osuji and Inerhunwa, 2015).

When runoff does occur, coarse gravel and rocky material exhibit a high resistance to particle mobilisation due to their mass. Erosion depends on the balance between the driving forces, such as the bed shear stress exerted by flowing water, and the resisting forces, primarily particle weight and interparticle friction. During extreme rainfall events, which produce exceptionally high peak flow runoff velocities and thus large bed shear stresses, gravel or rocky particles become susceptible to movement. Even then, the movement of larger particles is sporadic and occurs only when the boundary shear stress clearly exceeds the material-specific critical values, as described by conventional bedload transport equations, such as provided by Hjulström's diagram (Figure A2).

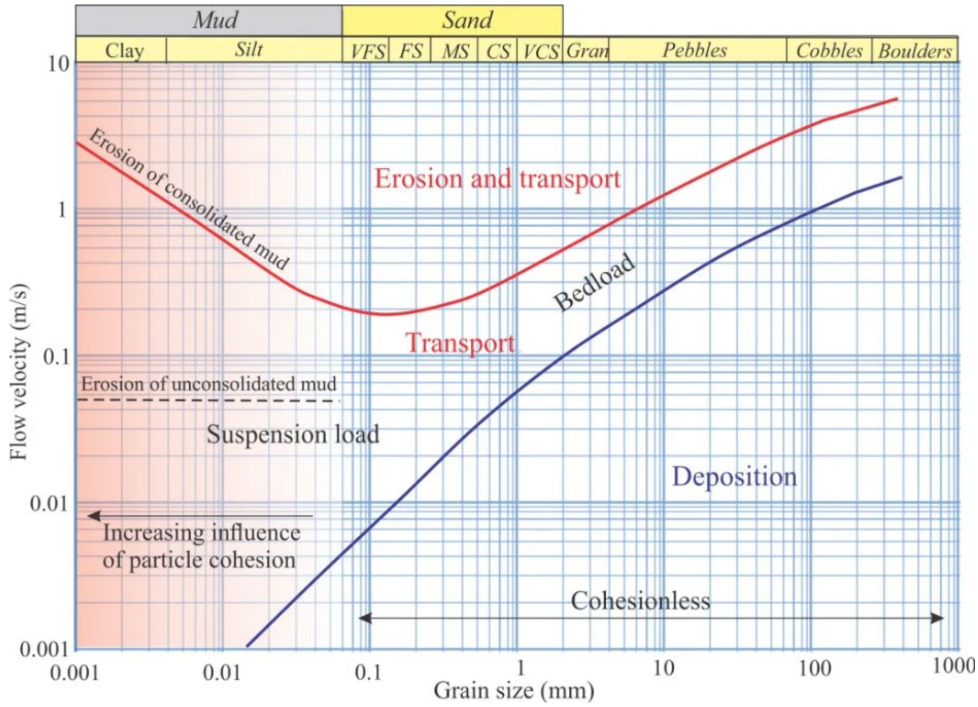

Figure A2: Hjulström plot delineating the principal domains of deposition, transport, and erosion (Hjulström, 1939).

Accounting for the latter, the CAESAR Lisflood model is designed to simulate erosion by coupling hydrodynamic flow routing with sediment transport. At its core, the model divides the simulated area into a grid of cells (or "pixels"), each of which is assigned initial topographic and material properties (e.g., PSD). For every time step, CAESAR Lisflood numerically calculates flow depth, flow velocity, and the associated bed shear stress within each cell by solving a simplified set of shallow-water equations. These hydrodynamic computations are directly linked to sediment transport algorithms that determine how much material is mobilised, transported, and deposited within each cell (Coulthard, 2013).

For coarse, rocky materials, CAESAR Lisflood sets a high critical bed shear stress value, reflecting the significant shear stress required to overcome the weight and interparticle friction. Because the model updates sediment flux based on the local flow conditions at each cell, any cell with flow velocity or shear stress below the specified critical bed shear stress effectively sees minimal or zero sediment movement. Consequently, cells representing coarse gravel or rocky materials will exhibit negligible bedload transport and minimal erosion under moderate flows. Only under exceptionally high-intensity rainfall or flood events, where flow depths and velocities increase substantially, the shear stress would exceed these large critical bed shear stress values, potentially mobilising coarse sand, gravel and boulders.

While the physical processes and modelling approaches discussed underscore the low erosion potential of rocky materials in the NWRD batters, it is important to note that material segregation and variability in the NAF waste rock PSD can still create localised erosion risks. Fine grain accumulation, if present in sufficient quantity within the rock matrix, can reduce infiltration capacity and lead to concentrated surface flow channels that can mobilise coarser particles. These finer layers or pockets can potentially become preferential erosion pathways, initiating rills or gullies, particularly if runoff velocities are elevated during high intensity storm events. As a result, further specific hydraulic analysis of the NWRD batters is recommended to determine the minimum PSD requirements per area that minimise erosion based on potential flow velocities. Such evaluations may include additional field investigations to assess average PSD and detailed numerical modelling aimed at evaluating runoff peak flow velocities at the NWRD batter slope.