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Memorandum: Characterisation of erosion potential of mineral wastes for use in developing rehabilitated landform designs, Western Range, Paraburdoo and Eastern Range

1. Introduction

Across Australia, mining regulatory bodies provide guidance on the required state of rehabilitated landforms. In Western Australian regulators require safe, stable, non-polluting post-mining landforms, with resilient and self-sustaining vegetation. Fundamental to creating non-polluting landforms is the development of stable land surfaces that do not erode at rates likely to be unstable in the long-term, and that are sufficiently stable such that vegetation can establish. In essence, land surfaces that are unstable are likely to erode and generate sediment that will impact the surrounding landscape and render establishment of vegetation more difficult.

Rio Tinto Iron Ore (WA) has been involved in the development of erosion assessment of waste landforms for a long time, with the first application of erosion models to mining landforms occurring in 1998. Since that time, the use of models has improved and been refined to the point where final landform shapes can be informed through models calibrated using site specific materials erodibility and climate data.

Rio Tinto Iron Ore (WA) undertook a project in 2010-2012 in which a database of mineral waste erodibility parameters was established and materials assigned erosion classes (low, medium, and high). The broad objective of the project was to define appropriate landform batter characteristics for key mineral wastes and soils across their Pilbara operations, and to use this information to develop practicable final landform batter criteria that will satisfy long-term erosional stability requirements. This project aimed to establish a means by which material characteristics can be objectively used within mine planning activities.

To achieve this, available information on waste material types were collated from Rio Tinto waste drilling records. These were used to determine the range of major waste types for sites across the Pilbara. Erodibility parameters for these major waste types were then gathered using simulated rainfall and overland flow techniques and used within erosion models to develop rehabilitated landform design criteria for a range of climates and mineral wastes. Validation of the techniques used to develop the erodibility parameters was conducted (and has continued to this day and now includes many sites).

This memorandum seeks to:

1. Outline the approach taken to identify and classify key wastes types present at Rio Tinto iron ore sites across the Pilbara.
2. Detail how samples of these waste types were characterised, and the resulting data used to develop stable rehabilitation batter geometries.
3. Provide specific detail on the data that is available for mineral wastes at Greater Paraburdoo (Western Range, Paraburdoo and Eastern Range).

2. Identification and classification of key minerals wastes

2.1 Waste type classification

The following section seeks to describe the different geologies and waste types extracted from Rio Tinto (WA) mines and explain the rationale behind the selection of the key mineral wastes for which more detailed testing of erodibility was conducted.

Rio Tinto Iron Ore (WA) defines mineral waste materials initially based on deposit geology which is described in detail in *Geology and mineralogy of the Hamersley Province ores*[1]. These include the Banded Iron Formation derived Brockman and Marra Mamba hosted deposits, and Channel Iron Deposits. Other deposits such as Detrital Iron Deposits can occur as overburden to the more extensive Banded Iron Formation - hosted ore.

Materials within each deposit geology are subsequently classified by their ‘waste geozone’. These geozones are well-defined sequences of rock that have consistent characteristics across broad regions of the Pilbara. Eighteen waste geozones were identified for Brockman deposits, 18 for Marra Mamba deposits and 8 for channel iron deposits. Each waste geozone can then be further classified into individual waste types. Table 1 lists the waste types defined by Rio Tinto. The same waste types are found within different waste geozones. However, the abundance of the different wastes can vary.

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[1] Rio Tinto Iron Ore (2010) Geology & mineralogy of the Hamersley Province ores, Rio Tinto Iron Ore.

Table 1: Waste material types found within various wastes

Banded Iron Formation (BIF)	Pyrolusite*	Aluminous Shale
Magnetic BIF	Pyrite*	Pisolite
Quartz*	Dolerite (fresh)	Calcite
Siliceous Goethite	Manganese*	Clay
Cherty BIF	Dolomite	Water Reactive Clay
Ferruginous Chert	Dolerite	Soil
Secondary Silica*	Hematite*	Powdery BIF
Jasperlitic BIF	Shale	Cavity Fill
Goethitic BIF	Ferruginous Shale	Dolerite (weathered)
Silcrete	Goethitic Shale	Crocidolite*
Goethitic Chert	Carbonaceous Shale	Calcrete
Magnetite	Manganiferous Shale	Ochreous Hematite

* These minerals may be indicated as present in the waste material, but do not represent an actual waste rock type that is delineated within the geology/mining model.

2.2 Abundance of different waste types

The abundance of each waste type within the various waste geozones was assessed across the entire Pilbara Rio Tinto drill hole and geological database with specific focus on existing operations, Greater Paraburdoo, Western Turner Syncline, Brockman 2, Brockman 4, Mount Tom Price, Marandoo, Nammuldi, Silvergrass East, Hope Downs 1 (North and South), Mesa A, Mesa J, and Mesa K.

For Brockman and Marra Mamba deposits, the assessment utilised existing drilling records that generally list geozone, material type, and material hardness for each drilling sample length (typically a vertical interval of 1.5m or 2.0m depending on the age of the database). Wastes can be described as hard, medium, or soft, with hard wastes being more competent and slow weathering, and likely to present as rocky waste once blasted and transported to a waste stockpile. Soft wastes tend to be more weathered and/or fine-grained or unconsolidated. In terms of erosion, they tend to represent more problematic materials than the hard wastes. Medium wastes are neither hard nor soft, and for the sake of this assessment were considered more erodible than the harder wastes. For each of the sites listed above, the drilling records were first separated into the different waste geozones. Then, within each waste geozone, the abundance of different waste types was determined. To assist in assessment of the large database of materials, these waste types were then grouped into 'hard', 'medium', and 'soft' wastes[2]. In doing so, the abundance of different wastes within each waste geozones could be determined and the major wastes (typically those comprising more than ~90% of the waste) identified. Sections marked as ore were excluded.

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[2] Hard wastes include Banded Iron Formation (BIF), Calcrete, Magnetic BIF, Quartz, Siliceous BIF, Cherty BIF, Ferruginous Chert, Secondary Silica, Jasperlitic BIF, Goethitic BIF, Silcrete, Goethitic Chert, Magnesite, Pyrolusite, Fresh Dolerite, and Manganese. Medium wastes include Dolomite and Hematite. Soft wastes include Shale, Ferruginous Shale, Goethitic Shale, Carbonaceous Shale, Manganiferous Shale, Aluminous Shale, Pisolite, Calcite, Clay, Water Reactive Clay, Soil, Powdery BIF, Cavity Fill, Dolerite (weathered), Crocidolite, and Ochreous Hematite.

It is noted that geozones describe a mixture of waste types. Given that individual waste types are not segregated during mining, defining wastes more broadly by their geozones and assessing these mixtures will provide a more realistic basis from which to assess erosion potential rather than considering waste type in isolation from their geologies. For this reason, wastes were described based on geozone rather than individual waste types.

For Channel Iron Deposits, geozones are not defined, and in these cases individual waste types were assessed.

The assessment of wastes for the Brockman and Marra Mamba deposits and Channel Iron Deposits are described below.

Waste materials within Brockman and Marra Mamba hosted deposits

A summary of the waste type and geozone assessment for the Brockman hosted deposits are shown in Table 2[3]. Also listed are the major waste types for each geozone. A summary of the wastes from the Marra Mamba deposits are shown in Table 3[4]. These data were sourced from *Final Landform Design Criteria for Mine Planning*[5].

The following points can be made:

- The proportion of individual waste types contained within a particular geozone remains relatively consistent irrespective of the ore body in question.
- The Dales Gorge waste geozones (401, 411, 421, 431), Joffre waste geozones (201-261), Footwall zone geozone (501), and the Marra Mamba geozones (711-781) excluding West Angelas Shale (701) contain similar proportions of hard waste types and similar dominant wastes. Therefore, these geozones can be considered to be similar.
- West Angelas Shale (701, 705) are similar to each other but different to other Marra Mamba geozones.
- The Whaleback Shale waste geozones (301,311) contain similar proportions of hard and soft materials and the same dominant waste types.
- Detritals appear variable in their abundance of the hard wastes, though they tend to be dominated by clay and shale wastes.

Given these findings, and the fact that different waste types within a geozone are not segregated during mining, geozones were used as the material types to assess materials erodibility and from which landform batter geometries were developed.

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[3] Deposits included SEC6, SEC7, 4EST, 4WES, 5W, 94E, CHE, 84E, 64E, 47E, 37E, 32E, 23E, 24E, 11W, B1, SE17, and SE10.

[4] The assessment used a range of Marra Mamba mine site, including Silvergrass, Hope Downs 1 North, Hope Downs 1 South, Marandoo, and Nammuldi.

[5] Landloch Pty Ltd (2012) Final landform design criteria for mine planning, Report prepared for Rio Tinto Iron Ore (WA)

Table 2: Proportion of hard and soft+medium wastes within the Brockman waste geozones.

Waste Geozone	Mean Proportion (%)of:		Major Waste Types	
	Hard Materials	Soft + Medium Materials	Hard	Soft/Medium
201 – Joffre 6	78	22	BIF	Shale
211 – Joffre 5	83	17	BIF	-
221 – Joffre 4	84	16	BIF	-
231 – Joffre 3	80	20	BIF	-
241 – Joffre 2	82	18	BIF	-
251 – Joffre 1	77	23	BIF	Shale
261 – Undifferentiated Joffre	78	22	BIF	Shale
265 – Joffre Hydrated	34	66	BIF	Shale
301 – Whaleback Shale 2	38	62	BIF	Shale, Ferruginous Shale
311 – Whaleback Shale 1	49	51	BIF	Shale, Ferruginous Shale
321 – Undifferentiated Whaleback Shale	48	52	BIF	Shale
325 – Whaleback Shale Hydrated	25	75	BIF	Shale, Ferruginous Shale
401 – Dales Gorge 3	83	17	BIF	Shale
411 – Dales Gorge 2	75	25	BIF	Shale
421 – Dales Gorge 1	83	17	BIF, Magnetic BIF	Shale
431 – Undifferentiated Dales Gorge	70	30	BIF	Powdery BIF, Shale
435 – Dales Gorge Hydrated	31	69	BIF	Shale
501 – Footwall Zone	62	38	BIF	Shale
601 – Mount McRae Shale	5	95	BIF	Shale, Carbonaceous Shale

Table 3: Proportion of hard and soft+medium wastes within the Marra Mamba waste geozones.

Waste Geozone	Mean Proportion (%)of:		Major Waste	
	Hard Materials	Soft + Medium Materials	Hard	Soft/Medium
701 – West Angelas Shale	16	84	BIF	Shale, Clay
705 – West Angelas Shale Hydrated	12	88	-	Shale, Clay
781 – Undifferentiated Marra Mamba	74	26	BIF, Goethitic BIF	-
711 – Undifferentiated Newman	83	17	BIF, Goethitic BIF	-
741 – Newman	45	55	BIF, Goethitic BIF	Shale
721 – Newman	75	25	BIF, Goethitic BIF	-
731 – Newman	75	25	BIF, Goethitic BIF	-
751 – Newman	83	17	BIF, Goethitic BIF	-
761 – MacLeod	64	36	BIF, Goethitic BIF	Shale
771 – Nammuldi	71	29	BIF, Magnetic BIF, Goethitic BIF	Shale
785 – Marra Mamba Hydrated	15	85	BIF	Shale, Clay
7 – Detritals	6	94	-	Clay, Shale
8 – Calcrete Detritals	9	91	-	Calcrete, Clay
9 – Lignite Detritals	4	96	-	Clay, Shale
11 – Colluvium Detritals	27	73	-	Clay, Shale
12 – Rounded Detritals	25	75	-	Clay, Shale
31 – Cemented Limonitic Detritals	15	85	-	Clay
81 – Siderite Detritals	5	95	-	Clay, Dolomite

Channel Iron Deposit waste materials

Channel Iron Deposits are different to the Brockman and Marra Mamba materials in that they do not have readily defined waste geozones. However, underlying and overlying waste types can be analogous to those encountered in the detrital or bedded iron deposits. Therefore, these materials were directly classified based on the individual waste types present. For the Robe Valley channel iron deposits (Mesa A, Mesa J), waste material types include surficial alluvial and weathered pisolite materials. Weathered clay-rich pisolite tends to be the dominant waste type. The proportion of Channel Iron Deposit wastes in the Robe Valley expressed as a proportion of the total reserve is shown in Table 4. Although there is considerable variation in the proportion of these materials (likely to be exaggerated by how the limits of the reserve calculations are set), it is noted that alluvium and weathered pisolite are present in large proportions at both Mesa J and A. For Yandicoogina, no data was available. However, a large proportion of wastes were identified as clay-rich alluvials[6].

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[6] Rio Tinto Iron Ore (2010) Geology & mineralogy of the Hamersley Province ores, Rio Tinto Iron Ore.

Table 4: Proportion of Channel Iron Deposit wastes as a proportion of total reserve

Waste types	Mesa J	Mesa A
Quaternary Alluvium	17	43
Surficial Unit	12	-
Weathered Pisolite	72	57

2.3 Material selection

Based on the assessment of materials, the following key materials were identified:

- Dales Gorge Member, Footwall Zone, and Marra Mamba wastes (considered collectively);
- Joffre Member,
- Whaleback Shale;
- West Angelas Shale;
- Weathered pisolite;
- Alluvials; and
- Detritals.

Hydrated zone materials were also considered separately because it was recognised by Rio Tinto geologists that:

- They are available at the start of mining for all deposits;
- They tend to include stable, coarse, blocky material with minor fine-grained components;
- They are likely to be more similar in appearance to materials from the natural landscape than some wastes and hence are preferred in this sense;
- Being weathered, they are relatively inert (low ARD risk);
- They are generally available in large volumes; and
- There may be more flexibility to stockpile them and use in final waste dumps.

3. Material testing

Studies have been carried out on 48 waste samples from across Rio Tinto's Pilbara iron ore mining operations. The waste types tested include Alluvials, Calcrete, Clay Waste, Coarse Tails, Dales Gorge Member, Detritals, Footwall, Hydrated Zone, Joffre Member, Mount McRae Shale, Powdery BIF, Tertiary Pisolite Clay, Topsoil, Weathered Dolerite, Whaleback Shale, Weathered Pisolite, and West Angelas Shale.

3.1 Material characterisation testing

Samples of the fine component (<2 mm) of all materials were sent to a commercial soil laboratory and analysed for:

- Soil $pH_{1:5}$;
- $EC_{1:5}$ as a measure of salinity;
- $EC_{1:2}$ as a measure of salinity ;
- Exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+});
- Effective Cation Exchange Capacity (ECEC);
- Exchangeable Sodium Percentage (ESP); and
- Particle size distribution (coarse sand, fine sand, silt, and clay).

These properties were used to define risks to vegetation growth inherent in the wastes (e.g. salinity and poor structure), and to consider risks associated with tunnel erosion. The data was also used to assist in parameterising the runoff and erosion model.

The coarse component (>16 mm) of the rocky wastes were further assessed for properties that indicate their likely durability, tendency to weather, and usefulness as an armour material. Properties assessed include:

- Rock particle size;
- Rock particle density; and
- Rock water absorption.

Results

Broadly, the wastes and soils assessed were consistent with reference soil sites located across Rio Tinto's mine sites, and have the following properties:

- Low salinity, with values unlikely to adversely affect plant germination or growth.
- Acidic to mildly alkaline pH values.
- Some wastes have elevated Exchangeable Sodium Percentage (ESP). However, when coupled with the rocky nature of most wastes, the appreciable proportion of sands, the low Effective Cation Exchange Capacity (ECEC) and low Na concentration, dispersion is not likely to be a significant risk to rehabilitation.
- The fine fraction (< 2 mm diameter) of the samples tends to have a sandy loam texture, although some wastes (particularly Channel Iron Deposit Wastes) can contain higher clay contents.
- The materials dominated by hard wastes (Dales Gorge, Joffre, Footwall Zone, some hydrated zone materials) contain higher proportions of rock than other materials. Channel Iron Deposit wastes tend to be less rocky than wastes from bedded iron deposits.
- The rocky component of wastes tends to contain quite dense rocks that are likely to be useful for armouring (if they are of an appropriate size). Rocky materials with mean particle sizes in the order of 80mm are useful as they will likely withstand erosive surface water flows.

- The rock water absorption values are low to moderately high. This indicates that some rocks (those with water absorption values >~7%) are somewhat porous and potentially more weathered than rocks with lower water absorption values. More porous rocks are likely to represent shale type materials, whereas less porous rocks tended to be dominated by Banded Iron Formation and ironstone. Therefore, the BIF-dominated wastes are likely to be more erosion resistant than the shale-dominate wastes.

3.2 Material erodibility

Assessment of long-term erosion potential for each of the materials was assessed using the Water Erosion Prediction Program (WEPP) model. WEPP describes erodibility using a number of specific parameters: Interrill erodibility (K_i); Rill erodibility (K_R); Critical shear for rill initiation (τ_c); and Effective hydraulic conductivity (K_e).

These WEPP erodibility parameters were derived for each of the 48 samples from data collected using application of:

- Simulated rain to a soil or waste surface, and measurement of runoff and sediment in runoff to obtain estimates of K_i and K_e; and
- Surface water flows to obtain estimates of K_R and τ_c.

Rainfall simulation and overland flows

Rainfall and overland flow simulation have been widely used to define the erodibility of mine wastes in WA. The process is briefly described below.

For rainfall simulation, flat fan nozzles mounted on an oscillating manifold positioned ~2m above a test surface produce the simulated rain (Figure 1). The kinetic energy generated by the nozzles are ~29.5 J/m2/mm, consistent with the energy of natural rainfall at intensities >40 mm/h. The nozzles uniformly sweep back and forth across the test plots, achieving high spatial distribution (<10% coefficient of variation) of the generated rainfall. For each material triplicate plots are subjected to a rainfall event sufficiently intense (usually 80-100mm/hr) to ensure runoff occurs. This allows measurement of rainfall infiltration and interrill erodibility.

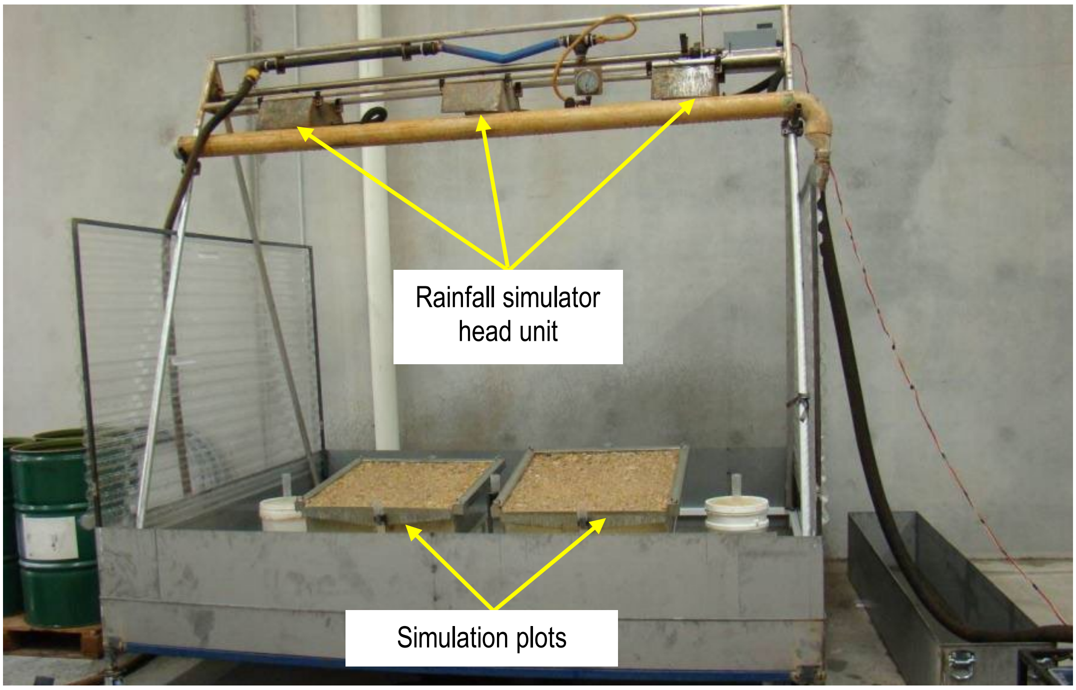

Figure 1: Typical laboratory-based rainfall simulator installation

For overland flow simulations, rill erodibility parameters are derived by applying various rates of overland flow to flumes 0.4 m wide and 2.0 m long set at gradients ranging from 10-30% (Figure 2). Rill erodibility and critical shear were derived on the basis of relationships between flow shear stress and sediment detachment rates measured from these flumes.

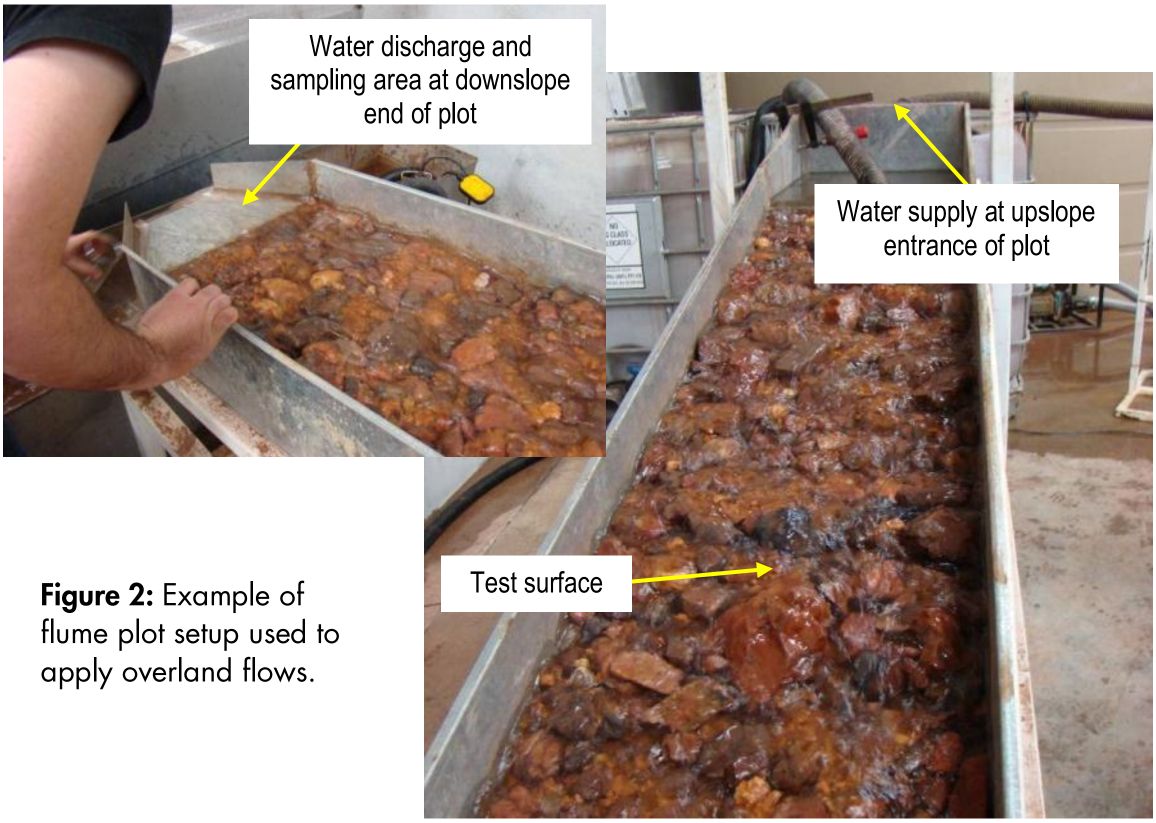

Figure 2: Example of flume plot setup used to apply overland flows.

Results

A summary of the parameter values adopted for each broad waste type (combining like samples) is also listed below in Table 5. The adopted parameter values of Table 5 represent an average value for each parameter.

Table 5: Parameter values adopted for each waste material.

Material	**K_e (mm/h)**	**K_i (kg.s/m^4)**	**K_R (s/m)**	**τ_c (Pa)**
Alluvials	20	246,568	0.0072	28
West Angelas Shale	28	609,814	0.0030	19
Calcrete	34	349,975	0.0016	46
Clay waste	10	285,844	0.0043	13
Detritals	26	236,317	0.0116	28
Dales Gorge	33	203,540	0.0033	28
Dolerite	20	335,337	0.0027	11
Footwall	33	203,540	0.0033	28
Hydrated Zone	103	63,860	0.0030	28
Joffre	33	203,540	0.0033	28
Limonite	25	448,929	0.0029	40
MacLeod Member	33	203,540	0.0033	28
McRae Shale	25	763,560	0.0010	20
Nammuldi Member	33	203,540	0.0033	28
Mt Newman Member	25	311,045	0.0034	44
Powdery BIF	12	531,064	0.0090	10
Tertiary Pisolite Clay	11	435,600	0.0016	37
Weathered pisolite	15	612,276	0.0097	6
Whaleback Shale	46	100,207	0.0042	26

3.3 Erosion modelling

The WEPP model

The WEPP model was used for simulations of runoff and erosion. 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.

Climate data

All WEPP simulations developed by Landloch use a 100-year stochastic climate sequence for Rio Tinto sites derived from observed data from the sites themselves and nearby Bureau of Meteorology weather stations. Nine associated climate sequences were created for 15 mine sites:

- Brockman 2, Brockman 4, and Nammuldi;
- Tom Price and Western Turner Syncline;
- West Angelas;
- Channar, Eastern Range, and Paraburdoo;
- Marandoo;
- Hope Downs 1;
- Hope Downs 4;
- Mesa J and Mesa A; and
- Yandicoogina.

Each of the 9 sequences contain 36,525 daily climate data sets that describe rainfall total, storm duration and intensities, temperature, solar radiation, and wind. The largest daily rainfall event in each climate sequence can be considered to be a rare event. Each climate sequence was assessed against the Bureau of Meteorology's Design Rainfall Data System to consider the Annual Exceedance Probabilities (AEP) of the larger rainfall events. The findings were summarised in Table 6.

The rarest event within the climate sequences typically has an AEP <0.2%, equivalent to rainfall storms with an annual recurrence interval (ARI) of more than 500 years. These storms are defined within the Australian Rainfall and Runoff Guidelines (AR&R) as 'very rare' rainfall events. In several cases, the rarest event has an AEP of <0.05% (>2,000 year ARI). These are consistent with 'extreme' rainfall events as defined by AR&R. The Hope Downs sequences' rarest event has an AEP of 0.3% (333 year ARI). These are defined as very rare events.

It is also noted that there are several extreme to very rare rainfall events in each of the climate sequences. Therefore, it was considered that these climate sequences represent climate consistent with long-term averages, including the presence of extreme rainfall events. The resultant erosion modelling is therefore also consistent with long-term averages, including the erosion that would occur from extreme rainfall events.

Table 6: EP and ARI values of the three rarest rainfall events per climate sequence.

Climate Sequence	**Rainfall Event Details**					
	Rarest		**2nd Rarest**		**3rd Rarest**	
	Total & Duration	AEP & ARI	Total & Duration	AEP & ARI	Total & Duration	AEP & ARI
Annual Exceedance Probability (%)						
Brockman 2, Brockman 4, and Nammuldi	268mm 5 hours	<0.05	175mm 5 hours	0.07	171mm 4 hours	0.1
Tom Price and Western Turner Syncline	256mm 4 hours	<0.05	145mm 3 hours	0.05	135mm 7 hours	0.7
West Angelas	145mm 5 hours	0.2	140mm 4 hours	0.2	147mm 11 hours	1
Channar, Eastern Range, and Paraburdoo	317mm 13 hours	0.1	176mm 6 hours	0.2	140mm 4 hours	0.2
Marandoo	289mm 9 hours	<0.05	223mm 6 hours	0.05	165mm 6 hours	0.2
Hope Downs 1	195mm 7 hours	0.3	194mm 7 hours	0.3	203mm 10 hours	0.5
Hope Downs 4	254mm 12 hours	0.3	211mm 10 hours	0.5	189mm 9 hours	1
Mesa J and Mesa A	301mm 7 hours	0.05	282mm 11 hours	0.2	181mm 7 hours	1
Yandi	219mm 4 hours	0.07	177mm 5 hours	0.5	143mm 4 hours	0.7
Annual Recurrence Interval (Years)						
Brockman 2, Brockman 4, and Nammuldi	268mm 5 hours	>2,000	175mm 5 hours	1,500	171mm 4 hours	1,000
Tom Price and Western Turner Syncline	256mm 4 hours	>2,000	145mm 3 hours	2,000	135mm 7 hours	150
West Angelas	145mm 5 hours	500	140mm 4 hours	500	147mm 11 hours	100
Channar, Eastern Range, and Paraburdoo	317mm 13 hours	1,000	176mm 6 hours	500	140mm 4 hours	500
Marandoo	289mm 9 hours	>2,000	223mm 6 hours	2,000	165mm 6 hours	500
Hope Downs 1	195mm 7 hours	333	194mm 7 hours	333	203mm 10 hours	200
Hope Downs 4	254mm 12 hours	333	211mm 10 hours	200	189mm 9 hours	100
Mesa J and Mesa A	301mm 7 hours	2,000	282mm 11 hours	500	181mm 7 hours	100
Yandi	219mm 4 hours	1,500	177mm 5 hours	200	143mm 4 hours	150

Erosion of differing batter geometries

Erosion predictions were made for a range of batter geometries that were specific both to the different materials and the different climates within which Rio Tinto's mines are located. The acceptability of each geometry (combination of slope height and gradient) was determined using the erosion threshold values of long-term average erosion rate (<5t/ha/y, averaged over the entire slope), and long-term maximum erosion rate at any point on the slope of (<10 t/ha/y).

These rates are consistent with rates at which the potential to rill is low. Using this rate aims to ensure both rill and gully erosion is minimised. A recent review of acceptable erosion rates for the Pilbara region[7] also demonstrated that this rate is consistent with rates:

- Measured for unmined land in the Pilbara and adjacent regions;
- Modelled using erodibility parameters collected for undisturbed land in the Pilbara;
- Of soil renewal (soil formation & accumulation from deposition) for the Pilbara; and
- At which rills and gullies have been observed to be rare.

Validation of WEPP modelling

WEPP model validation data is provided to demonstrate that it is able to adequately predict erosion in a mining context. The WEPP model has been extensively validated by Landloch for mine site batters (Figure 3).

Erosion data for this validation were sourced from 27 locations on 12 waste landforms on mine sites in Western Australia. Several sites were located at Rio Tinto's Pilbara iron ore sites. The observed erosion data were collected using cross-slope transects 30-50 m wide, located on upper and lower sections of waste dump batters. Batter shapes include both linear and concave cross-sectional profiles. Gradients assessed are consistent with the slopes commonly used for mining landforms. Surfaces assessed include loamy soils, clay soils, and rocky sandy loam soils. The ages of the batters range from 3–8 years. Slope conditions range from minimally eroded to heavily eroded.

The measured cumulative erosion rates show good agreement with rates predicted by WEPP. Given that these data include predictions from both the upper and lower section of landform batters, WEPP is shown to be able to suitably predict changes in erosion rates with changing slope lengths and gradients. Model output can adequately represent both runoff accumulation down the slope, and flow concentration across the slope. The accuracy of the predictions shown in Figure 3 also indicates that the methods used to derive the essential model parameters are producing well calibrated model results. This gives confidence that accurate calibration of the WEPP model can be achieved provided suitable laboratory and field-based methodologies are used.

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[7] Howard, E.J. and Loch, R.L (2019) *Acceptable erosion rates for mine waste landform rehabilitation modelling in the Pilbara, Western Australia*, in AB Fourie & M Tibbett (eds), Proceedings of the 13th International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 1545-1560

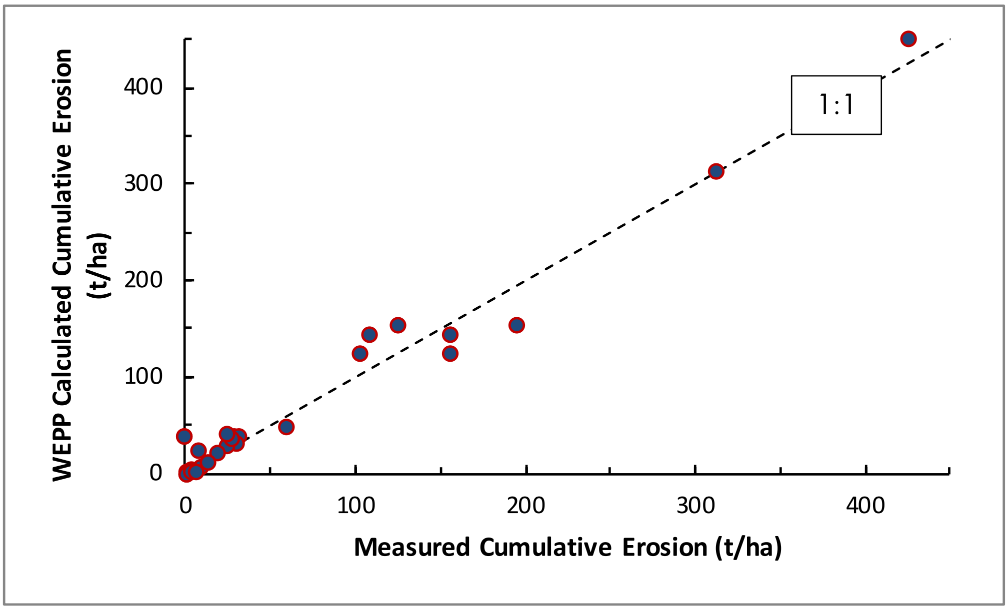

Figure 3: WEPP-predicted cumulative erosion and observed cumulative erosion rates for 27 batter slope locations from Western Australian mine sites.

Summary

Erosion modelling has used data collected from 48 samples of key wastes across Rio Tinto's Pilbara operations. These samples have been subjected to testing to measure their erodibility, with these erodibility parameters used to model long-term erosion using the WEPP model. The climate sequences used in the modelling contain a wide range of rainfall events including several extreme and rare events. The model results have been compared against acceptable erosion rate values consistent with measured erosion for undisturbed land in the Pilbara, soil renewal rates, and rates at which the risk of rill and gully erosion is low. The model output has been validated at 27 locations on mine sites in Western Australia and shown to agree with observed erosion.

4. Materials of Western Range, Eastern Range, and Paraburdoo

The data generated specifically from Eastern Ridge and Paraburdoo materials were compared against the data from which the erosionally stable batter geometries were developed. The proportion of the different wastes are given in Table 7. These data were sourced from the Western Range Closure Plan[8], Eastern Range Closure Plan[9], and Paraburdoo Closure Plan[10].

Based on these data, the major waste types (>10%) present at these sites include Dales Gorge, Hydrated Zone, Joffre, and Whaleback Shale. Site specific data exists within the database of 48 samples tested for erodibility for:

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[8] Rio Tinto (2019) *Western range closure plan*, September 2019.
[9] Rio Tinto (2019) *Eastern range closure plan, Order of magnitude study*, September 2019
[10] Rio Tinto (2019) *Paraburdoo Closure Plan*, September 2019.

- Dales Gorge from Eastern Range
- Joffre from Eastern Range
- Hydrated Zone from Eastern Range; and
- Whaleback Shale from Paraburdoo.

Table 7: Waste abundance

Material	**Total Waste (%)**		
	Eastern Range	**Western Range**	**Paraburdoo**
Dales Gorge (DG)	86	14	16
Footwall Zone (FWZ)		2	3
Hydrated Zone (HYD)		17	3
Joffre (JOF)		19	27
Mount McRae Shale (MCS)	9	4	7
Whaleback Shale (WS)		27	11
Dolerite (DOR)	5	9	10
Detritals (DET)	-	2	<1
Mt Sylvia Formation (MTS)	-	1	0
Nammuldi Member (NAM)	-	-	<1
Weeli Wolli (WW)	-	-	10
Wittenoom Formation-Dolomite (WD)	-	1	-
Yandicoogina Shale (YS)	-	1	5
Other	-	2	7

Western Range is currently in the process of applying to Part IV EPA approval and there are currently no disturbed materials available for testing. Given the similarity in materials within geozones across the Pilbara, the data sourced from Eastern Range and Paraburdoo are analogous to those that will be disturbed from Western Range in the future (if approval is granted). Landloch understands that once mining is approved and the mine is operational, Rio Tinto is committed to undertaking site specific testing to confirm this.

Table 8 shows the site specific erodibility parameters compared to the parameters adopted for erosion modelling and from which Rio Tinto develops rehabilitation batter geometries.

The impact of this variation is erodibility parameters was assessed by conducting additional modelling with the WEPP model. Predicted erosion for all materials are lower than those predicted using the parameter values adopted within the previous WEPP modelling (Whaleback Shale, Dales Gorge, Hydrated Zone), or slightly higher but still below the acceptable erosion thresholds (Joffre) (<5t/ha/y). Therefore, it is concluded that batter geometries generated using the adopted erodibility parameters will be suitable for use at Eastern Range, Western Range, and Paraburdoo.

Table 8: Site specific erodibility parameters and those generally adopted for erosion modelling.

Material	**Erosion Class**	**K_e (mm/h)**	**K_i (kg.s/m^4)**	**K_R (s/m)**	**τ_c (Pa)**
Joffre					
Adopted Values	Low	33	203,540	0.0033	28
Eastern Range sample	*Low*	*25*	*321,593*	*0.0030*	*25*
Whaleback Shale					
Model	Med	46	100,207	0.0042	26
Paraburdoo sample	*Med*	*28*	*68,604*	*0.00140*	*28*
Dales Gorge					
Adopted Values	Low	33	203,540	0.0033	28
Eastern Range sample	*Low*	*100*	*48,535*	*0.00010*	*19*
Hydrated Zone					
Adopted Values	Low	103	63,860	0.0030	28
Eastern Range sample	*Low*	*35*	*93,068*	*0.00054*	*34*

5. Closing

Erosion modelling has used data collected from 48 samples of key wastes across Rio Tinto's Pilbara operations. These samples have been subjected to testing to measure their erodibility, with these erodibility parameters used to model long-term erosion using the WEPP model. The climate sequences used in the modelling contain a wide range of rainfall events including several extreme and rare events. The model results have been compared against acceptable erosion rate values consistent with measured erosion for undisturbed land in the Pilbara, soil renewal rates, and rates at which the risk of rill and gully erosion is low. The model output has been validated at 27 locations on mine sites in Western Australia and shown to agree with observed erosion.

An assessment of the samples specific to Eastern Range, Western Range and Paraburdoo show that the batter geometries generated using the averaged adopted erodibility parameters will be suitable for use at Eastern Range, Western Range, and Paraburdoo.

Regards

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