HASTINGS
Technology Metals Limited

APPENDIX 6-1

Landform Evolution Study

Hastings Technology Metals Limited

Yangibana Rare Earths Project

Landform Evolution Study

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EXECUTIVE SUMMARY

Trajectory has completed a Landform Evolution Study in support of the Feasibility Study and approvals processes associated with the Yangibana Rare Earths Project (Yangibana).

The scope of this study is to assess the ability for all Waste Rock Landforms (WRL), Tailings Storage Facilities (TSF) and ponds (i.e. Evaporation Pond (EP)), to be constructed such that the embankments will remain as permanent features in the landscape.

The objective of the study is to demonstrate, via a modelling and aspect analysis process, that the long term erosional stability for landforms at Yangibana is demonstrated to perform in an acceptable manner for a 1000-year design period.

This study determines the primary **Design Considerations** and **Aspects,** which can be adjusted via options for specific **Methodologies,** to realise the desired design period. **Specifications** are set and objective **Performance Measures** presented as being acceptable and which conform with the regulatory approach to criteria being SMART (specific, measurable, achievable, results-focused, and time-bound).

The determination of what is acceptable is a matter that ultimately requires input and feedback from internal and external stakeholders to be finally established. For landform evolution, Trajectory recommends the following attributes for acceptability to be achieved:

- Erosion features (which are an unavoidable occurrence) must be self-armouring, which means that the substrate in which they occur must have durable fraction sufficient to stop continuing development of the feature once established.
- Rates of sediment emission should be sufficiently low that they do not create significant impacts on down gradient ecologies (either rehabilitation ecologies or undisturbed ecologies).
- The surface hydrology assessment should be based on realistic hydraulic conductivity and run-off estimates with surface water management measures sized accordingly to ensure the measures can accommodate and be resilient for very large storm events.
- Surface conditions, vegetation cover and soil health should all contribute to an enhancement of erosional stability after the initial establishment period (nominally 3 years).

It should be noted that many landform evolution studies rely upon one or two design considerations (generally associated with erosion modelling) whereas this study addresses a full range of considerations. Erosion modelling inputs provide a basic level of assurance that the design configuration will endure for the design interval selected, however the many additional aspects and specifications provide support to the assessment as to how a landform will perform as a perpetuity structure in the post mining landscape and that the rate of any emissions associated with the evolution of the landform will be within the capacity of the surrounding landscape to assimilate.

The design aspect, objective, specification and performance measure for each design consideration are presented in Table 1 below:

Table 1: Landform Evolution Study Summary

Design Consideration	Design Aspect	Design Objective	Method	Specification	Performance Measure
Slope Profile	Lift height and slope length	Limit erosion feature development to <1m depth in model	Constrain lift height in model to <60m	Maximum 40m lift height (provides conservatism against model)	A). Erosion features average <0.5m depth B). Erosion < 5 tonnes/ha/year after 3-year establishment period
	Slope angle (overall)	Limit run-off velocity	Slope angle < 20 degrees	Average slope angle 17.5 degrees	A and B above and post construction angle QA/QC survey
	Slope shape	Reduce off velocity at mid-point of slope	Concave slope shape	20 degrees in upper 50% of Slope and 15 degrees in lower 50% of slope	A and B and post construction angle QA/QC survey
Slope Hydrology	Run-on	Ensure there is no run-on to batter surfaces	Perimeter and cell bunds	Hydrology measures to PMP estimate to limit run-on from top surface or berms to batters below. Nominal 1m crest bund.	Post construction angle QA/QC survey Zero run-on from up gradient surfaces demonstrated via foot traverse inspection after three years
	Infiltration	Maximise infiltration to limit run-off and build Plant Available Water	High/moderate infiltration waste rock at final surfaces and cell/cross bunding to limit cross flow	Cell bunding of 0.7m and perimeter bunding of 1m. Infiltration + Evapotranspiration > 100% of incident rainfall on flat surfaces	Permeameter testing demonstrates infiltration in as constructed and 3 years post revegetation

Design Consideration	Design Aspect	Design Objective	Method	Specification	Performance Measure
	Berm sizing	Ensure that berms, where installed (in this case only at Bald Hill) will contain a minimum 1:2000 rain event	Calculate berm sizing using run-on model	Berms for 20m high batters (Bald Hill) are 20m wide after reprofiling	Post construction angle and berm width QA/QC survey
	Slope discharge	Ensure that discharges from slopes (water and sediment) can be sustainably assimilated by receiving environment	All of the considerations listed to stabilise slopes and toe interception bunds around the toe perimeter of the landform	0.5m high bunds at 10m offset from final toe position. Cross bunds installed where natural ground at gradient greater than 2 degrees	Post construction QA/QC survey
Surface Conditions	Surface treatments	Minimise downgradient or cross flow on batter, top or berm surfaces	Contour ripping to create large trough banks	Rip lines ***on contour*** and minimum 0.5m deep and 1m wide at base of windrow	Post construction QA/QC survey
	Waste rock armouring	Ensure that majority of rain energy is dissipated through durable waste rock exposed at surface	Durable fresh granite waste dominates waste rock exposed after reprofiling	40% of exposed surface comprised of durable fraction equal to or greater than gravel	Post reprofiling stability mapping QA/QC survey
	Soil armouring	Ensure that the soils selected for sloped surfaces have at least 20% gravels or cobbles to form armoured soil layers	Select Hill Soils or armouring subsoils only for spreading on batters	Armouring subsoils spread at 150 – 200mm over reprofiled waste rock. 20% of final exposed surface after 3-year stabilisation period will be gravels/cobbles form the soil	Post reprofiling stability mapping QA/QC survey

Design Consideration	Design Aspect	Design Objective	Method	Specification	Performance Measure
	Management of adverse material	Ensure no adverse material (saline or sodic) within 2m of final surfaces	Schedule mine waste to encapsulate adverse soils and/or install durable armour covers over high fines content embankments/batters	Minimum 2m of in situ or imported durable armouring granite waste rock after final reprofiling	Post Construction validation survey
Biological Factors	Plant cover	Maximise plant cover to limit erosive force of rain impact	Configure surfaces for water harvesting and amenable to plant establishment	Provenance seed mix of grasses, shrubs and woody plants	25% plant cover after three-year establishment period
	Plant roots	Maximise plant cover to provide diverse plant root matrix to contribute to erosion resistance	Configure surfaces for water harvesting and amenable to plant establishment	Provenance seed mix of grasses, shrubs and woody plants	50% of pre-mining diversity after three-year establishment period
	Cryptograms	Improve soil structure and resilience to rain impact and surface flow	Identify initiatives to improve soil health and encourage cryptogram establishment	Include introduction of biological matter and soil inoculants in revegetation process	Presence/absence of cryptograms in survey after three-year establishment period
	Humus layer	Maximise development of humus layer to improve soil structure, organic matter and as a rain impact resilience layer	Configure surfaces for water harvesting and amenable to plant establishment	Provenance seed mix of grasses, shrubs and woody plants	5% surface cover by humus layer after three-year establishment period

Contents

1. INTRODUCTION

Hastings Technology Metals Limited (Hastings) is currently in the process of developing the Yangibana Rare Earths Project (the Project), located in the Gascoyne region of Western Australia. The Project will initially consist of four open pits initially at Frasers and Bald Hill and later open pits including Yangibana North and West, waste rock dumps, tailings storage facilities, processing plant and associated support infrastructure. The current mine life is seven years. Trajectory has been engaged to review available landform stability information and conduct further studies to develop a landform evolution evaluation for the Project in support of the preparation of the Feasibility Study, government approvals and the Mine Closure Plan.

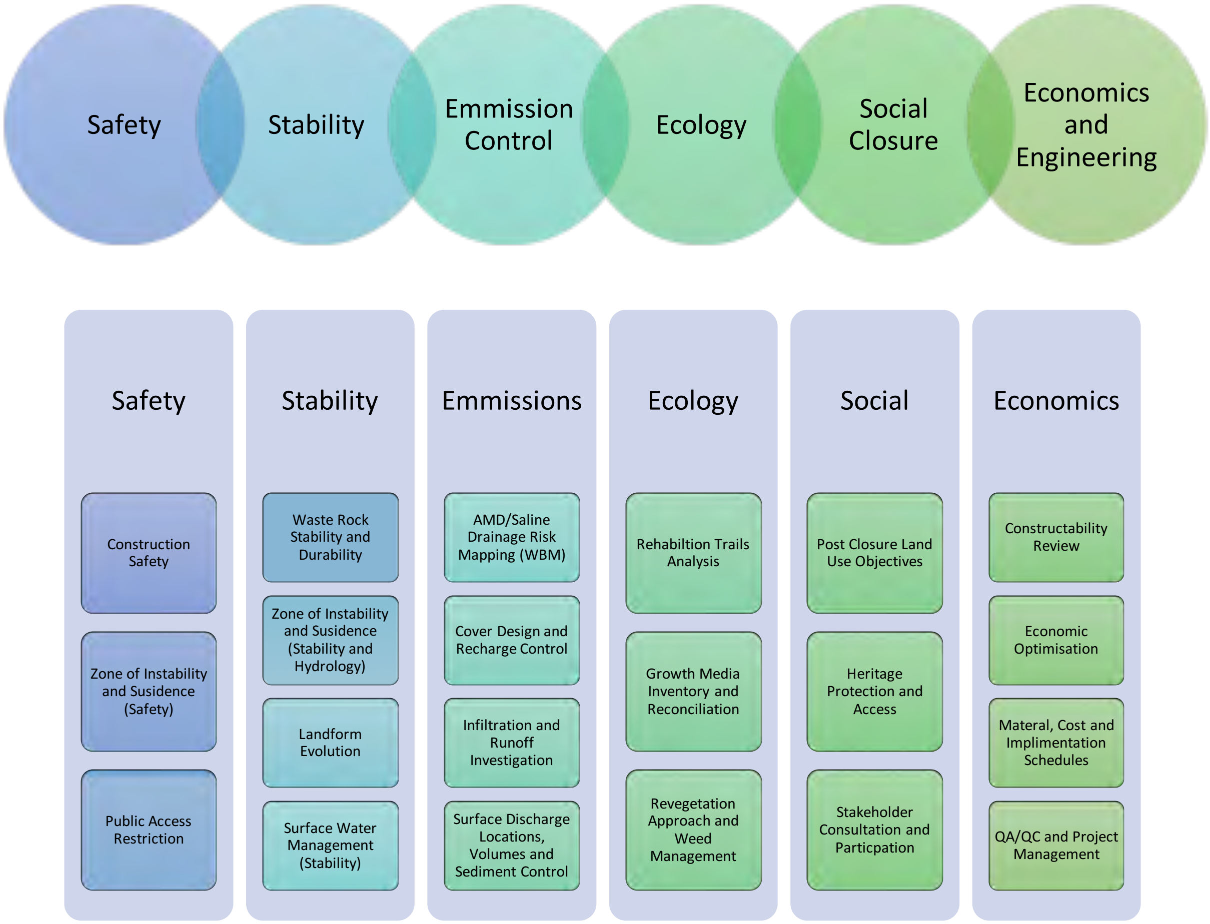
This Study deals with the design aspects associated with erosion stability inclusive of typical erosion modelling processes and further expands to an examination of other considerations and measures, which are relevant to long term landform evolution, and aspects that erosion modelling does not specifically address.

Erosion modelling tools such as Siberia and WEPP have contributed to the development and selection of reprofile shapes, which are more favourable from an erosion minimisation perspective (as detailed in Appendix 1: Erosion Modelling Methodology). Other aspects which the erosion models do not consider, include localised heterogeneity of substrate fraction size and durability, local infiltration characteristics, surface armour evolution (from both soils and waste rock), surface treatments (e.g. contour ripping) and the contribution of established vegetation, humus layers and cryptograms.

Although some of these factors cannot be examined via empirical modelling processes to produce numerical outputs, which erosion modelling tools *appear* to do, these additional factors are as relevant to the long-term evolution of landforms as are the outputs of erosion modelling, if not more so.

The level of accuracy of erosion models should be viewed as indicative and primarily for comparative analysis between profile options rather than accurate predictions of performance (Appendix 2 – Limitations of Erosion Modelling). The landform evolution processes described in this study draw on multiple aspects of design input and lines of evidence. Section 9 – Monitoring and Validation presents an opportunity to generate comparatively accurate in-field landform construction validation and evolution performance data to confirm erosional stability performance at a comparatively low cost after initial profiling and after the stabilisation period following revegetation.

Figure 1 indicates how landform evolution fits within the broader planning matrix for the preparation of landform designs.



Safety	Stability	Emmissions	Ecology	Social	Economics
Construction Safety	Waste Rock Stability and Durability	AMD/Saline Drainage Risk Mapping (WBM)	Rehabilton Trails Analysis	Post Closure Land Use Objectives	Constructability Review
Zone of Instability and Susidence (Safety)	Zone of Instability and Susidence (Stability and Hydrology)	Cover Design and Recharge Control	Growth Media Inventory and Reconciliation	Heritage Protection and Access	Economic Optimisation
Public Access Restriction	Landform Evolution	Infiltration and Runoff Investigation	Revegetation Approach and Weed Management	Stakeholder Consultation and Particpation	Materal, Cost and Implimentation Schedules
	Surface Water Management (Stability)	Surface Discharge Locations, Volumes and Sediment Control			QA/QC and Project Management

Figure 1: Landform Evolution within the Landform Planning Process

2. SCOPE AND OBJECTIVES

2.1 Scope

The scope of this study is to:

- Review and analyse landform evolution studies regionally, and
- consider and interpret information in the local context of site-specific climate, material properties, vegetation and drainage conditions.

This activity has been undertaken such that design inputs into all landforms (i.e. waste rock landforms, tailings storage facilities and evaporation ponds) consider landform evolution and the proactive development of erosional stability.

2.2 Objectives

The objectives of this study are to:

1. Generate, analyse and compare a range of credible alternative slope profile and treatment options such that the selection of landform profile shapes and treatments at individual locations across the Project landforms are technically justified as creating stable landforms (from an erosion perspective) over a 1000-year design period.

2. Design processes will respond to the following considerations such that designs are cognisant of all relevant factors:

   a. Slope profile
   b. Slope hydrology
   c. Surface characteristics
   d. Biological factors

3. Methodologies and specifications are prescribed for each landform to promote long-term landform stability.

4. Performance measures are developed to permit objective measurement against criteria considered to be representative of acceptable erosional stability performance

3. SETTING

The Project is located approximately 280 km north east of Carnarvon and 900 km north of Perth in the arid interior of Western Australia (Figure 2). The project (Figure 3) is located on tenements that cover 650 km^2. Pre-feasibility drilling studies have been undertaken and indicate that the most economic resources are located in the eastern and western belts. The current planned mining schedule will focus on the Bald Hill South and Fraser's areas in the first years before moving to Yangibana West and Yangibana North in later years. This schedule will mean a mine life of approximately seven years with 7 Mtpa of waste rock and 1 Mtpa of ore generated from these open cut pits (Hastings, 2015).

The project is seeking to extract rare earths (mainly, neodymium, praseodymium, dysprosium and europium) from ironstone-hosted mineralisation and potentially from carbonatite hosted mineralisation at greater depths. The country rock is Pimbyana granite and migmatite / anatectic granite of the Gascoyne Complex. This granite has been intruded by dykes, veins, and sills of the Gifford Creek Ferrocarbonatite Complex, a feature of which are the ironstone veins that are associated with the target ore (Pearson *et al* 1995, Pirajno *et al*. 2014, Pirajno *etal* 2015). The target ironstone-associated ore dips towards the south and the main waste types will be the overlying regolith, granite hanging wall, and footwall at varying states of weathering (Landloch 2016a).

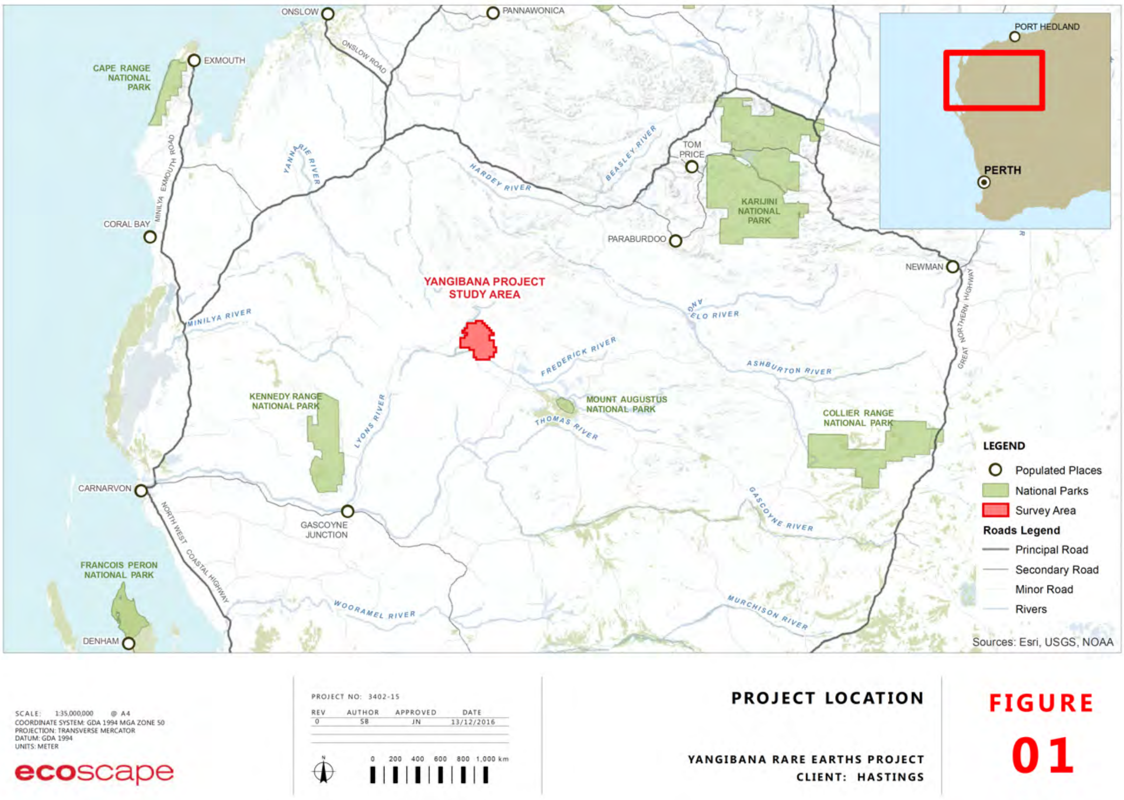
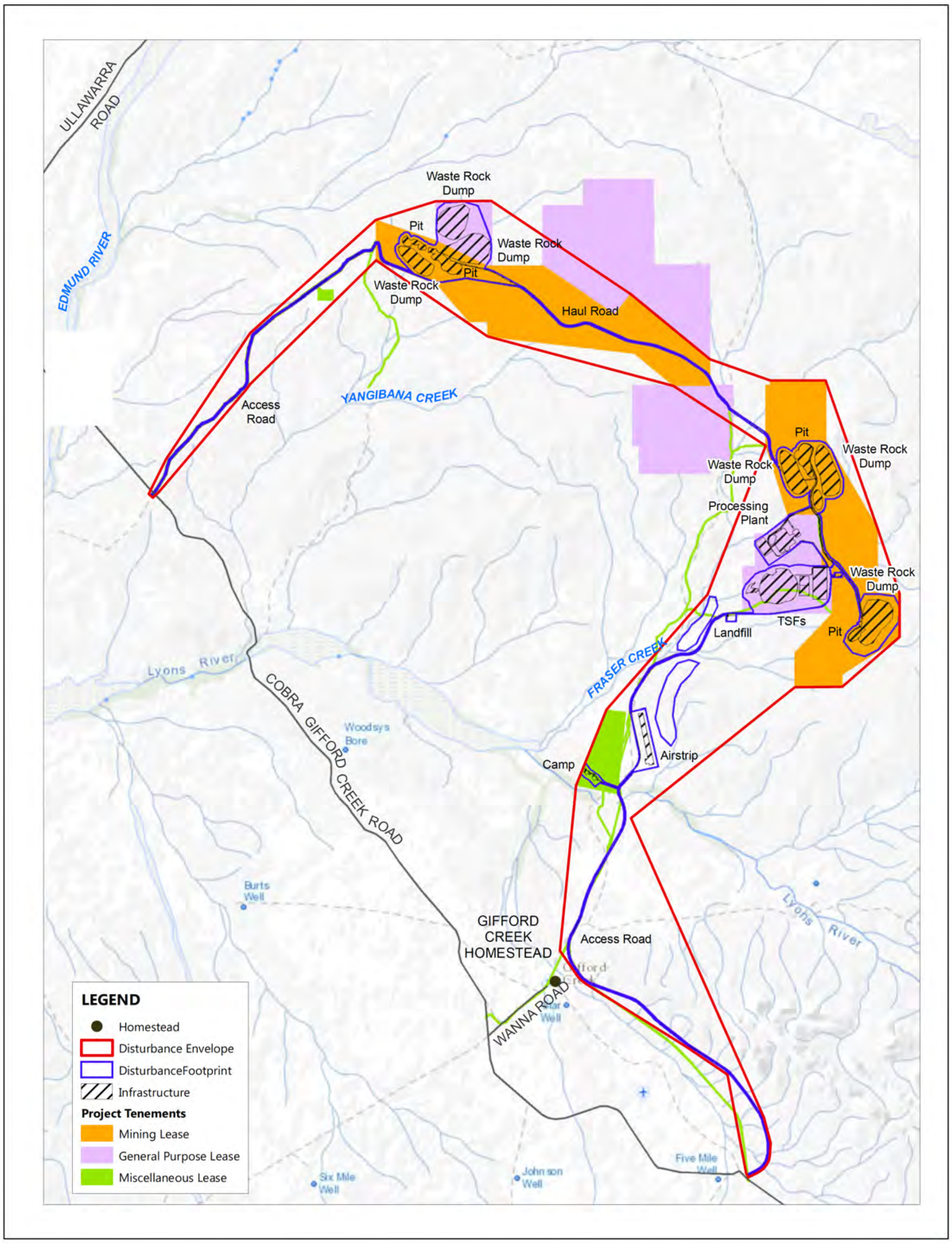


Figure 2: Hastings Location and Tenements



SCALE: 1:150,000 @ A4
COORDINATE SYSTEM: GDA 1994 MGA ZONE 50
PROJECTION: TRANSVERSE MERCATOR
DATUM: GDA 1994
UNITS: METER

DATA SOURCES:
TOPOGRAPHIC LAYERS: GEOSCIENCE AUSTRALIA
SERVICE LAYERS: GEOSCIENCE AUSTRALIA

ecoscape

PROJECT NO: 3402-15

REV	AUTHOR	APPROVED	DATE
0	SB	JN	13/12/2016

N
0 1 2 3 4 km

PROJECT TENEMENT
AND SITE LAYOUT

YANGIBANA RARE EARTHS PROJECT
CLIENT: HASTINGS

FIGURE
02

Figure 3: Proposed Hastings Mine Site

4. REGULATORY REQUIREMENTS AND GUIDELINES

The Commonwealth and State Governments have legislation and guidelines in place that are relevant to material characterisation and mine site waste and the development of post closure landscapes, which are sustainable. The aim is to protect environmental aspects such as biodiversity, water resources (quantity and quality), landforms, existing and potential future land uses, and cultural and environmental heritage (Department Industry, Tourism and Recourses, 2007).

4.1 Commonwealth

The key relevant regulatory instruments provided by the Commonwealth Government relating to landforms, and their associated materials characterisation and management, are:

- *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
- National Environment Protection Measures established by the Environment Protection and Heritage Council

4.2 State Government

At a State level, recommendations for landforms, and the effective materials characterisation and management, occur in two key guidelines, as outlined below, issued by the EPA and DMIRS (formerly DMP, DME etc).

1. Guidelines for Preparing Mine Closure Plans

The Guidelines for Preparing Mine Closure Plans (DMIRS / EPA, 2015) provide considerable guidance regarding materials characterisation such that it can be configured to produce stable and non-polluting landforms.

2. Draft Guidelines Materials Characterisation Baseline Data Requirements

A Draft Guidance document was developed by the Department of Mines and Petroleum in March 2016, for Materials Characterisation Baseline Data Requirements.

4.3 Specific Project Requirements

The Environmental Scoping Document (approved 22 May 2017) for Yangibana Rare Earths Project (Assessment number 2115, EPBC Reference number 2016/7845) requires the following study to be undertaken:

36. Conduct long term (1000 years) Landform Evolution Modelling of behaviour and performance of landforms associated with containment systems including TSFs, modelled under a range of climatic events. Include the modelling of the appropriate Probable Maximum Precipitation (PMP) and associated Probable Maximum Flood (PMF) scenarios.

For the purposes of this study this is interpreted to require both erosional stability assurance of a 1000-year design period and surface hydrology measures, which can accommodate a PMP/PMF scenario.

5. SOILS AND WASTE ROCK CHARACTERISATION

The characterisation of waste rock and soils is central to the understanding of their erosional stability and long-term durability. Comprehensive studies have been undertaken with respect to both aspects by Landloch (2016) and Trajectory (2016). These are summarised briefly below.

5.1 Soils

As detailed in the Landloch Surface Erodibility Assessment Report (November 2016), results of the analysis of the soil materials are shown in Table 2. A more detailed description of the project's soils (including other parameters such as fertility) is contained in Landloch, 2016b. Generally, the results show that the Hill Soil is a dark brown sandy duplex approximately 300mm deep with neutral pH, low salinity, and low exchangeable sodium and exchangeable sodium percentage (ESP). The Plain Soil is typically a dark brown sandy loam with massive structure with strong alkaline trends down the profile and can be saline and sodic (prone to clay dispersion).

Table 2: Chemical Characteristics of Soil

Analyses		**Unit**	**Hill Soil**	**Plain Soil**
pH - Water		pH units	6.51	8.91
Electrical Conductivity (EC)		dS/m	0.01	0.55
	Calcium	meq/l00g	1.67	1.73
	Magnesium	meq/l00g	1.04	0.73
	Potassium	meq/l00g	0.36	0.32
Exchangeable Cations	Sodium Aluminium	meq/100g	0.14	0.35
	Effective Cation	meq/l00g	0.01	0.01
	Exchange Capacity	meq/100g	3.22	3.14
	Exchangeable Sodium Percentage (ESP)	%	4.44	11.27
Particle Size Distribution of <2mm Fraction	Coarse Sand	%	38.3	34.9
	Fine Sand	%	44.9	30.7
	Silt	%	4.6	12.9
	Clay	%	12.1	21.4

Coarse sand: 2.0-0.2mm; Fine sand: 0.2-0.02mm; Silt: 0.02-0.002mm; Clay: <0.002mm

5.2 Waste Rock

The summary below is derived from *Yangibana Project: Geochemical and Physical Characterisation of Mine-Waste Samples and Implications for Mine-Waste Management Waste Rock Characterisation (Trajectory 2016)*.

There is no duricrust for the pits. A characteristic feature of the style of mineralisation within the pits is that saprolites and saprocks have spatially variable occurrences, which may extend to some depth. This reflects enhanced permeability arising from mineralization influences and the structures that host the mineralisation. Therefore, the layered configuration of 'saprolite-over-saprock' commonly observed at hard-rock mines on the Yilgarn block is **not** observed for the Project. Due to the geological nature of the waste-zone, the saprolites – the most erosion prone units – will not be mined in thick blocks as is usually the case at goldmines on the Yilgarn block. Rather, when mining deeper than 10-15m the saprolites occurring are generally as thin expressions of weathering / alteration immediately proximal to fresh-waste and will generally be mined as a mixture (i.e. saprolite/fresh-rock and saprock/fresh-rock mixtures).

With respect to pH and salinity, the samples were either **circum-neutral or alkaline** with varying salinity, due to halite (NaCl) and gypsum. The colluvium samples were consistently saline; the isolated saline samples of saprolite and saprock were shallow samples (within 5-6m of ground-surface). All lithologies are **NAF** due to negligible-sulphides (less than 0.1 %; mostly less than 0.01 %). Isolated samples contained 'trace-carbonates'.

The multi-element-analysis results for all samples had element contents below, or close to, those typically recorded for soils, regoliths and bedrocks free from mineralisation influences (Bowen 1979). Varying enrichment was recorded for some samples. However, none of these enrichments were marked. As a group, the Ironstone-Saprock samples stood out with the highest degree of minor element enrichment.

Of the samples subjected to Emerson dispersion testing, only one sample, a Fenitic-Granite-Saprock from Fraser's Pit, dispersed. There is however lower stability material as a minor proportion <10% of the Yangibana and Frasers pits but with a greater proportion (approximately 30%) at Bald Hills. This lower stability material occurs as weathered saprolites including kaolin clays, however smectitic clays are not present.

The lithologies encountered at the project are not associated with the occurrence of asbestiform minerals.

Segregation of waste via deep encapsulation or within purpose constructed containment cells due to geochemical characteristics is not warranted for the Waste Rock Landforms based on characterisation results. Characterisation of some tailings (TSF 3 in particular) streams however suggest infiltration and seepage controls will be required (See Yangibana Tailings Characterisation Trajectory/GCA 2017) as per the planned TSF design criteria described in Hastings referral documentation submitted to the EPA (31 January 2017).

Although there are some materials, which can be considered erosive, and one sample classified as dispersive, the configuration of the Project deposits is such that generally more durable waste rock forms the majority of the waste being mined and this will form the outer slopes of the WRL's. TSF embankments are typically constructed of high fines content material in order to fulfil their function and consequently these slopes will need to be armoured.

6. LANDFORM EVOLUTION

There are a limited number of specific interacting aspects or variables that determine erosional stability on reconstructed landforms. Each variable has a range of options, which might be employed to optimise erosional stability. As with all design aspects these need to be calibrated to accommodate sometimes competing design objectives. For instance, the most erosionally stable waste rock may have little capacity to sustain an ecosystem, which meets sustainability objectives because they do not present good revegetation conditions (low fines content, low nutrients and low plant available water). Hence the designs may require compromise and some elevated levels of erosion may need to be tolerated in order to meet ecological, land user or aesthetic requirements.

The design aspects below are the primary drivers of long term erosional stability. They often interact and this is discussed in detail following the design influence for each aspect:

1. Slope profile
2. Slope hydrology
3. Surface characteristics
4. Biological factors

6.1 Slope Profile

Modelling of typical slope geometries has been undertaken using parameters representative of transitional and fresh waste rock, which best represent the site material. Derived from a number of erosion modelling projects throughout WA in the past decade, the angles and shapes have been developed independently in a number of studies by various consulting houses and generally converge into a handful of basic profiles.

It is important to note that the estimation of erosion parameters has been carried out using information on climate, the physical and chemical properties of the slope materials and has drawn on erosion modelling work at Argyle Diamond Mine, Telfer, Wodgina and several large nickel mines in the WA Goldfields.

Generic options for a 60m high WRL lift have been used in this assessment. This is conservative as in most cases lift heights will be less than 60m high with generally a 40m maximum, although due to the fall of the ground in some locations, lifts may be higher than 40m locally (hence the inclusion of taller slopes in the analysis to ensure the model anticipated local maximum heights).

Three options for the WRL slope profile have been considered as a screening process to identify less erosive slope shapes:

1. A single concave slope profile with a starting profile derived from a 250-year eroded 20° planar profile.
2. A benched slope with 5m wide benches at 10m vertical intervals; inter-bench batter slopes of 20° and back slopes of 5° on the benches. This is the configuration for WRL's originally included in regulator guidelines in the late 1990's and early 2000's.
3. A benched slope with 20 - 30m wide benches at 20m vertical intervals with concave slopes derived from 250-year erosion simulations (as above). The benches have 1m high perimeter bunds on the WRL crest and cross bunds and 0.7m high across benches and cell bunded on top surfaces to limit cross flow.

The slope concavity derived from a 250-year eroded profile for a 60m high single slope of 20° is indicated in Figure 4 and is generally specified as a 20° slope in the upper 50% of slope height and 15° degrees in the lower 50% of slope height.

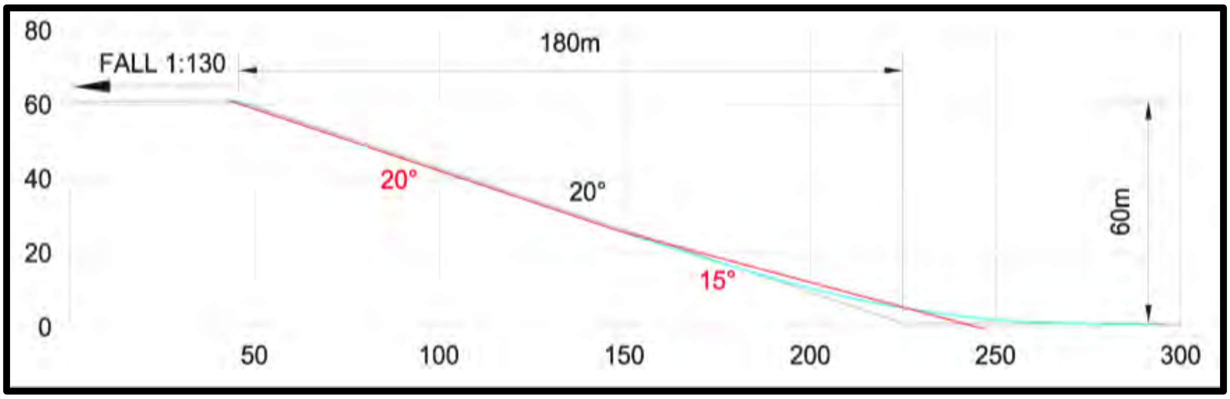


Figure 4: Deriving a concave shape via erosion of planar shape with Siberia

6.1.1 Option 1: Single Concave Slope

The base case profile for the Single Concave Slope is based on the derived slope, which forms when a planar slope is eroded in the model. The objective of this slope is to anticipate probable erosion performance in the long term and form the slope to this shape at construction and hence circumvent the initial era of erosion which occurs, even for durable batter material. This shape tends to stabilise in the longer term. The other objective of a concave slope is to balance catchment and velocity. A steep slope which is planar, will often begin to erode above the mid-point in the batter due to the build-up of run-off velocity. If the slope becomes shallower at the inflection point this can slow flow and limit erosions. This slope is also considered more "aesthetic" than planar slopes and a closer reflection of local natural slope shapes.

The screening phase study was completed on a 60m slope, however some studies are referenced which suggest that slopes of greater height can be achieved with similar stability results where waste rock material is **primarily of durable** fraction and resilient revegetation is introduced.

Figure 5 shows the profile and performance of single concave slope over 500 and 1000 years.

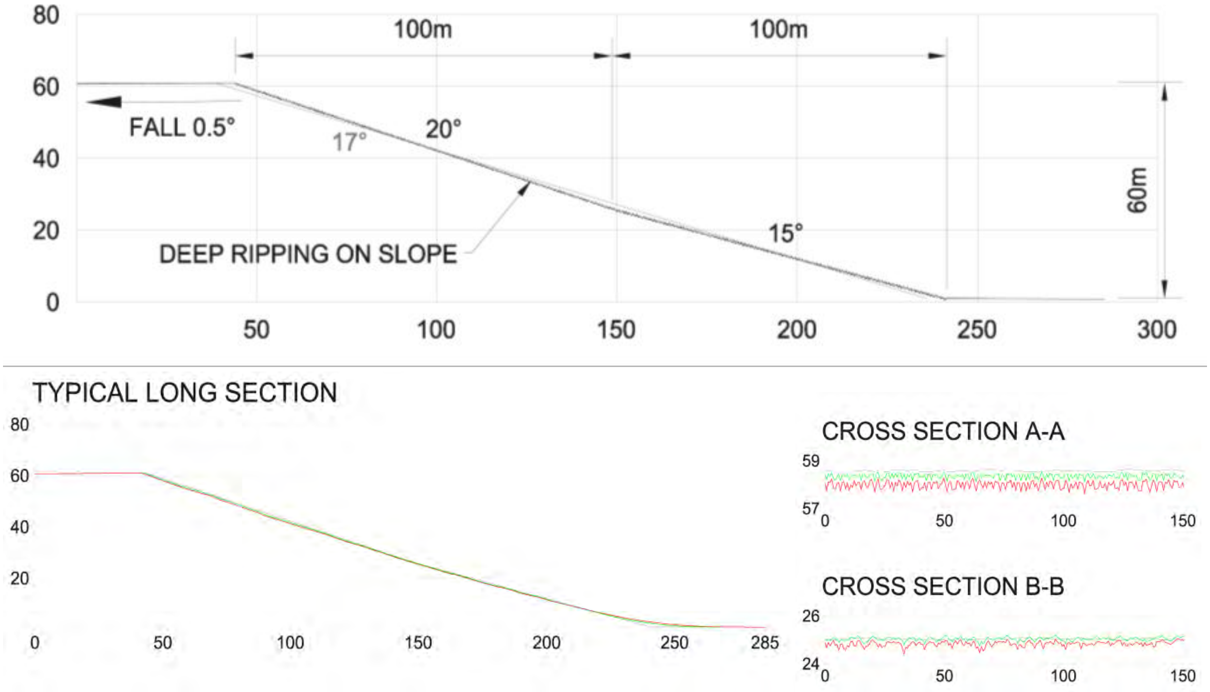


Figure 5: Profile and Performance of Single Concave - 500 years (green) and 1000 years (red)

The analysis of this shape suggests that, even without the considerations discussed in 6.2 to 6.4 erosion is minor to moderate in the long term. Individual gullies are generally less than 1m and overall loss of surface profile after 100 years is also generally less than 1m.

6.1.2 Option 2: Superseded DME "Guideline" Profile

Option two once represented standard practice in the mining industry in WA and is still sometimes specified where no investigation is made regarding the weaknesses of this design and no other options are examined. The primary issue with this profile is that there is insufficient freeboard on the narrow benches to store both the run-off from the batters and the inevitable sediment discharges which consume storage volume on the bench.

A great many waste rock dumps have been constructed to this design and some have also been constructed with the same setting except for a 20m lift height rather than a 10m lift. In most cases, these designs have not performed well, although it should be pointed out that a contributing factor has often been poor adherence to the designs in construction (most notably overtipped batters leaving benches <5m and cross fall on top sections and benches which lead to run on concentrations locally) which has exacerbated the design weakness of the already narrow berms.

Figure 6 shows the cross section and performance of a “Guideline” profile over 500 and 1000 years.

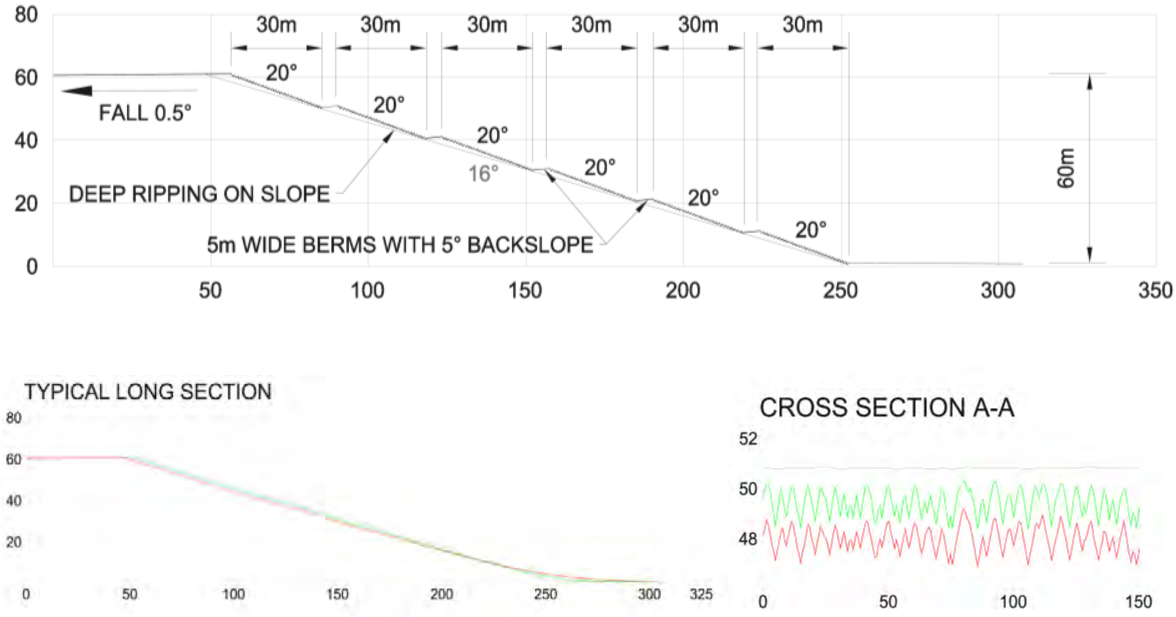


Figure 6: Cross Section and Performance of “Guideline” profile- 500 years (green) and 1000 years (red)

Analysis of trends for these slopes suggest that erosion rates are more severe with an average overall loss of profile of nearly 3m and gully depths at a maximum of approximately 2m. The profile erodes more severely because the narrow berms act as energy stores, concentrating and then discharging volumes of flow which escalate downslope leading to local areas of failure, accumulation of batter catchment flows and more severe erosion.

6.1.3 Option 3: Wide Berms and Concave Slopes

In the past 15 years, Trajectory and others have trialled and constructed slope configurations which combine the benefits of a concave slope with the capacity to store all sediment and flow reporting to an inter batter berm and hence stop the aggregation of flows on long batters. To achieve this, inter batter berms need to be of sufficient storage capacity to contain both runoff from the batter above and the sediment, which accumulates in berms. This is especially important during the early years after rehabilitation when erosion is more likely to occur prior to soil surfaces and erosion features armouring and when erosion rates tend to fall.

The primary difficulty with this configuration is that it can result in shallower slopes overall due to the width of the benches. The bench widths, lift heights and individual slope angles can each be calibrated to suit local conditions which can mitigate this issue to an extent.

Figure 7 shows Option 3 - wide berms and concave slopes profile- 500 and 1000 years.

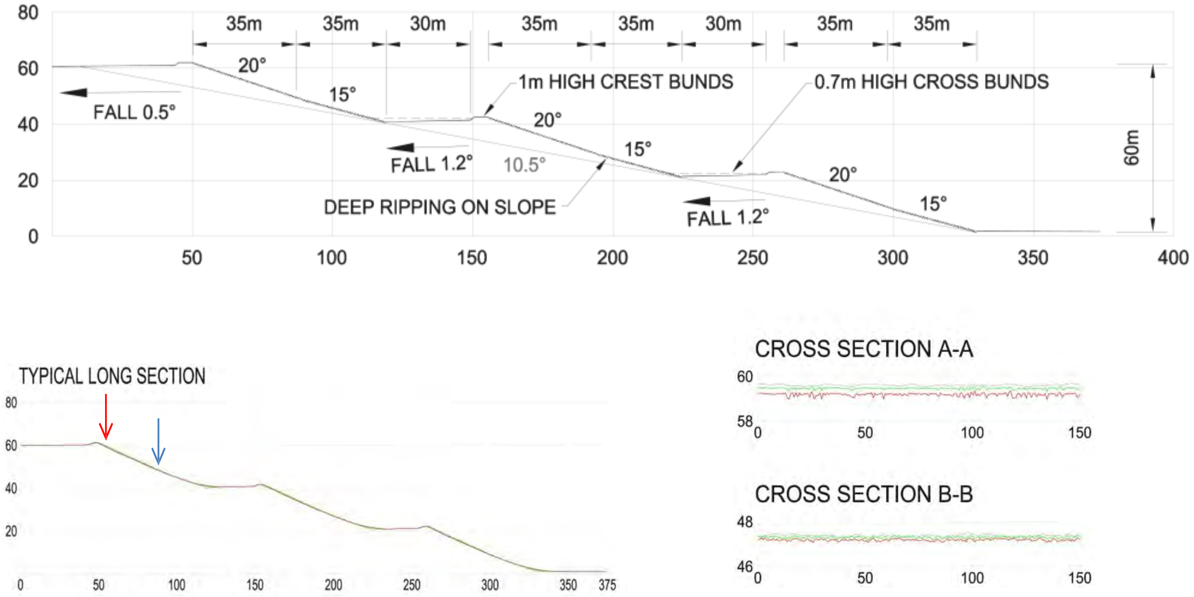


Figure 7: Wide Berms and Concave Slopes profile- 500 years (green) and 1000 years (red)

Unsurprisingly, the wide berm option performs the best. Overall slope lengths are constrained between benches with enough capacity to permanently interrupt flow. Although the fact that this design is superior has long been acknowledged, it has the effect of significantly extending overall slope length and landform footprint and hence reduces the total overall volume stored per unit of area. This is frequently sub optimal due to a range of factors including perimeter constraints (approval boundaries, infrastructure, pits etc) or the cost of reconfiguring waste rock material post operations if they have not been placed to suit this configuration from the outset.

6.1.4 Slope Profile – Influence on Design

The outcomes of the analyses indicate that the deepest erosion gullies typically form close to the landform crest areas. Cross sections taken along the crest areas of the Option 1 and 3 slopes indicate that the gullies will be relatively shallow. Without considering the contributions to stability of the aspects discussed in 6.2 to 6.4 below, a layer of material approximately 1m thick would be removed after 1000 years of erosion and maximum erosion depths of the same depth would occur.

Deeper gullies are formed over the surface of Option 2. Option 2 has 5m wide benches at 10m vertical intervals, but these erode and fail relatively quickly. Figure 8 indicates the comparison of average gully depths for each option expressed as a percentage of the worst performing Option (Option 2 at 100%). Overall, Option 3 performs the best as overall slope length is shorter, however both Options 1 and 3 could be considered to perform well.

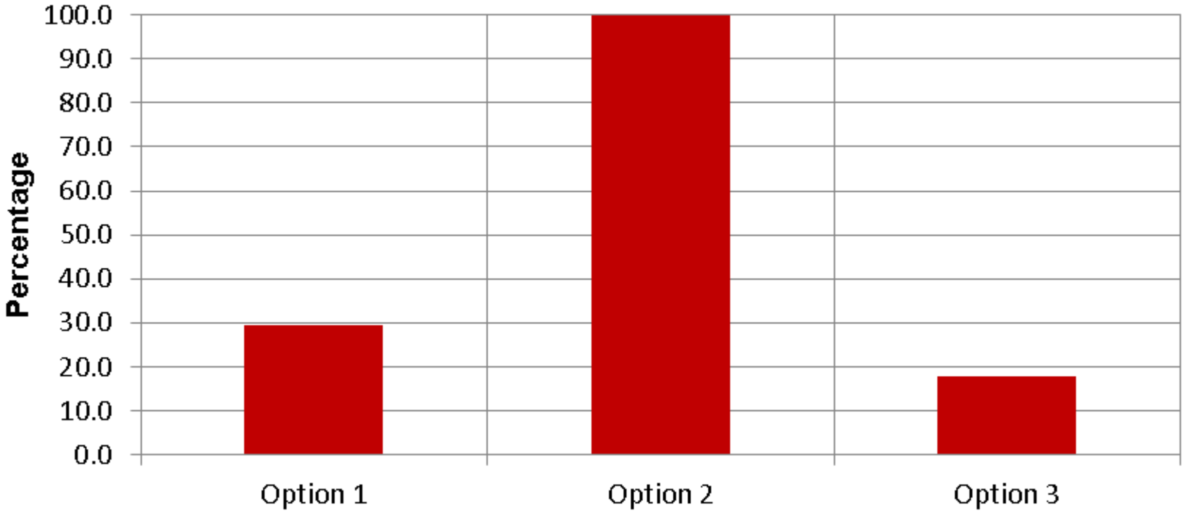


Figure 8: Relative performance of options in terms of gully depth.

The outcome of the slope profile aspects of analysis is that:

- A concave slope will anticipate post eroded profile and balance catchment area and flow velocity;
- If berms are to be included in design they need to be sufficiently wide to contain sediment discharges over the long term while maintaining run off storage freeboard; and,
- Where overall slope length is reduced, erosion performance improves and hence taller slopes are required; multiple erosion mitigation measures will need to operate.

6.2 Slope Hydrology

This section deals with specific hydrology characteristics of reconstructed slopes, which can inform design. These include:

- Run-on
- Hydraulic conductivity
- On slope storage
- Slope discharges

6.2.1 Run-On Control

Most WRL's in WA have no need to consider run-on as the WRL's in much of the rangelands are free standing landforms in the landscapes and only the top section needs to be controlled such that it does not discharge onto batters. In the northern Pilbara and Kimberley regions however, there are more frequently buttress waste rock landforms against escarpments or valley fill landforms. Erosion models generally preclude run-on from batter catchments unless benches fail and begin to deliver this water to the batter below.

In the case of Yangibana, run on from the top section can be limited entirely via the installation of perimeter crest bunds and cell bunding. In the prevailing rainfall environment perimeter bunds of 1m, with 2-5 degree grading away from the crest for 20m and cell bunds of 0.7m enclosing cells of 2-4 ha will contain a PMP rain event and ensure there is no run-on to the batters below. This configuration can be applied to top sections and berms.

6.2.2 Hydraulic conductivity

The hydraulic conductivity of the surfaces is directly related to run-off, which drives the potential volume and velocity of flow. Very low hydraulic conductivity translates to the majority of rainfall discharging from sloped surfaces and ponding/infiltrating on flat surfaces or discharging off the WRL. In some instances, hydraulic conductivity is ***potentially*** high but due to material traits (such as hard setting or hydrophobic characteristics) it generally runs off in sloped configurations. That is, on flat surfaces these materials will “wet up” and hence store plant available water. On sloped surfaces however they will shed water off because the water takes time to penetrate, and this does not occur on slopes.

Recent field studies at other large mine sites (including Argyle Diamonds) with long established rehabilitation on revegetated surfaces and compacted flats have indicated that hydraulic conductivities are generally moderate such that 2 – 20mm an hour is likely to infiltrate.

This suggests that for most closure surfaces (which do not have adverse materials), rainfall events of these magnitudes will contribute to the development of plant available water but not rapidly report to deep drainage. The average functional hydraulic conductivity on rehabilitated surfaces is one of the key attributes, which governs the depth of wetting and the nature and frequency of wetting fluxes can guide cover material types and depths and permit more accurate estimation of seepage. This issue is only relevant to Tailings storages facilities because the WRL’s have no requirement to limit infiltration. These recent investigations suggest that infiltration rates will reduce once the as tipped angle of repose slopes (which are comparatively high infiltration surfaces) are reconfigured into shallower, fully revegetated surfaces, which will have moderate infiltration.

6.2.3 On Slope Storage

The overall outcomes of this study indicate that in most cases single slopes of the proposed maximum of 40m will achieve the intended design period of 1000 years. In the case of the Bald Hill WRL an inter batter berm is specified in order to reduce slope lengths in response to the fact that at this location there is a higher proportion of low stability waste rock in the overall waste rock balance.

Hydrological and hydraulic modelling has been undertaken to develop berm configurations to ensure the closure design for the Bald Hills is sound for a surface hydrology perspective.

The DRAINS model was utilised to determine the maximum slope height based upon an average slope angle of 17.5° and berm width of 20 m assuming a 5° backslope. The modelling assumed incidental rainfall only; there was no allowance for discharge from upstream sources. The batters were assessed with an allowance to account for the additional height associated with the berm, to identify the maximum slope height before the berm no longer met design criteria (Figure 9).

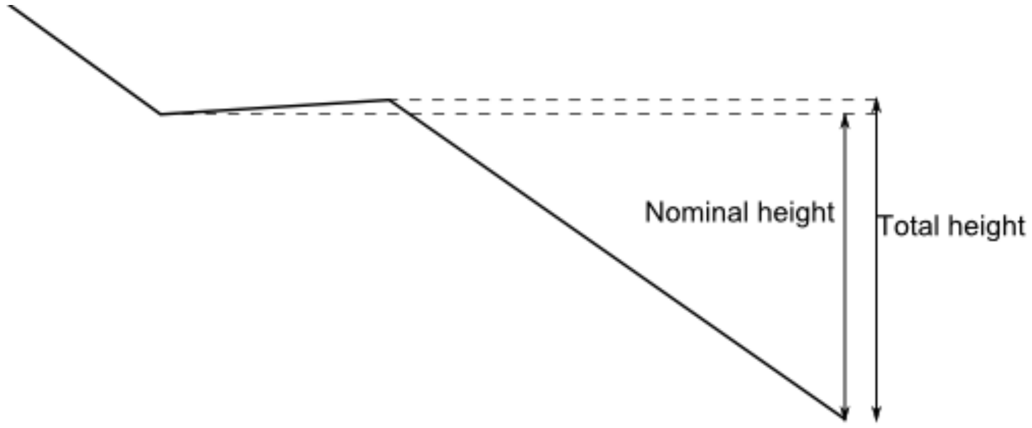


Figure 9: Slope height modelling

The design criteria applied for the berm were the ability to contain the critical duration 2000-year average recurrence interval (ARI) rainfall event with a minimum 300mm freeboard and the ability to contain the critical duration PMP ARI without overtopping, based upon the initial condition of the berm.

The hydrological modelling assumed that the modelled hydraulic conductivity was comparable to the values derived from the rehabilitated batters from analogue mine sites (as there is no site specific field data available) with a hydraulic conductivity of 200 mm/hr when dry, an antecedent moisture condition of three (very wet, and reducing the initial hydraulic conductivity rate to 37.5 mm/hr) and a final hydraulic conductivity of 13 mm/hr. A 5 mm depth for storage was applied to the batters before runoff generation commenced. The berm was modelled as a 100 m long section. Modelling assumed no concentration of flows and no run-on from upstream catchments.

The hydraulic model utilised a K_{sat} of 3×10^{-7} m/s, based upon the results of the K_{sat} at the analogue areas area. The design rainfall data was sourced from the Bureau of Meteorlogy's Rainfall *Intensity-Frequency-Duration* tool. Average rainfall intensity for design rainfall events were sourced for the 2000 year and PMP ARI 24 hour, 48 hour and 72 hour rainfall events.

The 12 hour ARI event for the 2000 and PMP year ARI was calculated using a log sequence of the 20 – 100 year ARI events. The average rainfall intensity for each of the design rainfall events is presented in

. The rainfall events were entered in the DRAINS model to develop a hyetograph for each design rainfall event. An example hyetograph is presented in Figure 10.

Table 3: Average intensity of design rainfall events (mm/hr)

Duration	2000 year ARI	PMP ARI
12 hour	15.7 mm/hr	18.2 mm/hr
24 hour	11.3 mm/hr	13.9 mm/hr
48 hour	7.6 mm/hr	9.4 mm/hr
72 hour	6.1 mm/hr	7.5 mm/hr

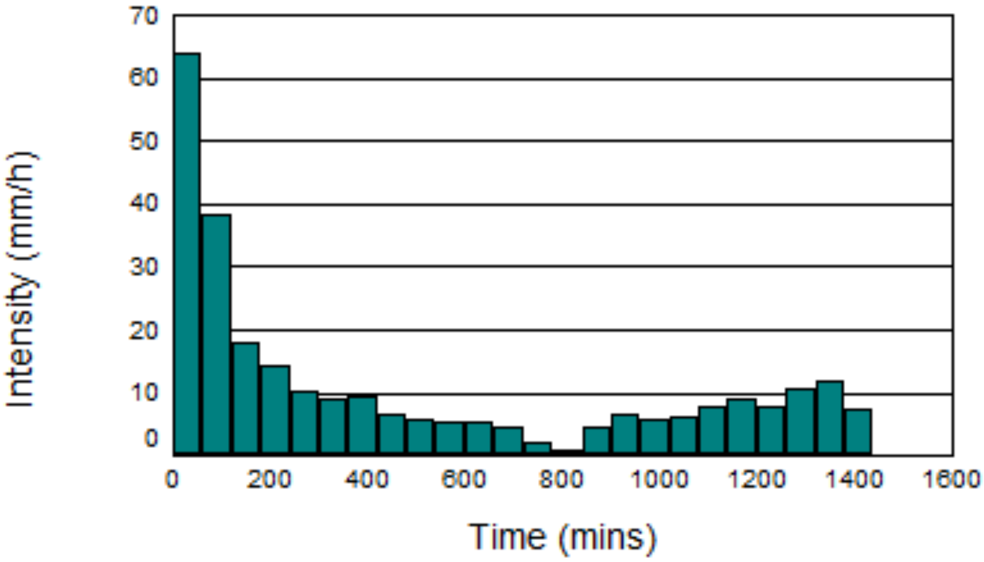


Figure 10: Typical hyetograph as established by DRAINS

Based upon the modelling, the preliminary recommended maximum slope heights were calculated for each of the berm configurations (Table 4). These maximum slope heights are only based upon the hydraulic capacity of the berms and do not account for slope stability, which is the rationale for constraining slope height below the values presented here.

Table 4: Maximum modelled slope height for given berm configurations

Berm width	**Berm angle**	**Slope angle**	**Maximum slope height**	**Volume of sediment before failure**
20 m	5°	17.5°	31.75 m (nominally 30 m)	378.3 m^3/ha

This confirms that a 20m wide bench will certainly be able to store the run on from a PMP event. It can notionally store up to 31m high lifts, however a factor of safety is introduced to allow for the consumption of the bench freeboard by sediment accumulation.

6.2.4 On Landform Storage

Provided the underlying area is not comprised of hostile material (See section 6.3.4) water can be stored on WRL designated as high infiltration or store and release. This is routinely achieved via cell bunding across top flat surfaces or wide benches. In these cases, the flat surfaces need to be constructed such that cross fall is minimised. Perimeter bunds of approximately 1m in height and cell bunding of 0.7m in height would comfortably contain a PMP as calculated in 6.2.2 above. Figures 11 and 12 provide examples of how cell bunding can be effectively implemented on a convex-shaped TSF.

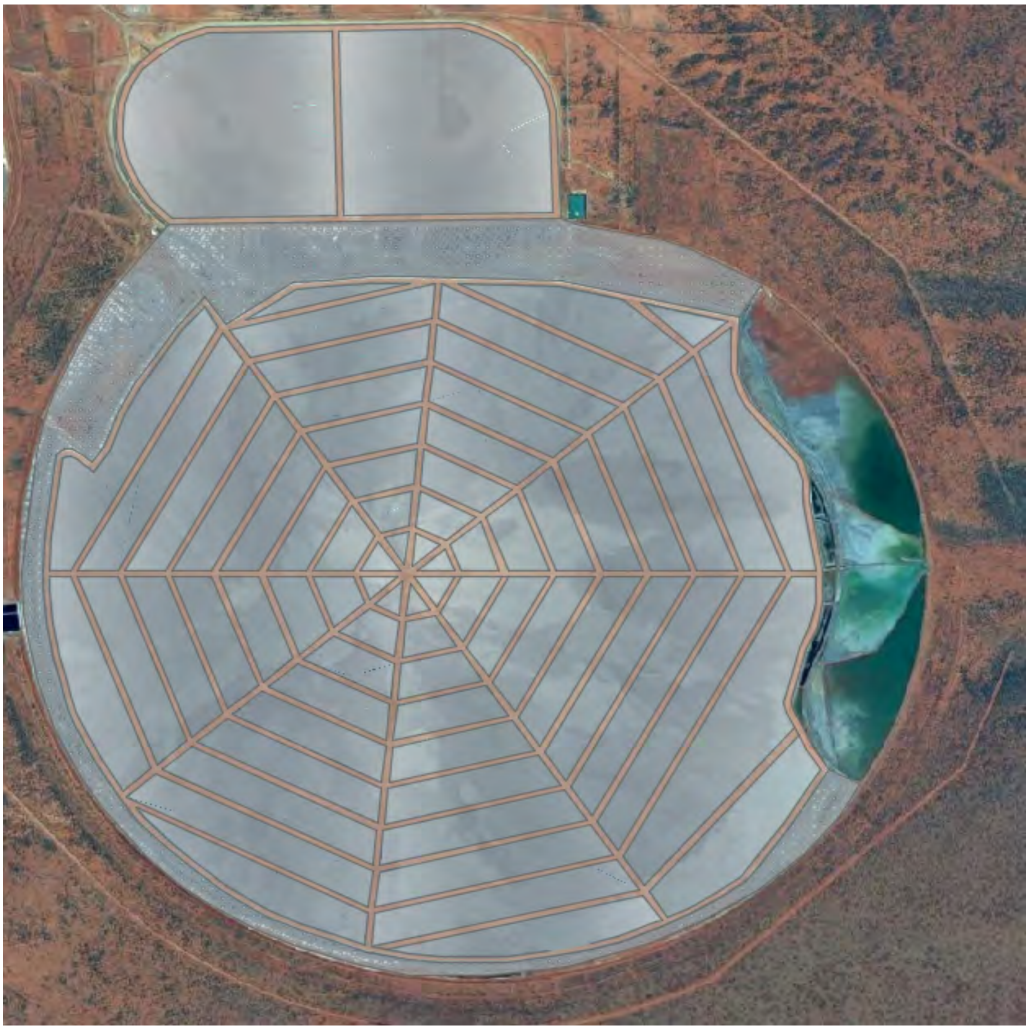


Figure 11: Example of cell bunding on a Convex TSF as proposed for Yangibana

Figure 12: Examples of Cell Bunding at Mt McClure

6.2.5 Discharges from Slopes and Flat Surfaces

These are instances where surfaces are designed to discharge via a purpose built discharge structure generally armoured with rip rap along the flow path and reporting to natural ground, which is durable (solid rock or self-armouring substrates) via hardened spillways to existing drainage channels.

Such measures can be configured such that they only discharge in the high flow portion of the hydrograph with lower flow stores on the berms or top sections (see above) to evaporate or evapotranspire.

Discharge measures are not required for any of the Project WRLs or for TSF 1 as the material stored in these facilities is benign and control of leachates is not a management objective. Designs for these landform storage facilities, such that a 1:2000 rainfall event or a PMP rainfall event could be managed effectively via emergency spillways.

In the case of TSF 2 and 3 and the Evaporation Pond footprint, low permeability basal liners will be constructed for the operational era to prevent hostile materials within the landform storage facilities from leaching to groundwater. As such, purposed designed discharge structures, including spillways and drop structures, will be required. These structures may be required to carry all run-off, including high flow run-off, from the surface of the landform storage structure. The majority of rainfall events will be managed via a store and release cover or attenuated in holding zones with impervious liners. It should be noted that discharge will need to be facilitated from top surfaces only, with batter surfaces, like that of the WRL's, functioning based on a water harvesting approach.

6.2.6 Hydrology Considerations – Impact on Design

The key impact regarding hydrology considerations on design at Yangibana are that:

- The landforms, which are primarily composed of benign and durable waste rock (i.e. Frasers, Yangibana North and South WRLs), are constructed with <18 degree slopes and are <40m in height.
- The landforms, which are composed of benign but variable durability waste rock (i.e. Bald Hill WRL), are constructed with <18 degree slopes and are <20m in height.
- The TSFs and Evaporation Pond embankments, which are constructed of fines material, are rock armoured and are constructed with <18 degree slopes and are <20m in height.
- The landforms composed of durable material on the outer surfaces and hostile material contained within lined facilities (i.e. TSF 2 and 3, and Evaporation Pond) are constructed with cover systems, which limit infiltration via PMP drainage measures and/or store and release cover systems overlying impervious liners.

6.3 Surface Characteristics

A key aspect of long term landform stability is the behaviour of the materials at the surface. The initial treatment is the method of surface preparation, which will operate during the stabilisation era. After this era, the way in which the outermost layer of the material stabilises can drive long term stability as much as slope profile.

6.3.1 Surface Treatments

Surface treatments are often undertaken after the placement of topsoil to integrate topsoil into waste rock and/or to encourage water to infiltrate into the root zone rather than run off. Large deep and wide rip line structures as depicted in Figure 13 have frequently provided a valuable contribution to stabilising slopes until the various other mechanisms discussed above and below establish. Large trough banks are generally very successful in the Goldfields and Pilbara where average and peak rainfalls can generally be controlled by these measures. Deep, wide ripping can be effectively achieved by using adjustable winged tines (Figure 14).

Figure 13: Contour ripping on freshly completed reprofiling

Figure 14: Example of adjustable winged tines to produce deep wide rip lines

6.3.2 Waste Rock Fragment Size and Durability

Hastings has completed materials characterisation to understand the durability and probable fragment size traits of the waste rock. The vast majority of the material tends towards durable minerology at Frasers and Yangibana North and South. At Bald Hill 30% of the material is lower stability material and scheduling controls will be required to ensure that the surfaces exposed by reprofiling post closure will be dominated by durable fraction.

For the TSF and Evaporation Ponds, the short batters specified in the designs will require a minimum 2m of durable fresh/durable waste rock (primarily granite at Yangibana) for the <18 degree batters, topsoiled (to a depth of 100-150 mm) and seeded to ensure long term stability.

6.3.3 Soil Armouring

This is an aspect of slope stabilisation not well captured with erosion modelling processes. Many slopes in nature composed of sandy soils will exhibit very little erosion due to the surface armouring of gravel and cobble size stones, which form a dense cover over the soil layers after a stabilisation period and absorb the raindrop energy and distribute flow. As presented in the photographs below (Figure 15), this type of armouring can operate on comparatively steep slopes and demonstrate resilience and very little sediment emission in large rain events.

Figure 15: Examples of stabilising subsoil (left) and an example of self-armouring topsoil (right)

6.3.4 Adverse Soil Characteristics

Many soils recovered and respread in mining processes have adverse traits, which frequently, in net terms, make their use a negative rather than a positive contribution to rehabilitation outcomes. Saline, sodic, hydrophobic or hard setting soils and soils with a very narrow particle size distribution can all be adverse in terms of erosional stability or plant establishment.

In the case of Yangibana, characterisation studies have demonstrated that Plains Soils and Saprolites are the two units that are likely to have unfavourable characteristics in rehabilitation. Fortunately, the vast majority of the disturbance footprint overlies the Hill Soils and basic harvesting and storage controls can ensure that the Plain Soils are not incorporated into the topsoil inventory. Similarly, Yangibana is fortunate in that durable fresh waste rock dominates the waste rock balance and generally the lower stability materials (saprolites) will be mined early in the sequence and encapsulated by durable materials that are mined later in the sequence. However, at Bald Hill where balances are less favourable a more conservative waste rock landform profile has been recommended.

6.4 BIOLOGICAL FACTORS

The following biological factors are discussed in further detail:

- Cover layers
- Plant roots
- Cryptograms
- Humus layers

As noted, erosion modes do not compensate for the contribution of vegetation cover to landform stability. Many soils that are highly erosive which have been mined in tropical Asia and South America have been entirely stabilised through the action of vegetative cover and to entirely disregard the contribution, even in the rangelands, is excessively conservative.

6.4.1 Cover Layers

The first contribution of vegetation is the reduction of rainfall energy dissipation through rain falling onto plants rather than soil. Where multiple layers of cover such as grasses and shrubs (a likely configuration at Yangibana) occur, the proportion of rain falling directly on the ground will be reduced. The plants will frequently interact with water so that it falls within a drip zone or is directed to the main plant stem to maximise uptake by roots.

6.4.2 Plant Roots

Plant roots can make significant contributions to stability. In the case of Yangibana annual and perennial grasses and herbs contribute to the root network and the deeper taproots of woody tree species also contribute such as acacias and eucalypts.

6.4.3 Cryptograms and Soil Organisms

Cryptograms are organisms, which form layers of living tissue material on the soil surfaces. They are an indicator of soil health and contribute to stability. Other soil organisms also contribute to soil aeration and the storage of plant available water. These organisms naturally recolonise healthy revegetation ecosystems but may also be encouraged via soil inoculation and the rehandling (where this is available) of timber debris stockpiled separately during land clearing.

6.4.4 Humus Layers

The Goldfields and Pilbara can feature long term humus layers where revegetation is successful. These layers dissipate rainfall and graduate evaporation, in addition to limiting the formation of hard setting or low permeability soil layers.

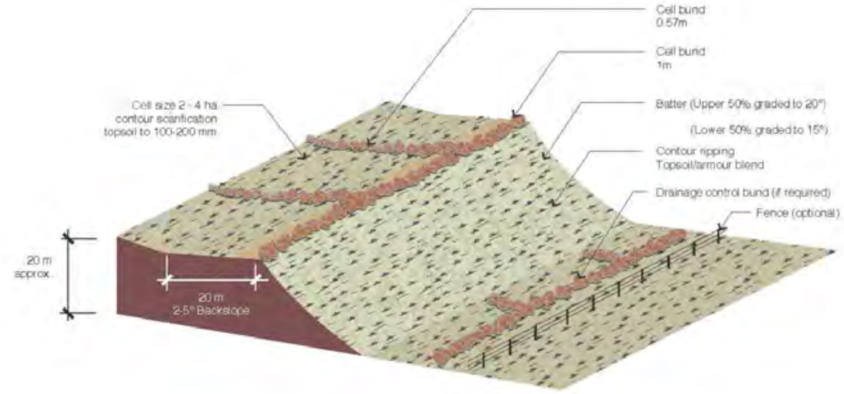
Taken as a whole, the characteristics of the waste rock and soils at Yangibana, the capacity for rapid, multilayers and moderately dense vegetation and the configuration opportunities to enhance stability all translate to a landform evolution conceptual model that has comparatively high levels of confidence that stability will be acceptable over the long term.

7. LANDFORM DESIGN SPECIFICATIONS FOR LONG TERM STABILITY

The following specifications are developed via information developed from the characterisation studies to date, erosion modelling and long term monitoring studies of revegetation in mining. The management implications are set forth based on domains, providing guidance on the five primary landforms.

7.1 Frasers and Yangibana North and South Waste Rock Landforms

The Frasers WRL will be constructed from NAF waste rock. The fresh granite waste rock dominates the waste inventory and hence it is expected that the outer surfaces of the waste rock will be primarily of armouring with low erodibility material. The landform will be water harvesting and concentration of runoff in drains or benches should be avoided. Hill soils will be preserved for respreading on the batter surfaces. Plains soils or suitable subsoils will be spread on top surfaces. Soils should be spread at 100-150 mm and integrated into the waste rock with ripping or scarification. The maximum WRL height is 40m with the average slope angle of 17.5 degrees, which is comprised of a 20-degree slope for the upper 50% of the slope height and a 15 degree slope for the lower 50% of the slope height (as per Figure 16).



NOTES
Does not include Bald Hill - See Figure 2

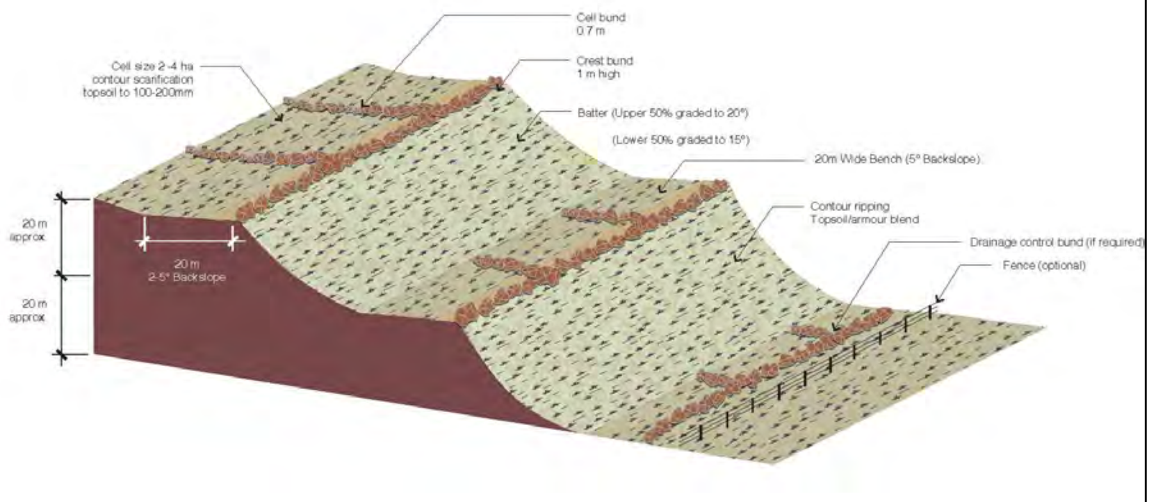
YANGINBANA NORTH AND SOUTH AND
FRASERS RANGE WRD LANDFORMS

FIGURE
16

7.2 Bald Hill Waste Rock Landform

The Bald Hill WRL will be constructed from NAF waste rock. The volumes of ironstone and fresh granite waste rock are sufficient in the waste inventory to ensure that the outer surfaces of the waste rock will be primarily armoured with low erodibility material however the mine schedule will need to respond to this requirement. The landform can be water harvesting. The inclusion of one inter batter berm will shorten the overall slope length of the batter in response to the probability of lower stability material being included in the substrate matrix. Hill soils will be preserved for respreading on the batter surfaces, whilst plain soils will not be harvested and stored as they are unsuitable for revegetation. Suitable subsoils, will be spread on top/flat surfaces to 100-150 mm and will be integrated into the waste rock with ripping or scarification. Figure 17 outlines the typical landform specifications for Bald Hill WRL.

Bald Hills is also one area where a 1:100 flood event will reach the reprofiled batter. In order to respond to flood events the 1:2000 or PMP flood event will be selected and an additional armour layer of durable coarse fresh waste rock will be placed to this level.



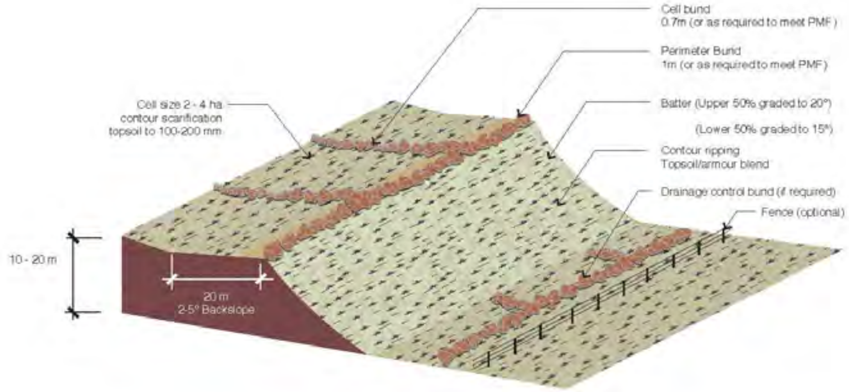
BALD HILL
WASTE ROCK DUMP PROFILE

FIGURE
17

7.3 Tailings Storage Facility 1

Tailings Storage Facility 1 is expected to be constructed as a central discharge configuration. As such it will have a low perimeter embankment (<10m) and water management / return structure raising to a central mound. The tailings are expected to be NAF without significant neutral mine drainage issues, however the concentration of salts via the water return / recycle process in the plant could potentially lead to some salinity in the tailings. The likely closure specification for these tailings will be armouring of the outer embankment such that there is at least 2m of rock armour cladding the high fines content material utilised to construct the embankment. A 0.5m cover of benign, durable fresh waste, ideally with a mixed particle size distribution will be placed for the purposes of dust minimisation and revegetation reestablishment. As with WRL's the batters and top surface would be covered with 100-150 mm of Hill Soil topsoil or suitable subsoil.

From a drainage perspective, a network of cells will be created, which will have the capacity to contain a PMP rainfall event. These cells will be constructed via the excavation of in situ tailings to create 1m high causeways with the addition of 500mm of durable fresh waste as a running surface with the remainder of the cell surface to be covered. The average cell size will be 3ha. See Figures 11 and 12 for the top surface drainage controls and Figure 18 for the batter surface specifications.



NOTES

YANGIBANA PROJECT
TSF LANDFORM

FIGURE
18

7.4 Tailings Storage Facility 2 and Tailings Storage Facility 3

Tailings Storage Facility 2 is expected to be a paddock TSF of approximately 8-10ha. It is currently expected to be NAF with slight to moderate enrichments of some metals. The TSF may be fully lined or have a compacted clay liner depending on the outcome of leach testing currently underway.

Tailings Storage Facility 3 is expected to be a paddock TSF or approximately 8-10 ha. It is currently expected to be NAF with moderate enrichments of some metals. The TSF is expected to be fully lined at the base with a synthetic liner.

Closure specification for these tailings will be armouring on the outer embankment and a cover depth suitable for the purposes of mitigating radionuclide readings to acceptable levels (1m depth is calculated to achieve this, JHRC 2017) and revegetation reestablishment.

The recommended cover will likely be between 1-2 m of benign durable waste rock (however this will need to be established with trials) and 100-150 mm of Hill Soil topsoil or suitable subsoil. The closure top cover will need to be a water shedding cover and limit infiltration into the tailings. Dewatering the tailings to permit trafficability for cover placement may require a fallow period. The batter section in Figure 18 is representative of the TSF 2 and 3 embankments. Figure 19 should the TSF's general arrangements.

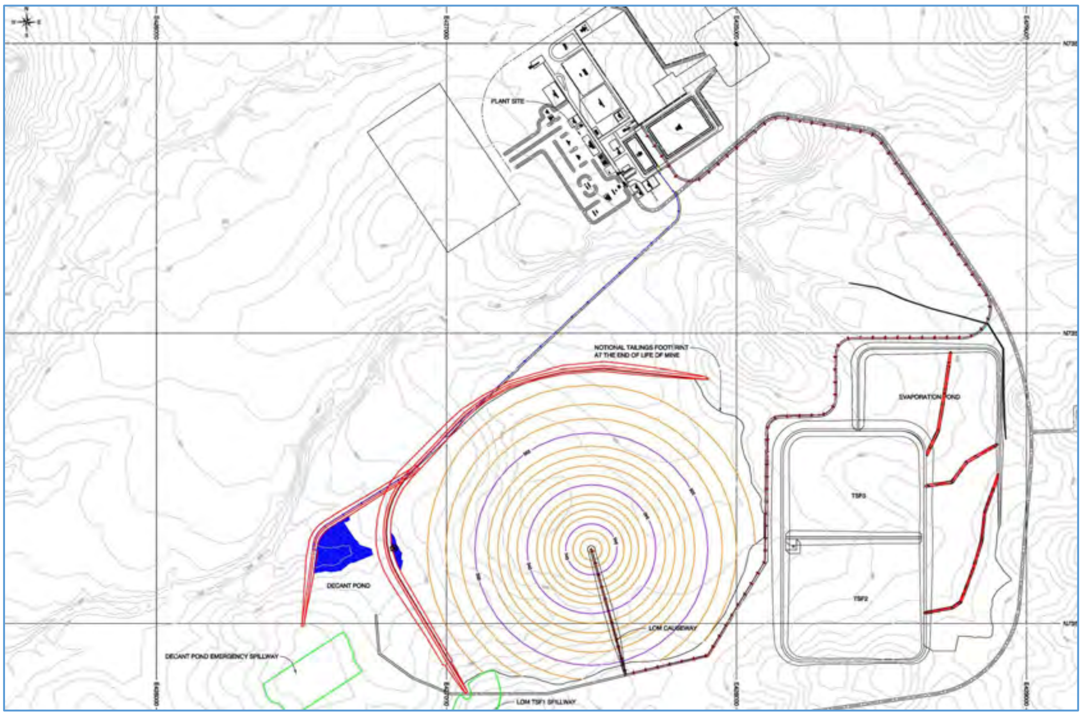


Figure 19: TSF General Arrangements

7.5 Evaporation Pond

The Evaporation Pond is expected to be a lined structure enclosed by a low embankment. It is currently expected to be NAF with moderate enrichments of some metals. The Evaporation Pond is expected to have a compacted clay liner at the base. The likely closure specification for these tailings will be armouring on the outer embankment and a cover depth suitable for the purposes of encapsulating the materials contained in the pond and revegetation reestablishment. The recommended cover will likely be between 1-2 m of benign durable waste rock and 100-150 mm of Hill Soil topsoil or suitable subsoil. The closure top cover will need to be a water shedding cover and limit infiltration into the tailings.

8. BENCHMARKING

8.1 Batters and Embankment

Extensive benchmarking has been undertaken to ensure that the designs being proposed here are consistent with good practice and have demonstrated, in field performance of up to 20 years, to be durable and successful approaches. The principal of Trajectory has participated in the development of design, the implementation and monitoring of dozens of waste tock landforms and tailings storage facilities including facilities at Jundee, Bronzewing, MT Leyshon, Argyle Diamonds, Mt Keith, Pardoo, Mt Dove, Wodgina, Woodcutters, Pajingo, Mt Rawdon, Cracow, Granny Smith, KCGM and Boddington.

The key aggregate learning is that concave slopes add value and that slopes of 17-18 degrees, where constituted with durable material and sheeted with growth media can stabilize and perform well where drainage run on is restricted.

8.2 Tailings Storage Facility Covers

The installation of TSF covers from the perspective of landform evolution need only deal with long term stability, however covers may have other objectives such as limiting infiltration, limiting radioactivity at surface or establishing sustainable ecosystems. From a purely landform evolution perspective, current industry practice and modelling suggests that a 0.5m depth of durable fresh waste rock will stabilise the TSF surface such that wind and water erosion and limited. In the case of the central discharge TSF this may require cell bunding to ensure incident rainfall does not migrate to the perimeter, as shown in Figure 11. Covers of this nature have been specified for mine sites in the eastern Goldfields and nickel mines in the northern Goldfields.

8.3 Drainage

As discussed above, benign materials, such as the WRL's and TSF 1 can be "water harvesting", which is a very common approach throughout WA whereby as much water as possible is infiltrated or ponded to add to the store of plant available water. In the case of TSF 2 and 3, and possibly the final footprint over the salts in the evaporation pond will need to be constructed such that run off drains away from these materials or is effectively managed via a store and release cover.

8.4 Flood Armouring

Flood armouring will be constructed as a buttress against areas up to the elevation where 1:2000 or PMP flood events reach up the dump or TSF batter. It is important to note, as was the case with a study at Pardoo in the Pilbara, that the water reaching this elevation has little if any velocity and as such the armour is primarily required to stabilise the embankments during an ephemeral saturation episode. As such an additional 1m of durable, coarse fresh waste rock is specified.

Please note that the benchmarks referred to are often for very recent work, often not yet published.

9. PERFORMANCE MEASURES AND MONITORING

This study has determined that the primary Design Considerations and Aspects, which can be adjusted via options for specific methodologies, will realise the desired design period of 1000 years without significant erosion or embankment failure. Specifications are set and objective performance measures are presented as being acceptable, and conform with the regulatory approach to criteria being SMART (specific, measurable, achievable, results-focused, and time- bound).

Below are the specifications and the methods through which performance will be assessed.

9.1 Tolerances and Performance Measures

The table below sets out the measures to demonstrate the performance of the landforms based on the design considerations and aspects which informed the design.

Table 5: Specifications and Performance Measures

Specification	Performance Measure
Maximum 40m lift height (provides conservatism against model)	A). Erosion features average <0.5m depth B). Erosion < 5 tonnes/ha/year after 3-year establishment period
Average slope angle 17.5 degrees	A and B above and post construction angle QA/QC survey
20 degrees in upper 50% of Slope and 15 degrees in lower 50% of slope	A and B and post construction angle QA/QC survey

Specification	Performance Measure
Hydrology measures to contain a PMP estimate to limit run-on from top surface or berms to batters below. Nominal 1m crest bund adjusted based on final surface.	C) Top and bench tolerances <.5m variability. Post construction angle QA/QC survey Zero run-on from up gradient surfaces demonstrated via foot traverse inspection after three years
Cell bunding of .7m and perimeter bunding of 1m. Infiltration + Evapotranspiration < 100% of incident rainfall on flat surfaces	C and Permeameter testing demonstrates infiltration in as constructed and 3 years post revegetation
Maximum Lift Height for TSF's 20m	Post construction angle and berm width QA/QC survey
0.5m high bunds at 10m offset from final toe position. Cross bunds installed where natural ground at gradient greater than 2 degrees	Post construction QA/QC survey
Rip lines ***on contour*** and minimum 0.5m deep and 1m wide at base of windrow	Post construction QA/QC survey
40% of exposed surface comprised of durable fraction equal to or greater than gravel	Post reprofiling stability mapping QA/QC survey
Armouring subsoils spread at 150 – 200mm over reprofiled waste rock. 20% of final exposed surface after 3-year stabilisation period will be gravels/cobbles form the soil	Post reprofiling stability mapping QA/QC survey
Up to 2m of in situ or imported durable armouring granite waste rock after final reprofiling	Post Construction validation survey
Provenance seed mix of grasses, shrubs and woody plants	25% plant cover after three-year establishment period
Provenance seed mix of grasses, shrubs and woody plants	50% of pre-mining diversity after three-year establishment period
Include introduction of biological matter and soil inoculants in revegetation process	Presence/absence of cryptograms in survey after three-year establishment period
Provenance seed mix of grasses, shrubs and woody plants	5% surface cover by humus layer after three-year establishment period

9.2 Progressive Rehabilitation and Trials

At each of the landforms (4 WRL's, 3 TSF's and the Evaporation Pond) it would be advantageous to install trials in the near term or to complete progressive rehabilitation in accordance with the specifications to provide early opportunities to demonstrate performance.

Ideally designs for the TSF's can incorporate the construction of embankments to full height as of the initial construction and therefore all embankment walls can have the full closure treatments applied at construction.

In the case of the WRL's the 40m high WRL's will require the full height to be reached before slope completion as these cannot be progressively constructed. In the case of Bald Hills, it may be possible to close the lower lift while the upper lift is still under construction.

9.3 QA/QC and Verification

When any surface is constructed such that it is prepared as the final closure surface and no further work is to be undertaken, the following parameters should be measured as QA/QC either using field based survey or remote sensing (as per Table 5):

- Total landform height above natural ground – minimum and maximum
- Batter angle – steepest, shallowest and average
- Top surface variability across top (<.5m desirable)
- Berm tolerance/fall laterally (<.5m desirable)
- Perimeter 1 m and Cell Bund .7m Height confirmed
- Cross Ripping adherence to contour
- Randomized samples of 1m square quadrat of % durable fraction exposed - substrate
- Depth of Armouring Cover (where specified)
- Depth of growth media cover
- Effective width of benches (where specified)
- Seed Mix – Diversity against baseline flora studies

This a verification review and should be conducted for each tranche of closure works and included in the MCP reporting process.

9.4 Change Management and Review

Where design parameters are changed or new satellite workings are brought into the Project, this report inclusive of the various settings and specifications should be reviewed to ensure it responds to:

- Newly identified or emerged risks
- Improvements in the knowledge base
- Changes to operational approaches
- Stakeholder feedback
- Monitoring results

9.5 Monitoring Program

When any surface has been prepared as the final closure surface and no further work is to be undertaken after three years the following measures should be taken either using field based survey or remote sensing (as per Table 5):

- Field traverse of bunds to ensure they are functioning according to intention
- Field or remote sensing measurement of erosion features (depth and spacing)
- Field observational reporting on the percentage cover of substrate durable fraction, topsoil gravel/cobble, humus, cryptogams (presence/absence)
- Field or remote sensing of plant cover and diversity

This monitoring could be repeated every 2-3 years to confirm the stabilizing function of the various aspects and identify local areas of failure where rework may be required.

10. REFERENCES

Australian and New Zealand Environment Conservation Council (2000), Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

Australian and New Zealand Minerals and Energy Council (2000), Strategic Framework for Mine Closure

CIRIA. (2007). The Rock Manual. The use of rock in hydraulic engineering. (2"d Edition).

C683, CIRIA, London.

Department of Mines and Petroleum, Environmental Protection Agency (2015), Guidelines for Preparing Mine Closure Plans.

Department of Mines and Petroleum (2016), Draft guidance materials characterisation baseline data requirements for mining proposals.

Graeme Campbell and Associates (2016), Yangibana Project: Geochemical and Physical Characterisation of Mine-Waste Samples and Implications for Mine-Waste Management Waste Rock Characterisation

Landloch (2016a), Hastings Surface Erodibility Assessment, November 2016.

Landloch (2016b), Yangibana Project Soil Assessment, 2274.16a.

Pearson, J.M, Taylor, W.R., and Barley, M.E. 1996. Geology of the alkaline Gifford Creek Complex, Gascoyne Complex, Western Australia, *Australian Journal of Earth Sciences.* v 43 pp 299-309.

Pirajno, F, Ganzalex-Aivarez, Chen, W., Kyser, K., Simonetti, A Leduc, E., and leGros, M. 2014. The Gifford Creek Ferrocarbonatite Complex, Gascoyne Province, Western Australia: Associated fenitic alteration and a putative link with the1 075MA Warakurna LIP. *Lithos.* v 202-203. pp 100-109.

Pirajno, F, Mernagh, T., Huston, D., Creaser, R., and Seltmann, R. 2015. The Mesoproterozoic Abra polymetallic sedimentary rock-hosted mineral deposit, Edmund Basin, Western Australia. *Ore Geology Reviews.* v 76. pp 442-462.

Radiation Professionals (2016) Baseline Radiation Report Hastings Yangibana Project.

Radiation Professionals (2016) Radiation Waste Characterisation Report Hastings Yangibana Project.

Singh, B., and Goel, R.K. 1999. Rock mass classification: A practical approach in civil engineering. Elsevier Science, Oxford UK.

11. ABBREVIATIONS AND ACRONYMS

ANZECC	Australian and New Zealand Environment Conservation Council
AMD	Acid Mine Drainage
DITR	Department of Tourism and Industry
DMP	Department of Mines and Petroleum
EC	Electrical Conductivity
EPA	Environmental Protection Agency
ESP	Exchangeable Sodium Percentage
GARD	Global Acid Rock Drainage
ha	Hectares
ICMM	International Council on Mining and Metals
m	Metres
m^3	Cubic metres
mg/l	Milligrams per Litre
mm	Millimetres
mtpa	Million tonnes per annum
NAF	Non Acid Forming
NEMP	National Environment Protection (Assessment of Site Contamination) Measure
NORM	Naturally occurring radioactive material
PAF	Potentially Acid Forming
pH	Hydrogen Potential
ppm	parts per million
PSD	particle size distribution
ROM	Run of Mine
TDS	Total Dissolved Solids
TSF	Tailings Storage Facility
TSS	Total suspended solids

12. GLOSSARY

Acidic and metalliferous drainage	AMD is inclusive of: acidic drainage metalliferous drainage (encompassing all metals/metalloids/non-metals which may be contaminants of concern) and saline materials and/or drainage.
Dispersive material	Dispersive materials are structurally unstable. They disperse into basic particles sand, silt and clay in fresh water.
Fibrous material	A mineral with an aspect ratio of 5:1 (http://www.dmp.wa.gov.au/documents/Guidelines/MSH_G_ManagementOfFibrousMineralsInWaMiningOperations.pdf)
Kinetic Testing	Kinetic testing encompasses a group of tests where the acid generation characteristics of a sample are measured with respect to time.
Metalliferous drainage	Metalliferous drainage (encompassing all metals/metalloids/non-metals, which may be contaminants of concern)
Mineralogy	The mineral assemblage of the rock. There are several methods for determining this including X-Ray powder diffraction.
Silicate Material	A compound containing an anionic silicon compound.
Static geochemical testing	Static geochemical tests provide information on the bulk geochemical characteristics of material at a point in time. They do not provide information on rates of chemical processes or the rates of release of weathering products. Static tests include acid base accounting tests where measurements are made over a short fixed period of time.

APPENDICES

APPENDIX 1. Erosion Modelling Methodologies

1. Siberia Modelling Assumptions

Construction and cover materials applied in the erosion models for the various facilities were limited to three material types:

- High competency mine waste materials which represent hard, durable, fresh rock;
- Medium competency mine waste materials represent transitional, weathered rock and cap rock; and
- Low competency soil and mine waste materials – represented by tailings, dispersive oxide, kaolinite, sands and top soil.

Erosion modelling was carried out assuming no surface water ‘run-on’ occurs from the top surfaces, i.e. erosion analyses consider only the erosion arising from rainfall falling directly onto the slope from the top crest downwards. Run-on water has a significant impact on the erosional performance of a dump as a whole. Run-on prevention structures, such as surface water containment cells or paddocks, crest bunds and cross bunds on benches, particularly at low points, have been incorporated into the closure design where required. This has been included in the assumptions and modelling applied in both the erosion modelling and the surface water considerations in the review. In some cases there may be potential for severe erosion to compromise the run on controls, exacerbating erosion where this occurs, however these run on inputs due to such failures are not captured within the model.

2. Description of Siberia Software

SIBERIA is a long-term erosion model developed in 1991 to simulate the linkages between the time evolving geomorphic form of natural landscapes and the hydrology and erosion processes occurring on them, and how these processes, in turn, determine the future evolution of the natural landform. SIBERIA works with a gridded digital terrain model, which evolves in time in response to runoff and erosion derived from physically based erosion models. These models are based on commonly accepted erosion physics specifically relationships between catchment area and runoff rate.

Erosion modelling has been undertaken using the SIBERIA software to generate long term erosion models by applying linkages between the time evolving geomorphic form of natural landscapes and the hydrology and erosion processes occurring on them. SIBERIA works with a gridded digital terrain model which evolves in time in response to runoff and erosion derived from physically based erosion models. SIBERIA is the only commercially available erosion simulation software that is able to model gully development as well as overall erosion rates.

These models are based on commonly accepted erosion physics, specifically relationships between catchment area and runoff rate such as that typically used in regional flood frequency analysis:

$$Q = \ {}_3A^{m_3} \qquad (1)$$

Where Q is the characteristic discharge out of the catchment, ${}_3$ is the runoff rate, *A* is the catchment area and *m₃* is a coefficient. The characteristic discharge is the mean peak discharge.

The erosion model is similar to that used in traditional agricultural sediment transport models where the rate of sediment transport is related to discharge, slope and a transport threshold:

$$Q_s = \ {}_1Q^{m_1}S^{n_1} - \textit{threshold} \qquad (2)$$

Q_s is the mean annual sedimentation rate, ${}_1$ is the erodibility (including the material erodibility, vegetation cover factor and any cropping practice factors (Universal Soil Loss Equation (USLE) terminology), S the slope, and m_1 and n_1 are parameters to be calibrated for the erosion process. The erosion is relatively insensitive to the exponent n_1 which is commonly taken as 2. The exponent m_1 is modified during calibration to ensure that the concavity of the modelled slope is similar to the prototype. Commonly m_1 is in the range 1 to 1.5. The threshold is a simple allowance for shear stress mobilisation of the material.

The threshold term applies to armoured slopes of clean (no fines) or bound materials which is unlikely to be the case for the competent waste rock materials and may therefore be discarded.

Equations (1) and (2) may be combined to yield equation 3 below:

$$Q_s = \ {}_1 \ {}_3^{m_3} A^{m_1 m_3} S^{n_1} - \qquad (3)$$

Solution of the above two equations by finite elements at each grid point is effected by SIBERIA to derive the eroded position of the grid point at the end of each time step. The eroded topography is therefore being continuously updated thus enabling the simulation of gulley formation.

Over an extended period the parameters β_3 and m_3 remain essentially constant. It is therefore possible to write equation (3) as:

$$Q_s = \ {}_1^{'}A^{m_1 m_3} S^{n_1} - \qquad (4)$$

3. WEPP Modelling

The WEPP model was used in the Yangibana project for simulations of runoff and erosion for soils. It was developed by the United States Department of Agriculture (USDA) to predict runoff, erosion, and deposition for hillslopes and watersheds.

WEPP is a simulation model with a daily input time step, although sub-daily parameters are used to describe storm events used to calculate runoff and erosion (enabling more accurate estimation of runoff and erosion potential than achievable with daily time step models).

Soil characteristics important to erosion processes are updated every day. When rainfall occurs, those soil characteristics are considered in determining the likelihood of any runoff. If runoff is predicted to occur, the model computes sediment detachment, transport, and deposition at points along the inputted slope profile.

The erosion component of the WEPP model uses a steady-state sediment continuity equation as the basis for the erosion computations. Soil detachment in interrill areas is calculated as a function of the effective rainfall intensity and runoff rate. Soil detachment in rills is predicted to occur if the flow hydraulic shear stress is greater than the soil's critical flow hydraulic shear stress, and when the sediment load of the flow is below its capacity to transport sediment. Deposition in rills is computed when the sediment load is greater than the capacity of the flow to transport it.

WEPP models were completed for the soil aspects only at Yangibana (Landloch 2016) however WEPP Models conducted for other relevant benchmark sites were referred to via literature studies.

APPENDIX 2: Limitations of Erosion Modelling

Notwithstanding the limitations, erosion modelling remains a good indicative tool to make assessments of probable indicative erosion performance in comparing performances of cases when all factors other than slope geometry and material erodibility are controlled. However, it is important to note that analysis of performance based on the model results should not lead to an expectation that the results provide insights into real or absolute performance but rather that they allow for indicative and comparative performance.

It is not unusual for erosion modelling processes to be taken on face value as an objective predictor of erosion performance on artificial landform slopes. As such the primary metrics which are delivered by erosion modelling - sediment emission volumes per hectare and gully depth, both expressed as average and peak - are frequently viewed, including by regulators, as reasonable indicators of erosion performance, at the very least indicative estimates of actual performance.

On this bases erosion modelling outputs are utilised by study teams and regulators variously as Basis of Design guidance or Closure Criteria performance metrics. This note is intended to provide some contextual discussion which may challenge this generally accepted view. The authour has initiated, scoped, co-ordinated or reviewed a number of erosion modelling projects involving primarily Siberia but has had exposure to WEPP, Caesar, field rainfall simulation trials, flume studies and more recently some outputs for Applied Geofluv.

The author sees significant value in erosion modelling processes, however, unless robust calibration is undertaken, this value is in ***comparative analysis***, not accurate performance forecasting. Most of the comments and limitations below relate to Siberia however they are applicable to some degree or other with respect to many other erosion forecasting science tools, especially those that make assumptions about the representativeness of the material being studied.

The modelling should be considered and reviewed taking into account the following limitations:

- SIBERIA uses the average annual rainfall for the location repeated within the model each year during which the model is run. In environments such as the rangelands of Western Australia, where rainfall is episodic and/or seasonal, the high intensity rainfall events typical of these climatic conditions suggest that erosion may be under represented rather than over represented within the model, although studies by Landloch (2016) suggest that over the long term the averages provide are reasonably representative, with the observations that large stochastic events early in the post closure era accelerates the occurrence of erosion which would otherwise occur in much later era's. Therefore the reviewers "perception" of the erosion model timeframe should be that the "worst" performance, seen late in the mode, can happen "early" dependant on stochastic events.

- Erosion modelling parameters applied in the analyses take material type, particle size distribution, erosion potential, and mean annual rainfall into account. Parameters can be obtained from calibration of erosion data for a specific site. As this study is intended to review and carry out high level analyses for each of the facilities, erosion parameters applied in the various models have been based on similar soil and mine waste materials used on similar projects. The erosion parameters have been adjusted to make allowance for site specific average annual rainfall.

- No vegetation cover factor is taken into account in the erosion assessments cited. This means that all profiles must be compared with no contribution for stabilisation provided by vegetation being considered. The stabilising effect of vegetation is variable and is a function of the final slope geometry, cover material available, seed and organic matter inputs and climate. To calibrate erosion models to the extent they could accurately reflect the contribution of vegetation to stability for analysis beyond the capacity of most models without long term representative data to calibrate to, which is not available in this, nor most, cases. However, it should be noted that good quality revegetation does play a part in long term slope stability, albeit less so in the rangelands than in other more well-watered environments, but still merits consideration during review as erosion models always over predict erosion due to this factor.
- The model does not include wind erosion impacts or effects. Wind erosion can have a considerable impact on large exposed areas of both tailings and topsoil, and in some scenarios, has can have higher rates of erosion than that resulting from water erosion. In the case of Yangibana it is expected that both WRL and TSF surfaces will have covers which contain fractions of durable waste rock and hence provide controls for wind erosion.
- The model does not account for a change to “run on” conditions when planned up gradient drainage control measures are compromised by erosion. Some concave TSF surfaces rely on perimeter controls to contain substantial ephemeral ponding. Where erosion through these measures occur very significant erosion features form but are not anticipated in the model. In the case of Yangibana, surface hydrology control measures will be installed to meet a 1:2000 storm event with hardened discharge structures to convey water for greater magnitude events off the landforms
- The model assumes precise construction to design and does not account for any variation to slope geometry or elevation that may result from consolidation and / or settling of materials during or post construction.
- The model assumes homogeneity of soil and mine waste characteristics material characteristics within material type. Most waste dumps display at least modest heterogeneity, some very high variability. Waste from high stability durable fresh waste, low durability transitional wastes, sodic/dispersive wastes, kaolin type clays and laterites can all be present on one batter face. They can be in panels, they can overly and underlie each other, can be layered sequentially as tipped rill at 37 degrees or in layers of pushed out paddock dumped lifts with variability in each pushed layer.
- The long tip head/rill dumped waste always self-segregates such that large blocky waste sorts towards the lower 30% of the slope face, only to be buried at reprofiling by difficult to observe wastes from the cut section above. Material characterisation data is very

unrepresentative in this environment and is generally driven by assumptions made around a small number of samples. In the face of all of this heterogeneity a detailed modelling process may select three or more roughness setting, whereas many models, as was the case with Yangibana, must aggregated data to a median and this effectively may not represent any class of material accurately.

- To reinforce this point, consider the fact that the primary source of roughness data is PSD (Particle Size Distribution). These data are often based on samples which can in reality sample from the field only a portion of the fractions presented. Many waste dumps have large proportions of the material greater than 200mm or greater than 500mm in some cases. It is very difficult to judge these proportions in a PSD based on samples of 10kg with the volume of a bucket. The most telling demonstration of this is to compare the B_1 settings (roughness/durability) in the model between different consultants. They vary in some cases by two orders of magnitude for the same class of material.

- As with the roughness question, infiltration is variable across slope surfaces. This can have the effect of increasing or decreasing run off and hence erosion locally on a panel surface. Very coarse, low fines content material can perform at infiltration up to 100% in even very heavy rain events whereas an adjacent portion of slope dominated with hydrophobic soils would repel virtually 100% of the incident rainfall or run on. High infiltration layers overlying dispersive, hydrophobic or impervious materials can lead to tunnelling or seepage discharge further down slope.

- Perhaps the greatest concern Trajectory holds with respect to erosion modelling is the very wide spread of B_1 input data which different consultants are using for roughness/durability. Trajectory has the good fortune to have reviewed erosion models from several different consulting houses and different reports from the same consulting house over a number of years. This variability of B_1 is exemplified below and encourage any reviewer of erosion modelling outputs to be cautious as to the extent of their veracity.

B_1	m_1	***Service Provider***	***Descriptor***	***Location***
0.00001	1.406	Consultant 1	“Topsoil and Rocky Waste”	Pilbara
0.01	1.2	Consultant 2	“High Competency Waste”	Goldfields
0.000907	1.36	Consultant 3	“High Competency”	Kimberley
0.002117	1.36	Consultant 1	“Mixed Waste”	Murchison

Conclusion

Taken as a whole, these considerations demonstrate that erosion modelling is an indicative type of tool, which can help in the generation of more desirable shapes from an erosion minimisation perspective compared to less desirable shapes. They are general predictors of performance for comparative analysis purposes and that is all. Numerical outputs, in this authors opinion, should never be used as Basis of Design or Completion Criteria, beyond their purely comparative value.

Should the mining industry choose to invest in rigorous studies, which accurately measure and calibrate in field erosion against models over a long time frame (20+ years), which would be very valuable and is entirely feasible, the use of erosion modes should be approached with care, and always used as one of a number of informing approaches to develop final landforms which are considered stable in the long term.