Laboratory erodibility measurement and assessment of landform designs using rock armour.

Prepared for Middlemount Coal Pty Ltd

September 2019

The landscape is not uniform. Because of this non-uniformity, no monitoring, testing or sampling technique can produce completely precise results for any site. Any conclusions based on the monitoring and/or testing presented in this report can therefore only serve as a 'best' indication of the environmental condition of the site at the time of preparing this document. It should be noted that site conditions can change with time.

The information contained in this document produced by Landloch Pty Ltd is solely for the use of the Client identified on the cover sheet for the purpose for which it has been prepared and Landloch Pty Ltd undertakes no duty to or accepts any responsibility to any third party who may rely upon this document.

TOOWOOMBA
PO Box 57
HARLAXTON QLD 4350
Phone (07) 4613 1825

PERTH
PO Box 5175
SOUTH LAKE WA 6164
Phone (08) 9494 2837

NEWCASTLE
PO Box 7017
Redhead NSW 2290
Phone (02) 4965 7717

Landloch Pty Ltd
A.C.N. 011 032 803
A.B.N. 29011032803

Web site: www.landloch.com.au
Email: admin@landloch.com.au

Project Number: 1404.19b

Report Title: Laboratory erodibility measurement and assessment of landform designs using rock armour.

Client: Middlemount Coal Pty Ltd

Review History

Version Number	Prepared by:	Reviewed by:	Date
Draft	Rob Loch	G. Sharp	03/10/2019
Final	Riki Lewis	Rob Loch	16/08/2021

CONTENTS

EXECUTIVE SUMMARY

Middlemount Coal Pty Ltd (MCPL) are currently rehabilitating selected areas on the Middlemount Mine in the Bowen Basin. The current priority is the Eastern Overburden Dump (EOD). This particular dump is close to the lease boundary and requires steep slopes to ensure it will stay within the mining lease area.

Three materials were provided to Landloch for testing. These materials were a good quality Permian rock, quarry rock, and topsoil. From these materials, three mixtures were created for laboratory scale erosion testing. These mixtures were:

- 4:1 Permian rock: topsoil,
- 4:1 quarry rock: topsoil, and
- topsoil.

Due to the size of the rock provided, large flumes with dimensions 0.77 x 3 m were used for erosion testing of the rock soil mixtures. Regular 0.4 x 2 m flumes were used for the topsoil erosion testing. Simulated rain with kinetic energy equivalent to natural rain was applied to plots at an intensity of 90 – 130 mm/h for 25 minutes. Runoff was sampled at 2-3 minute intervals to allow derivation of sediment loads, runoff rate, and infiltration.

For overland flow testing, flumes were set to various gradients and subjected to a sequence of increasing flow rates, each applied for 5 minutes. Runoff samples were collected at 1, 2, 3 and 5 minute intervals. These samples were used to determine sediment concentrations and erosion rates.

Erosion testing results were used to determine erodibility parameters for each of the three materials tested. Erodibility factors were used in WEPP modelling to predict erosion rates from modelled landscapes.

Initial WEPP modelling used two slope gradients of 16.66 and 33.33 %. These gradients were run for both rock: topsoil mixtures and compared to a bare surface with 40 % ground cover. The initial modelling showed that most bare slopes were predicted to have unacceptable erosion rates (>10 t/ha/yr) for both slope gradients. Slopes which had 40 % ground cover had mostly acceptable erosion rates for both materials.

A second modelling scenario was established to test landform height and material characteristics. The new landform parameters included a slope with 65 m height, Permian rock mixes with either 47 Pa or 74 Pa critical shear, and 60 % ground cover. The two slope gradients and surfaces either bare or with 40 % ground cover were also considered.

The revised modelling showed that predicted erosion rates for bare areas were still unacceptable (>10 t/ha/yr) for both slope gradients. Permian rock with 47 Pa shear stress with a slope gradient of 33.33 % and 40% ground cover was the only other scenario with unacceptable modelled erosion.

Simulated slopes and model predictions have been used to make recommendations for slope construction and management.

For short term stability, simulations suggested that a minimum critical shear of 50 Pa needs to be achieved, which is the equivalent to using rock with a D_{50} of approximately 80 mm.

Model outputs showed that ground cover establishment is critical to stabilising slopes over the medium to long term. A minimum of 40 % ground cover is required, with greater than ≥60 % ground cover being preferable. Ground cover species recommended for site include Rhodes grass (Tolgar or Reclaimer cultivars), Saraji Urochloa, Digit grass (*Digitaria eriantha* ssp. eriantha) cv. Premier, and Indian bluegrass or Indian couch (*Bothriochloa pertusa*) cvv. Keppel, Medway, Bowen. It is critical that legumesspecies be included in any seed mix, as the legumes will provide soil nitrogen in the long term.

Rock quality and layer thickness needs to be considered when constructing a slope. Effective rock: soil mixes require a layer thickness of 1.5 to 2 times the D_{50} of the rock used.

Growth medium layer preparation is important to ensure vigorous establishment and continued growth of ground cover on slopes. The aim is to establish plant growth media with pH, electrical conductivity, exchangeable sodium percentage, and chloride within acceptable ranges for plant species chosen. In addition critical plant nutrients, nitrogen, phosphorus, potassium, sulphur, boron, and zinc should be at levels that will ensure vigorous initial plant establishment.

1 BACKGROUND

1.1 Rehabilitation trials using rock mulch – Middlemount Mine

Middlemount Coal Pty Ltd (MCPL) are currently rehabilitating selected areas on the Middlemount Mine in the Bowen Basin, with the Eastern overburden dump being the current rehabilitation priority. The site is spatially constrained within mining leases and the Eastern overburden dump is currently close to the lease boundary, creating a need to be able to construct and stabilise relatively steep batter slopes. Inclusion of rock into a rehabilitated surface is widely recognised as enabling stabilisation of steeper slopes.

Rock mulch trials have been implemented on multiple batters, and store and release cover profiles have been constructed on one dump top. For the existing trials, the source materials have been characterised, as has the rock:soil mix formed. Pit rock used in some mixtures has limited durability and this has constrained the effectiveness of the rock mulch layer in some locations.

Current trials are using two rock types to determine which produces the most durable rock armour and best supports plant growth. A rock:soil mix of 4:1 is used with a settled depth of 1m over sodic and saline overburden. These field trials use a single gradient, which limits the potential for the trials to provide sufficient information to allow a range of slope designs to be matched to site requirements.

Erosion modelling offers the ability to consider the placement of rock:soil mixtures over a wider range of slope gradients and lengths, and has been recommended as a way to greatly extend the value of the current field trials. Consequently, this report presents results of laboratory testing and provides the input parameters needed for runoff and erosion modelling to be used to predict likely performance of rock:soil covers of interest for a range of slope options at the Middlemount Mine.

The modelling identified maximum gradients, slope lengths and drainage methods for the materials on site to inform landform design decisions. This would also help MCPL schedule efficient placement of the materials currently being excavated from the pit.

1.2 Work scope

Erosion modelling and landform design studies to determine safe, stable and non-polluting landform designs have been shown to produce accurate and effective results provided the parameters input to the models are soundly based (Howard and Roddy 2012; Robinson and Finucane 2019). Specifically, the modelling requires parameters derived from erosion experiments on material from site. Use of material from site in erosion laboratory experiments ensures that subsequent modelling and design criteria are directly relevant to the site.

Consequently, the work scope to parameterise and run runoff/erosion modelling to inform landform designs using placement of soil/rock covers on the site included:

- Laboratory measurements of runoff and erosion on rock:soil mixes of materials sourced from the site;

- Derivation of WEPP erosion model parameters from the laboratory data; and
- WEPP simulations to develop landform design rules.

An associated study will be carried out to assess the likely performance of the rock:soil mixes in terms of water retention for plant growth and the quantities of deep drainage that will reach the underlying saline and sodic wastes. It will be reported separately.

Deliverables from the erodibility study were planned to include:

- Detailed infiltration, runoff, and erodibility data for the rock:soil mixtures tested;
- Assessment of mixing ratios of “rock” and soil, and information on potential runoff/erosion impacts of deviations from the specified design;
- Landform design information including:
  - Landform design rules for a range of rock sizes (typically presented as a relationship between maximum gradient and contributing area)
  - Some consideration of the long-term role and management of East dump constructed drains and benches ;

The associated water balance study will provide:

- Information on the likely interactions between rock mulch layer thickness and underlying wastes in terms of:
  - Effects of waste properties on acceptable rock mulch layer thickness for revegetation success; and
  - Interactions of rock mulch layer thickness with waste properties in terms of tunnel erosion risk.

It is anticipated that some form of design document will be generated from this project.

2 MATERIALS AND MIXTURES STUDIED

2.1 Materials supplied

On 2 June 2019, two (2) cubic metres of each of:

- Good quality Permian rock (including fines);
- Parrot Quarry Rock (including fines); and
- Topsoil

were delivered to Landloch’s Toowoomba laboratory.

2.2 Mixtures tested

Mixtures and materials fully tested under both simulated rain and overland flow were:

- 4:1 Permian rock : topsoil;
- 4:1 Quarry rock : topsoil; and
- Topsoil.

Infiltration of simulated rain was also measured on a 2:1 mix of Quarry rock:topsoil.

It is Landloch's understanding that the use of Quarry rock has subsequently been ruled out due to cost, unless shown by testing to be a significantly better option in terms of rehabilitation outcomes. Consequently, this report focusses largely on mixture of topsoil with the rocky Permian waste.

2.3 Material properties

2.3.1 Topsoil and rock fine fractions

For each of the mixtures tested and for each individual material, samples of the fine fraction were taken and analysed for key physical and chemical properties. Results are summarised in Tables 1 and 2, and information on ratings from Hazelton and Murphy (2007) applied to the ranges of the properties measured is given in Appendix 1.

Table 1: Chemical properties of the fine component of mixtures and materials. Values shown in red are of concern – largely high – with the exception being for Ca:Mg ratio (too low).

Analyses	Unit	4:1 Quarry: Soil	2:1 Quarry: Topsoil	4:1 Permian: Topsoil	Topsoil	Quarry	Permian
pH - Water	pH units	9.21	9.22	9.88	7.38	9.54	9.95
Electrical Conductivity	dS/m	0.34	0.29	0.47	0.07	0.32	0.50
Chloride	mg/kg	326	208	186	49.2	235	218
Cation Extraction Method	Rayment & Lyons	15C1	15C1	15C1	15C1	15C1	15C1
Cation Exchange Capacity (CEC)	meq/100g	6.2	5.6	4.8	1.4	7.4	5.9
Exchangeable Calcium	%	3.40	5.9	20.1	47.2	1.35	17.7
Exchangeable Magnesium	%	35.8	37.6	40.2	39.6	35.5	41.3
Exchangeable Potassium	%	3.40	3.72	3.08	8.10	2.87	2.93
Exchangeable Sodium	%	57.2	52.5	36.3	4.29	60.2	37.9
Exchangeable Aluminium	%	0.18	0.20	0.26	0.77	0.15	0.19
Ca : Mg Ratio	-	0.10	0.16	0.50	1.19	0.04	0.43

The fine fractions from both rock types show high pH (9.54 – 9.95), which is very strongly alkaline, and likely to cause problems for growth of many plant species.

Similarly, Electrical Conductivity (EC), which is a measure of soil soluble salt content, is rated “moderate” for the Quarry rock and “high” for the Permian rock. For both rock types, chloride is somewhat elevated and may reduce growth of some sensitive species.

Fines from both rock types are highly sodic ,with Exchangeable Sodium Percentage (ESP) of 60.2 and 37.9 for Quarry and Permian rock respectively. As ESP >14 % is normally classed as strongly sodic, fines from both rock types can be expected to be strongly dispersive. Clay dispersion potential is exacerbated by relatively high Magnesium, and low Ca:Mg ratios, particularly for the Quarry rock.

In comparison to fines from the two rock types, the topsoil shows generally suitable chemical properties.

Where topsoil is mixed with rock, the fine fraction of the resulting mixture is generally strongly controlled by the properties of the rock fine fraction, with the end result that the mixtures will reflect the sub-optimal properties of the rock fine fractions.

Table 2: Fine fraction and topsoil particle size distribution

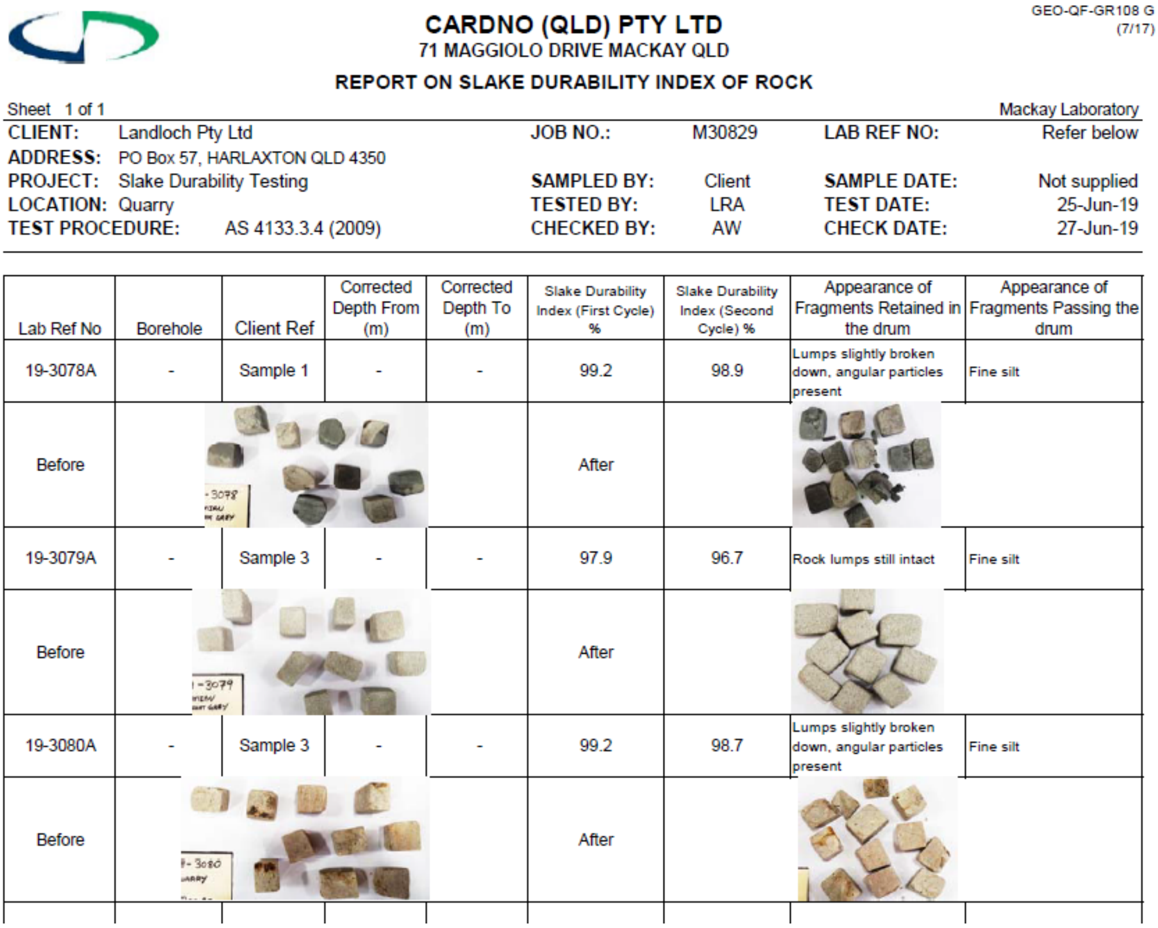
Analyses	Unit	4 Quarry : 1 Topsoil	2 Quarry : 1 Topsoil	4 Permian : 1 Topsoil	Topsoil	Quarry	Permian
Gravel >2.0mm	%	0.0	0.1	0.0	5.0	0.3	1.2
Coarse Sand 0.2-2.0mm	%	55.0	54.5	40.9	30.6	61.5	41.1
Fine Sand 0.02-0.2mm	%	30.2	28.8	34.7	54.4	21.2	35.7
Silt 0.002-0.02mm	%	8.4	6.4	14.1	5.9	6.5	8.2
Clay <0.002mm	%	6.5	10.1	10.3	4.1	10.4	13.8

All of the fine fractions showed low clay and silt contents, indicating that water-holding capacity of the materials and mixtures is likely to be low, especially where a significant proportion of the volume of the upper profile is occupied by rock. It could be expected that vegetation established in soil layers of low water holding capacity is likely to be dominated by deep-rooted species such as shrubs and small trees, with lower abundance of grasses.

2.3.2 *Rock durability*

Samples of both rock types were analysed for slake durability. Results are shown in Figure 1, and indicate that both materials are quite durable. An ideal slake durability result for a material to be placed on the surface of a rehabilitated slope would be >90% after two cycles (Santi 2006), whereas both materials, in this case, had durability in the range 96.7 – 98.9%.

Consequently, it appears that either rock type would be suitable for placement on the surface to stabilise rehabilitated areas.



GEO-QF-GR108 G
(7/17)

CARDNO (QLD) PTY LTD
71 MAGGIOLO DRIVE MACKAY QLD

REPORT ON SLAKE DURABILITY INDEX OF ROCK

Sheet 1 of 1
Mackay Laboratory

CLIENT:	Landloch Pty Ltd	**JOB NO.:**	M30829	**LAB REF NO:**	Refer below
ADDRESS:	PO Box 57, HARLAXTON QLD 4350				
PROJECT:	Slake Durability Testing	**SAMPLED BY:**	Client	**SAMPLE DATE:**	Not supplied
LOCATION:	Quarry	**TESTED BY:**	LRA	**TEST DATE:**	25-Jun-19
TEST PROCEDURE:	AS 4133.3.4 (2009)	**CHECKED BY:**	AW	**CHECK DATE:**	27-Jun-19

Lab Ref No	Borehole	Client Ref	Corrected Depth From (m)	Corrected Depth To (m)	Slake Durability Index (First Cycle) %	Slake Durability Index (Second Cycle) %	Appearance of Fragments Retained in the drum	Appearance of Fragments Passing the drum
19-3078A	-	Sample 1	-	-	99.2	98.9	Lumps slightly broken down, angular particles present	Fine silt
Before					After			
19-3079A	-	Sample 3	-	-	97.9	96.7	Rock lumps still intact	Fine silt
Before					After			
19-3080A	-	Sample 3	-	-	99.2	98.7	Lumps slightly broken down, angular particles present	Fine silt
Before					After			

Figure 1: Slake soundness testing results.

2.4 Rock size

The size distribution of Quarry and Permian rock was measured from photographs of flume surfaces following applications of flow, which were sent for computer analysis of particle size.

Initial assessment of the rock placed in flumes (which had some large particles >200 mm diameter removed) indicated a median diameter (D_{50}) of approximately 80 mm for the Quarry rock and 77 mm for the Permian rock.

It could be assumed that – in field practice – the effective rock D_{50} values would be at least slightly larger than those measured on material in flumes.

3 EROSION MODELLING METHODOLOGY

3.1 Soil loss targets

This study used runoff and erosion modelling to identify landform options that would erode at rates low enough to provide long-term stability. Effectively, the landforms are planned to be consistent with **tolerable** rates of soil loss. Wischmeier and Smith (1978) defined tolerable soil loss for cropland as "*the maximum rate of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely.*"

A value of 11.2 t/ha/yr averaged over an area of interest is often cited as a tolerable soil loss rate, but that value was derived by US soil conservation agencies for deep, fertile cultivated soils, and has little relevance to most rehabilitated minesites. Using similar criteria to those applied for crop land, a lower soil loss tolerance value of 4.5 t/ha/y was developed by US agencies for erosion of rangeland soils and shallow cultivated soils (Wight and Siddoway 1979).

Lower tolerance values are relevant to rangeland and minesite situations, as not only are the soils shallower and more susceptible to fertility decline, but the lack of regular tillage or disturbance means that any rills or points of scour that form are more likely to extend and develop into gullies over time. These are typically of concern for minesite landforms where there is no bedrock layer at depth to limit long-term depths of incision.

For that reason, a key priority in setting a tolerable erosion target is the prevention of significant rill or gully development. On that basis, for slopes where long-term erosion risk (for a range of reasons) is considered low, then an average erosion rate for the slope of 5 t/ha/y and a maximum of 10 t/ha/y has commonly been applied by Landloch. Typically, the low risk category includes slopes where:

- The surface layer contains a significant component of durable rock;
- The material underlying the topsoil layer is not dispersive and unlikely to be highly erodible if exposed;
- The vegetation established is not dominated by buffel grass[1], which tends to divert and concentrate flow around tussocks and increase potential for rill formation;
- Rainfall in the area and soil fertility/productivity are such that there is a reasonable probability of vegetation stabilising any rill lines formed during site establishment[2]; and
- The overall landform height is not great (≤50 metres, for example).

In this case, several aspects of the landform do not meet the "low risk" requirements, but the anticipated presence of durable rock cover is

---

[1] Dominance of buffel grass would be assessed in terms of the rehabilitated area having >50% of its area covered by stands of buffel grass with little (<10% approximately) or no other grass species present.

[2] This would be assessed on the basis of observations of colonisation of bare areas in existing rehabilitation with similar topsoil and subsoil.

considered to be sufficient to render the landform "low risk" in terms of erosion model targets for batter slope design.

3.2 Strategy adopted

In developing landform designs, the strategy applied was to:

a) measure erodibility of key materials used in mine rehabilitation; and

b) use the WEPP model (Flanagan and Livingston 1995) to consider runoff and erosion from a range of landform and rehabilitation options as its flexibility and detailed output is ideal for that purpose.

WEPP is used to consider 2-dimensional slope profiles, and cannot, therefore, consider impacts of flow concentration over areas of tens of hectares. However, the detail provided by WEPP with respect to runoff and erosion and the location and timing of significant losses makes it an excellent design tool.

See Appendix 2 for greater detail on the WEPP model and its application.

4 ERODIBILITY MEASUREMENTS ON BULK SAMPLES

Measurements were made using simulated rain and overland flows to enable calculation of erodibility parameters for the WEPP runoff/erosion model.

4.1 Rainfall simulation

4.1.1 Rainfall simulator

The rainfall simulator used is of the design described by Loch *et al.* (2001), and applies simulated rain with a kinetic energy equivalent to that of natural rainfall at intensities >40 mm/h. In this case, intensities applied were in the range 90 – 130 mm/h for 25 minutes, which is consistent with storm return periods of 20 years for Tieri. (As the simulated rain study is used to derive infiltration and interrill erosion parameters, the actual intensity applied does not affect the parameters obtained, provided it is sufficient to cause runoff and of appropriate kinetic energy.)

4.1.2 Plot sizes

Due to limitations in the quantity of sample available to enable the various rates of mixing, simulated rainfall was – for most mixtures and materials – applied to flumes rather than to smaller plots. For the topsoil, flumes used are 0.4 X 2.0 m. For the rock:soil mixtures, larger flumes of dimensions 0.77 X 3.0 m were used. Photographs of the various surfaces following application of rain are shown in Figures 2 to 5.

However, for the 2:1 Quarry rock:topsoil mixture, triplicate plots 0.75 m square and 0.2 m deep (Figure 3) were used to measure infiltration rates of simulated rain and interrill erosion.

.

4.1.3 Plot preparation and rainfall application

Plots were prepared and lightly compacted during packing so that the re-packed samples were consistent with soil that had consolidated naturally under rainfall, and were subjected to wetting and drying to further consolidate the surface prior to application of simulated rain.

Plots were set at 20% gradient and simulated rain was applied for a period sufficient for the samples to reach steady infiltration/runoff rates.

Runoff generated by simulated rain was sampled at regular intervals (2-3 minutes), and sediment concentrations were measured gravimetrically.

Rain water was used in all measurements to avoid any potential impacts of water quality on infiltration and on the disaggregation of sediment to finer sizes.

Figure 2: Topsoil surface following application of simulated rain, 0.4 m wide flume

Figure 3: Surface of 4:1 Permian spoil:topsoil mix following application of simulated rain, 0.77 m wide flume.

Figure 4: Surface of 2:1 Quarry rock:topsoil mix following application of simulated rain, 0.75 m wide plot.

Figure 5: Surface of 4:1 Quarry rock:topsoil mix following application of simulated rain, 0.77 m wide flume.

4.2 Overland flows in flumes

As noted previously, studies of rill erodibility used flumes 2 m long and 0.4 m wide for the topsoil, and flumes 3 m long and 0.77 m wide for the rock:topsoil mixtures (Figure 6). For all materials, three flumes were run, set at various gradients, ensuring that a wide range of flow tractive force was applied. In all cases, samples were lightly compacted during placement in the flumes (to achieve a field bulk density for the material), then exposed to several wetting and drying cycles over several days to develop a hard, cohesive soil surface crust (consistent with typical field conditions) prior to application of overland flow.

For each flume, a sequence of increasing overland flow rates was applied. Each flow rate was maintained for 5 minutes and samples of runoff were taken at 1, 2, 3, and 5 minutes from the commencement of each flow rate for sediment concentration measurement.

The 4:1 Quarry rock:topsoil mixture was found to be so coarse that overland flow could not be generated effectively, and – consequently – erodibility parameters were not able to be generated for this mixture.

Figure 6: Flumes showing application of flow to (L-R) 4:1 Quarry rock:topsoil mix, 4:1 Permian rock:topsoil mix, and topsoil.

4.3 WEPP parameter derivation

4.3.1 *Erodibility parameters*

Erodibility parameters required for the WEPP model are K_i (interrill erodibility), K_R (rill erodibility – a detachment parameter), and τ_C (critical shear for rill initiation). These parameters are used to predict changes in erosion processes and rates in response to changes in runoff, slope length, and land management. Also important are the Hydraulic Conductivity parameter (K_e) used in the model to predict runoff, and sediment settling velocity distributions.

Parameters for the topsoil and the Permian waste:topsoil mix calculated from laboratory measurements are shown in Table 3. The table also shows erodibility parameters for a 2:1 Quarry rock:topsoil mixture, based on a combination of measured and estimated data.

Based on the measured D_{50} value for Permian rock, and assuming a sandstone bulk density of 2.4 g/cc, the Shields equation (Shields 1936) indicates that a critical shear value of approximately 47 Pa should have been measured; considerably larger than the 19.3 Pa actually measured. This is consistent with the observation that the proportion of fine particles in the mixture tested was high, and that the dominance of the fine particle matrix within the mixture was responsible for the poor infiltration and relatively high erodibility measured.

Although the mixture prepared in Landloch's laboratory was comprised of a 4:1 ratio of waste to topsoil, it appears that the functional ratio between coarse and fine particles was closer to 1:1, with the bulk of the additional fines coming from the waste. Consequently, the high proportion of fine particles in the mixture drastically reduced its erosion resistance.

Table 3: WEPP erodibility parameters derived from laboratory measurements.

Parameters	Units	Material tested		
		Topsoil	4:1 Permian waste:topsoil	2:1 Quarry rock:topsoil
Interrill erodibility (K_i)	kg.s.m^{-4}	4,384,058	1,897,066	1,923,735
Rill erodibility (K_R)	s/m	0.00133	0.00206	0.00206^A
Critical shear for rilling (τ_C)	Pa	11.1	19.3	63.5^B
Effective hydraulic conductivity (K_e)	mm/h	2.2	1.1	15
Steady infiltration rate	mm/h	7.5	6.5	30.3

^{A}: *Assumed to be similar to that of the Permian rock as D_{50} values are similar, and chemical properties of the associated fine fractions are also similar (Table 1).*

^{B}: *Calculated using Shields equation and estimated rock density of 2.4 g/cc.*

4.3.2 Sediment properties

To measure properties of "sediment available for detachment", samples of the surface seal layer were taken from plots immediately following application of simulated rain using the method outlined by Loch (1994). Settling velocity distributions of those samples were measured in a modified top entry settling tube (Loch 2001).

Rain water was used in all measurements to avoid any potential impacts of water quality on infiltration and on the disaggregation of sediment to finer sizes.

Results were expressed as "equivalent sand size distributions", and showed sediment from the topsoil (CR25) to have similar proportions of finer size classes to sediment from the Permian rock:topsoil mix, but to be somewhat finer than the Permian rock mix sediment in the equivalent sand sizes >0.1 mm (Figure 7). Input files detailing the measured equivalent sand size distributions were prepared and input to WEPP for simulations of runoff and erosion.

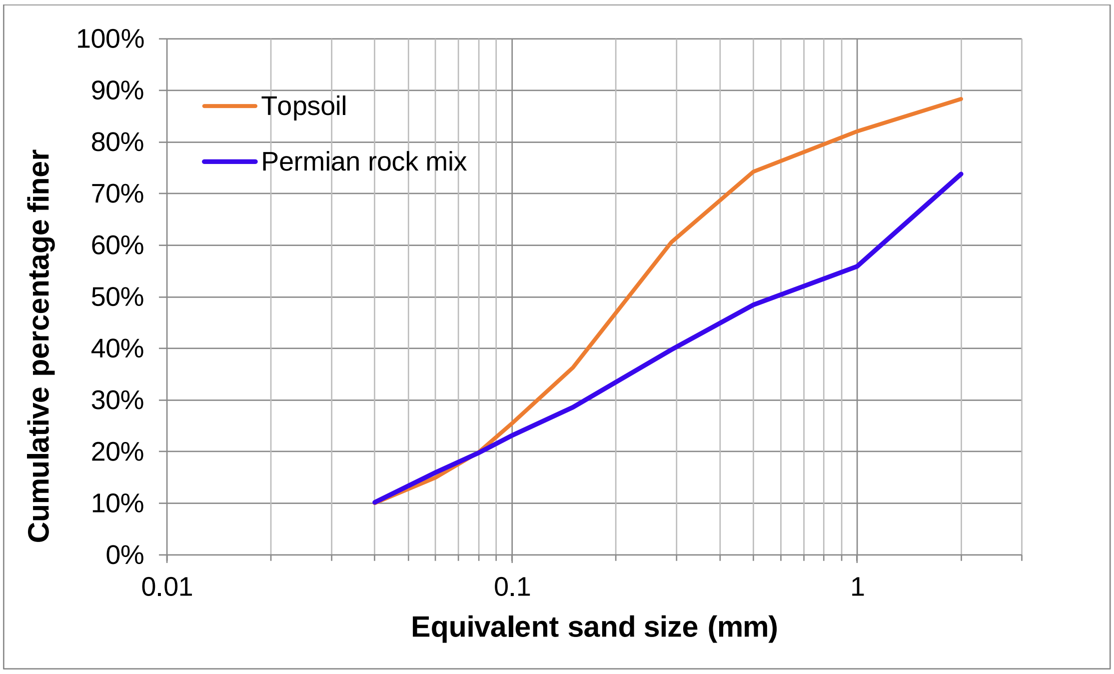


Figure 7: Settling velocity distributions of sediment, presented as equivalent sand sizes.

5 WEPP SIMULATIONS FOR LANDFORM OPTIONS

5.1 Climate file used

For a range of central Queensland mine sites, Landloch has used climate files for either the Comet Post Office, some 80 km to the south of Middlemount Mine, or Moranbah, some 170 km to the north of Middlemount. Both files have reasonably similar annual rainfall amounts, and – when used in simulations – provide reasonably similar predicted erosion amounts. Given the geographic spread between the two locations, it appeared reasonable to consider that variation in rainfall erosion potential across the intervening distance was minimal.

However, after discussion with Middlemount staff, rainfall stations closer to the site were investigated, and the station 35109 Booroondarra was identified;

approximately 20 km west of Middlemount. This site had 98 years of record, and annual rain of 634 mm, considerably higher than that of Comet and Moranbah (578 mm and 553 mm respectively in those climate files).

Consequently, a 100 year climate sequence compatible with WEPP's input requirements was developed for Booroondarra using statistical methods. Two climate datasets were used to prepare the climate file:

(a) SILO Patched Point data for 35109 Booroondarra from 01/01/1921 to 31/12/2018 for rainfall, maximum and minimum temperatures, and solar radiation were sourced from the Australian Bureau of Meteorology (BoM).

(b) The sub-daily pluviograph data used to inform the storm intensity and duration parameters was sourced from 35147 Emerald DPI Field Station from 01/03/1983 to 31/08/2009. Coordinates are -23.4669, 148.1519. This site is 80km south south west of Middlemount. It is the closest pluviograph data available for the site with record longer than 15 years.

The synthetic climate sequence retains the same following characteristics as the observed daily data in terms of:

- Mean daily precipitation on wet days for each month,
- Standard deviation of daily precipitation for each month,
- 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 maximum temperature for each month,
- Standard deviation of daily maximum temperature for each month,
- Mean daily minimum temperature for each month,
- Standard deviation of daily minimum temperature for each month,
- Mean daily solar radiation for each month and
- Standard deviation of daily solar radiation for each month.
- Mean maximum 30-min rainfall intensity for each month, and
- Probability distribution of the time to peak storm intensity.

A 100-year climate sequence was generated using CLIGEN version 5.1 (Yu 2003). Average annual rainfall for the file is 636 mm, and the CLIGEN file corresponds closely with both measured monthly rain and rainfall return periods (Figures 8 and 9). It contains considerable variation through the 100-year period of data (Figure 10).

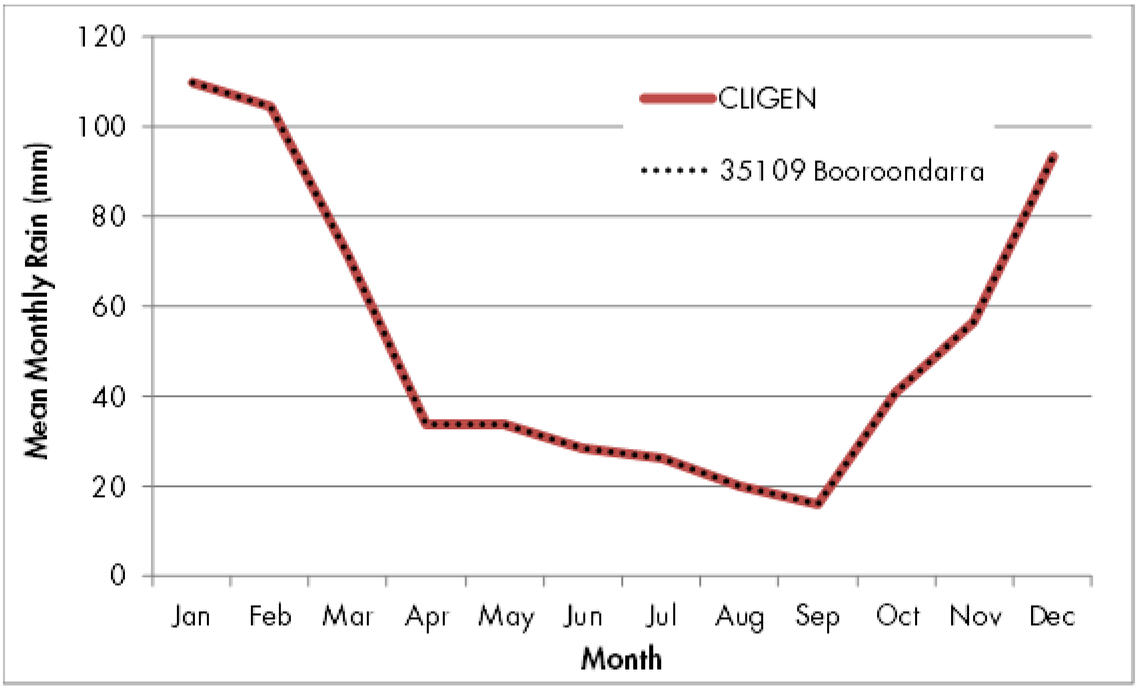


Figure 8: Comparison of average monthly rainfall in measured and synthetic files.

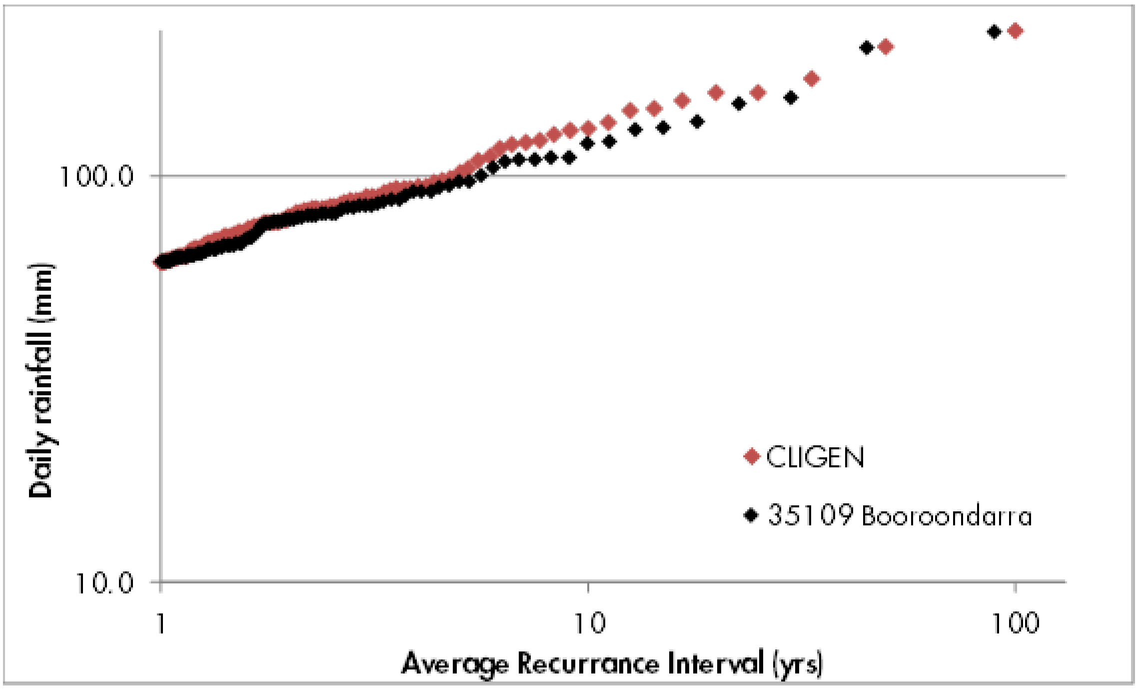


Figure 9: Comparison of rainfall amounts for various return periods for measured and synthetic files.

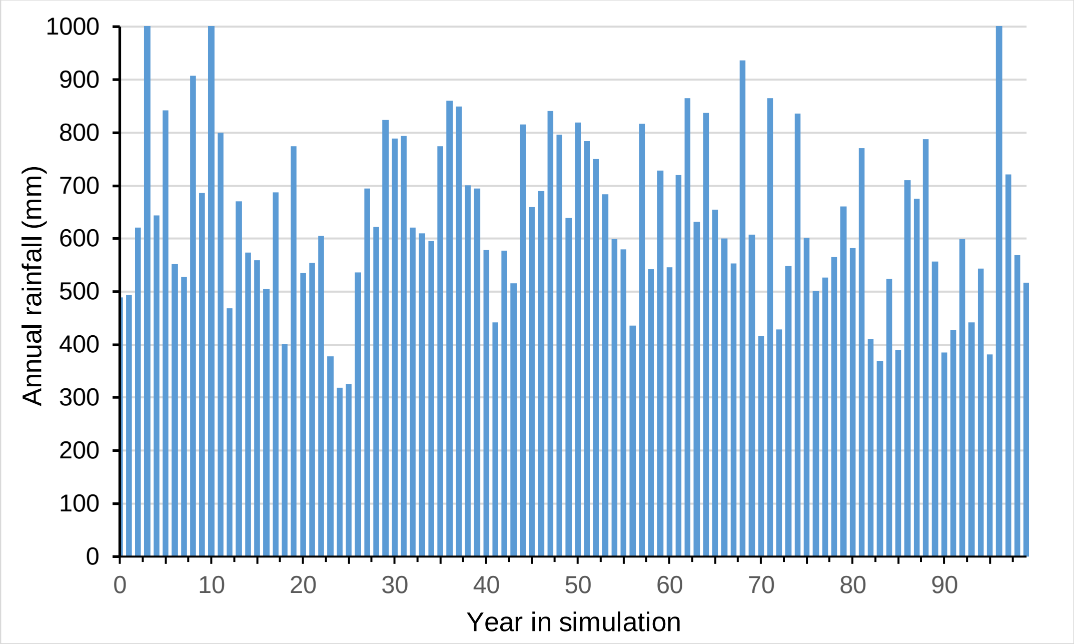


Figure 10: Annual rainfall variation within the 100-year climate file used for WEPP simulations.

5.2 Materials considered

As the 4:1 Permian rock:topsoil mixture was observed to have an unduly high proportion of fine particles, simulations considered not only the mixture tested, but also possible alternative mixtures with parameters estimated on the basis of available data.

For alternative mixtures, it was assumed that methods of handling the Permian rock could be altered such that the fine fraction of that waste, e.g. >20 mm, was able to be excluded, leaving only the coarser fraction. This would require a change in waste handling to exclude fines, which could be achieved through use of a skeleton bucket on the excavator used to load the waste for transfer to the waste landform for placement and mixing with topsoil. However, this practice would be likely to not only remove much of the fines, but also some of the moderate particle sizes (e.g., up to 50 or up to 75 mm diameter), and could result in rock with a somewhat larger D_{50} being delivered for placement on rehabilitated areas. Consequently, a mix of rock with a somewhat larger D_{50} was also considered.

This gave:

- 4:1 Permian rock:topsoil mix as tested (critical shear for rilling of 19.3 Pa);
- 4:1 Permian rock:topsoil mix with a reduced proportion of fines, so that its critical shear for rilling of was 47 Pa, based on rock D_{50} of 77 mm; and
- Permian rock:topsoil mix with rock D_{50} of 120 mm and critical shear (calculated) of 74 Pa.

For all mixtures, infiltration capacity of the mix was not altered, as increasing the proportion of topsoil relative to Permian fines in the mix was not indicated by experimental data to have significant potential to change infiltration rates.

5.3 Surface conditions tested

5.3.1 Slopes

Initial simulations considered linear slopes of 100 m horizontal length, at gradients of 16.66% and 33.33%. Effectively, changing gradient in these simulations did change the height of landform considered.

Subsequent simulations considered a landform 65 m high, with gradients of 16.66% and 33.33%.

Importantly, for all slope options considered, **it was assumed that runoff on the top of the waste landform would NOT be discharged onto the outer batter slopes.** It is assumed that an appropriate perimeter bund and cross-bunding will be installed to contain any rainfall excess on the top of the landform.

5.3.2 Vegetation cover

Three surface conditions were considered:

(a) bare surface with rill spacing set to 3 metres to allow for some spreading of surface flow by the rock.

(b) vegetated surface, assumed to have achieved 40% grass cover. Hydraulic conductivity of the mix was increased to allow for an increase in infiltration rate of 7 mm/h per 10% increase in grass cover (based on data of Kato et al. 2009), though recent data from another site indicate that that level of increase may not be achieved on dispersive soils. Rill spacing was reduced from 3 to 2 metres to account for higher surface hydraulic roughness, and a cover factor of 0.10 applied. This value was taken from the SOILLOSS Manual (Rosewell 1993).

(c) vegetated surface, assumed to have achieved 60% surface cover. Hydraulic conductivity was adjusted to account for the increase in infiltration capacity associated with grass cover, and rill spacing was kept at 2 metres.

Greater detail on the methods used to account for vegetation impacts is given in Appendix 3.

5.4 Model output – initial simulations

5.4.1 Impacts of vegetation on predicted annual runoff

For bare surfaces, predicted annual runoff was 298.5 mm/y, reducing to 49.7 mm/y for 40% vegetation cover, and to 22.5 mm/y for 60% vegetated cover. Consequently, the assumed impact of vegetation on infiltration capacity resulted in a drastic reduction in annual runoff, and would also have consequently also greatly reduced predicted rates of erosion.

5.4.2 Predicted erosion rates – 40% cover and lower test slope

Data on average and peak predicted erosion rates on the test slope used in simulations are shown in Table 4.

Generally, to achieve a sustainable and stable batter slope, Landloch would aim for average erosion rates <5 t/ha/y, and maximum rates at any point on the slope <10 t/ha/y. If a slope is considered high risk, more stringent conditions may be applied, though that has not been considered necessary in this case.

Based on those conditions, cells with erosion rates considered "acceptable" are highlighted green.

The data show that, irrespective of the rock sizes placed, vegetation establishment has a major impact on erosion potential of the slopes considered. However, there is also a large impact of rock size and critical shear on erosion risk.

The initial data – both measured and modelled – indicate that the 4:1 Permian:topsoil mixture,as tested, is unlikely to deliver successful rehabilitation if placed on steep (33.3%) slope gradients. At the lower gradient of 16.66%, there was potential for 100 m long slopes to be stable, provided at least 40% surface vegetation cover was established.

Its relatively high erodibility is due to the relatively high proportion of fine particles in the mixture – almost certainly largely from the Permian waste. If that proportion of fines can be reduced, then the potential for the Permian rock to enable construction of stable rehabilitated slopes is much greater, and slope gradients up to 33.3% could be constructed (provided sufficient vegetation cover was established).

Table 4: Erosion rates predicted by WEPP simulations for a range of material properties, surface conditions, and batter gradients – 4:1 Permian rock:topsoil mixture.

Material tested	Surface condition	Gradient (%)	Average erosion rate (t/ha/y)	Peak erosion rate (t/ha/y)
4:1 Permian waste:topsoil mixture	Bare	33.3	488.7	1061
		16.66	154.4	435
	Vegetated (40% cover)	33.3	9.4	20.8
		16.66	2.7	8.1
4:1 Permian waste:topsoil mixture, but with reduced fines	Bare	33.3	80.2	317
		16.66	7.3	24
	Vegetated (40% cover)	33.3	1.3	4.9
		16.66	0.28	0.37
Increased D_{50} and increased critical shear	Bare	33.3	11.3	43
		16.66	4.8	4.9
	Vegetated (40% cover)	33.3	0.39	0.56
		16.66	0.27	0.27

5.4.3 Increased landform heights and higher levels of vegetation cover

Following discussions of likely final landform options, further WEPP simulations were carried out to consider:

- Landform height of 65 metres

- Gradients of 16.66% and 33.3%
- Permian rock mix with either 47 Pa or 74 Pa critical shear
- Vegetation cover of 40% and 60%

For 60% vegetation (grass) cover, final infiltration rate and effective hydraulic conductivity of the mix was increased to allow for an increase in infiltration rate of 7 mm/h per 10% increase in grass cover. A cover factor of 0.042 was applied, taken from the SOILLOSS Manual (Rosewell 1993).

Results of those simulations are shown in Table 5. In this case, cells with erosion rates considered "acceptable" are highlighted green.

The simulations show large impacts on predicted erosion rates from material properties, gradient, and vegetation cover level.

Table 5: Erosion rates predicted by WEPP simulations for a range of material properties, surface conditions, and batter gradients – 4:1 Permian rock:topsoil mixture and 65 metre high landform.

Material tested	Surface condition	Gradient (%)	Average erosion rate (t/ha/y)	Peak erosion rate (t/ha/y)
Permian rock mix, critical shear of 47 Pa	Bare	33.3	277	872
		16.66	122	451
	40% cover	33.3	4.5	15.1
		16.66	1.5	5.8
	60 % cover	33.3	1.1	3.6
		16.66	0.4	1.3
Permian rock mix, critical shear of 74 Pa	Bare	33.3	57.3	264
		16.66	15.5	73
	40% cover	33.3	0.8	3.4
		16.66	0.3	0.8
	60 % cover	33.3	0.2	0.8
		16.66	0.01	0.2

For 40% grass cover, the simulations indicate that the current Permian rock size distribution – if its fine component can be reduced – will definitely be stable to erosion if placed on a 65 metre high landform at 16.55% gradient, and is likely to be reasonably stable if placed at a gradient of 33.3%. If the rock size becomes coarser (and critical shear increases to 74 Pa) as a result of changed handling practices, then the data show that both slope gradients will be extremely stable for this cover level.

For 60% grass cover, the simulations indicate slopes of either gradient, placed on a 65 metre high landform, will be extremely stable. This highlights the importance, for this landform, of achieving vegetation cover targets and establishment of sustainable and vigorous vegetation cover.

5.5 Alternative materials

5.5.1 Other samples constructed from supplied materials

Other samples analysed were:

- Topsoil (without any added rock);
- 2:1 Quarry rock: soil mix; and
- 4:1 Quarry rock:topsoil mix.

Of those materials, the 4:1 quarry rock:topsoil mix did not register runoff, and the ratio of coarse to fine particles was clearly too high for this mixture to achieve a suitable rehabilitation outcome. Effectively, the proportion of fine particles in the mixture was so low that there is insufficient growth medium to support plant growth.

5.5.2 Topsoil and vegetation

Simulations were carried out to assess:

- Potential rates of erosion of topsoil prior to vegetation establishment; and
- Potential for long-term stability if vegetation is established.

Slope gradients tested were 33.3% and 16.66%, both for 65 m slope height.

Bare soil, and soil with 40% and 60% vegetation cover. For 40% cover, rill spacing was set to 3 metres, as there was no surface roughness from rock. For 60% cover, the spacing was reduced to 2 metres. Infiltration rates were adjusted to account to increased vegetation cover as outlined previously.

For 33.3% gradient, the simulations (Figure 11) showed that the bare soil had extremely high erosion potential, reaching a maximum of 638 t/ha/y and an average along the slope of 446 t/ha/y. It is worth noting that – for the topsoil – the pattern of erosion along the slopes is such that average rates for the slope are not greatly less than the maximum erosion rates. This is in contrast to the situation where rock is added to the surface, where the differences between average and maximum erosion rates are much greater (Tables 4, 5, and 6), a consequence of rill development occurring at longer slope lengths and detachment rates being slower.

The simulations also showed that achievement of 60% cover was essential for the slope to achieve the target erosion rate of <5 t/ha/y.

To control the potentially high erosion rates from bare soil during vegetation establishment, the use of berms (to shorten effective slope length) and contour ripping (to incease surface depression storage and reduce runoff) will be essential to avoid excessive damage to the prepared slope surface during that period.

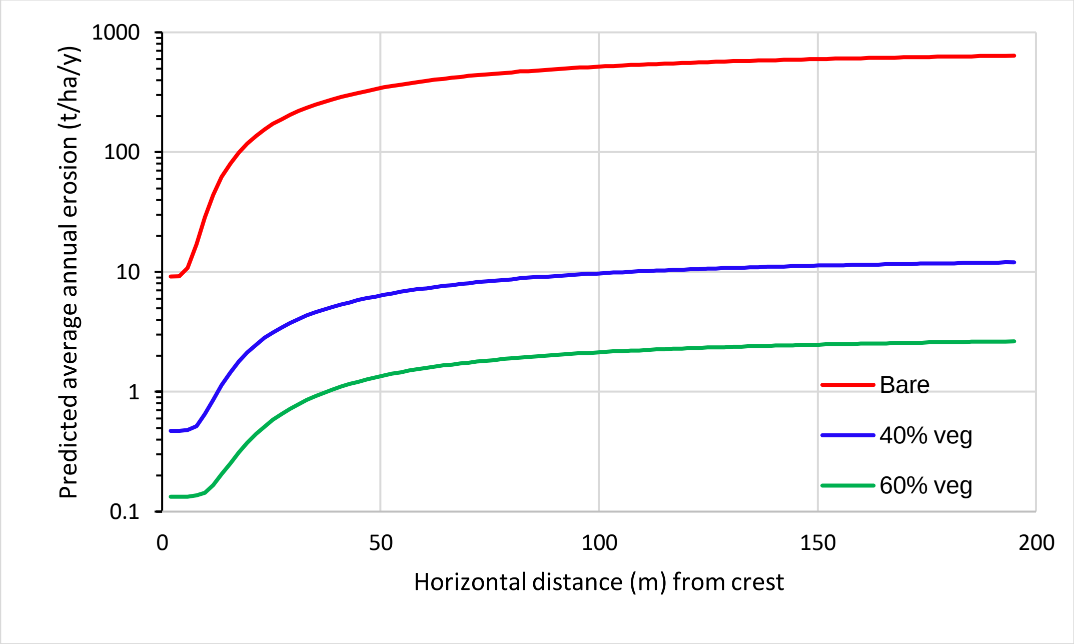


Figure 11: Predicted impacts of vegetation cover and slope length on erosion rates along batter slopes on 33.3% gradient.

At 16.6% gradient, predicted erosion rates were lower (Figure 12), though still high for the bare slope surface, reaching an average of 268 t/ha/y and a maximum rate of 342 t/ha/y. At this gradient, 40% vegetative cover would just be sufficient to achieve the erosion target of <5 t/ha/y.

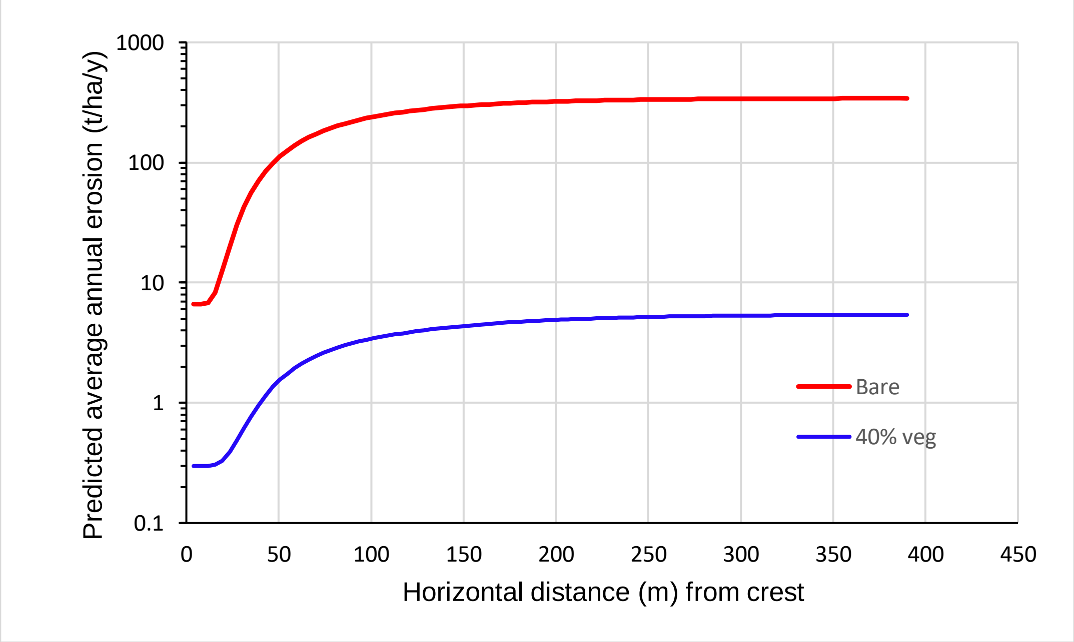


Figure 12: Predicted impacts of vegetation cover and slope length on erosion rates along batter slopes on 16.6% gradient.

5.5.3 *Quarry rock:topsoil mix*

Not all erodibility parameters were able to be measured for this material with some needing to be inferred. Specifically:

- Measured values were used for interrill erodibility and effective hydraulic conductivity, with the latter being considerably higher than that measured for the topsoil on its own.
- Critical shear of 63.5 Pa was calculated on the basis of measured D_{50} of 90 mm and a rock specific gravity of 2.6 g/cc.
- Rill erodibility was left at the same value as that measured for the 4:1 Permian rock:topsoil mix.

For the same slope options as tested previously (65 m high and gradients of 33.3% and 16.66%), a bare surface (3 m rill spacing) was predicted to produce 59.4 mm runoff per year. Predicted erosion rates for bare and vegetated surfaces are shown in Table 6, with green shading again indicating surfaces for which predicted erosion rates are acceptable. The same procedures for accounting for vegetation impacts were applied.

The data in Table 6 indicate that – in terms of erosion stability – this material offers significant advantages. It should be noted, however, that its agronomic quality is both low and not greatly different to that measured for the 4:1 Permian rock:topsoil mix.

Table 6: Erosion rates predicted by WEPP simulations for the 2:1 Quarry rock:topsoil mixture.

Material tested	Surface condition	Gradient (%)	Average erosion rate (t/ha/y)	Peak erosion rate (t/ha/y)
2:1 Quarry rock:topsoil	Bare	33.3	34.6	130
		16.66	10.7	42
	Vegetated	33.3	0.7	2.7
		16.66	0.24	0.8

5.6 Managing erosion risk during vegetation establishment

For a newly rehabilitated site, in the period – typically September to November – when vegetation is establishing, a once-off total erosion amount of 30-40 t/ha could be acceptable.

5.6.1 *Impacts of added rock during vegetation establishment*

If the predicted erosion rates for bare soil for a full slope height 65 m and on 33.3% gradient are considered as an indication of erosion risk during vegetation establishment, it is clear that the risk of severe erosion during that period can be quite high.For topsoil without any added rock, predicted erosion in that period (Figure 13) is in the order of 76 t/ha, much larger than the value of 30-40 t/ha considered acceptable.

For a bare surface with critical shear of 47 Pa due to added rock and infiltration capacity consistent with bare condition, simulations (Figure 13) suggest an average erosion amount in the September to November period of 45 t/ha, slightly higher than the suggested target values. As well, the predicted rate at the lower end of the slope is approximately 4 times the average for the full length of slope, indicating that – for that rock D_{50} - there would be areas at the toe of the long slope for which erosion would be unacceptable and one or more temporary berms would be required to reduce effective slope length while vegetation established.

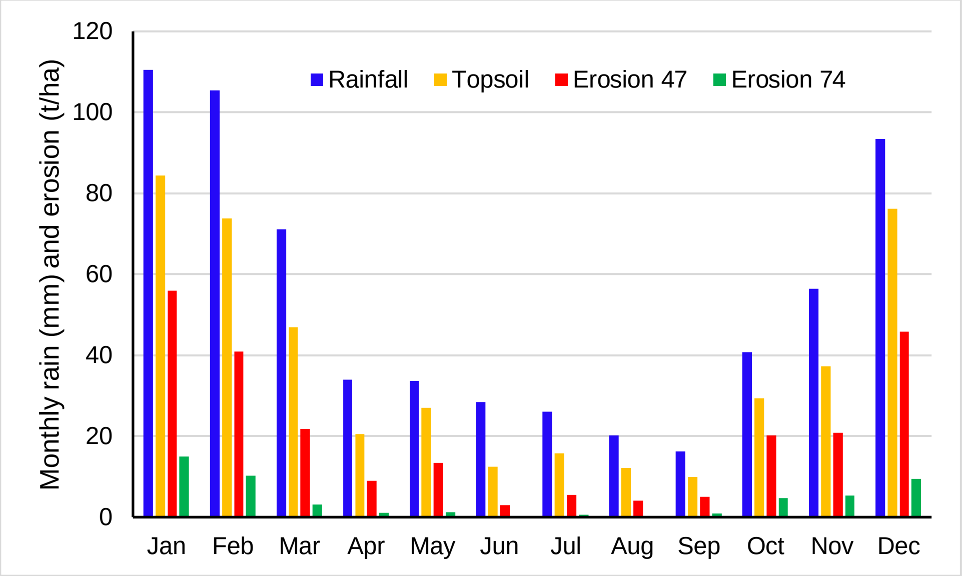


Figure 13: Predicted monthly rainfall and erosion for bare surfaces of topsoil and rock:soil mixes with critical shear of either 47 or 74 Pa. Rill spacing 5 m for topsoil, and 3 m when rock added.

5.6.2 Use of temporary berms

Topsoil only

For topsoil on 33% gradient, the predicted pattern of erosion (Figure 11) shows a rapid increase in erosion rate at a quite short slope length, with erosion rate reaching a maximum determined by sediment properties and sediment transport capacity. For berms to be effective on topsoil at this high gradient, they would need to so closely spaced as to be impractical. Consequently, berms are not recommended for steeper slopes when topsoil is placed without added rock.

For topsoil on 16.6% gradient, predicted erosion in the vegetation establishment period September – November is higher than the target value, indicating that some form of erosion control would be needed for these slopes. Assuming that – based on predicted values – erosion in the critical period is approximately 16% of the total annual erosion, then an annual rate at a point on the slope of ~186 t/ha/y equates to the tolerable amount of 30 t/ha. Based on that value, simulations indicate a maximum berm spacing of 74 m, which, with allowance for berm width, would be consistent with construction of 4 berms to break the 65 m high slope into 5 equal sections.

Added rock, 47 Pa critical shear

At 33.3% gradient, where added rock increases critical shear to 47 Pa, the predicted rate of erosion for a bare surface at a slope length of 65 m is approximately 30 t/ha for the entire year, and would, therefore, be acceptable. (Erosion in the critical vegetation establishment period would be much lower again.) Installing berms at 65 m slope length would enable the full 65 m high slope to be protected using two temporary berms installed at distances of 65 and 130 m from the crest of the slope.

At 16.6% gradient, erosion at the toe of the slope during the critical revegetation period is slightly more than double the target amount. In this case, a slope length of 280 m is predicted to meet the 30 t/ha target. For slope lengths between 280 and 390 metres, a single, mid-slope berm would be the most practicable option and should provide effective erosion control during the establishment period.

Coarse added rock, critical shear 74 Pa

If rock D_{50} was 120 mm and critical shear increased to 74 Pa, simulations indicate that – for a 65 m high slope with 33.3% gradient - erosion in that critical period of vegetation establishment would be reduced (Figure 13). Predicted erosion in that period then averages 22 t/ha along the complete slope, with the rates of erosion at the toe of the slope being approximately 5 times higher the the slope average. That means that cumulative erosion at the toe of the slope during the period of risk is unlikely to be acceptable and, some additional measures to stabilise the surface would be required.

However, for both 33.3% and 16.6% gradients, a more practicable option would be to rely on use of contour ripping to reduce erosion risk during vegetation establishment rather than to install berms for this material.

5.6.3 Contour ripping

A key impact of ripping on the contour is to increase surface detention storage, thereby reducing runoff. However, Landloch generally only recommends significant contour ripping for rocky materials. Where surface materials contain little rock, cross-slope rip lines tend to overtop easily and establish a rapidly eroding rill network that can increase rates of erosion quite significantly.

Consequently, in this case, impacts of cross-slope ripping were only considered for the surface with 120 mm rock D_{50}, and critical shear of 74 Pa. For that situation, furrow overtopping would be less likely to permanently damage furrows, and the surface detention storage would be more persistent.

Within the WEPP model, detention storage is accounted for by a Random Roughness term (RR), with effective surface storage being related to both RR and slope gradient. Simulations assumed that the "standard" surface ripping treatment for rehabilitation would involve dozer rip lines at approximate spacing of 1 m, with a typical dozer ripping depth of 300 to 400 mm. The assumed furrow cross section was roughly V-shaped, and effective furrow depth was assumed to be 200 mm. At a 20% slope gradient, that gave surface detention storage of 35 mm and RR value of 13 cm.

For that value of RR, a bare slope 65 m high on 33.3% gradient with critical shear of 74 Pa was predicted to have annual erosion at its toe of 23 t/ha, confirming that – for surfaces with coarser rock – cross-slope ripping would be sufficient to achieve the necessary short-term erosion control and berms would not be required.

(Long-term simulations used a RR value of 3 cm to represent a long-term surface that has smoothed out under raindrop impact and various surface process and that would apply over the large proportion of the time periods simulated.)

5.7 Concave slope options

In this case, the material/vegetation combinations tested generally showed that linear slopes on 33.3% gradient up to 65 m high are likely to be stable, therefore rendering concave slope profiles unnecessary.

The only linear slope/vegetation combination that was shown to be marginally stable was rock with critical shear of 47 Pa, and vegetation cover of 40%. For that combination, a concave slope option was investigated, with the resultant slope 225 m long profile shown in Figure 14. Effectively, the design reduces gradients on the lower 20 m of fall from the top of the slope, with the effect of flattening out the toe of the slope and (probably) giving a slightly smoother transition from the batter slope to the adjoining land surface.

The graph shows gradients for each slope segment, with changes in gradient at slope lengths/elevations (m) of:

- 133/20.7 and
- 180/8.9

Overall, the concave profile, for the critical shear and vegetation levels considered, reduces predicted erosion on the slope (relative to a linear profile of the same height and length) by 44%.

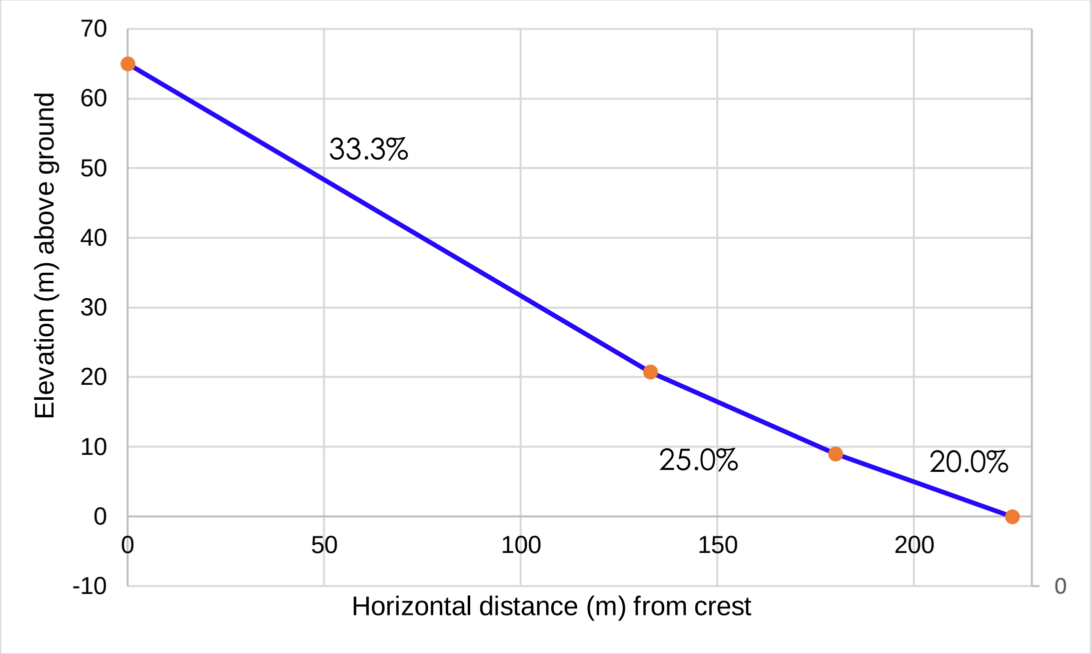


Figure 14: Concave profile developed for material with critical shear of 47 Pa and vegetation cover of 40%.

It may well be more cost-effective for rehabilitation works to focus on delivering higher levels of vegetative cover than on installation of a concave profile.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Priorities for achieving stable batter slopes

6.1.1 Gradients

Simulations demonstrated interactions between slope gradient, critical shear for rilling (as influenced by added rock), and vegetation cover. Generally, at the steeper gradient, achievement of long-term stability required addition of rock and achievement of at least 40% cover and, for some slope options, 60% vegetation cover.

6.1.2 Rock diameters

In the very short term, a major priority for achieving stable slopes is the placement of a rock:topsoil mix that will have appropriate mixing ratios of coarse and fine particles and a suitable critical shear to resist erosion. Simulations in this study suggest that a **minimum** critical shear of approximately 50 Pa – consistent with a rock D_{50} of approximately 80 mm – is desirable.

However, there appears to be significant advantage in terms of initial slope rehabilitation requirements from use of a slightly coarser rock, and a rock D_{50} closer to 120 mm is recommended.

6.1.3 Vegetation

For the medium to long term, the model output shows that establishment of sustainable surface cover of at least 40%, and preferably 60% or greater, is essential. This will be particularly so if, over the longer term, the rock added to the surface layer gradually weathers and effectiveness in controlling erosion reduces.

Importantly, the need for surface (contact) cover puts focus on establishment of grasses, as shrubby vegetation produces canopy cover but generally considerably less contact cover.

However, given the high pH and moderate to high salinity of the fine fractions in the waste rock, it could be considered likely that the vegetation established may become dominated by salt - tolerant shrubby genera such as *Atriplex* if the rock:topsoil mix has chemical properties similar to those measured for the mixtures used in this study (Table 1).

Salt-tolerant grass species that should be suitably adapted include:

- Rhodes grass (Tolgar or Reclaimer cultivars);
- Saraji Urochloa;
- Digit grass (*Digitaria eriantha* ssp. eriantha) cv. Premier; and
- Indian bluegrass or Indian couch (*Bothriochloa pertusa*) cvv. Keppel, Medway, Bowen.

Other grass species should also be trialled.

A range of forb, shrub, and tree species could be included in the seeding mix, preferably with a component of leguminous (N-fixing) species, and a component of highly salt tolerant species such as *Atriplex* sp.

6.2 Rock/soil layer depth

A key consideration for rock layer installation is the depth of layer (and quantity of rock) required.

There is ample logical and observational evidence that the rock layer may not need to be overly deep, provided it is stable (able to resist movement by overland flows). Logically, if a layer of rock does not move, then it is likely to persist for long periods (probably thousands of years).

For placement of rock layers on waste landform slopes, one consideration is that riprap construction typically uses layers 1.5 to 2.0 times the D_{50} of the rock being placed, depending on the degree of variation in rock diameters. Where D_{50}/D_{90} is 0.8, then a layer thickness of 1.6 x D_{50} is recommended (IECA 2010). However, where D_{50}/D_{90} is 0.5, then recommended riprap thickness increases to 2.1 x D_{50}. Because control of larger sizes occurring in waste rock may not be as strict as in supply of rock for engineering construction, the higher ratio is recommended as a minimum.

For example, for a D_{50} of 120 mm, this would indicate a rock/topsoil layer depth of approximately 250 mm. For D_{50} of 77 mm, layer depth would be 161 mm.

However, there are concerns with respect to the depth of rock layer that can be formed reliably. For example, if the accuracy of rock layer placement is ±300 mm, then an average layer depth of 500 mm would have some areas where layer depth was barely sufficient. Consequently, the accuracy with which layer depth can be controlled during construction will also be a factor in setting a target rock layer depth.

6.3 Preparation of an effective growth medium layer

From the data shown in Table 1, it is clear that exclusion of the fine fraction from the Permian waste so that the mixture created was solely composed of topsoil and Permian rock, would result in a growth medium with greatly improved agronomic properties:

- pH close to neutral;
- lower salinity
- lower chloride
- non-sodic.

As removal of fines from the Permian waste could also be expected to increase the mixture's rock D_{50} and, therefore, erosion resistance, there appear to be considerable benefits from exclusion of fines.

It is likely that, over time, there may be some release of salts from the rock, as Permian rock from the Middlemount pit tends to the either highly saline or highly alkaline (MCPL, 2018). Consequently, the development of vigorous vegetation with strong root development to increase water movement and salt leaching to depth in the profile is important for long-term vegetation sustainability.

Fertilisation to achieve rapid vegetation growth and surface stabilisation will be essential. It will also be advisable to use slow-release formulations as well as the more commonly used soluble products to enable not only greater addition of nutrients, but also to prolong the initial period of vigorous growth.

6.4 Summary

Gradients:

- Gradients ranging from 16.5% to 33.3% could be constructed, provided surface rock diameters and levels of vegetation achieved are consistent with requirements to achieve stability (Table 4 and Figures 11 and 12).

Materials:

- Provided vegetation cover level is sufficient, a range of materials (topsoil and topsoil/rock mixes) could achieve soil erosion targets at gradients up to 33.3%.
- Levels of vegetation required for achievement of long-term stability are reduced by placement of rock and for coarser rock diameters, meaning that achievement of erosion stability is less challenging when coarser rock is placed.
- Handling rock so that the fine component (<5 mm diameter) is discarded prior to placement will enable more reliable delivery of a 2:1 coarse:fine mixture.
- Discarding the fine component (<5 mm diameter) from Permian rock prior to placement is likely to greatly improve the agronomic quality of the rock:soil mixture placed.

Batter stabilisation during revegetation

- For topsoil at 33.3% gradient, it is unlikely that initial erosion rates can be reduced sufficiently for this gradient/material combination. Consequently, the high risks of erosion during vegetation establishment mean that use of topsoil alone is recommended to be restricted to gradients of approximately 16.6%.
- For topsoil at 16.6% gradient, a maximum (temporary) berm spacing of 74 m horizontal distance is recommended.
- For topsoil with added rock, critical shear of 47 Pa, a berm spacing of 65m horizontal is recommended for slopes of 33.3% gradient, increasing to a maximum horizontal distance of 280 m at 16.6% gradient.
- For topsoil with added rock, critical shear of 74 Pa, temporary berms are not recommended; contour ripping should be sufficient to achieve the target erosion rate.

Contour ripping

- Although contour ripping will undoubtedly be applied to all treatments, the only material for which a reduction in runoff was modelled and considered was the rock:topsoil mix with 74 Pa critical shear. It is assumed that – for more erodible materials – overtopping of furrows will rapidly render the ripping treatment ineffective in terms of runoff and erosion control.

Rock layer depth

- The minimum depth of rock:topsoil mixture to be placed is calculated as 2.1 X D_{50}. For a D_{50} of 120 mm, this would indicate a rock/topsoil layer depth of approximately 250 mm. For D_{50} of 77 mm, layer depth would be 161 mm.
- There are concerns with respect to the depth of rock layer that can be formed reliably, and it is possible that operational constraints may dictate placement of a somewhat deeper layer.

Vegetation

- Establishment of sustainable surface cover of at least 40%, and preferably 60% or greater, is essential.
- The need for surface (contact) cover puts focus on establishment of grasses
- A range of salinity and drought-tolerant grass species are recommended in section 6.1.3.
- Forb, shrub, and tree species included in the seeding mix should have a component of leguminous (N-fixing) species and a component of highly salt tolerant species.

7 REFERENCES AND RELEVANT DOCUMENTS

Chaves, H.M.L, and Nearing, M.A. (1991). Uncertainty analysis of the WEPP soil erosion model. *Trans. Am. Soc. of Agric. Engrs.* 34: 2437-2444.

Flanagan, D.C., and Livingston, S.J. (1995). WEPP user summary. NSERL Report No 11, USDA-ARS-MWA.

Flint, J.J. (1974). Stream gradient as a function of order, magnitude, and discharge. *Water Resources Research*. 10:969-973.

Ghidey, F., and Alberts, E.E. (1996). Comparison of measured and WEPP predicted runoff and soil loss for Midwest claypan soil. *Trans. Am. Soc. of Agric. Engrs.,* 39: 1395-1402.

Gilbert, G. (1909). The convexity of hillslopes. *J. Geol.* 17:344-350.

Hazelton, P. and Murphy, B. (2007): *Interpreting soil results: What do all the numbers mean?* CSIRO Publishing.

Howard, E.J., and Roddy, B.P. (2012). Evaluation of the water erosion prediction project (WEPP) model: validation data from sites in Western Australia. In *Mine Closure 2012*, A.B. Fourie and M. Tibbett (eds). 2012 Australian Centre for Geomechanics, Perth, ISBN 978-0-9870937-0-7.

Kato, H., Onda, Y., Tanaka, Y., and Asano, M. (2009). Field measurement of infiltration rate using an oscillating nozzle rainfall simulator in the cold, semiarid grassland of Mongolia. *Catena* 76: 173–181.

Liu, B.Y., Nearing, M.A., Baffaut, C., and Ascough II, J.C., (1997). The WEPP watershed model: III. Comparisons to measured data from small watersheds: *Trans. Am. Soc. of Agric. Engrs*., 40(4): 945-951.

Loch, R.J. (1994). A method for measuring aggregate water stability of dryland soils with relevance to surface seal development. *Australian Journal of Soil Research* 32: 687-700.

Loch, R.J. (2000a). Effects of vegetation cover on runoff and erosion under simulated rain and overland flow on a rehabilitated site on the Meandu Mine, Tarong. *Australian Journal of Soil Research* 38: 299-312..

Loch, R.J. (2000b). Using rainfall simulation to guide planning and management of rehabilitated areas: I. Experimental methods and results from a study at the NorthParkes mine. *Land Degradation and Development* 11: 221-240.

Loch, R.J. (2001). Settling velocity – a new approach to assessing soil and sediment properties. *Computers and Electronics in Agric*. 31: 305-316.

Loch, R.J. and Orange, D.N. (1997). Changes in some properties of topsoil at Tarong Coal – Meandu Mine coalmine with time since rehabilitation. *Australian Journal of Soil Research* 35: 777-784.

Loch, R. J., Robotham, B. G., Zeller. L., Masterman, N., Orange, D. N., Bridge, B. J., Sheridan, G., and Bourke, J. J. (2001). A multi-purpose rainfall simulator for field infiltration and erosion studies. *Australian Journal of Soil Research* 39: 599-610.

Middlemount Coal Pty Ltd (2018) Middlemount Coal Mine Western Extension Project Environemntal Assessment Report, Prepared by Resource Strategies, September 2018, project MCPL-02

Nearing, M.A. and Nicks, A.D. (1998). Evaluation of the Water Erosion Prediction Project (WEPP) model for hillslopes: in "*Modelling Soil Erosion by Water*" (J Boardman and DT Favis-Mortlock, eds.), Springer-Verlag NATO-ASI Series I-55, Berlin: 45-56.

Nearing, M.A., Dear-Ascough, L, Laflen, J.M. (1990). Sensitivity analysis of the WEPP Hillslope Erosion Model. *Transactions of the ASAE*, 33: 839-849.

Renard, K.G., Foster, G R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (1993). *Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE)*. US Department of Agriculture, Agriculture Handbook No. 703. National Technical Information Service, Springfield, Virginia.

Robinson, S.L. and Finucane, S.J. (2019). Key outcomes of functional benchmarking for waste rock landform closure at a Western Australian iron ore mine. In *Mine Closure 2019* - AB Fourie & M Tibbett (eds), © 2019 Australian Centre for Geomechanics, Perth, ISBN 978-0-9876389-3-9, pp. 871-882.

Rosewell, C. J. (1993). SOILOSS. A program to assist in the selection of management practices to reduce erosion. Technical Handbook 11, 2nd edition. Soil conservation Service of NSW.

Santi, P.M. (2006). Field Methods for Characterizing Weak Rock for Engineering. Environmental & Engineering Geoscience, Vol. XII, No. 1, pp. 1–11.

Shields, A. (1936). Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung [Application of similarity mechanics and turbulence research on shear flow]. *Mitteilungen der Preußischen Versuchsanstalt für Wasserbau (in German).*

Strahler, A.N. (1964). Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*, ed. Ven T. Chow, pp. 4-39 – 4-76.

Tiwari, A.K., Risse, L.M., and Nearing, M.A. (2000) Evaluation of WEPP and its comparison with USLE and RUSLE. *Trans. Am. Soc. of Agric. Engrs. 43: 1129-1135.*

Wight, J.R. and Siddoway, F.H. (1979). Determinants of soil loss tolerance for rangelands. In "*Determinants of Soil Loss Tolerance*", American Society of Agronomy (ASA) Publication 45, pp. 67-74.

Wischmeier, W. H., and Smith, D. D. (1978). *Predicting rainfall erosion losses - a guide to conservation planning*. US Department of Agriculture. Agriculture Handbook No. 537. US Government Printing Office, Washington, DC.

Yu, B. (2003).. An assessment of uncalibrated CLIGEN in Australia. *Agricultural and Forest Meteorology*, 119: 131-148.

Yu, B., and Rosewell, C.R. (2001) Evaluation of WEPP for runoff and soil loss prediction at Gunnedah, NSW, Australia. *Australian Journal of Soil Research* 39: 1131-1145.

Zhang, X.C., M.A. Nearing, L.M. Risse, and K.C. McGregor, (1996). Evaluation of runoff and soil loss predictions using natural runoff plot data. *Trans. Am. Soc. Agric. Eng.* 39(3): 855-863.

APPENDIX 1: RANGES AND RATINGS OF SOIL PROPERTIES

A range of soil properties were measured in this study to compare materials and, where possible, to identify materials with properties that could be considered "of concern".

The concept that there are "ideal" ranges of soil properties is, itself, of concern. In practice, parent materials, soils, and vegetation adaptation can vary widely, so that a value that is outside the normal range may, in a given situation, actually be "normal". For that reason, we strongly recommended that the following information be regarded as a guide only.

For the properties measured, the following ratings from Hazelton and Murphy (2007) can be applied.

pH	Rating
>9.0	Very strongly alkaline
9.0 - 8.5	Strongly alkaline
8.4 – 7.9	Moderately alkaline
7.8 - 7.4	Mildly alkaline
7.3 – 6.6	Neutral
6.5 – 6.1	Slightly acid
6.0 – 5.6	Mildly acid
5.5 – 5.1	Strongly acid
5.0 – 4.5	Very strongly acid

Soil salinity rating	Electrical conductivity (1:5, dS/m) for 10-20% clay
Very low	<0.07
Low	0.07 – 0.15
Medium	0.15 – 0.34
High	0.34 – 63
Very high	0.63- 0.93
Extreme	>0.93

Chloride concentrations in surface soils would be considered of concern if greater than 300 - 400mg/kg

Sodicity rating	Exchangeable sodium percentage (ESP)
Low	0 – 6
Marginally sodic to sodic	6 - 14
Strongly sodic	>14

Ca:Mg ratios are of concern if <1.0 and of definite concern if <0.5.

Cation exchange capacity (CEC) rating	CEC in m.eq./100g
Very low	**<6**
Low	**6-12**
Moderate	**12-25**
High	**25-40**
Very high	**>40**

APPENDIX 2: OVERVIEW OF THE WEPP MODEL

The Water Erosion Prediction Program (WEPP) (Flanagan and Livingston 1995) was developed by the United States Department of Agriculture (USDA) to predict runoff, erosion, and deposition for hillslopes and watersheds. It is a simulation model with a daily input time step, but internal calculations can use shorter time steps. For example, the climate file (for each day) includes information on:

- Amount of rain
- Duration of the rain
- Time to peak intensity
- Ratio between peak intensity and average intensity.

This information is used in infiltration calculations, so that the model takes intensity and duration of rainfall into account. For every day, plant and soil characteristics important to erosion processes are updated. When rainfall occurs, those plant and soil characteristics are considered in determining whether runoff occurs. If runoff is predicted to occur, the model computes sediment detachment, transport, and deposition at points along the slope profile, and, depending on the version used, in channels and reservoirs.

Conceptually, the WEPP model can be divided into six components: climate generation, hydrology, plant growth, soils, management, and erosion.

The erosion component 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 critical shear and the flow sediment load is below transport capacity. Deposition in rills is computed when the sediment load is greater than the capacity of the flow to transport it.

Validation of WEPP

The WEPP model can be considered "industry standard".

It has been widely used and validated for application in agricultural situations (Nearing and Nicks 1998; Ghidey and Alberts 1996; Liu *et al*. 1997; Zhang *et al*. 1996; Tiwari *et al*. 2000; Yu and Rosewell 2001).

It has also been widely used in design of constructed landforms for minesites across Australia. Erosion of minesite landforms modelled with WEPP using parameters derived using Landloch's methods has shown extremely strong correlation with observed rates for the same time periods, rainfall and surface conditions (Howard and Roddy 2012), confirming the accuracy of WEPP simulations for waste landform designs.

APPENDIX 3: METHODS USED TO DESCRIBE IMPACTS OF VEGETATION

To simulate varying various levels of vegetative cover:

- the WEPP hydraulic conductivity parameter (K_e) was modified to account for impacts of cover on steady infiltration rate as shown by rangeland research (Kato et al. 2009) (Figure A3-1). Effectively, steady infiltration rate generally increases by 7-10 mm/h for each 10% increase in surface cover.
- rill spacing (degree of flow concentration across slope) was modified so that flows were less concentrated as surface cover increased, with spacings of 5 m (bare soil), 3 m (50% cover), and 2 m (75% cover) being applied.

Cover (C) factors for the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997) were derived from reported values for rangeland grass cover (Table D-5 in Rosewell (1993)).

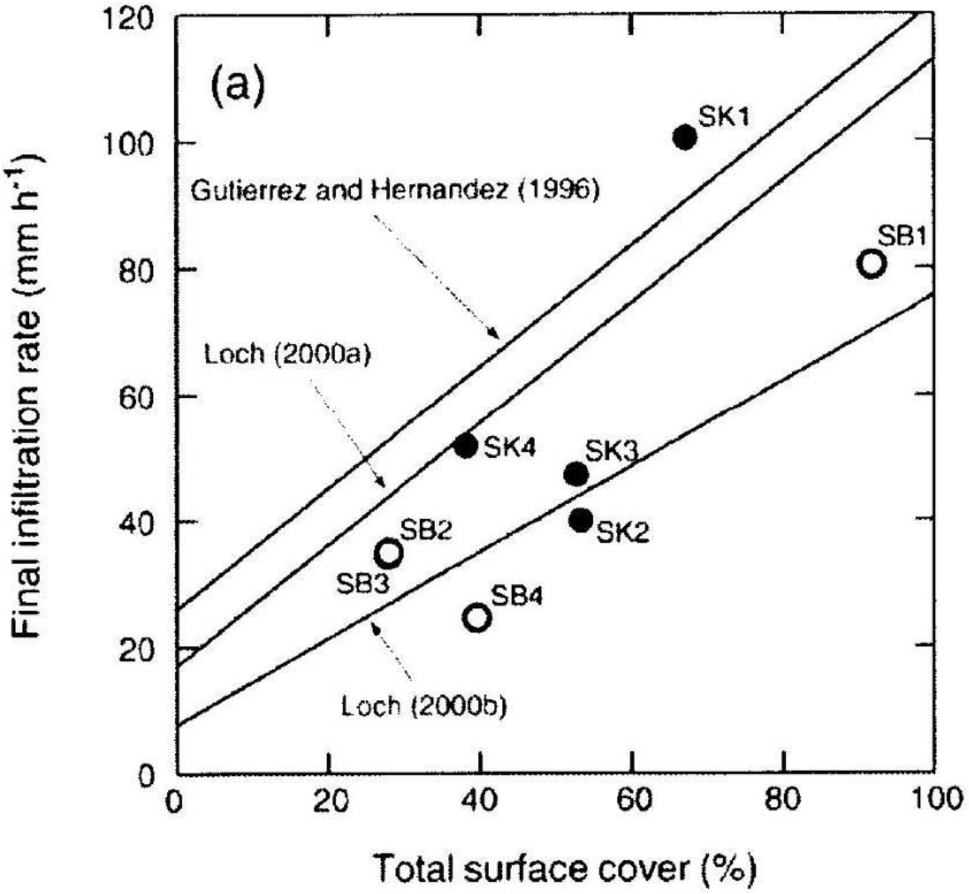


Figure A3-1: Impacts of cover on steady infiltration rate. (Figure based on a number of research studies and taken from Kato et al (2009)).