APPENDIX 5-3

Preliminary Landform Surface Erodibility Assessment
PRELIMINARY LANDFORM SURFACE ERODIBILITY ASSESSMENT

Hastings Technology Metals Limited

November 2016
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<th>Reviewed by:</th>
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1 INTRODUCTION

Landloch was recently engaged by Ecoscape on behalf of Hastings Technology Metals Limited (Hastings) to undertake an assessment of the undisturbed soil resource at the Yangibana Rare Earths Project (the project) as part of a mining proposal submission. Hastings also agreed that while on site, material should be collected to undertake a preliminary material characterisation study to identify wastes that are potentially beneficial (or hazardous) for rehabilitation and closure planning. Early characterisation of materials can have the following benefits:

- Identification of useful materials for segregation and stockpiling so that they are available for closure works and not lost in waste dumps;
- Characterisation of the main wastes will rank them in terms of their erodibility so that erodible materials can be planned to be appropriately managed;
- Identifying the erosional limits of materials so that safe, stable, and sustainable preliminary waste landform designs can be derived before mining commences. These designs are modified and refined once access to as-blasted, as-trucked materials become available; and
- Knowing the design before mining operations means that waste landforms can be constructed to minimise the bulk movement of wastes for the final closure shape which results in significant cost savings.

Landloch’s usual approach to material characterisation is to derive the key erodibility parameters of a material experimentally by applying erosional stresses in the field or laboratory using rainfall and overland flow simulations. These parameters are then used to calibrate the WEPP\(^1\) and SIBERIA models to simulate long term erosion and landform evolution of the material under site specific climate conditions. The approach used in this study was to conduct a limited assessment on samples that could be sourced and transported from site during the soil assessment field work. Laboratory-based assessments were conducted on these samples to indirectly derive the key erodibility parameters to run WEPP and produce initial landform design guidance for the project. The typical waste landform configurations used in this study have been derived from prefeasibility studies (PFS) produced by the Snowdon Group, but will likely change in the definitive feasibility study (DFS) phase.

2 BACKGROUND

The project is located approximately 280km north east of Carnarvon and 900km north of Perth in the arid interior of Western Australia (Figure 1). The project is located on tenements that cover ~650km\(^2\). Pre-feasibility drilling studies have been undertaken and indicate that the most economic resources are located in the eastern and western belts (Figure 2). The 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 7 years with 66Mt of waste generated from these open pits (Hastings 2015).

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\(^1\) Water Erosion Prediction Project
Figure 1: Tenement map for the Yangibana Rare Earths Project (Source: Hastings).

Figure 2: Proposed mine infrastructure design for the Bald Hills, Fraser’s, and Yangibana (West and North) pits (Source: Hastings).
The project is seeking to extract rare earths (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 et al. 2015). The target ironstone-associated ore dips towards the south (Figure 3) and the main waste types will be the overlying regolith, granite hanging wall, and footwall at varying states of weathering.

Figure 3: Example of south dipping ironstone vein from drilling data at Yangibana North (Hastings 2015).

3 METHODOLOGY

3.1 Samples

During the three day soil assessment site visit, bucket-sized samples (~60kg) of selected materials were collected. A total of four materials were considered in this study and were selected based on the following criteria:

- Abundant within the soils and/or waste resource;
- Can be used either by themselves or within a mixture to produce a suitable plant growth medium; and
- Can be used either by themselves or within a mixture to produce a rocky surface with increased erosional resistance.
As such, two growth media and three rocky waste samples were selected and sampled. They were:

- Hill Soil\(^2\) growth medium (Figure 4);
- Plain Soil\(^2\) growth medium (Figure 5);
- Ironstone rock armour (Figure 6);
- Surface granite rock armour (Figure 7); and
- Weathered granite rock armour (Figure 8).

The main Hill and Plain Soils would be potential growth media, the Surface Granite and Weathered Granite would represent the main waste type as differing states of weathering, and surface Ironstone (not associated with the ore) could be a useful and available rocky waste resource.

The Hill and Plain Soil were collected from Pit 3 and Pit 15 respectively (Landloch 2016). Ironstone samples were collected from various outcrops around the proposed site of the Yangibana North pit, and surface granite was collected from various sites along Fraser’s pit road. The weathered granite was collected from the excavated material pile from a sump dug around Bald Hills drilling area. Care was taken to try and take the most competent rock (and not fine waste) from this pile.

![Image of Hill Soil type](image)

**Figure 4:** Example of Hill Soil type.

\(^2\) See Landloch 2016.
Figure 5: Example of Plain Soil type.

Figure 6: Example of Ironstone.
Figure 7: Example of Surface Granite.

Figure 8: Example of Weathered Granite.
3.2 Material assessment

The samples were returned to Landloch’s erosion assessment facility and tested for properties shown in Table 1. The Ironstone, Surface Granite and Weathered Granite samples were hand-picked in the field to be representative of the material observed. Therefore similar materials within the profile were not sampled. The actual material once blasted, excavated, trucked, and dumped may vary from these samples and hence it is important that full characterisation of the extracted waste types be undertaken once mining commences. No particle size distribution (PSD) of the rocky material was undertaken.

**Table 1**: Chemical and physical properties analysed.

<table>
<thead>
<tr>
<th>Chemical Analyses</th>
<th>Physical Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material pH^</td>
<td>Particle size distribution</td>
</tr>
<tr>
<td></td>
<td>(sand, silt, clay)^</td>
</tr>
<tr>
<td>Material EC (salinity)^</td>
<td>Clay dispersion^</td>
</tr>
<tr>
<td>Effective cation exchange capacity^</td>
<td>Rock particle density*</td>
</tr>
<tr>
<td>Exchangeable cations</td>
<td>Rock water absorption*</td>
</tr>
<tr>
<td>(Ca^{2+}, Mg^{2+}, Na^+, K^+, Al^{3+})^</td>
<td></td>
</tr>
<tr>
<td>Exchangeable sodium percentage^</td>
<td>Slake durability*</td>
</tr>
</tbody>
</table>

^ Soil only; * Rock only

The chemical analyses were used to consider the structural stability of the soils, with these data assisting in the parameterisation of the WEPP model, and in defining risks associated with tunnel erosion.

The Ironstone, Surface Granite, and Weathered Granite were also analysed for properties useful in defining their durability against weathering and break down by abrasion. Rock water absorption indicates the susceptibility for water to penetrate a rock, with higher rates indicating a potentially less durable material. Lower rock particle densities are often associated with more weathered rock, and hence lower densities often indicate materials that are less suitable for use as rock armour. For these two tests, rock samples are soaked in water, weighed, then dried and reweighed to determine absorption rates. During this process the volume of water displaced by the rock is also measured and used to calculate density. Slake durability indicates the durability to weathering of rocks to abrasive forces such as truck-tipping and bulldozer trafficking. It is less useful in considering atmospheric weathering. The rock samples are cubed and placed in the rock baskets and tumbled in water for 10 minutes (Figure 9). The rocks are dried and the process repeated. The results are expressed as a percentage of the dry final weight against the initial starting dry weight.

The rocky samples were also assessed for Thorium-232 by ICP-MS to measure the relative concentrations of the isotope in the three rock types, as Thorium concentration in the tailings dams has been raised as a potential issue and should not be capped with rock that has an elevated Thorium concentration.
Figure 9: Slake durability testing apparatus. Note clear plastic fluid containers associated with each rock basket (Civilblog 2016).

Based on these results (see Section 5.2), four test surfaces were prepared for rainfall simulation. The test surfaces considered were:

- Hill Soil only;
- Plain Soil only;
- 1:1 Hill Soil-rock mixture; and
- 1:1 Plain Soil-rock mixture.

The samples were subjected to simulated rain, and assessed for:
- Effective hydraulic conductivity,
- Interrill erodibility,
- Rock cover percentage and rain-armoured surface particle size distribution\(^3\) from which critical shear was estimated, and
- An estimate of rill erodibility based on surface rock cover.

The rain-armoured surfaces were also sampled and used to assess sediment characteristics using settling columns. WEPP was calibrated with the derived parameters, and used in conjunction with a site-specific climate file to model erosion potential of various batter design options.

4 THE WEPP MODEL

4.1 WEPP parameters

In the WEPP model (Flanagan and Livingston 1995) used in assessing batter erosion potential in this report, erodibility is described via a number of specific parameters:

- Interrill erodibility (K);

\(^3\) Photographs were used to estimate the mean rock size (for particles greater than 20mm) at each photo point; this in turn was used to estimate critical shear, a key input to the WEPP erosion model.
• Rill erodibility (K_r);
• Critical shear for rill initiation (τ_c);
• Effective hydraulic conductivity (K_e);
• Sediment density distribution; and
• Sediment particle size distribution.

4.1.1 WEPP erodibility parameters

Interrill erodibility (K) describes the detachment and movement of particles by the combined action of raindrops and shallow overland flows. Rill erodibility (K_r) describes the detachment of particles by shear stresses caused by concentrated flows. Critical shear for rill initiation (τ_c) is the shear stress applied by concentrated flows to the surface above which rill detachment rapidly increases. Within WEPP, effective hydraulic conductivity (K_e) defines the rate of water movement through a defined soil profile in response to wetting by rainfall, and is derived through analysis of a material’s steady infiltration and runoff rates. Effective hydraulic conductivity is different to saturated hydraulic conductivity.

These WEPP erodibility parameters were derived from data collected using laboratory-based experimental methods involving the application of simulated rain to a surface and measurement of runoff and sediment in runoff to obtain estimates of K_r and K_e. Estimates of K_e and τ_c were made by analysing images of the rain-armoured surfaces.

The Hill Soil only, Plain Soil only, Hill Soil-rock mix, and Plain Soil-rock mix were subjected to ~90 minutes of simulated rainfall to establish steady state infiltration, create an armoured surface, and to measure runoff and interrill erosion. Images of the rain-armoured test surfaces were taken after rainfall simulation and these images were digitised to calculate a D_{50} and rock cover level (considering only particles with a diameter greater than 20mm). The measures of D_{50} and rock particle density were used to estimate critical shear. Rill erodibility values were estimated by the WEPP model, but these estimates were confirmed by using the PSD data of each material and comparing with similar materials in Landloch’s database that have undergone the full material characterisation.

These parameters were then used in WEPP computer simulations of runoff and erosion in determining the landform design options that are presented in this report.

4.2 Computer simulation of erosion of landform batters

4.2.1 The WEPP model

The WEPP model was used in this project for simulations of runoff and erosion. It was developed by the United States Department of Agriculture to predict runoff, erosion, and deposition for hillslopes and catchments. WEPP is a simulation model with a daily input time step, although internal calculations use shorter time steps on rain days when predicting runoff and erosion. Plant and soil characteristics important to erosion processes are updated every day. When rainfall occurs, those plant and 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 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 shear stress, and when the sediment load of the flow is below transport capacity. Deposition in rills is computed when the sediment load is greater than the capacity of the flow to transport it. Adjustments to soil detachment are made in WEPP to incorporate the effects of canopy cover, ground cover, and buried residue.

4.2.2 WEPP climate file

WEPP requires both daily climate observations of rainfall, temperature, and solar radiation, and sub-daily data (e.g. 6-minute) of rainfall to create the long-term climate sequence. For each day of simulation, WEPP requires ten daily weather variables:

- Precipitation (mm),
- Precipitation duration (hr),
- Peak storm intensity,
- Time to storm peak,
- Average minimum temperature,
- Average maximum temperature,
- Dew point temperature,
- Solar radiation,
- Wind speed, and
- Wind direction.

Of these, the four precipitation-related variables (underlined in the list above) are of particular importance because previous studies have shown that predicted runoff and soil loss are most sensitive to these variables.

Very few sites around the world have complete historical weather data of these variables, and data must be sourced from various locations and combined in a way that is justifiable. Landloch’s approach is to develop synthetic weather sequences that statistically preserve the mean and variations in the historical observations from nearby weather stations. This approach allows for missing data points to be patched with values that do not statistically skew the data set.

CLIGEN is a stochastic weather generator that can be used to provide WEPP climate input files. CLIGEN has been extensively assessed for a wide range of climates in Australia, and it was found that CLIGEN was most suitable to provide the required climate input for WEPP to predict runoff and soil loss in Australia.

Daily climate data were sourced from the Australian Bureau of Meteorology (BoM) through the SILO Patched Point data facility. Rainfall intensity data was also sourced from the BoM. Both daily and sub-daily data were sourced from Wanna Station (BoM station 007028, <20km from the site).
Using these data sets, the following CLIGEN parameter values were computed and used to develop the synthetic climate sequences:

- Mean daily precipitation on wet days for each month,
- Standard deviation and skewness coefficient of daily precipitation for each month,
- Probability of a wet day following a dry day for each month,
- Probability of a wet day following a wet day for each month,
- Mean daily max. temperature for each month,
- Standard deviation of daily max. temperature for each month,
- Mean daily min. temperature for each month,
- Standard deviation of daily min. temperature for each month,
- Mean maximum 30-min rainfall intensity for each month, and
- Probability distribution of the dimensionless time to peak storm intensity.

These parameter values were assembled to create a CLIGEN parameter file for the site. Wind data (used to calculate soil evaporation) were not synthesised by CLIGEN because Priestley-Taylor’s method for estimating the potential evaporation (that does not require wind speed) is used by WEPP. A 100-year climate sequence was generated using CLIGEN version 5.1. Figure 10 shows the CLIGEN synthetic data set for the Yangibana site compared to the Wanna and Mount Phillip actual climate data sets for mean monthly rainfall.

4.2.3 Definition of acceptable erosion rates

The concept of acceptable or tolerable soil loss is widely mentioned in literature, but it appears to have little relevance to minesite rehabilitation. Tolerable soil loss is traditionally defined as a rate of erosion such that land productivity is not reduced, and is therefore of greatest relevance to agricultural situations. For mining, unacceptable erosion is more closely aligned to requirements to:

- Keep problematic materials encapsulated in the long-term;
- Limit requirements for future remediation works;
- Enable vegetation establishment; and
- Meet visual amenity goals set by stakeholders.

Currently, there is no widely applied methodology for assessing what is an acceptable erosion rate for rehabilitated lands. Landloch’s approach to landform design acknowledges that limiting rill and gully erosion are of particular importance for rehabilitation, as their presence increases the risk of exposure of underlying materials and is often considered to have unacceptable visual amenity. Further, slopes dominated by rilling or gullyng can have erosion rates orders of magnitude greater than non-rilling slopes and produce considerably more sediment that can have adverse off site impacts. With these things in mind, Landloch’s designs aim to create slopes on which rilling will be minimal or absent. Such slopes will have little potential to become heavily gullied in the future. If rilling and gullyng is avoided, the slope should be erosionally stable in the long term.
Figure 10: Comparison mean monthly rainfall for the CLIGEN climate file for Yangibana against the Wanna and Mount Philip weather data.

Landloch has considerable experience in modelling erosion, and assessing erosion processes and rates in the field. Landforms designed with a predicted long term average annual erosion rate (averaged over the whole slope) less than 5t/ha/y, together with a predicted maximum long term average annual erosion rate (at any point on the slope) less than 10t/ha/y exhibit a low tendency to rill. These erosion threshold values were adopted in this report to differentiate between acceptable and unacceptable slope options.

These threshold values align with soil loss tolerance guidelines reported by Li et al (2009) for soils that overlie more hostile subsurface materials where soil tolerance rates were set to limit their exposure; soil loss tolerance values of 2.57.5 t/ha/y are reported for soil profiles 25-50cm thick. To date, observations made by Landloch on several sites indicate that this erosion threshold definition has produced batters with low rilling potential that have been consistent with rehabilitation success (DRET 2009).

4.2.4 General input conditions and assumptions

WEPP runoff and erosion simulations were conducted on the materials using the following general model settings:

- Rill spacing was set at 2.5m for the rockier wastes.
- Surface roughness was set at 3cm for all materials, consistent with the value used when calibrating the model runoff predictions using the rainfall simulator data.
- No allowance was made for the effects of vegetation on erosion.
- No allowance was made for water from the top of the landform to discharge onto the batter slopes.
5 RESULTS

5.1 Basic soil material characteristics

Results of the analysis of the soil materials is shown in Table 2. A more detailed description of the project’s soils (including other parameters such as fertility) is contained in Landloch (2016). Briefly, the Hill Soil is a dark brown sandy duplex approximately 300mm deep with neutral pH, low salinity, and low exchangeable sodium and 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>
<thead>
<tr>
<th>Analyses</th>
<th>Unit</th>
<th>Hill Soil</th>
<th>Plain Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH&lt;sub&gt;1.5&lt;/sub&gt; - Water</td>
<td>pH units</td>
<td>6.51</td>
<td>8.91</td>
</tr>
<tr>
<td>Electrical Conductivity (EC&lt;sub&gt;1.5&lt;/sub&gt;)</td>
<td>dS/m</td>
<td>0.01</td>
<td>0.55</td>
</tr>
<tr>
<td>Calcium</td>
<td>meq/100g</td>
<td>1.67</td>
<td>1.73</td>
</tr>
<tr>
<td>Magnesium</td>
<td>meq/100g</td>
<td>1.04</td>
<td>0.73</td>
</tr>
<tr>
<td>Potassium</td>
<td>meq/100g</td>
<td>0.36</td>
<td>0.32</td>
</tr>
<tr>
<td>Sodium</td>
<td>meq/100g</td>
<td>0.14</td>
<td>0.35</td>
</tr>
<tr>
<td>Aluminium</td>
<td>meq/100g</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Effective Cation Exchange Capacity</td>
<td>meq/100g</td>
<td>3.22</td>
<td>3.14</td>
</tr>
<tr>
<td>Exchangeable Sodium Percentage (ESP)</td>
<td>%</td>
<td>4.44</td>
<td>11.27</td>
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</table>

<table>
<thead>
<tr>
<th>Particle Size Distribution of &lt;2mm Fraction</th>
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<tr>
<td>Coarse Sand</td>
</tr>
<tr>
<td>Fine Sand</td>
</tr>
<tr>
<td>Silt</td>
</tr>
<tr>
<td>Clay</td>
</tr>
</tbody>
</table>

Coarse sand: 2.00.2mm; Fine sand: 0.20.02mm; Silt: 0.020.002mm; Clay: <0.002mm

5.2 Basic rock material characteristics

Results for the rock characterisation are shown in Table 3, and the quality of each material was assessed against values provided in CIRIA (2007), except for slake durability, which was assessed against values provided by Singh and Goel (1999). The Ironstone and Surface Granite both had excellent rock particle density values (>2.7g/cm<sup>3</sup>). The rock particle density of the Weathered Granite was poor (2.0g/cm<sup>3</sup>). The water absorption results were good for the Ironstone, marginal for the Surface Granite, and poor for the Weathered Granite. This was reflected in the slake durability tests where the Ironstone performed the best with an indicated very high durability after two cycles, and medium high durability for the Surface Granite and Weathered Granite. As expected the Ironstone had <sup>232</sup>Th levels over seven times that of the granites.
Table 3: Physical characterisation data of the rock samples.

<table>
<thead>
<tr>
<th>Analyse</th>
<th>Unit</th>
<th>Ironstone</th>
<th>Surface Granite</th>
<th>Weathered Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Particle Density</td>
<td>g/cm³</td>
<td>3.8</td>
<td>2.9</td>
<td>2</td>
</tr>
<tr>
<td>Rock Water Absorption</td>
<td>%</td>
<td>1.3</td>
<td>3.4</td>
<td>17.1</td>
</tr>
<tr>
<td>Slake Durability (2nd Cycle)</td>
<td>%</td>
<td>99.5</td>
<td>95.5</td>
<td>88.5</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>PPM</td>
<td>188</td>
<td>25.4</td>
<td>23.7</td>
</tr>
</tbody>
</table>

5.3 Rain-armoured surfaces

Figure 11 shows images of the rain-armoured rainfall simulation plots from which the WEPP model was calibrated.

Figure 11: Rain armoured trial plots; A) Hill Soil and rock mix, B) Plain Soil and rock mix, C) Hill Soil, and D) Plain Soil.
5.4 WEPP input parameters

The WEPP input parameters used are shown in Table 4. The 1:1 Soil/rock mix had a $D_{50}$ range of 35 – 55mm which resulted in critical shear calculations of 34 - 35Pa. The unarmoured soils had a much lower result. The Hill Soil had the lowest $K_s$ values and Figure 11-D shows the surface sealing and cracking to the test surface after packing and wet/drying cycling. Upon simulated rainfall, the cracks sealed and runoff was rapidly generated. Rill erodibility was an order of magnitude higher for the soil only versus the soil/rock mixes as would be expected. The Plain Soil had a high interrill erodibility result but much lower when mixed with rock.

<table>
<thead>
<tr>
<th>Material</th>
<th>Effective hydraulic conductivity, $K_s$</th>
<th>Intermor erodibility, $K_i$</th>
<th>Rill erodibility, $K_r$</th>
<th>Critical shear, $\tau_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill Soil/rock</td>
<td>14</td>
<td>146,215</td>
<td>0.0085</td>
<td>35</td>
</tr>
<tr>
<td>Plain Soil/rock</td>
<td>8</td>
<td>93,422</td>
<td>0.0117</td>
<td>34</td>
</tr>
<tr>
<td>Hill Soil</td>
<td>25</td>
<td>166,226</td>
<td>0.0236</td>
<td>13</td>
</tr>
<tr>
<td>Plain Soil</td>
<td>10</td>
<td>571,492</td>
<td>0.0346</td>
<td>9</td>
</tr>
</tbody>
</table>

6 WEPP MODEL RUNS

The WEPP input parameters were used to assess the long term erosional stability of the material for a range of waste landform batter shapes. Landloch has used indicative batter heights and gradients for the waste rock dumps (WRD) from the PFS designs. Information available from Hastings (2015) which indicate the likely geometries of the pits and waste dumps. Landloch georeferenced the apparently largest waste dump (Bald Hills) into GIS software (Figure 11). The dump top was assumed to be level and the RL was estimated by picking up the elevation from the natural surface level where it meets the crescent shaped northern section of the WRD (RL1). The largest batter section in the south was measured and the batter toe/natural surface was used to estimate the toe elevation (RL2) and horizontal batter footprint (red arrow in Figure 11). The batter configuration was estimated to be approximately 33m high, 150m from crest to toe (horizontal), with an average gradient of 12.4°. Again, this design is from PFS and will likely change in the DFS phase.

The estimations from Figure 12 provide some guidance for the configurations of the WEPP model runs of the Yangibana materials. It should also be noted that there appears to be a berm in the southern batter, indicating that there are two batter sections; ~15m high and steeper than the 12.4° estimated. For these reasons WEPP was used to consider erosion potential for linear batter profiles with gradients of 10°, 12°, 15°, and 18°, and batter heights between 10m and 40m. These configurations encompass likely PFS batter configurations at Yangibana to provide initial landform design guidance for the DFS phase.
Figure 12: Planned pit and WRD at Bald Hills (Hastings 2015).

Model predictions are given in Table 5. Cells shaded in red indicate batter configurations that have predicted erosion rates that exceed the thresholds established for acceptable erosion in Section 4.2.34. Cells shaded in green indicate batter configurations that have predicted erosion rates that are lower than the thresholds set for this project.

The results show that the Plain Soil is more erodible than the Hill Soil, but both exceed acceptable erosion thresholds at the batter configurations simulated. The addition of rock increases the erosion resistance of the soils so 10m lifts are possible, but peak erosion increases with increasing batter gradients.

---

4 Note that both mean and peak erosion must be within the acceptable range to be shaded green.
Table 3: Erosion results for linear batter configurations.

<table>
<thead>
<tr>
<th>Batter Height (m)</th>
<th>Batter Gradient (°)</th>
<th>Hill Soil Mean</th>
<th>Hill Soil Peak</th>
<th>Plain Soil Mean</th>
<th>Plain Soil Peak</th>
<th>Hill Soil + Rock Mean</th>
<th>Hill Soil + Rock Peak</th>
<th>Plain Soil + Rock Mean</th>
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6.1 Possible modifications to linear profiles to increase stability

The results show that the soils and soil-rock mixes will exceed acceptable thresholds for slopes on a linear batter with a gradient of 12 degrees and height of 30m, which is the planned profile for the waste dump.

The erosion potential for the soils was shown to be transport limited, meaning that erosion reaches high rates at very short slope lengths, and then remains at high rates as slope length increases. This is shown diagrammatically in Figure 13. Erosion rates for transport limited materials can most effectively be modified by reducing slope gradient. Reducing slope height and using more complex shapes such as concave profiles are of limited benefit, simply because erosion becomes very high over such short slope lengths. The soil-rock mixes were more erosionaly resistant. Erosion for these materials is shown to be detachment limited. Hence, erosion remains low for a considerable length of slope and then rapidly increases as flow accumulation creates sufficient runoff shear stresses to initiate detachment of particles within rills. Erosion of these types of materials can be modified through alteration of slope gradient and by using more complex slope shapes.

![Figure 13: Conceptual diagram of the erosion rates of transport limited versus detachment limited materials over a linear sloping batter length.](image)

6.2 Concave slopes

As mentioned, detachment limited materials (i.e., the soil-rock mixes) are amenable to slope gradient alteration to lower erosion rates to acceptable levels. The Hill Soil-rock mix was used to demonstrate that use of a concave slope could be used to reduce peak and mean erosion rates to acceptable levels. The result is shown in Figure 14, which combines the concave slope profile (red line) with the slope erosion rate (blue line). The erosion rate does increase with the slope length, with the peak rate being reached at the toe of the slope (8.4t/ha/yr). However, the peak erosion rate remains below the 10t/ha/yr threshold. The average erosion for this slope option is 1.4t/ha/yr. The horizontal distance from crest of the concave design is 190m compared to 150m for the
linear option. However, this profile is predicted to be stable, whereas the linear profile is predicted to be unstable.

![Graph showing elevation and erosion rates.]

**Figure 14:** Concave slope option.

## 7 DISCUSSION

### 7.1 Importance of rock

The material characterisation and long term erosion simulations show that sourcing durable rock and incorporating it into soil to produce a rock mulch for rehabilitation will be critical for successful mine closure. Durable rock is more difficult to detach by runoff, provides a matrix that anchors the fine materials into the soil profile, and protects the surface against interrill erosion.

The ratio of soil to rock used in this study was 1:1, and this is an obvious area to focus on to improve the erosional resistance of the materials. The relationship between increased surface rock cover and reduced erosion is well established (Figure 15). The creation of a waste dump sheeting material that increases surface rock cover will also stretch the Yangibana topsoil resource further.

The water absorption testing for rock durability showed that although the Surface Granite was deemed to be marginal in quality, the samples collected from a weathered stockpile rapidly disintegrated when immersed. That observation indicates that the Ironstone is the preferable rock resource on site. The caveat to this recommendation is that it is based on surface samples/observations only and the weathering/durability of the Ironstone at depth is unknown. Consequently, mine planners should focus on refining the block models to source Ironstone from the ore zone, determine its durability, and investigate...
the variability of granite from the hanging wall/footwall zones, or identifying other sources of durable rock not captured in this report.

The suitability of the Ironstone identified in this report should also be weighed against its $^{232}$Th concentration against the granites, particularly as it could be potentially used to sheet the tailings storage facilities (TSF) on site. Radiological measurements of trial covers using Ironstone should be included as part of its further assessment to be used as a sheeting material.

![Graph](image)

**Figure 15:** Modelled erosion rate changes in response to increasing surface rock cover.

### 7.2 Limitations and implications of this study

This study was based on small samples (~60kg) that could be transported back from site in a light vehicle, and that could be sourced largely from surface or near surface sources. The material will likely be dissimilar to the materials that is created as the wastes is blasted, trucked, placed, and reshaped within waste landforms.

The WEPP input parameters are estimates derived from limited lab-based assessments and visual observations. These parameters are ideally derived from larger experimental test plots and flumes packed with as-blasted, trucked, and dumped materials. Derivation of these parameters from extracted wastes will increase the confidence of modelling results. This can be done only once materials start to be extracted.

For these reasons, the results in Table 3 are intended to provide initial guidance on the potential limitations of the waste materials. This initial guidance indicates that without appropriate management of the materials, the required footprints may be large. Landloch has observed that a key limitation to rehabilitation success is the lack of available footprint once the landform is reshaped to an erosionally stable shape. Footprint is strongly influenced by material properties and material management (segregation and placement). The initial guidance have also highlighted that additional erosion and landform design studies that more robustly define appropriate landforms...
shapes are important. These studies may indeed demonstrate that smaller landform footprints can be used, particularly if the rehabilitation surfaces developed are rocky and hence more resistant to erosion. Therefore planning for the sourcing and separation of suitable rocky materials should be considered early in the planning phase of the mine, including provision for storage without stockpiles.

7.3 Other landform design issues

7.3.1 Use of berms

It was observed from Hastings (2015) PFS designs that the proposed waste dumps appeared to be batter and berm designs (e.g., Figure 12). Landloch’s experience with berms in landform designs are that they are an engineered feature that increase the brittleness of the landform, and that will irreversibly fail when their design specifications are exceeded. Berms accumulate sediment which leads to their reduced capacity to store further sediment and runoff which in turn leads to overtopping and concentrated water flows that can cause extensive erosion. For this reason Landloch urges waste landform designs without berms, or at the very least berms designed to accommodate sediment and storm flows for the very long term. Further details can be found at Roddy and Howard (2016).

7.3.2 Water flow interactions with waste landforms

The WEPP simulations completed in this project assume that there are no flows onto the batter from dump tops. Poorly constructed dump tops that discharge runoff onto batters greatly increases erosion. Final landform designs will have to include adequate crest bunds and cellularisation of dump tops.

Waste landforms can alter natural flow lines depending on their location in the landscape. This can cause scouring along the toes of dumps, damming of water and potential seepage of encapsulated material, and alteration of natural flow regimes with impacts to natural ecosystems. Consideration to the placement of waste landforms at the planning stage can avoid these issues.

7.3.3 Waste landform shape

Where batters are not a simple shape in plan view, there is potential for water-concentrating areas (indents) to be created (Figure 16). Indents may be large or quite small, but are of concern irrespective of magnitude. Such features should be avoided if at all possible.

From Landloch’s experience with many waste dumps across Australia, one consistent observation is that erosion (rills, gullies) occurs most frequently on corners of waste dumps. Dozers are less successful at cross-ripping on-contour when the dozer works around corners, irrespective of the skill of the operator. Not surprisingly, the problem is accentuated when the corner is sharp. Ideally, all corners should have a radius of curvature of at least 100 m.
Figure 16: Conceptual plan view of a waste landform showing flow-concentrating features.

The decision to leave ramps in the final landform design can also have implications for long term erosion. The example shown in Figure 17 shows the long term modelling results of a Pilbara WRD with a batter and berm configuration and ramp remaining for closure. The ramp acts like a gutter to concentrate water flows onto the lower batters causing the deepest gullies.

Figure 17: SIBERIA model output of a Pilbara waste rock dump after 200 years.

7.3.4 Usefulness of other site materials

It was identified in Landloch (2016) that the Plain Soils associated with low lying areas of site are potentially dispersive, and should not be used on sloping land features (batters, dam walls) as they are likely to be prone to erosion (surface and tunnel erosion). However, the dispersive Plain Soils may be useful in areas where impermeable materials are needed. This could include impermeable layers under TSFs, bioremediation facilities, rubbish dumps, or other areas where a barrier to water percolation is required. There is specific criteria that a material must meet depending on its intended use, but Table 4 gives an example for using engineered soil to contain pollutants (WADW 2013).
Table 4: Parameters, test methods, and criteria for an engineered soil to be used to contain pollutants.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test Method</th>
<th>Acceptable criteria</th>
</tr>
</thead>
<tbody>
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<td>Texture</td>
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<td>CL, CI, GC, CH</td>
</tr>
<tr>
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<td>USCS&lt;sup&gt;5&lt;/sup&gt;</td>
<td>&gt;25%</td>
</tr>
<tr>
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<td>Linear Shrinkage</td>
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<tr>
<td>Emerson Test</td>
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<td>Permeability</td>
<td>AS1289.7.3</td>
<td>1.0x10&lt;sup&gt;-9&lt;/sup&gt;m/s</td>
</tr>
</tbody>
</table>

7.4 Further works

This study highlights the high erodibility of the soils present on the project, and the importance of sourcing durable rock to ensure long term erosional resistance of rehabilitation land, and the development of self-sustaining ecosystems. In accordance with the regulator’s requirements for increased closure detail as the project advances, Landloch would suggest the following activities:

- Discussions with mine planners on the feasibility of accessing durable rock and potential to alter proposed waste landform shapes;
- Full material characterisation on the identified rehabilitation resources (i.e., soil and rock) to provide detailed waste landform designs (including 3D modelling that will consider hydrological interactions with the waste landform and the surrounding landscape); and
- Development of rehabilitation strategies that will achieve mine closure goals. The rehabilitation strategy will be supported by tailored quantifiable measurements, trials, and continual monitoring, consistent with a system established for enable continual improvement at Yangibana;
- Testing site dispersive materials to examine the potential to use them as impermeable layers to separate potential pollutants from the water table.

8 CONCLUSION

Erosion potential for materials from the project has been assessed. The assessment is based on consideration of the prevailing climate and its erosivity, known factors critical for stability of natural and disturbed surfaces, characterisation of the erodibility of the typical surface materials present, computer simulations of runoff and erosion on the range of typical slopes, and issues relating to measured sediment characteristics. Consequently, the results are based on site data and its interpretation using well-validated procedures.

REFERENCES


