Appendix 10.

SLR Consulting Australia (2020a) *Rum Jungle Rehabilitation – Stage 2A Detailed Design – Erosion Assessment for the New Waste Storage Facility*. Report to the Department of Primary Industry and Resources, Northern Territory Government.

NORTHERN TERRITORY GOVERNMENT

Department of **Primary Industry and Resources**

RUM JUNGLE REHABILITATION - STAGE 2A DETAILED DESIGN

Erosion Assessment for the New Waste Storage Facility

Prepared for:

NT DPIR - Mines Division
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SLR Ref: 680.10421.90010-R03
Version No: -v1.0
June 2020

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BASIS OF REPORT

DOCUMENT CONTROL

Reference	Date	Prepared	Checked	Authorised
680.10421.90010-R03-v1.0	5 June 2020	Augusto Riascos	Dominic Trani	Danielle O'Toole
680.10421.90010-R03v0.1	12 November 2019	Augusto Riascos	Danielle O'Toole	Danielle O'Toole

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1 Introduction

1.1 Overview

The Northern Territory Government (NTG), represented by the Department of Primary Industry and Resources (DPIR), proposes the rehabilitation of the former Rum Jungle Mine site (the Project), located 6 km north of Batchelor, Northern Territory (NT), and approximately 105 km south of Darwin CBD as shown in **Figure 1**.

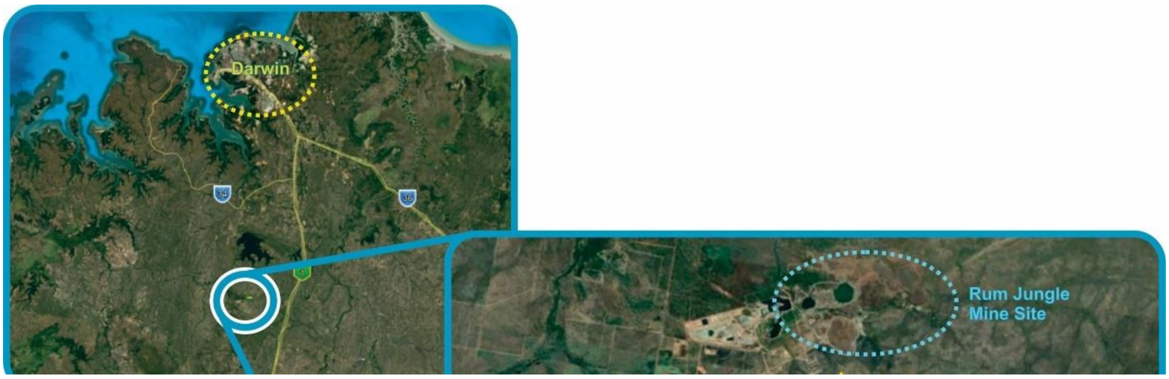


Figure 1 Former Rum Jungle Uranium Mine location

SLR Consulting Australia Pty Ltd (SLR) was engaged by DPIR to undertake the detailed design to meet the engineering requirements for construction of the rehabiliation design.

This report details the landform erosion modelling and assessment carried out to support the rehabilitation design of the new Waste Storage Facilities (WSFs). It is recommended that this report be read in conjunction with the SLR Detailed Engineering Design Report (SLR, 2020a).

1.2 Background Information

1.2.1 Overarching Project Objectives

The Project's high-level objectives are two-fold and focus on environmental remediation and restoration of cultural values of the site as described below:

- Improve the environmental condition onsite and downstream of site within the East Branch Finniss River (EBFR). This includes the following key outcomes:
  - Improved surface water quality conditions within EBFR in accordance with locally derived water quality objectives (LDWQOs).
  - Achieve chemically and physically stable landforms.
  - Support self-sustaining vegetation systems within rehabilitated landforms.
  - Develop physical environmental conditions supportive of the proposed Land Use Plan.
- Improve site conditions to restore cultural values. This includes the following key outcomes:
  - Restoration of the flow of the EBFR to original course as far as possible.

- Remove culturally insensitive landforms from adjacent to sacred sites and relocate ensuring a culturally safe distance from the sacred sites.
- Return living systems including endemic species to the remaining landforms.
- Preserve Aboriginal cultural heritage artefacts and places.
- Isolate sources of pollution including radiological hazards.
- Maximise opportunities for Traditional Owners to work onsite to aid reconnection to country.

A more detailed description of the overarching project objectives is contained in Section 1.2 of the SLR Detailed Engineering Design Report (SLR, 2020a).

1.2.2 Rehabilitation Strategy

One of the key actions planned to address contamination processes and improve prospects of future land use is to slow down or halt the Acid Metalliferous Drainage (AMD) production reactions from waste rock onsite by consolidating existing waste rock dumps (WRD) into one of three new facilities based on Potential Acid Forming (PAF) characteristics. These facilities are:

- Main Pit backfill zone;
- West WSF; and
- East WSF.

This erosion assessment addresses both the West WSF and East WSF.

1.2.3 Proposed WSFs

The footprints of the proposed WSFs in a 3-dimensional representation are shown in **Figure 2Error! Reference source not found.**. It is important to note that the WSF landforms used were in draft at the time of initial modelling, hence there are some variations in the final footprint with respect to the design issued in the SLRs Detailed Engineering Design Report (SLR, 2020a). Nonetheless, the results and recommendations from this report remain valid and have been applied to the final design.

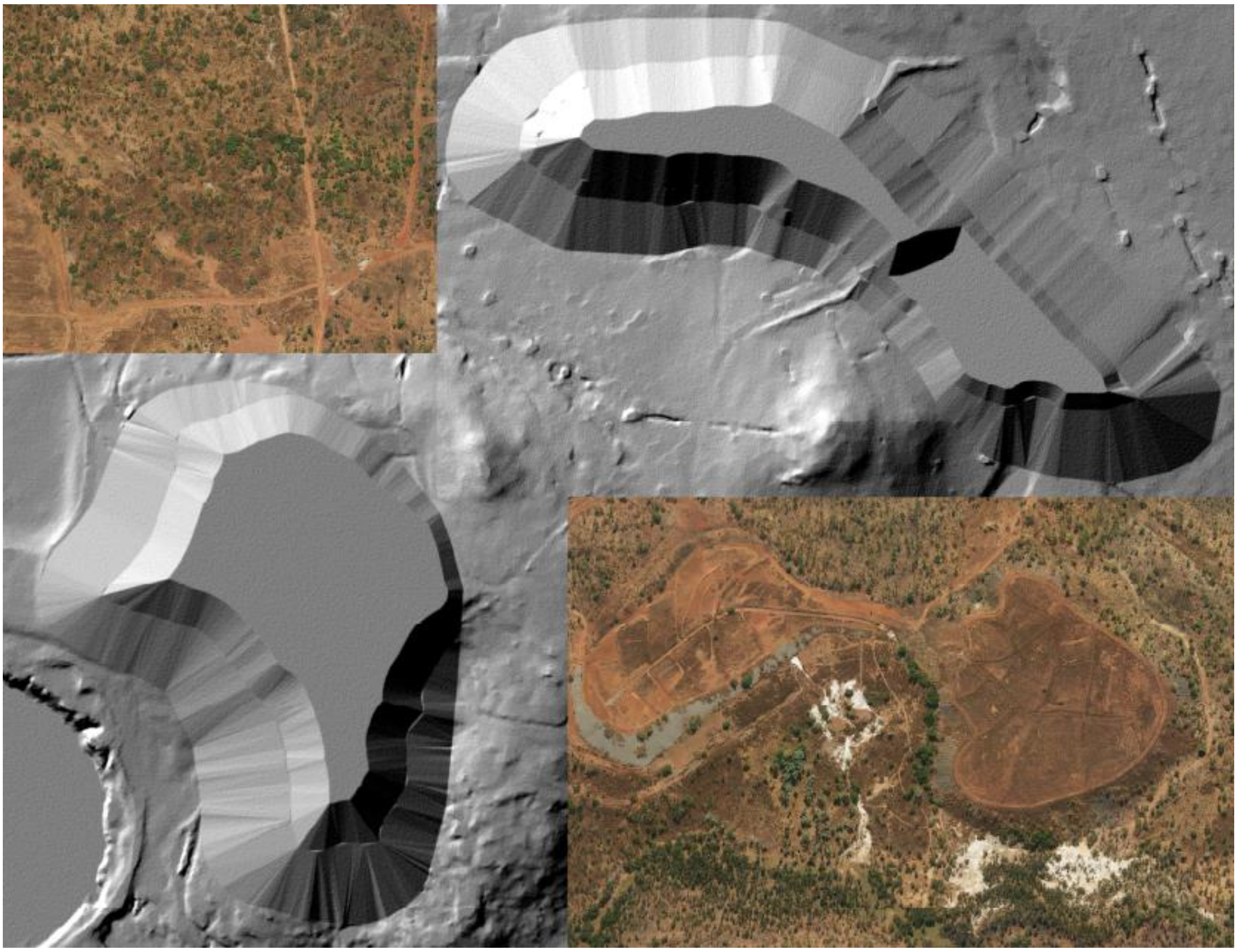


Figure 2 West and East WSF Proposed Locations

The WSF locations had been selected based on the following criteria:

- are not prone to flooding in a 1:100 Average Recurrence Interval (ARI) event;
- have suitable foundation geotechnical stability;
- require minimal clearing of established vegetation;
- minimise re-handling of radiological soils by covering the major remnants *in situ*;
- do not disturb Aboriginal places, objects or artefacts; and
- do not present unacceptable visual amenity impacts.

The details of the selection process are provided in the WSF Technical Memo on Site Selection (SLR, 2020b).

1.2.4 Existing Site Conditions

The Rum Jungle decommissioned uranium mine site consists of a 655ha parcel of land located immediately to the northeast of Rum Jungle Road and Litchfield Park Road intersection and immediately east of Browns Oxide Mine Site. The site extends approximately 2.6 km east and 2.0 km north from Rum Jungle Road – Litchfield Park Road intersection. Access to the site is typically from the east via Rum Jungle Road or Browns Oxide Mine. An unsealed access track also exists to the north of the site allowing access. For more details refer to Section 2 in the SLR Detailed Engineering Design Report (SLR, 2020a).

1.2.5 Capping Design of WSFs

The typical details of the proposed capping system is shown in **Figure 3** (extracted from (SLR, 2020a)). Typical details of the capping system overlying the side slopes and the starter bund is shown in **Figure 4**, and is composed of three layers:

- 1.0m thick High Compacted Waste Rock Starter Bund, which will be in direct contact with the Waste Material;
- 0.65m thick Low Permeability Clay Liner to limit water flow and oxygen ingress and retain water to provide moisture to the Growth Medium Layer; and
- 2.0m Growth Medium Layer to provide the selected vegetation with the required moisture and nutrients.

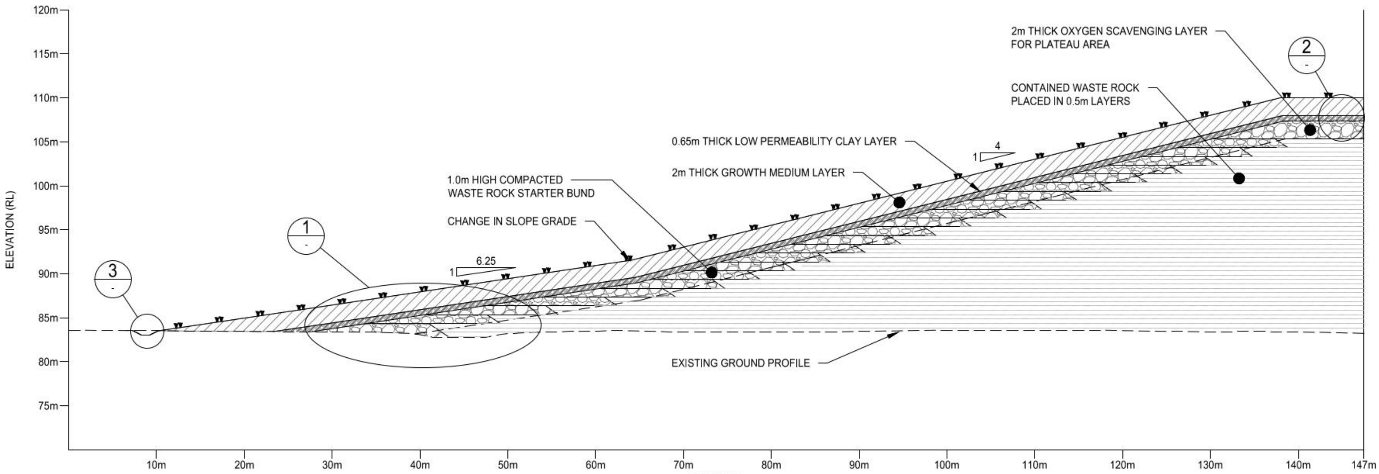


Figure 3 Typical WSF Capping Section.

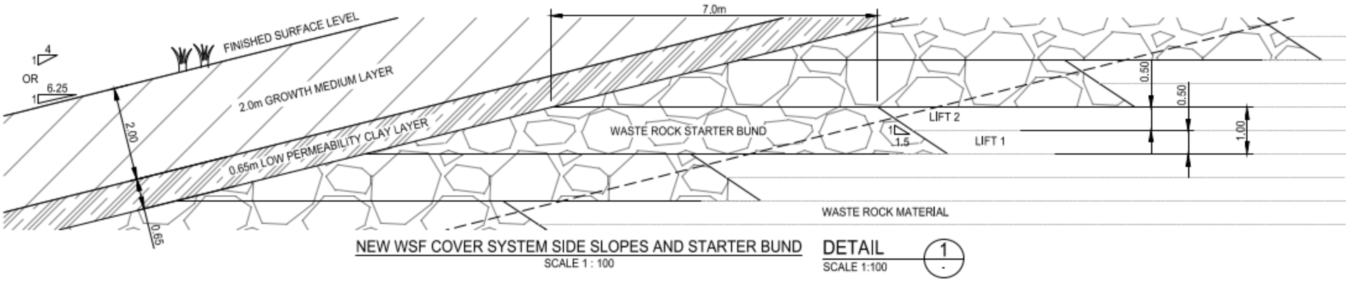


Figure 4 Typical WSF Capping Section, Side Slopes and Starter Bund - Detail 1.

The gradients of the natural topography surrounding the proposed WSFs were measured from the available LiDAR data. The natural gradients appear to be between 5° to 10° and observations on site would show minimal indication of erosion on these slopes over time. The objective of the design of the capping system is therefore to mimic the natural surrounding as practically as possible. This will not only provide more convergence in terms of visual impact but will also replicate as closely as possible the natural site characteristics which appeared to have withstood erosion over a geological timeframe. A comparison of the measured natural slopes and the selected slopes for the WSFs in terms of erosion performance is discussed in **Section 4**.

1.3 Assessment Specific Objectives

The main objectives of this assessment were to:

- Select the most appropriate WSF batter slopes based on long-term erosion performance; and
- Simulate the erosion performance of the WSFs over a period of 500 years including vegetation establishment.

1.4 Erosion Modelling Limitations

There are a number of limitations inherent in the erosion modelling, including:

- All materials are assumed that they are representative of the entire site;
- The compaction and surface roughness of the materials used to perform testing in laboratory setting may be very different to that of the site;
- The author can take no responsibility for any errors that may be the result of inadequacies in the coding or content of the software; and
- It is not possible to guarantee that any prediction or result contained in this report will or might occur.

2 Scope of Work

To address the above assessment objectives, the following scope of work have been completed:

- Collate available data on the cover material and the proposed geometry alternatives of the new WSF landform.
- Use calibrated erosion parameters determined from flume testing and literature for the new WSF cover materials.

- Carry out long term erosion modelling over a period of 500 years to assess the relative performance of the cover materials in terms of sheet and gulley erosion.
- Preparation of this report to document the findings of the erosion assessment.

3 Erosion Assessment Methodology

The erosion assessment for the new WSFs was carried out by adopting a two-stage approach, generally described as follows:

- Stage 1 – This stage involved the selection of the optimal slope or combination of slopes out of three options; and
- Stage 2 – This stage involved modelling of the slope with the optimal erosion performance from Stage 1 with a vegetation cover in various stages of establishment.

The methodology adopted in this assessment is outlined as follows:

1. Review of the proposed slope angles with representative model parameters obtained from the flume testing.
2. Review of the flume testing results carried out using materials extracted from the borrow areas to be used in the landform works to obtain the appropriate erosion parameters. Refer to Appendix A for details on Flume Testing.
3. Using the commercially available software SIBERIA, carry out Stage 1 long-term erosion simulation on three chosen slopes prepared from a 3D digital terrain model. The outcome of this stage is the optimal combination of slopes out of the three. Appendix B provides a more detailed description of SIBERIA.
4. Review a selection of suitable cover materials and vegetation species from literature to cope with local conditions and availability.
5. Using SIBERIA again, carry out Stage 2 long-term erosion simulation on the optimal combination of slopes from Stage 1 with select vegetation cover on it. This stage provides the recommended vegetation that would provide potentially the best long-term outcome against erosion.
6. Assess total erosion and deposition volumes and the locations of the occurrence for input into surface water control design (by others).

3.1 Stage 1 Modelling - Batter Slope Assessment

SLR has developed three alternative landform models (i.e. digital terrain models or DTMs) that would likely satisfy all the specifications and requirements from the agronomical, erosional, geotechnical and hydrological perspectives. The surface water requirements were not considered during this stage.

In order to represent ripping features, construction undulations and irregularities into the surface, the initial DTM was created using a "Random Surface" generating function in which surface irregularities have been simulated by incorporating a typical scatter variation of ±0.1 m in the vertical plane of a 1m × 1m grid.

The analysis-specific objectives of the Stage 1 modelling are as follows:

- To find a suitable slope to comply with agronomical, geotechnical and water surface management requirements;

- To test the erosion performance of the selected material under demanding conditions; and
- To know the locations where erosion is expected.

Specific factors such as batter slope, material types and timeframe implemented in Stage 1 are discussed in the following sections.

3.1.1 Slope

Historically, many reclaimed landforms have adopted linear slope designs. This approach offers simplicity, but the long-term landform performance is often unacceptable. Various studies have demonstrated that concave slopes offer a sediment transport reduction up to three-fold compared to linear ones (Priyashantha, 2009). As one of the main purposes for this assessment is to propose a landform able to minimise erosion, it was decided to test different concave shapes and determine the best option to implement in the final WSF design.

The initial WSF design contemplated the storage of more than 8.5Mm^3 which translated into a landform approximately 40m high accompanied by a trilinear concave slopes of 1:5 to 1:3.5 to 1:2.5 (see **Figure 5)**. According to (O'Kane Consultants Pty Ltd, 2016b), this configuration was designed to maximise long term stability, provided the combination of gradients and climate, vegetation is expected to establish favourably on the lower shallower slopes.

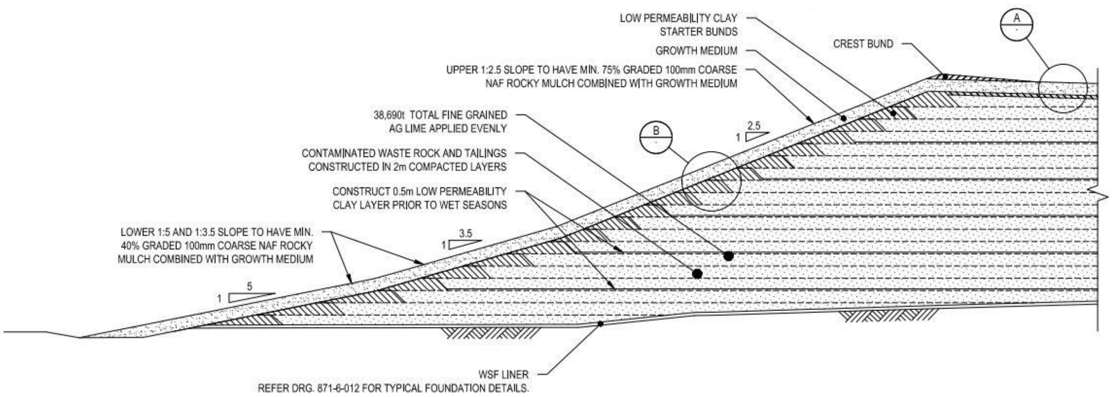
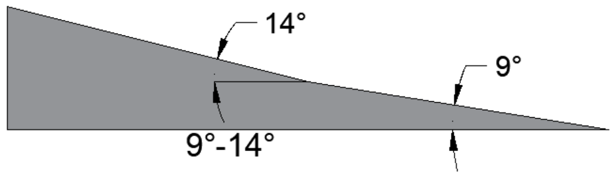
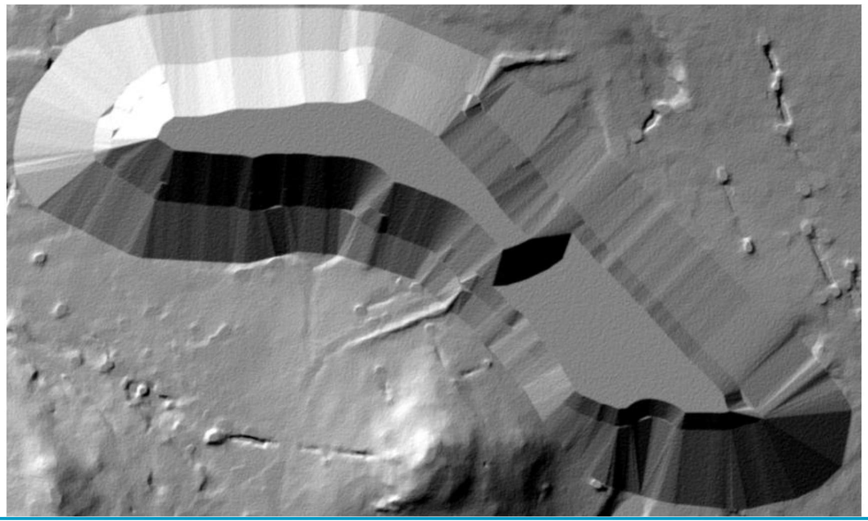
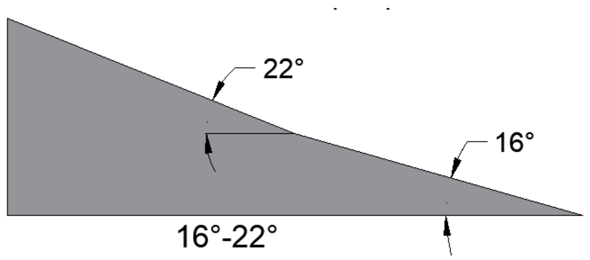
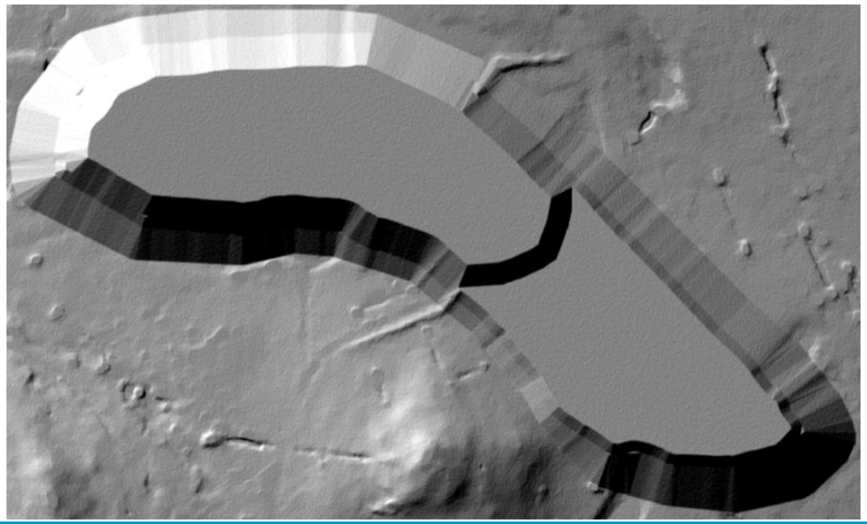
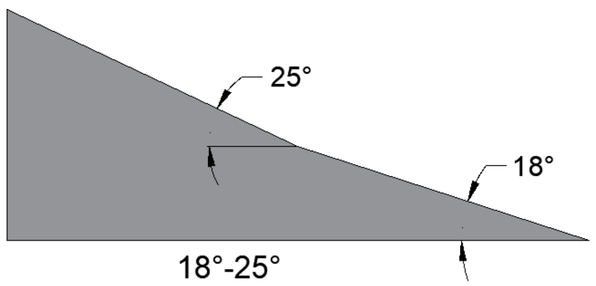
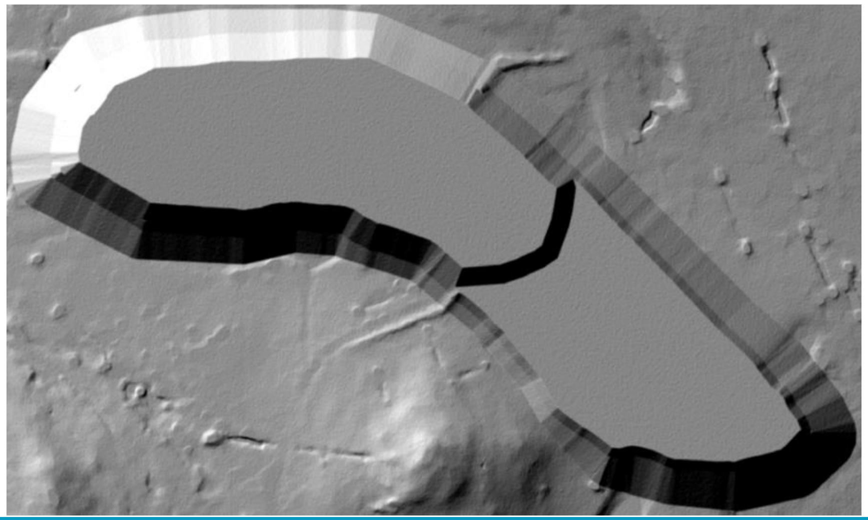


Figure 5 Typical Section, Containing a Trilinear Slope, Source: (O'Kane Consultants Pty Ltd, 2016a).

The updated WSF design would store a smaller volume of around 7Mm^3 and with a lower height. Consequently, the updated proposed slope configuration was decided by removing the flatter lower segment (1:5). Eventually, an option of 1:3.5 to 1:2.5 (or 16° to 22°) was proposed, and subsequently two additional dual-slope options were proposed for assessment, one steeper and one flatter. The change in slope is located at the mid-height of the batter.

The three slope scenarios were modelled using representative soil erosion parameters with no vegetation cover. The East WSF was selected to perform this series of analyses as it has more geometric variety compared to the West WSF. **Table 1** graphically represents the dual slopes that have been considered in these assessments, together with the hillshades of the three concave dual slopes for Stage 1 pre-erosion condition at East WSF.

Table 1 Dual-slope Scenarios and Their Respective Hillshade Representation for EWSF Pre-Erosion.

<table>
<tr><th>Dual Slope Scenarios</th><th>Hillshades</th><th>Description</th></tr>
<tr><td>
</td><td></td><td>Low Slope
9° to 14°
(1:6.25 to 1:4 (V:H))</td></tr>
<tr><td>
</td><td></td><td>Medium Slope
16° to 22°
(1:3.5 to 1:2.5 (V:H))</td></tr>
<tr><td>
</td><td></td><td>High Slope
18° to 25°
(1:3.08 to 1:2.14 (V:H))</td></tr>
</table>

3.1.2 Material Parameters

The key input parameters for SIBERIA modelling were developed based on the results of flume testing. The two material types considered for capping are laterite and saprolite, described as follows:

- Laterite material – clayey GRAVEL and/or gravelly/sandy CLAY with zones of COBBLES/BOULDERS found at 0.1 to 0.2m depth; and
- Saprolite material – typically silty/sandy CLAYS of medium to high plasticity and found at 3.00 to 4.00 m depth.

Representative samples of laterite and saprolite were taken from test pit NTP01 at Borrow Area A as part of the geotechnical investigation described in (SLR, 2019). The general location of Borrow Area A is shown in **Figure 6**.

Figure 6 Location of Test Pit NTP01 Where Laterite and Saprolite Materials Were Sampled

In lieu of testing *in situ*, the collected material samples were subjected to flume testing to measure soil erosion performance in a controlled environment. The results of the flume testing are then interpreted for use as input in SIBERIA modelling.

The flume testing of the collected soil samples was completed by Prof. Greg Hancock from the University of Newcastle (NSW, Australia). The samples were obtained by SLR from the test pit NTP01 as part of the geotechnical investigation which took place in July 2019 (SLR, 2019).

SIBERIA parameters were determined from the flume testing results, using a multiple regression for the β1, m1 and n1 values of the fluvial sediment transport equation q_{sf} for runoff, sediment load and each slope until the parameter combination was optimised. **Table 2** provides a summary of the developed parameters and full details of the flume testing are provided in Appendix A.

Table 2 SIBERIA Parameters for the Laterite and Saprolite Materials.

Parameter	Laterite (sample from 0.5m to 1.1m)			Saprolite (sample from 4.9m to 5.3m)		
Slope	5% (3°)	15% (9°)	25% (14°)	5% (3°)	15% (9°)	25% (14°)
β1	0.015	0.01	0.01	0.0015	0.0015	0.015
β3	1	1	1	1	1	1
m1	1.6	1.6	1.5	2.2	2	1.5
m3	1	1	1	1	1	1
n1	2	2	2.6	2.6	2.8	2

The conclusions from the flume testing (Aquaterra International, 2019) are:

- Both the laterite and saprolite are prone to erosion without vegetation cover.
- Revegetation would improve their erosional stability. This is supported by the pH and EC measured in both materials which implies no impediments to plant growth, although nutrient analysis was not undertaken.
- Improvement of both soils requires utilisation of fast-growing cover species such as Japanese Millet, but it is recommended to perform additional flume analyses to ensure this.

Based on the results of the flume testing, a 25% (14°) slope of laterite material was selected for the Stage 1 analyses, based on the following reasons:

- A basic rule of thumb for selecting an adequate material for soil loss resistance is to look for equilibrated contents of silt, clay and sand. The laterite material provides a better distribution than the saprolite (which contains a disproportionate percentage of silt, i.e. 70%).
- The highest slope was selected as this represent the most conservative scenario.
- A 25% (14°) slope with laterite material shows a combined β1, m1 and n1 coefficients of 0.01, 1.5 and 2.6, respectively. This combination typically characterises a material susceptible to rilling and/or gullying which is the more detrimental type of erosion. Thus, the selection of this set of parameters represent a highly conservative scenario.

3.1.3 Timeframe

The selection of the Stage 1 modelling timeframe is based on the following:

- Long-term analyses prevail over short-term ones as long-term performance represents a more demanding scenario.
- Timeframes beyond 500 years require the addition of the diffusivity component, which unnecessarily increases the level of complexity of models, making the prediction less accurate.

Therefore 200 and 500 years were used to undertake Stage 1 analyses.

3.2 Stage 2 Modelling - Cover Material Assessment

The outcome of Stage 1 modelling is then used for the Stage 2 analysis. Stage 2 has an additional degree of complexity by introducing a vegetation cover that will be placed to improve the erosion resistance of the laterite material over time. The selected vegetation cover performance will be predicted over a long-term timeframe.

The analysis-specific objectives of the Stage 2 modelling are as follows:

- Include a long-term vegetation establishment plan, paying special attention to wet and dry seasons;
- Estimate the expected erosion rates and gully depths of the selected slope; and
- Obtain the locations and extent where erosion will occur.

Specific factors such as batter slope, material types and timeframe implemented in Stage 2 are discussed in the following sections.

3.2.1 Slope

The preferred dual slope obtained from Stage 1 modelling is applied to both the East WSF and West WSF.

3.2.2 Material Parameters

As the flume testing did not take into account vegetation, it is necessary to redefine the β1 parameter using the Revised Universal Soil Loss Equation (RUSLE). The process also involves the introduction of the soil erodibility (K) and reduction in the soil loss capacity (C) parameters. K value can be seen as the capacity to erode and C as the ability to minimize it (e.g., by vegetation or rock armoring). In other words, according to RUSLE, β1 is the result of multiplying K and C factors.

The remaining SIBERIA coefficients, i.e. β3, m1, m3 and n1 remain the same as Stage 1 and the processes to determine K and C factors are presented detailed in Appendix C. **Table 3** shows the β1 factors used for the erosion analyses in Stage 2.

Table 3 β1 Factors for the Stage 2 Modelling Over a 500 Year Timeframe.

Year	Time of Year	Total Cover (%)	Estimated C Factor	Estimated K Factor	β1=KxC
1	Start of wet season	≥40	0.22	0.04	0.00880
	Mid-wet season	≥75	0.03	0.04	0.00120
	End of wet season	≥95	0.001	0.04	0.00004
2	End of dry season	≥95	0.001	0.04	0.00004
	End of wet season	≥95	0.001	0.04	0.00004
3	End of dry season	≥95	0.001	0.04	0.00004
	End of wet season	≥95	0.001	0.04	0.00004
4	End of dry season	≥95	0.001	0.04	0.00004
	End of wet season	≥95	0.001	0.04	0.00004
5	End of dry season	≥95	0.005	0.04	0.00020

Year	Time of Year	Total Cover (%)	Estimated C Factor	Estimated K Factor	β1=KxC
	End of wet season	≥95	0.005	0.04	0.00020
10	End of dry season	≥80	0.04	0.04	0.00160
	End of wet season	≥95	0.005	0.04	0.00020
50	End of dry season	≥80	0.04	0.04	0.00160
	End of wet season	≥95	0.005	0.04	0.00020
100	End of dry season	≥80	0.04	0.04	0.00160
	End of wet season	≥95	0.005	0.04	0.00020
500	End of dry season	≥80	0.04	0.04	0.00160
	End of wet season	≥95	0.005	0.04	0.00020

3.2.3 Timeframe

The selection of the Stage 2 modelling timeframe is based on the following:

- Short and long-term performance are important as the former has a direct impact on the latter. It is a considered a concatenated process where simulation of early years is fundamental to improve the accuracy of erosion prediction in the longer term.
- As per Stage 1, timeframes beyond 500 years was not considered.
- Special attention to dry and wet seasons was made. A year by year model from 0 to 5 years was implemented as this timeframe represents the most crucial stage in the vegetation establishment. Then, longer periods of time were included.

Consequently, 5, 50, 200 and 500 years were selected.

4 Results and Discussion

4.1 Stage 1 Results and Analysis

The results from the Stage 1 modelling are summarised in **Table 4** and graphically shown in **Table 5.** The key points are summarised below:

- The lowest dual-slope angles (9° to 14°) provide the lowest erosion rates for all years, with between 1.2 and 1.40 m^3/ha/yr, followed by 16° to 22° with 1.97 to 2.47 m^3/ha/yr and 18° to 25° with 2.29 to 2.87 m^3/ha/yr., respectively.
- Maximum erosion depths at 500 years are 1.45m, 3.13m and 3.74m for the low, medium and high dual-slope angles, respectively.
- The low dual-slope provides the lowest mean erosion depth at 500 years, with 0.13m, followed by medium and high slopes with 0.24 and 0.29m, respectively.

Table 4 Stage 1 SIBERIA Results for Laterite Material on East WSF

Variable	9° to 14° dual-slope		16° to 22° dual-slope		18° to 25° dual-slope	
	200yr	500yr	200yr	500yr	200yr	500yr
Initial Average RL's (m)	86.14		88.32		88.90	
Average RL's (m)	86.12	86.07	88.28	88.19	88.85	88.76
Accumulated Erosion rate (m3/ha/yr.)	-1.20	-1.40	-1.97	-2.47	-2.29	-2.87
Max. Erosion depth (m)	-1.06	-1.45	-1.47	-3.13	-1.95	-3.74
Mean Erosion depth (m)	-0.05	-0.13	-0.10	-0.24	-0.12	-0.29
Max. Deposition height (m)*	0.80	1.08	1.29	1.81	1.42	2.04
Mean Deposition height (m)*	0.07	0.11	0.11	0.20	0.12	0.23

*Note that erosion is expressed as negative to differentiate from deposition at East WSF toe.

- The bar graph in **Figure 7** depicts the erosional rates of each slope scenario in the first 200 years as well as the remaining 300 years of analysis, and generally indicate the erosion rates in the first 200 years compared to the following 300 years increased in all the slope scenarios.
- All slopes present an erosion rate increase of 1.4 times, except for the low slope whose increase is slightly lower at 1.3 times.

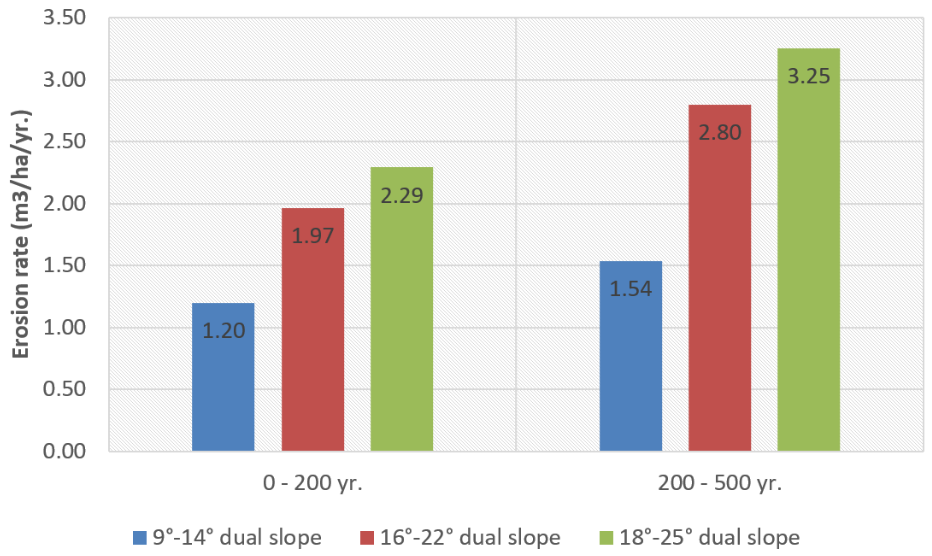


Figure 7 Stage 1 Erosion Rates in the First 500 Years

- Rill and gulley behaviour can be noticed in the several incisions present in the B-B and C-C cross sections in **Table 5** and become more pronounced in the medium and high dual slopes.

- As the modelled landforms used to run SIBERIA were provisional at the time of this analysis, some inaccurate details were allowed. The cross-sectional wrinkles (peaks) observed in the plan view are an example of this. The black line in **Figure 8** illustrates the pre-erosion surface of a typical cross section and the peaks as a result of the wrinkles. In the same figure, orange, blue and green lines show the time-progressive gully formation originated from the marked vertexes acting as seeds for localised erosion. In reality, these inaccuracies are unlikely to occur, therefore, it is likely that the erosion rates and erosion depths predicted in the models are exaggerated. Cross sections in all scenarios show abrupt changes in the original surface, that is a sign that this phenomenon is occurring in the analysed landform.

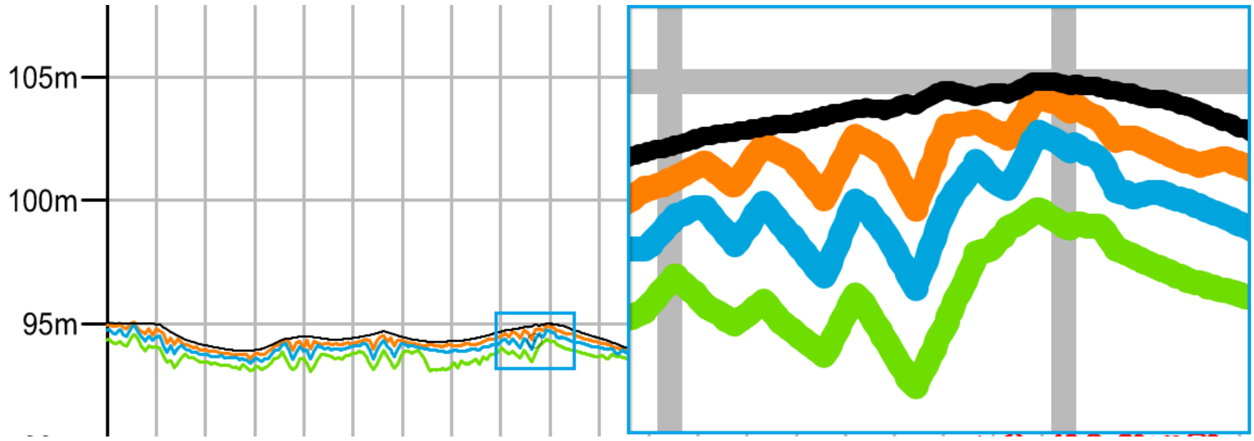


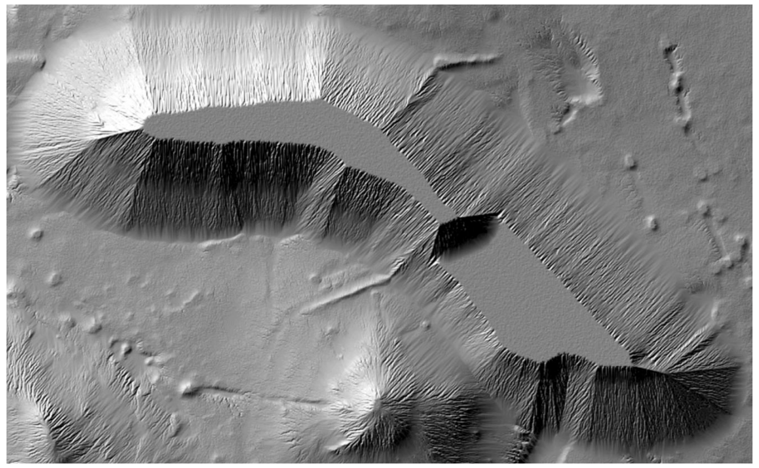
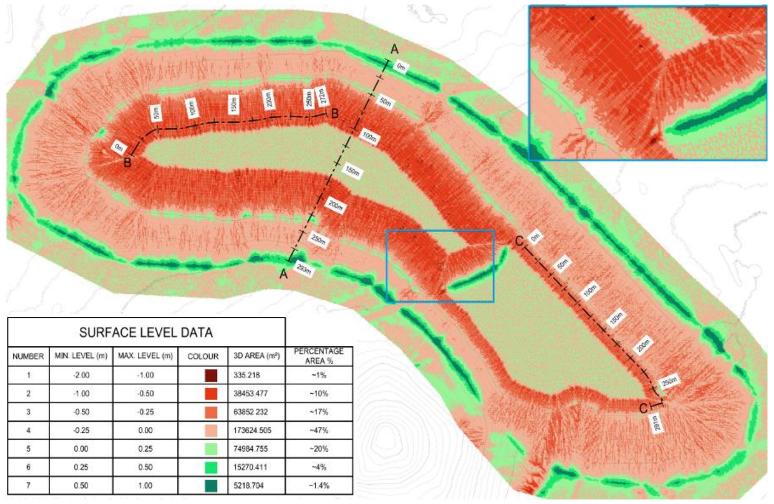
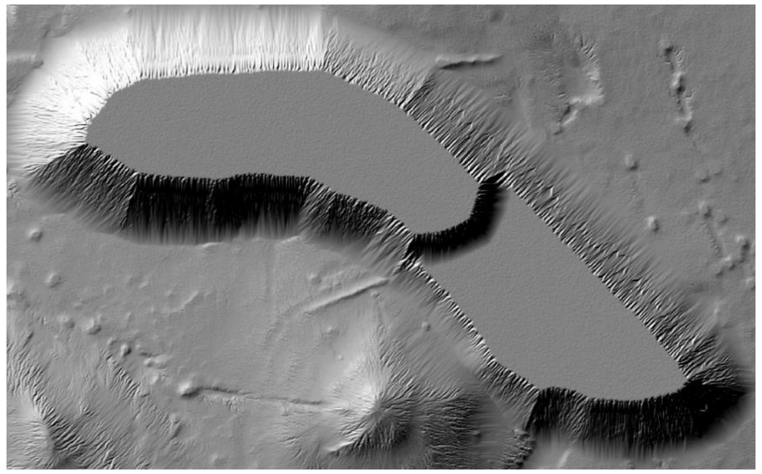
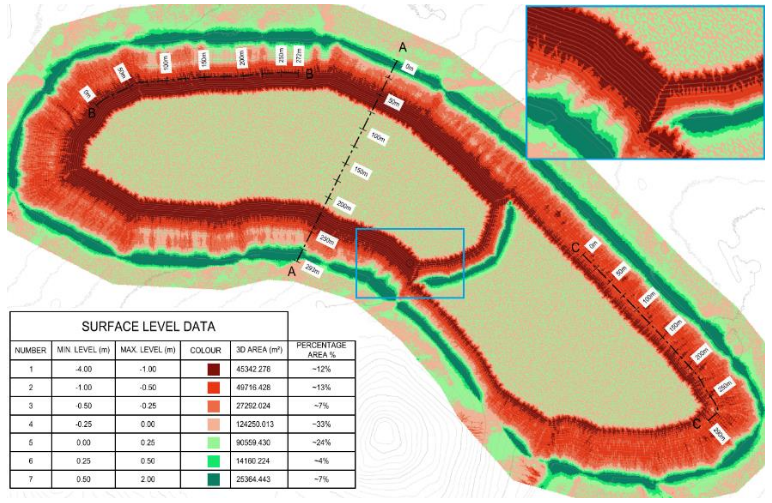
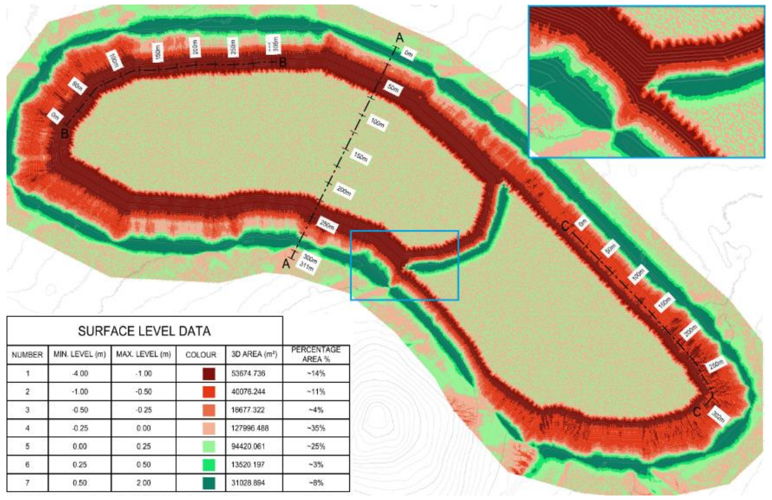
Figure 8 Typical SIBERIA Gully Seeding From Cross Sectional Wrinkles. Black Shows the Initial Profile; Orange, Blue, Green and Red Represent 200, 500 and 1000 Years of Erosion.

- The main purpose for Stage 1 is to select the best dual-slope scenario. This selection was driven by the analysis of erosion rates modelled with SIBERIA. In all points of comparison, the best scenario was the flattest dual slope (9° to 14°).
- Colour maps show that erosion depths larger than 1 m are unlikely in the 9° to 14° dual-slope scenario, only 1% of the total area is predicted to take over this depth. Medium and High slopes have 12 and 14% of total site area where erosion depth can erode further than the 2.0m cover depth.

The portion of the dual slope whose slope is 14° and localised near the top of the batter is the most vulnerable part of the East WSF.

Appendix D show the hillshades for Stage 1 after 500 years for all dual slopes. The erosion produced after 500 years on natural surfaces is similar to the ones produced on East WSF in the same timeframe. Appendix D also illustrates the colour maps and cross sections for the low, medium and high slope scenarios.

Table 5 Stage 1 Hillshades and their respective Soil Loss Maps for East WSF After 500 Years.

Eroded Hillshades	Soil Loss Maps	Description
		**Low Slope** **9° to 14°** (1:6.25 to 1:4 (V:H))
		**Medium Slope** **16° to 22°** (1:3.5 to 1:2.5 (V:H))
		**High Slope** **18° to 25°** (1:3.08 to 1:2.14 (V:H))

4.2 Stage 2 Results and Analysis

The results from the Stage 2 modelling are presented in **Table 6** and graphically illustrated in **Table 7** and key points are summarised as follows:

- In general, West WSF presents larger sheet erosion rates compared to East WSF.
- In terms of the maximum erosion depth at 500 years, East WSF has the larger figure, i.e. 2.10m and West WSF shows a 1.18m depth.
- Regarding mean erosion depth, the results are similar for both facilities, ranging from 0.01 to 0.04 m. Contrary to the Stage 1 results, the most eroded areas are localized and not representative for the whole WSF, only around 2% of erosion depths are larger than 1m, this is especially seen in the colour maps. This is discussed further below.

Table 6 Stage 2 SIBERIA Results for East WSF and West WSF.

Variable	East WSF				West WSF			
	5 yr.	50 yr.	200 yr.	500 yr.	5 yr.	50 yr.	200 yr.	500 yr.
Initial Average elev. (m)	87.67				82.53			
Average elevation (m)	87.67	87.67	87.66	87.66	82.53	82.53	82.52	82.51
Accum. Erosion rate (m3/ha/yr.)	-0.56	-0.24	-0.24	-0.25	-0.79	-0.35	-0.36	-0.37
Max. Erosion depth (m)	-0.29	-0.58	-0.92	-1.18	-0.45	-0.91	-1.42	-2.10
Mean Erosion depth (m)	-0.00	-0.01	-0.02	-0.04	-0.00	-0.01	-0.02	-0.04
Max. Deposition height (m)*	0.18	0.32	0.57	0.79	0.26	0.51	0.86	1.32
Mean Deposition height (m)*	0.01	0.01	0.03	0.07	0.01	0.02	0.03	0.06

*Note that erosion is expressed as negative to differentiate from deposition at East WSF and West WSF toe.

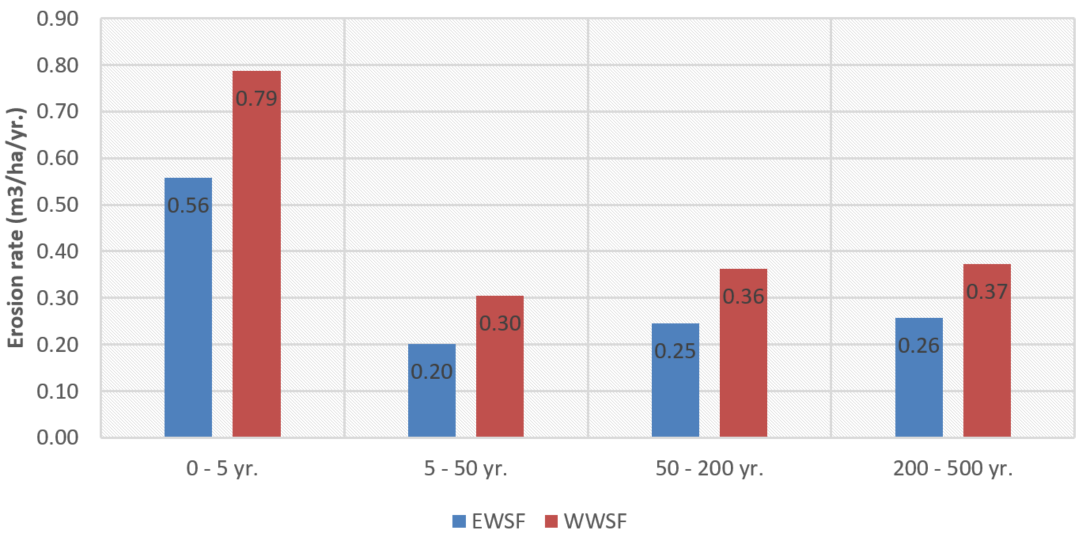


Figure 9 Stage 2, EWSF and WWSF Erosion Rates Comparison in the First 500 Years

- **Figure 9** shows the variability of erosion rates along the 500-year analysis, noting that the highest erosion rates are seen in the first 5 years, where the vegetation establishment takes place, especially in the first 2/3 of year where the total cover is expected to be around 40 to 75%.
- The erosion rates in the 550-year time period is reduced by almost 3-folds to the first 5 years. At least 95% cover is expected in the wet seasons and more than 80% in the dry seasons.
- West WSF erosion rates are in average 1.4 times larger than the ones obtained in the East WSF. This is likely due to:
    - Around 40% of the East WSF perimeter near the small plateau contains a lower portion of the higher slope, i.e. 14°, because of it is truncated by the lower plateau; and
    - East WSF is about 60% of West WSF footprint area, therefore the latter exposes more sloped area to erosion.
- Most of the soil loss is produced by sheet erosion.
- The vegetation inclusion has a direct impact on the reduction of soil loss. This is shown by comparing results from Stage 1 to Stage 2 after 500 years, in particular:
    - In average, the erosion rate is reduced around 4 times, that is 1.4 vs. 0.31 m^3/ha/yr.
    - Maximum erosion depth decreased by 20% and can be reduced further if cross-sectional wrinkles are avoided, i.e. 1.45 vs. 1.18 m.
    - The mean erosion depth is around 3 times smaller, in other words, 0.13 vs. 0.04 m.
    - Even though maximum erosion depths are still large in stage 2, the colour maps show that their significance is vastly reduced from 10 to 1%. This clearly indicates that after 500 years this is a negligible value.
- **Figure 10** shows a comparison of soil loss after 500 years for the East WSF compared to the natural surroundings. Although the model assumed one material for the whole site, the slopes for the natural landform present generally different values for slope as input parameter to the model. The erosional behaviour of both the capping and natural slopes are similar in terms of soil loss which lends to the overarching concept of the WSF slopes matching the natural surroundings. This is mainly driven by the fact that the chosen dual-slope of 9° to 14° which is similar to the surrounding natural slopes ranging between 5° and 10°.
- **Figure 11** illustrates a portion of the WWSF. It can be seen that at the change in concave slope interface there will be some deposition (shown in green). To mitigate this, an abrupt change in angle should be avoided, and a continuous and soft concave interface constructed.
- **Figure 12** shows the maximum deposition depth of 0.25m which needs to be taken into account in designing surface water management.
- Comparing Stage 1 and 2 cross sections, it is evident that the vegetation reduces the impact of erosion on the surfaces. The rill and gully behaviour persist; however, the scale of incisions is reduced.
- Under vegetated conditions both WSF's are unlikely to experience incision depths of more than 2.5m.

Presented in Appendix E are the hillshades for Stage 2 after 500 years for all both East WSF and West WDF.

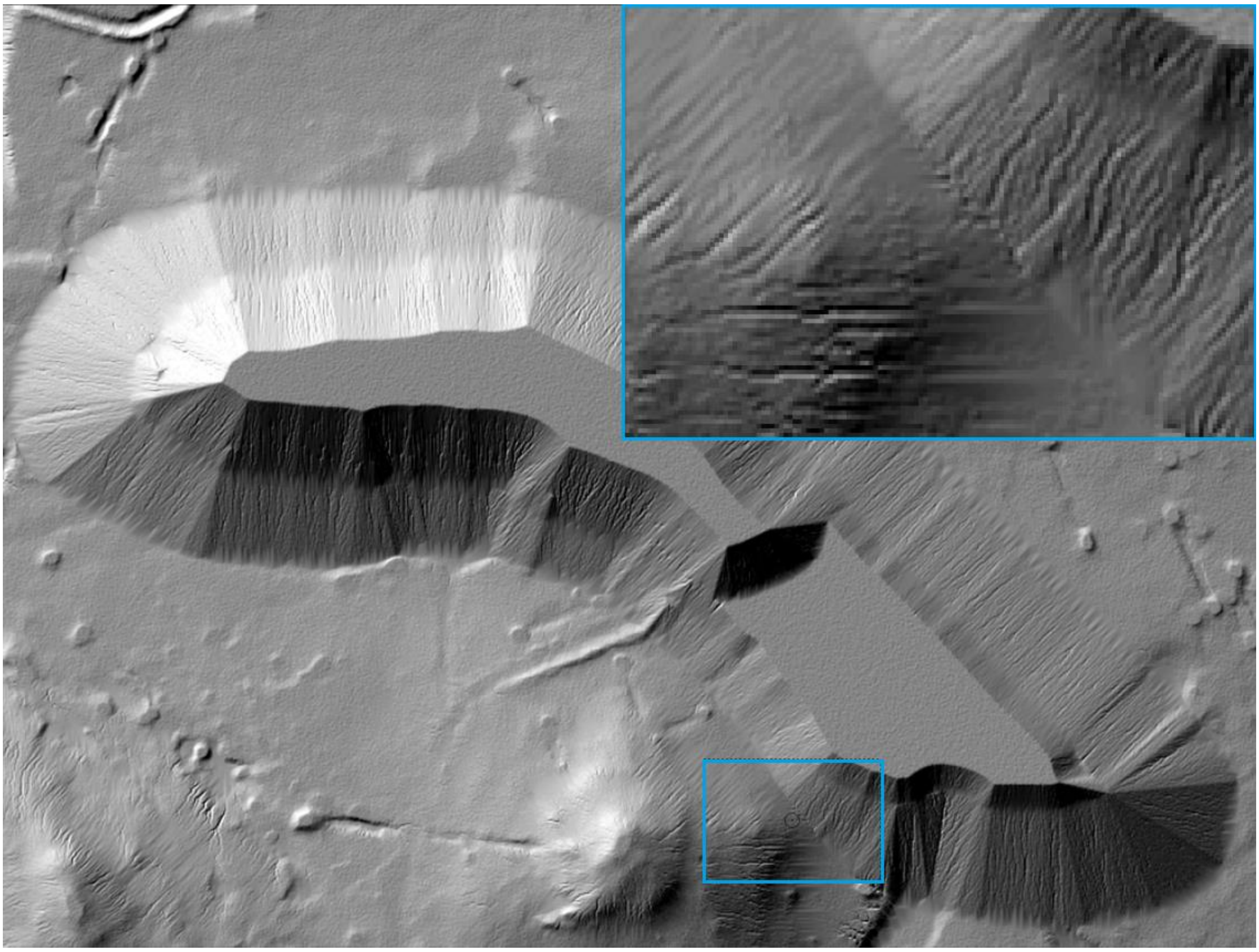


Figure 10 Soil Loss Comparison of Adjacent Natural and Manmade Volumes After 500 Years.

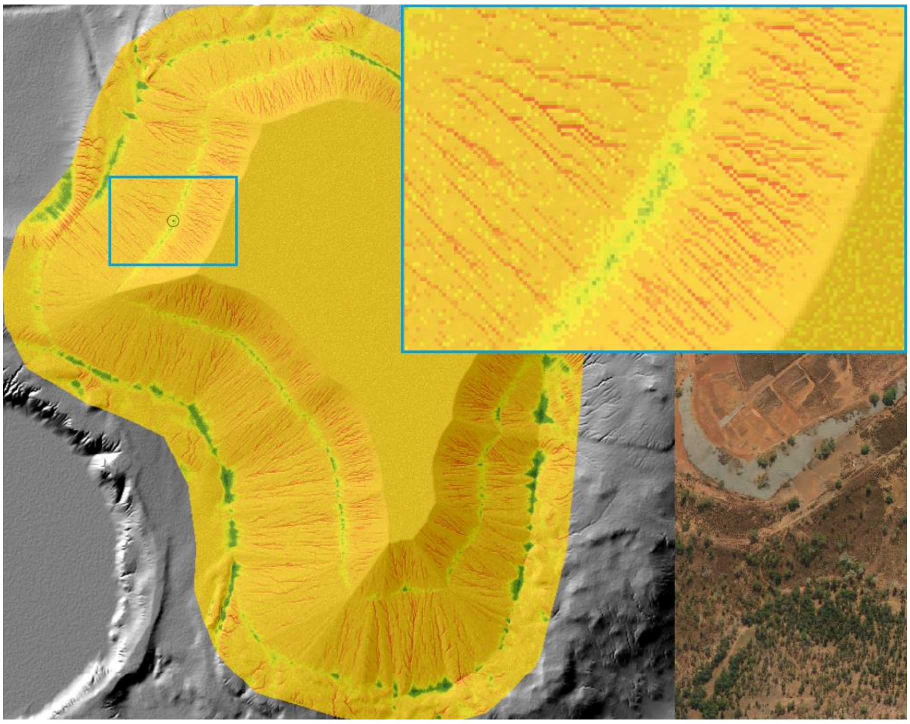


Figure 11 WWSF Zoom-in 1

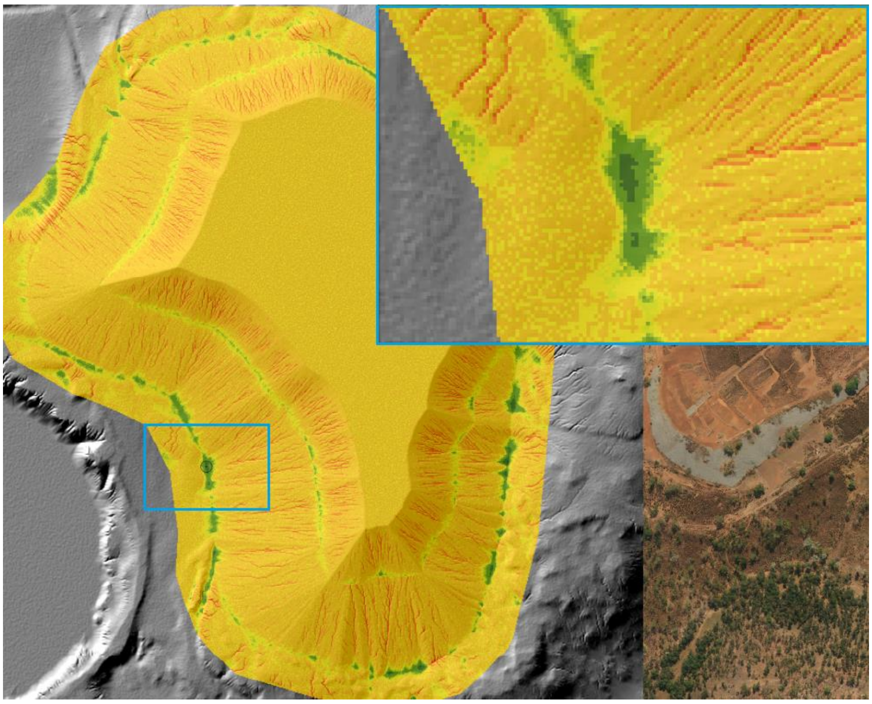
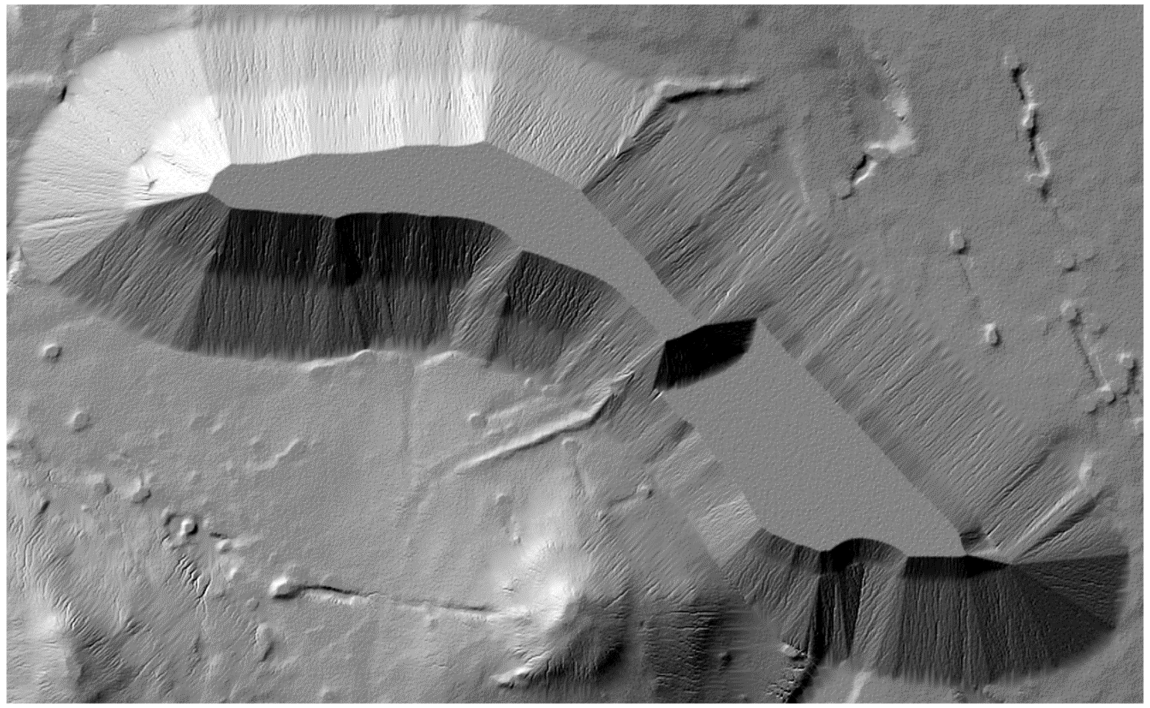
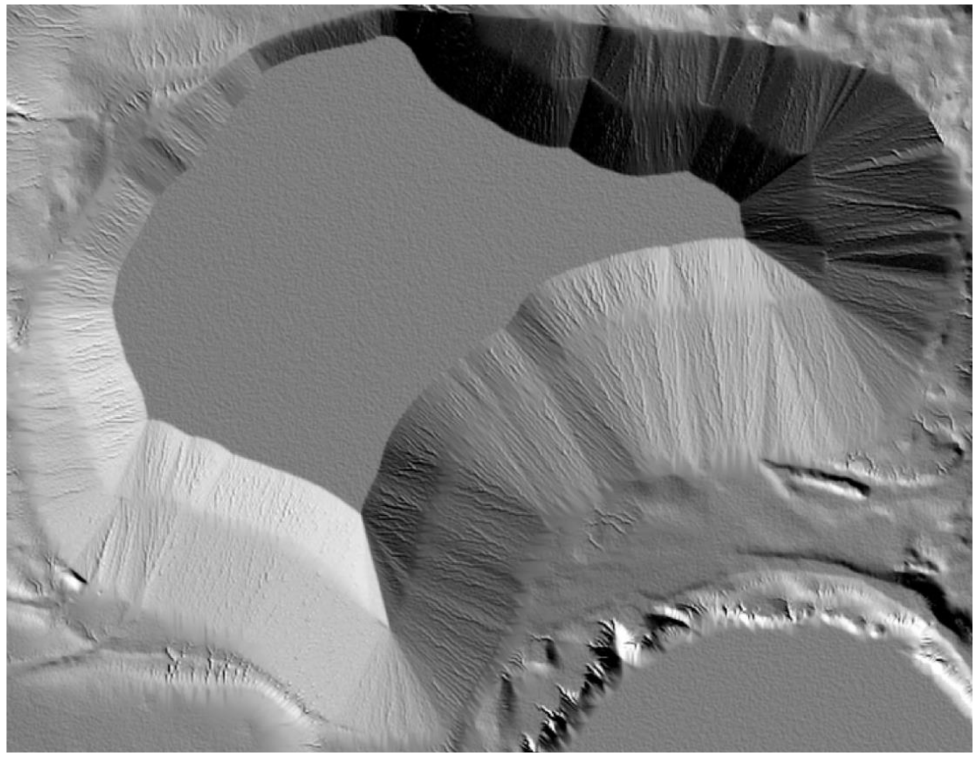


Figure 12 WWSF Zoom-in 2

Table 7 Stage 2 Hillshades and their respective Soil Loss Maps for EWSF and WWSF After 500 Years.

<table>
<tr><th>Eroded Hillshades</th><th>Soil Loss Maps</th><th>Description</th></tr>
<tr><td></td><td>
</td><td>East Waste Storage Facility

9° to 14° Dual Slope
(1:6.25 to 1:4 (V:H))</td></tr>
<tr><td></td><td>
</td><td>West Waste Storage Facility

9° to 14° Dual Slope
(1:6.25 to 1:4 (V:H))</td></tr>
</table>

5 Conclusions

Based on the results presented in this report it is conclude that:

- The recommended batter slope to prevent excessive erosion/gully incision into the capping materials is 9°to 14° dual-slope.
- Vegetated cover models predict that the proposed cover depth of 2.50 m is not likely to be reached after 500 years.
- The maximum gully depths are localised and represent a minor percentage in terms of area.
- Although the models show a good performance in terms of erosion, it is recommended that:
    - The portion of the dual slope whose slope is 14° and localised near the top of the batter is the most vulnerable part of the East WSF, so a different vegetation configuration should be prescribed, using species able to withstand larger runoff speed compared to the plateau;
    - The change in slope needs to be smoothed in the construction phase (refer Section 6), so the abrupt change does not become an erosion seeding feature;
    - A rapid and consistent vegetation cover should be chosen to minimise the chance to cause early deterioration of the bare soil; and
    - Rock armouring is a good option to prevent erosion, however, direct sun exposition can lead to hot temperatures that may 'cook' the vegetation in contact. Therefore, this solution should only be adopted under specific circumstances where the associated risk can be overcome.
- There is currently no wide agreement on what can be considered as 'acceptable' rate of erosion on a mine site. However, the Queensland Department of Minerals and Energy (QDME) 'target erosion rate' for rehabilitated spoil is 12 to 40 t/ha/yr (Society for Mining, Metallurgy, and Exploration, Inc., 2000). The proposed vegetation establishment shows that after 500 years the erosion rate is around 0.4 m^3/ha/yr. Considering a material bulk density of 1.25 t/m^3 the erosion rate can be expressed as 0.5 t/ha/yr. This value is significantly lower than the specified by QDME.
- The selected slope provides a landform able to accommodate the volume within the desired footprint. In addition, it offers a similar visual scenario compared to the existing surrounding natural features.

6 Recommendations for Construction Stage

As outlined in Section 1.2.3, it is important to note that the WSF landforms that have been used were in draft at the time of initial modelling. Although the results indicate that the erosional performance is acceptable, it is important to understand that modelling relies on assumptions and/or simplification in order to obtain results. These assumptions relate to shape (plan and elevation geometry) and material (soil and vegetation) and it is recommended that these be assessed or refined further before the design is ready for construction.

Recommendations for finalising the design relate to activities that can be undertaken during the construction phase, include:

- All borrow materials tested and modelled are assumed to be representative of all borrow materials. Geotechnical parameters should be reassessed via flume testing and/or field tests prior to construction to ensure that the they comply with specification envelopes; alternatively, materials can be conditioned to meet the values required here and/or modelling could be updated.
- The type and rate of revegetation is critical to controlling erosion. The Project revegetation plan (which is to be developed by DPIR prior to construction) should be representative of the data provided within this report; alternatively modelling to estimate likely erosion under the proposed revegetation plan should be undertaken.
- Sharp edges at crests, change of batter slope and the toe should be avoided as these act as seeds for localised gully erosion. A continuous and soft concave interface should be developed as shown in **Figure 13**.

  Smoothing the WSF's in these three aspects will result in a more natural, visually pleasant geometry which combined with the 9° to 14° dual-slope will blend with the natural surroundings.

Figure 13 Final expected concave shape including vegetation

- The final landform should be based on the DTMs that have been provided by SLR as part of the final design package (SLR, 2020a). However, it is acknowledged that the WSFs landform may change from the final design due to changes in material assumptions during construction (i.e. bulking factors, compaction factors etc.) or unexpected finds on site. Therefore, ongoing updates to the WSF design, including consideration of erosion requirements, will be required during design.
- Quality control is crucial in terms of material placement such as foundation preparation, density and compaction, layer thickness, organic material content or any other specification need to be among the desirable limits to assure integrity and stability. Failure to provide this will translate in failure of the designed facilities even at a small scale, where a simple settlement will act as an initial state to deteriorate a whole capping system.

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APPENDIX A

Flume Erosion Report

Material characteristics and erosion parameter determination for Rum Jungle materials

Cover image. Flow over the NPT01 material.

1 Introduction

SLR plan to employ the SIBERIA landscape evolution model (LEM) to assess rehabilitation designs for the Rum Jungle site. Before use, the SIBERIA LEM requires calibration for the surface materials.

Aquaterra International has been engaged by SLR to determine parameters for two materials that may be used at the site.

This report presents results for a flume assessment on erodibility and parameter derivation for two different potential surface materials. A basic characterisation and assessment was also conducted to assist in this.

The information here was used to determine input parameters for the SIBERIA landscape evolution model.

2 Methods

2.1 Basic material analysis

Basic material analysis was conducted – Electrical Conductivity, pH, % sand, silt and clay by hydrometer, sieve analysis (<2mm and >2mm size fraction) and bulk density.

Infiltration rate here was calculated from quantifying the groundwater leaving the flume (see below).

2.2 The use of laboratory scale flumes for the testing of soil and the calculation of erosion rates

The flume was constructed of a box 2.4m long, 0.2m wide and 0.3m deep. In the base a galvanised mesh frame was placed 0.05m above the base which was covered in geotextile material. 50mm of river sand was placed on top of this base which was then covered in geotextile material. This provided a free-flowing porous base which did not impede the infiltration of soil water and through which any groundwater could exit. At the base of the box at the lower end a 20mm diameter pipe allowed any groundwater to exit.

A header tank at the top of the box supplied runoff across the width of the flume (0.2m) at a constant rate.

The design of the flume was such that a specified discharge could be applied at the top of the slope and all water and sediment can be measured including groundwater (collected) at the outlet. As discussed above, water was also free to infiltrate through the material and be collected and quantified. A water balance is therefore able to be calculated.

The flume was mounted in a steel frame. Slope of the flume was able to be adjusted to any angle between 0 and 30%.

Water to the flume was provided by a header tank which provided an even distribution of water across the full width. Flow was adjusted by a valve which allowed discharge to be regulated from 0 to 20 l/min. Flow was quantified (checked) twice. Once by checking the flow entering the header tank (pre-test) and also by measuring what exited the flume both by surface water and groundwater flow at the outlet. For all experiments potable water was used.

2.3 Material placement

Depending on the material, this is a multistep process with a layer being placed, it then gently being compacted by a flat plate. Depending on the material and its water content, water may need to be added for each layer.

Once the maximum depth had been reached the surface is smoothed with a straight edge to provide a uniform surface.

Once placed in the flume, the material is packed with a flat plate, with particular emphasis along the edges so that there were no preferential flow paths or unevenness and resmoothed.

For multiple runs (i.e. different slopes), the surface material was removed and a layer of fresh material added (i.e. to a depth of 20-40mm) depending on the type of erosion and how deep (i.e. rilling) it was.

No attempt here has been made to simulate compaction generated by a bulldozer or other earth moving equipment. This can be done upon rrequest. Here it has been assumed that the surface would be ripped and any compaction would be minimal.

2.4 Flume operation

Once the material was placed in the flume, the surface was wet until it was saturated but not generating runoff. This was done several times and could take several days before the material was fully packed and was at field capacity.

Once packed and wet, the material was allowed to sit for at least 24 hours. This ensured that the material was wet to field capacity, fully settled as well as providing a consistent soil moisture and starting conditions for all experiments.

Each run was commenced with a low flow so to allow the material to slowly wet up and runoff commence. This was continued until a constant runoff and groundwater discharge occurred. Flows were increased to represent different rainfall/runoff rates. An adjustment period of at least 5 minutes for each new flow allowed runoff and groundwater to equilibrate for the new input flow.

For each flow rate between one and three water samples were collected with both time of sample collected the number of seconds to fill the container recorded. Surface flow and groundwater exiting the flume was therefore independently measured for each flow rate.

Each water/sediment sample was collected in pre-weighed containers which were then weighed when full (~2000ml in volume). These samples were then placed in an oven at 70 Celsius to drive off all water (for approximately 7 days) with the bottles containing the dried sediment then reweighed. Using the gravimetric method allowed both volume of runoff and mass of sediment to be calculated. This data was then used to determine SIBERIA model parameters.

3 Supplied samples

Samples were supplied from the positions displayed in Figure 1.

Test pit data supplied by SLR is displayed in Figures 2 and 3.

3.1 Materials for testing

Materials for testing were supplied in 20 litre containers (Figure 4).

These were labelled:

1. NPT01 0.5m-1.1m (3 x 20 litre)
2. NPT01 4.9m-5.3m (3 x 20 litre)

3.2 Material preparation

All material was removed from their containers and mixed before use (Figure 5). A sample was randomly selected for basic material analysis. Results area displayed in Table 1.

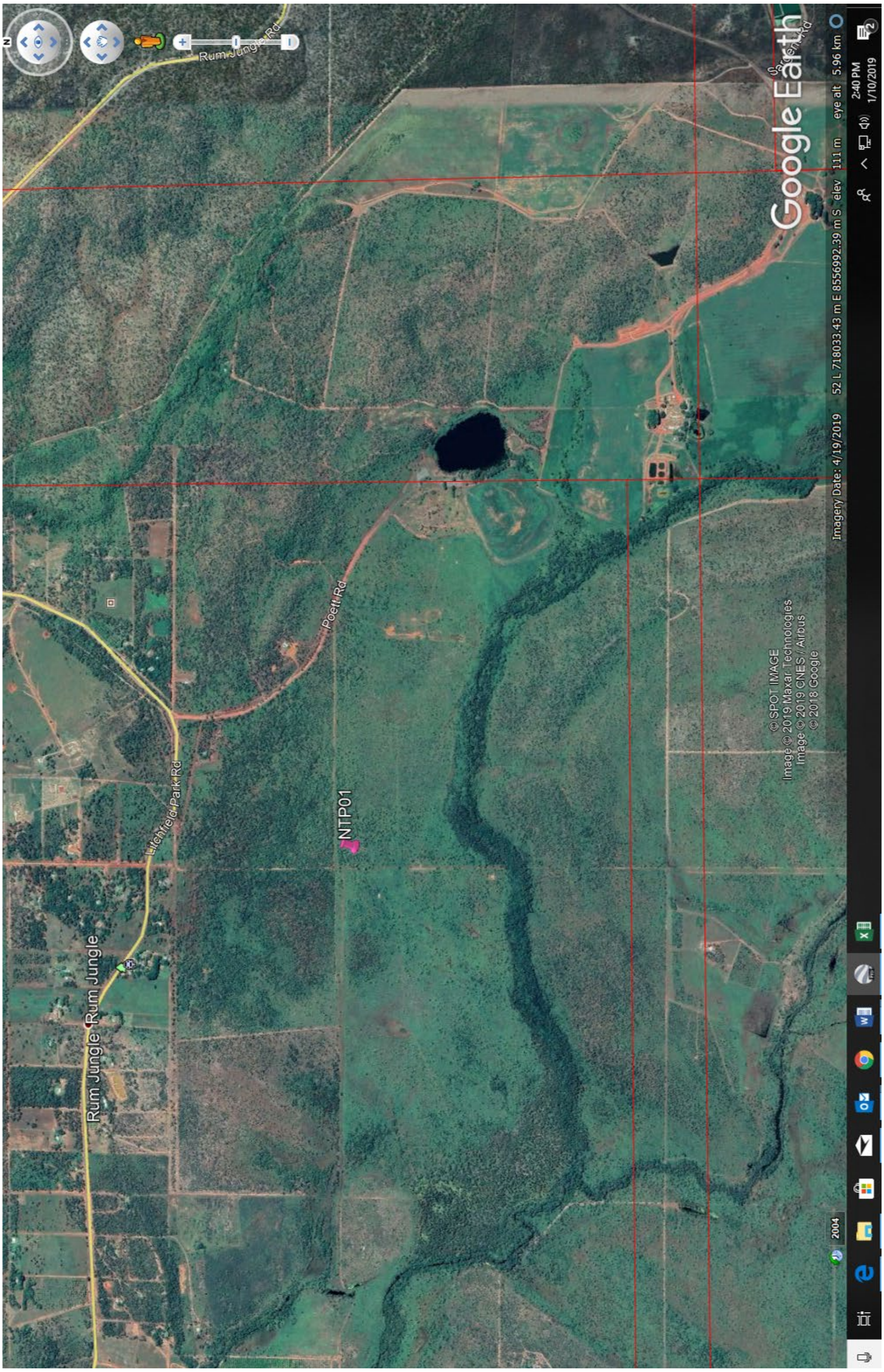
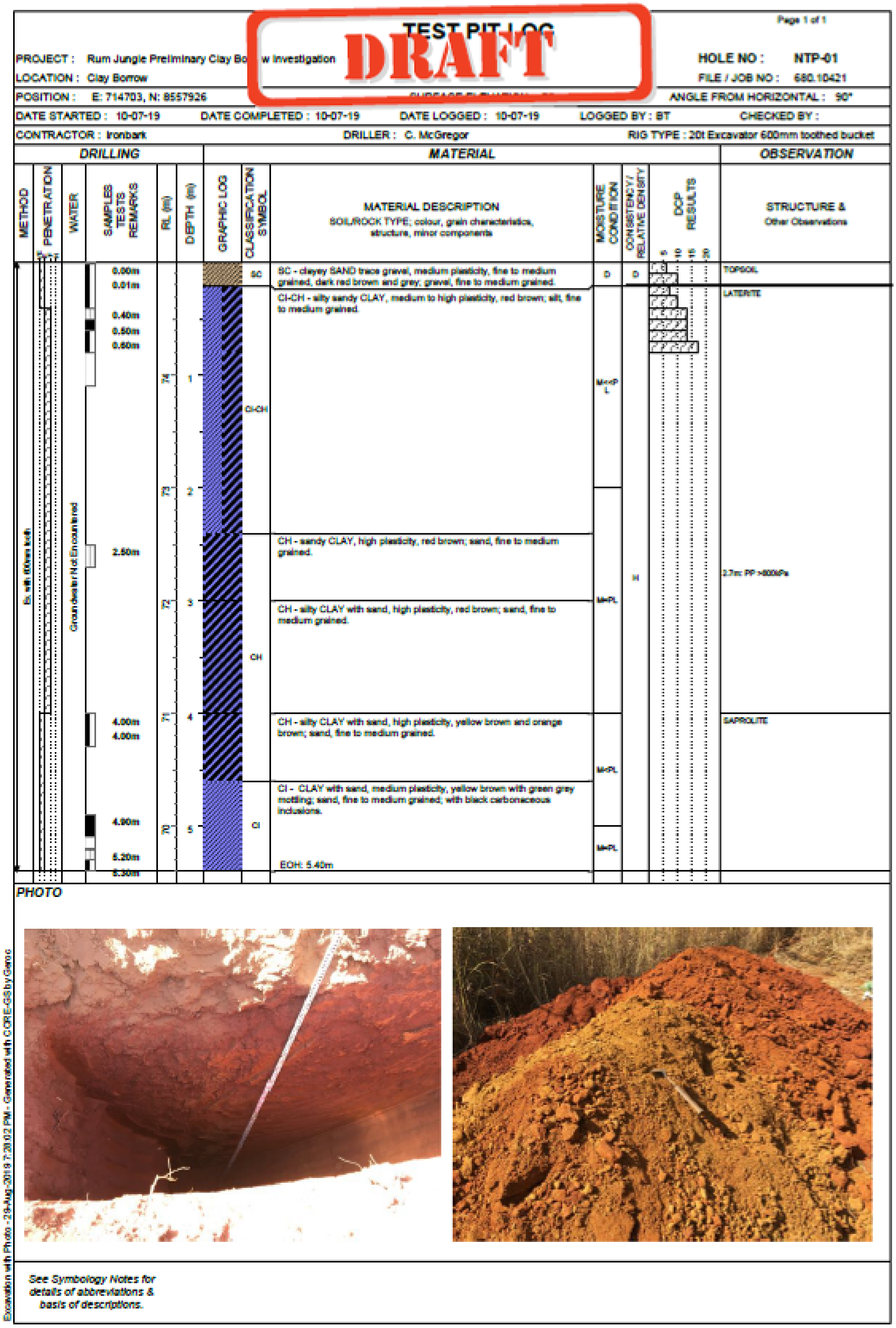


Figure 1. Location of material sampled (google earth). Coordinates supplied by SLR.

Figure 2. NPTO1 soil pit photo log (supplied by SLR).



TEST PIT LOG — DRAFT — Page 1 of 1

PROJECT : Rum Jungle Preliminary Clay Bo[…]w Investigation — HOLE NO : NTP-01
LOCATION : Clay Borrow — FILE / JOB NO : 680.10421
POSITION : E: 714703, N: 8557926 — ANGLE FROM HORIZONTAL : 90°
DATE STARTED : 10-07-19 — DATE COMPLETED : 10-07-19 — DATE LOGGED : 10-07-19 — LOGGED BY : BT — CHECKED BY :
CONTRACTOR : Ironbark — DRILLER : C. McGregor — RIG TYPE : 20t Excavator 600mm toothed bucket

METHOD: Ex. with 600mm tooth — WATER: Groundwater Not Encountered

Samples / tests / remarks: 0.00m, 0.01m, 0.40m, 0.50m, 0.60m, 2.50m, 4.00m, 4.00m, 4.90m, 5.20m, 5.30m

Classification symbol	Material description (SOIL/ROCK TYPE; colour, grain characteristics, structure, minor components)	Moisture condition	Consistency / relative density	Structure & other observations
SC	SC - clayey SAND trace gravel, medium plasticity, fine to medium grained, dark red brown and grey; gravel, fine to medium grained.	D	D	TOPSOIL
CI-CH	CI-CH - silty sandy CLAY, medium to high plasticity, red brown; silt, fine to medium grained.	M<<PL	H	LATERITE
CH	CH - sandy CLAY, high plasticity, red brown; sand, fine to medium grained.	M>PL	H	2.7m: PP >600kPa
CH	CH - silty CLAY with sand, high plasticity, red brown; sand, fine to medium grained.	M>PL	H	
CH	CH - silty CLAY with sand, high plasticity, yellow brown and orange brown; sand, fine to medium grained.	M>PL	H	SAPROLITE
CI	CI - CLAY with sand, medium plasticity, yellow brown with green grey mottling; sand, fine to medium grained; with black carbonaceous inclusions.	M>PL	H	
	EOH: 5.40m			

PHOTO

See Symbology Notes for details of abbreviations & basis of descriptions.

Excavation with Photo - 29-Aug-2019 7:28:02 PM - Generated with CORE-GS by Geroc

Figure 3. NPTO1 soil pit/drill log (supplied by SLR).

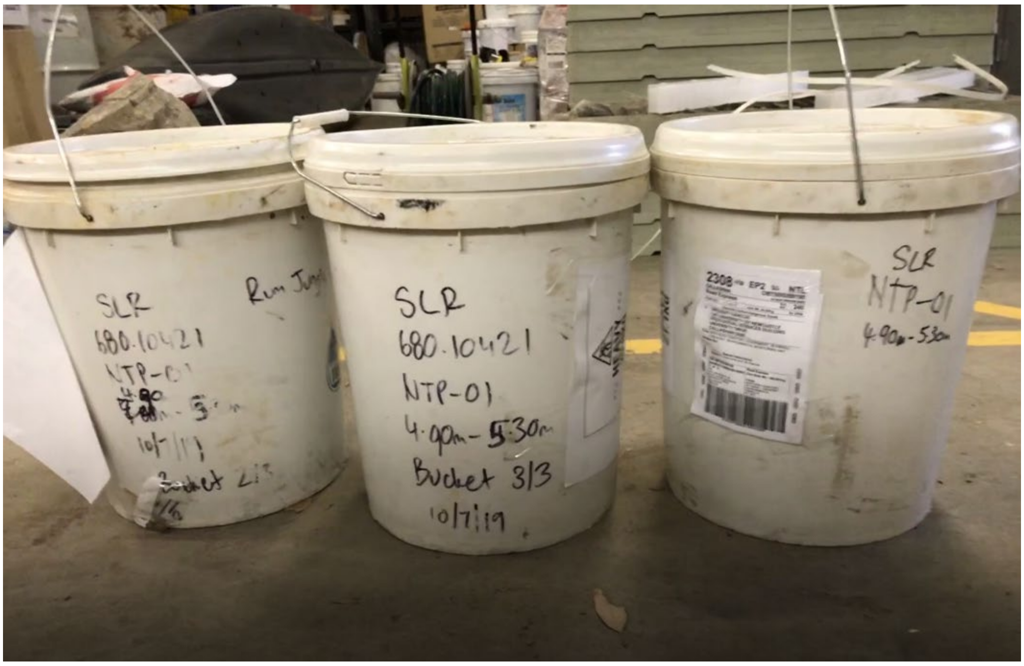


Figure 4. NPT01 0.5m-1.1m (Red) (top) and NPT01 4.9m-5.3m (Tan) (bottom) as received.

Figure 5. NPT01 0.5m-1.1m (Red) (top) and NPT01 4.9m-5.3m (Tan) (bottom) after removal from containers.

3.3 Material general characteristics

Table 1. Rum Jungle material properties

	NPT01 0.5m-1.1m (Red)	**NPT01 4.9m-5.3m (Tan)**
EC Soln (µS)	18.4	23.4
pH Soln	6.1	6.2
Moisture (%)	13.1	22.5
<2mm (%)	90	88
>2mm (%)	10	12
%Sand	29	16
%Silt	18	70
%Clay	53	13
Bulk density (<2mm)	1.25t/m^3	1.27t/m^3
Infiltration*	<5mm/hr	<5mm/hr
Material classification	silty clay	silty loam
K (RUSLE)**	0.025	0.055

*calculated from groundwater flow rates from base of flume
**K values from Hazelton and Murphy (2007)

3.3.1 NPT01 0.5m-1.1m (Red)

Description
Upon removal from the containers material was quite moist (13.1%). Colour was deep red/brown (and was named 'Red' for easy identification). This suggests an oxidised soil with a high iron content (Table 1). The material has a pedal structure with a clay peds present, some of which were quite large (Figure 5). These were broken and included in the mix. Small plant roots were present. Silty clay in texture. Quite sticky to work/mix.

pH (6.1) and EC suggests that there are no major impediments to plant growth (Table 1) however nutrient or elemental analysis was not undertaken. Infiltration was low and the soil texture suggests a high water holding potential.

The contents of the drums were mixed together and used as one material (Figure 5).

3.3.2 NPT01 4.9m-5.3m (Tan)

Description
Upon removal from the containers material was quite moist (23.4%) (Table 1).Colour was a tan with brown mottles (and was named 'Tan' for easy identification) suggestive of anaerobic conditions and having its origins at depth. The soil has a pedal structure with large peds present (Figure 5). These were broken and included in the mix. Silty loam in texture. Quite sticky to work/mix.

pH (6.2) and EC suggests that there are no major impediments to plant growth (Table 1) however nutrient or elemental analysis was not undertaken. Infiltration was low and the soil texture suggests a high water holding potential.

The contents of the drums were mixed together and used as one material (Figure 5).

4 Flume runs

Each material was packed in a series of layers, wet, and compacted and smoothed before the start of each run as described above.

For compaction and to ensure a complete wetting, each material was allowed to sit for at least 24hrs before the start of the run.

A number of flume runs at different slope angle were performed for each material. These were:

NPT01 0.5m-1.1m (Red)	5%, 15%, 25% slope
NPT01 4.9m-5.3m (Tan)	5%, 15%, 25% slope

5 Parameter calculation

The SIBERIA fluvial sediment transport equation is (q_{sf}):

$$q_{sf} = \beta_1 Q^{m_1} S^{n_1} \quad (1)$$

where Q represents the discharge per unit width (m^3/s/m width), S is the slope in the steepest downslope direction (m/m) while n_1, β_1 (soil erodibility) and m_1 are calibrated parameters which in combination will represent sheetwash, rilling or gullying.

The SIBERIA parameter determination was a multiple regression for the β_1, m_1 and n_1 for runoff, sediment load and each slope until the parameter combination was optimised.

The RUSLE K factor was used as the starting point for the determination of β_1 as it is a well-recognised measure of erodibility.

It is well known that the values of m_1 and n_1 (Equation 1) vary widely but for most fluvial systems they both range between 1 and 3 (Kirkby, 1971; Willgoose, 2005). However, n_1 has been measured to be as low as 0.5 in mining applications due to surface armouring (Willgoose and Riley, 1998; Willgoose and Sharmeen, 2006) with, everything else being equal, steeper slopes developing coarser, less erodible, surfaces than flatter slopes (Cohen et al., 2009 and Welivitiya et al., 2016).

SIBERIA operates using the 1:2 year storm as the most geomorphically active rainfall event. This is the storm that on average does the most geomorphic work (Willgoose, 2005). Here we use the Bureau of Meteorology Intensity-Frequency Duration data for Rum Jungle to determine this storm (Figure 6).

Rainfall and resultant runoff for the flume is based on this data and for each slope runoff starts from low intensity longer duration and progresses to higher intensity shorter duration. The higher intensity data also represents concentrated flow over the surface.

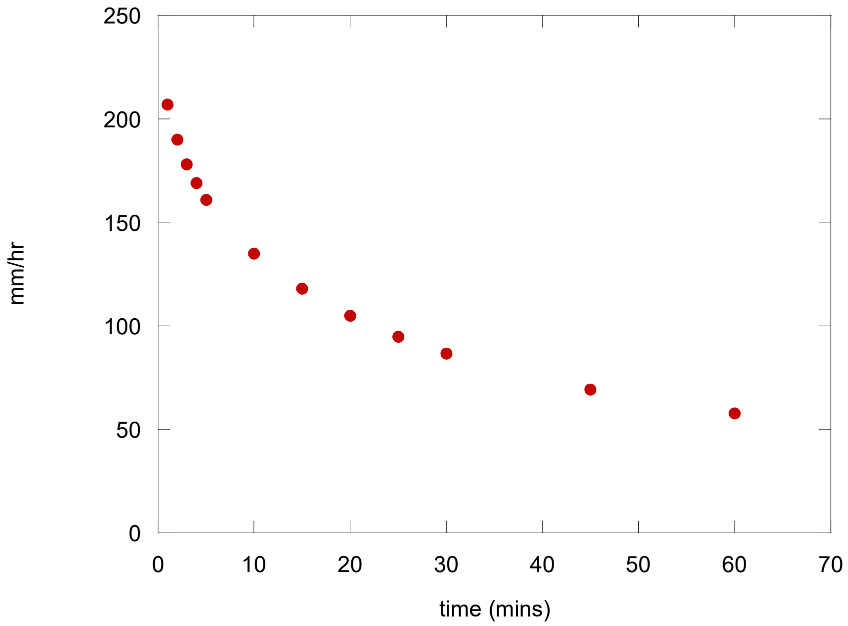


Figure 6. Intensity Frequency Duration curve for a 1:2 year storm for Rum Jungle (www.bom.gov.au).

6 Results

6.1 Erosion results and process – NPT01 0.5m-1.1m (Red)

The material was fully wet upon packing and allowed to settle for 24hours before the commencement of the run. The material had a very smooth texture but was difficult to finish to a smooth surface due to the high clay content. However, upon initial wetting a smooth surface resulted (Figure 7).

It is best to have a material thickness of at least 120mm (150mm optimal) to ensure sufficient depth of material to erode (i.e. severe erosion) and also to ensure a reliable infiltration rate and therefore runoff over the surface. Sufficient material is also needed to produce a good seal along the flume walls. Here, material was placed in the flume to a maximum depth of 80-100mm as this was the maximum depth allowed by the supplied material. This is the bare minimum for analysis.

Upon initiation of runoff the material immediately had a high erosion rate as evidenced by a high sediment discharge (Figure 8). Small rills appeared almost immediately. As runoff increased ‘pot holes’ developed in conjunction with the sheetwash and rilling (Figures 9-11). The pot holes were up to 40mm deep at the end of the run.

At the higher slopes and flow rates sediment output was erratic as clay peds were removed creating a knickpoint and more erodible material was exposed to be transported. This pulse like delivery of sediment made it difficult to sample as any result depended on when the sample was collected in the cycle of the pulses.

Fines were removed and the surface became armoured with more resistant peds for each flow. However, an increase in flow quickly increased shear stress until the fines again were washed through again leaving a coarse armour which was easily disturbed upon increased flow. Without vegetation or a surface cover this surface will be high erodible.

The material produced no groundwater. Therefore all rainfall will become runoff unless vegetation is present.

Sediment output (Figure 12) and fitted parameters are described below (Table 2)

The model parameters here are representative of a material which has a combination of both sheetwash and gullying due to its clay content. The clay binds the material for low flows but at higher flow the shear creates knickpoints at positions of concentrated flow. The material has thresholds that generate different erosion mechanisms as flow increases.

Revegetation will be key if this material is to be used. Given the chemically benign nature of the material, there is no reason why a rapid and consistent vegetation cover could not be established. Alternatively, a rock armour would reduce erosion.

This is a highly erodible material that will erode at low slopes (Figure 7).

Other material properties: The material was allowed to sit for several days before commencement of the runs. During this time the material was subject to several hot days (>30C) and dried. The material readily cracked. Given the seasonal nature of rainfall at the site, it can be expected that this material will crack with the potential for the cracks to act as points initiation for erosion.

Figure 7. NPT01 0.5m-1.1m (Red) material starting conditions.

Figure 8. NPT01 0.5m-1.1m (Red) material with eroded material deposited at the outlet of the flume at the end of the 5% run.

Figure 9. Eroded surface at the end of the 15% run for NPT01 0.5m-1.1m (Red) material.

Figure 10. Eroded surface at the end of the 15% run for NPT01 0.5m-1.1m (Red) material.

Figure 11. Head of rill 40mm deep after termination of the 25% run.

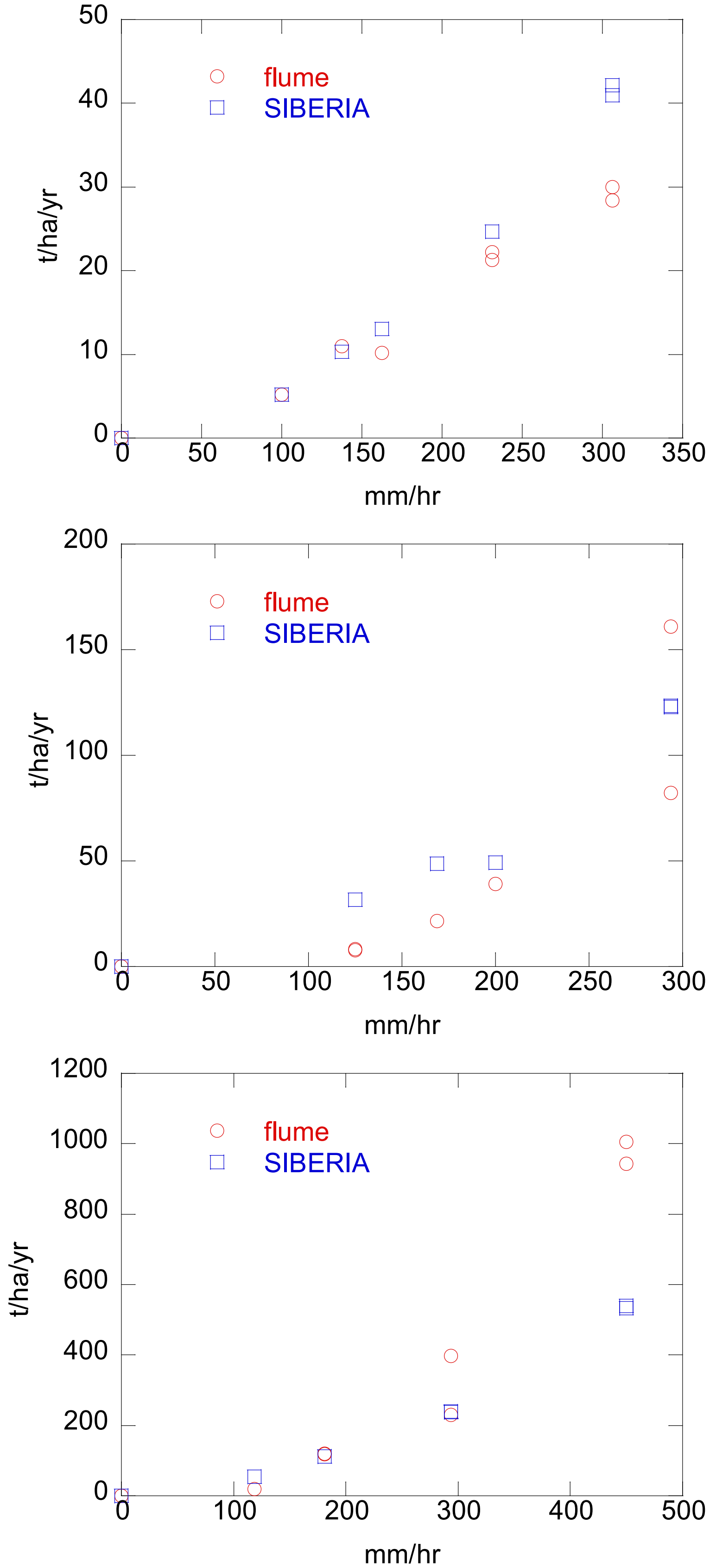


Figure 12. NPT01 0.5m-1.1m (Red) flume sediment output and SIBERIA predicted sediment output from 5%, 15% and 25 % slopes.

Table 2. SIBERIA parameters for the NPT01 0.5m-1.1m (Red) material.

	5%	**15%**	**25%**
β_1	0.015	0.01	0.01
β_3	1	1	1
m_1	1.6	1.6	1.5
m_3	1	1	1
n_1	2	2	2.6

6.2 Erosion results and process – NPT01 4.9m-5.3m (Tan)

The material was fully wet upon packing and allowed to settle for 24hours before the commencement of the run. The material had a very smooth texture and was difficult to finish to a smooth surface. However, upon initial wetting a smooth surface resulted (Figure 13).

It is best to have a material thickness of at least 120mm (150mm optimal) to ensure sufficient depth of material to erode (i.e. severe erosion) and also to ensure a reliable infiltration rate and therefore runoff over the surface. Sufficient material is also needed to produce a good seal along the flume walls. Here, material was placed in the flume to a maximum depth of 80-100mm as this was the maximum depth allowed by the supplied material. This is the bare minimum for analysis.

Upon initiation of runoff the material immediately had a high erosion rate as evidenced by a high sediment discharge. Small rills (~5mm deep) appeared almost immediately (Figure 14).

At the higher slopes and flow rates sediment output was erratic as peds were removed creating a knickpoint and more erodible material was exposed to be transported. This pulse like delivery of sediment made it difficult to sample as any result depended on when the sample was collected in the cycle of the pulses.

Fines were removed and the surface became armoured with more resistant peds for each flow. However an increase in flow quickly increased erosion until the fines again were washed through again leaving a coarse armour which was easily disturbed upon increased flow. Without vegetation this surface will be high erodible (Figure 15).

The material produced no groundwater. Therefore all rainfall will become runoff unless vegetation is present.

At the end of the runs there was both sheetflow erosion and rilling and the potholes suggest the potential for gullies (Figures 16 and 17). Erosionally, this material is very unusual. The parameters at 5% suggest the material will gully, however as slope increases the material erodes more by rilling and sheetwash. A point to note is the order of magnitude difference in β_1 between the 5% and 15% slopes with that of the 25% slope.

These properties are likely a result of the high silt content of this subsoil where a lack of clay results in loss of material cohesiveness at high flows.

Revegetation will be key if this material is to be used. Given the chemically benign nature of the material, there is no reason why a rapid and consistent vegetation cover could not be established. Alternatively, a rock armour would reduce erosion.

This is a highly erodible material that will erode at low slopes (Figure 7).

Sediment output (Figure 18) and fitted parameters are described below (Table 3).

Other material properties: The material was allowed to sit for several days after completion of the runs. During this time the material was subject to several hot days

(>30C) and dried. The material readily cracked (Figure 19). Given the seasonal nature of rainfall at the site, it can be expected that this material will crack with the potential for the cracks to act as points initiation for erosion.

Figure 13. NPT01 4.9m-5.3m (Tan) material starting conditions.

Figure 14. NPT01 4.9m-5.3m (Tan) 5% slope at the end run. Note the rill running the length of the flume.

Figure 15. NPT01 4.9m-5.3m (Tan) 15% slope at the end run. Note the rill running the length of the flume.

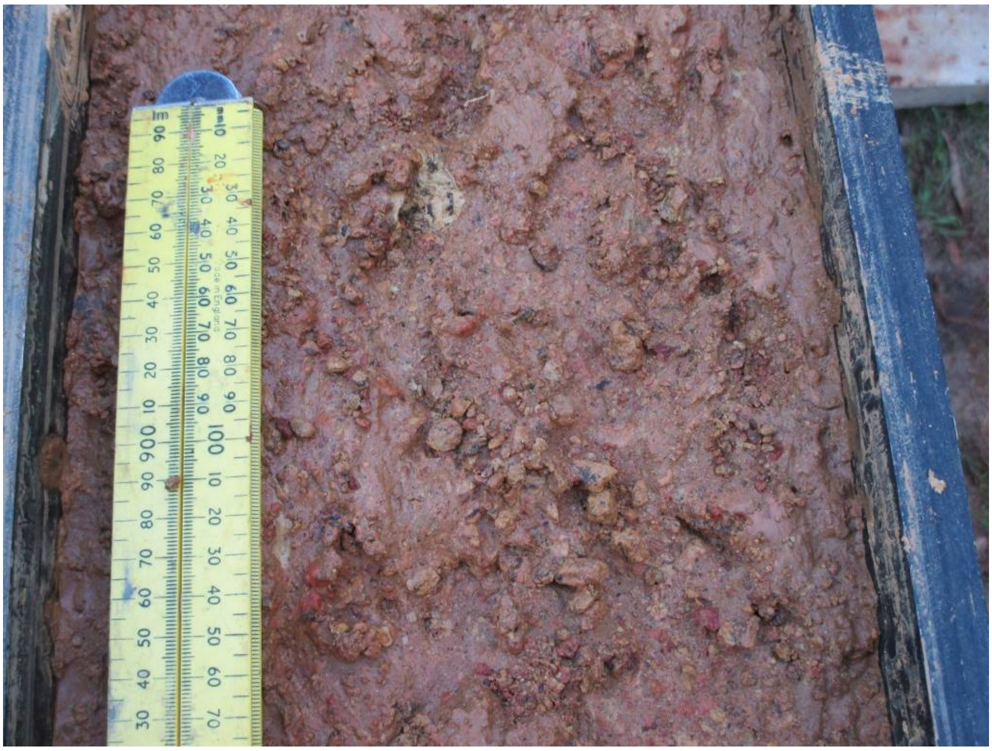


Figure 16. NPT01 4.9m-5.3m (Tan) material at the start (top) and end run (bottom).

Figure 17. NPT01 4.9m-5.3m (Tan) 25% slope at the end run. Note the rill running the length of the flume.

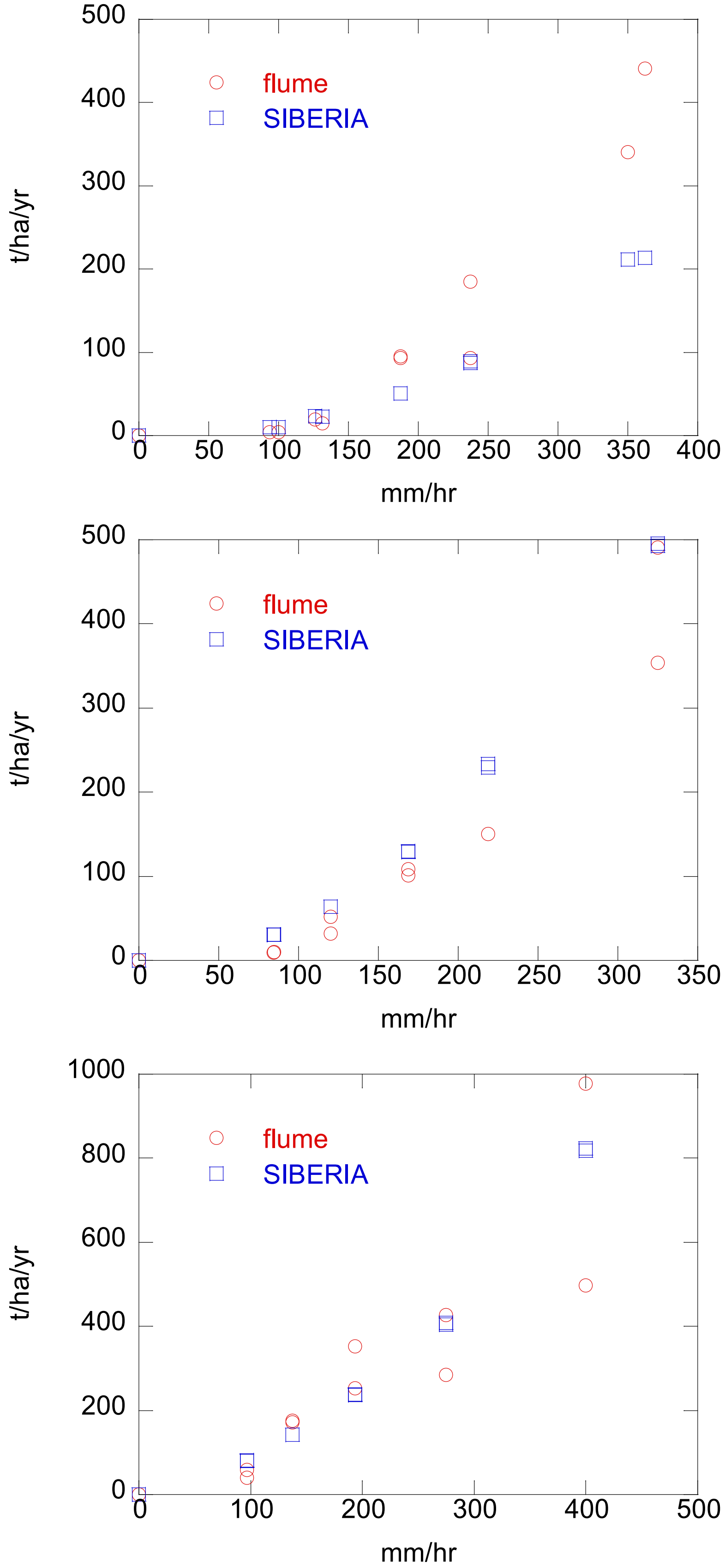


Figure 18. NPT01 4.9m-5.3m (Tan) flume sediment output and SIBERIA predicted sediment output from 5% (top), 15% (middle) and 25 % slope (bottom).

Table 3. SIBERIA parameters for the NPT01 4.9m-5.3m (Tan) material.

	5%	15%	25%
β_1	0.0015	0.0015	0.015
β_3	1	1	1
m_1	2.2	2.0	1.5
m_3	1	1	1
n_1	2.6	2.8	2

Figure 19. NPT01 4.9m-5.3m (Tan) material one week after the completion of the flume runs. Extensive cracking is evident.

6 Study limitations

1. All materials were supplied by SLR. There can be no guarantee that they are representative of the entire site.
2. The erosion parameters obtained represent bare materials with no vegetation or long-term environmental exposure. There is no way to guarantee that the parameters will or will not change if exposed for longer periods.
3. The compaction and surface roughness of the materials in the flume may be very different to that of the mine site. There is no guarantee that the erosion parameters will be the same or different under mine site conditions.

7 Summary

Here two different surface material were tested for their erosion properties. From this data parameters for the SIBERIA Landscape Evolution Model were developed.

The β_1 values for all materials are high indicating high erodibility. The values of m_1 and n_1 are all within the range expected for similar material at other sites and observed erosion behaviour matches that of the derived parameters (Willgoose and Riley, 1998; Willgoose and Sharmeen, 2006).

The results demonstrate that NPT01 0.5m-1.1m (Red) and NPT01 4.9m-5.3m (Tan) are erodible and revegetation would improve their erosional stability.

Revegetation could be tested by further flume analysis. This requires growing a fast growing cover species such as Jap Millet in the flume and then running the flume for different slopes and flows.

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10 October 2019

APPENDIX B

SIBERIA Erosion Modelling Description

Description of SIBERIA

SIBERIA is a long-term erosion model developed by Willgoose et al. in 1989 to model the interaction of the time evolving geomorphic form of natural landscapes with the hydrology and erosion processes taking place, and how these processes, dictate the shape of a natural landform. This piece of software utilises a digital terrain model (DTM) as a starting point, which evolves in time under the imposed runoff and erosion parameters extracted from erosion models.

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

$$Q = \beta_3 A^{m_3} \qquad (1)$$

Where Q is the characteristic discharge out of the catchment, β_3 is the runoff rate, *A* is the catchment area and m_3 is a coefficient. The characteristic discharge is the mean peak discharge.

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

$$Q_s = \beta_1 Q^{m_1} S^{n_1} - \textit{threshold} \qquad (2)$$

Q_s is the mean annual sedimentation rate, β_1 is the erodibility (including the material erodibility, vegetation cover factor and any cropping practice factors (USLE terminology), S the slope, and m_1 and n_1 are parameters to be calibrated for the erosion process. The erosion is relatively insensitive to the exponent n_1 which is commonly taken as 2. The exponent m_1 is modified during calibration to ensure that the concavity of the modelled slope is like the prototype. According to (Kirkby, 1971) (Willgoose, 2005) the values of m1 and n1 (Equation 1) vary widely but for most fluvial systems they both range between 1 and 3.

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

$$Q_s = \beta_1 \ \beta_3{}^{m_3} \ A^{m_1 m_3} S^{n_1} \qquad (3)$$

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

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

$$Q_s = \beta_1{}' A^{m_1 m_3} S^{n_1} \qquad (4)$$

Where

$$\beta_1{}' = \beta_1 \ \beta_3{}^{m_3} \qquad (5)$$

Where calibrations are conducted using surveys of dumps over an extended period, and where the rainfall that occurred over that period can be regarded as representative of the long term average and incorporates unseasonably high as well as low rainfall periods, it is possible to carry out the calibration to determine β_1' directly without the need to consider and specifically account for the rainfall-related parameters β_3 and m_3.

APPENDIX C

Development of K and C Factors for Stage 2

K Factor

The upper capping layer proposed for the waste rock capping is described in detail in the Waste Storage Facility, Clay and Sand Borrow Areas, Geotechnical Investigation report (SLR, 2019). From this description, the dominant soil profiles within the broader landscape are identified as Kandosols under the Australian Soil Classification (ASC) system. Kandosols are soils that lack strong texture contrast, have massive or only weakly structured B horizons, and are not calcareous throughout. More specifically, these soils have all of the following characteristics:

- B2 horizons in which the major part is massive or has only weak grade of structure;
- A maximum clay content in some part of the B2 horizon which exceeds 15% (i.e. heavy sandy loam, SL+);
- Do not have a tenic B horizon;
- Do not have a clear or abrupt textural B horizon; and
- Are not calcareous throughout the solum, or below the A1 or Ap horizon or a depth of 0.2 m if the A1 horizon is only weakly developed.

These soils have been selected to replicate on the waste rock capping (heavy clay) not only because they are the dominant soils within the broader landscape, but they have the following characteristics that make them ideal for a growth medium on a constructed hill of waste rock and capping:

- Tend to be deeply weathered profiles, which are suitable for a growth medium in the tropics;
- Have a sandier texture and good humus content in the surface horizon that provide for moderately rapid stormwater infiltration due to lack of surface crusting or hard setting properties;
- Have gradually increasing clay contents that provide for good water retention and cation exchange capacity;
- Have deep, less consolidated (massive to weak structure) profiles suitable for deep root penetration by grasses and shrubs (but not so deep as to penetrate a clay capping) and are moderately permeable; and
- Have moderately high humus and organic carbon levels as a result of good vegetation growth that in turn improves surface horizon texture and structure.

Should replication of the Kandosol soil prove problematic, the alternative preference would be to replicate a Dermosol soil, which has a fraction more clay throughout the profile, a structured B2 horizon that is more developed than weak and lacks strong texture contrast between the A and B horizons.

The growth material profile proposed to replicate a Kandosol (or Dermosol) and associated K factors for erosivity are shown in the table contained in the next page. Based on the respective soil textures and as recommended by the soil scientist the potentially worst K factor is 0.04 in the A2 to B21 horizons of the Kandosol, because it represents the material with the highest capacity to erode, so this value has been used for the erosion modelling as a worst scenario.

Growth Material Profile for Kandosol (or Dermosol) and Associated K Factors

Approx. Depth (cm)	Kandosol					Dermosol				
	Horizon	Texture	PSD (%)	Structure	K Factor Range	Horizon	Type of Soil (USDA)	PSD (%)	Structure	K Factor Range
0-20	A1	Sandy Loam to Sandy Clay Loam	Clay: 8-20 Silt: 2-10 Sand: 71-91 Clay: 18-33 Silt: 2-8 Sand: 65-82	Massive	0.030 to 0.025	A1	Sandy Clay Loam to Clay Loam, Sandy	Clay: 18-33 Silt: 2-8 Sand: 65-82 Clay: 21-35 Silt: 6-15 Sand: 50-70	Massive	0.02 to 0.03
20-60	A2	Sandy Clay Loam to Clay Loam, Sandy	Clay: 18-33 Silt: 2-8 Sand: 65-82 Clay: 21-35 Silt: 6-15 Sand: 50-70	Massive	0.025 to 0.04	A2 to B21	Clay Loam, Sandy, to Sandy Light Clay	Clay: 21-35 Silt: 6-15 Sand: 50-70 Clay: 27-40 Silt: 2-20 Sand: 40-71	Massive to Weak	0.0 to 0.025
60-120	B21	Clay Loam, Sandy, to Sandy Light Clay	Clay: 21-35 Silt: 6-15 Sand: 50-70 Clay: 27-40 Silt: 2-20 Sand: 40-71	Massive to Weak	0.04 to 0.025	B21 to B22	Sandy Light Clay to Sandy Light Medium Clay	Clay: 27-40 Silt: 2-20 Sand: 40-71 Clay: 40-45 Silt: 2-20 Sand: 35-58	Weak to Moderate	0.025- 0.018
120-200	B22	Sandy Light Clay to Sandy Light Medium Clay	Clay: 27-40 Silt: 2-20 Sand: 40-71 Clay: 40-45 Silt: 2-20 Sand: 35-58	Weak to Moderate	0.025 to 0.018	B22 to B23	Sandy Light Medium Clay to Sandy Medium Clay	Clay: 40-45 Silt: 2-20 Sand: 35-58 Clay: 45-55 Silt: 2-20 Sand: 25-53	Moderate	0.018- 0.015

C Factor

The upper capping layer proposed for the WSFs is described in detail in the Waste Storage Facility, Clay and Sand Borrow Areas, Geotechnical Investigation report (SLR, 2019). From the detailed description, the dominant vegetation communities within the broader landscape are identified as *Eucalyptus tetrodonta, E. miniata, Erythrophleum chlorostachys* woodland to open forest and *E. tetrodonta, E. miniata, Corymbia polysciada open woodland.*

Components of these vegetation communities have been selected to replicate on the WSFs not only because they are the dominant vegetation communities within the broader landscape, but they are also best suited to the proposed landform, slopes and growth material.

The proposed capping material vegetation cover will be established by broadcast seeding (hand spreading of seed) supplemented with infill planting of tubestock and follow-up broadcast seed. This is DPIF's preferred method of establishment based on past project experience.

There will be a four-year program of planting with an emphasis initially on establishing erosion protection with native annual grasses, with later focus shifting to developing a suitable final vegetation community. The vegetation community will comprise native annual and perennial grasses, ground cover shrubs, and possibly shallow rooted trees, which is DPIF's preferred species mix, with the final species mix to be decided in consultation with Traditional Owners.

In consultation with DPIF and their experience with previous similar projects, SLR proposed success criteria for the growth material cover design throughout the establishment phase and, subsequently, out to 500 years. The culmination of these proposed success criteria was predicted C factors for each year and major season with reference to section E3.5 C-factor of Book 2, Volume E of the IECA guidelines (IECA, 2008).

The growth material cover design, establishment method, success criteria, which are based on previous rehabilitation success using this approach, and resultant C factors are shown in the table contained in the following pagesError! Reference source not found..

Achievement of the success criteria for every year is based on the following general assumptions:

- Wet season starts as predicted, average wet season, minimal destructive rainfall events (e.g. intense storm cells, cyclones) to damage revegetation/wash away surface materials.
- Dry season starts as predicted, average dry season, not prolonged or excessively hot thereby killing off seedlings.

Soil Cover Program and Associated C Factors

Year	Soil Cover Description	Construction Complete By	Monitoring and Success Criteria								Total Cover %	C Factor (IECA, 2008)
			Time of Year	Shrub Foliage Cover (%)[1]	Grass Foliage Cover (%)[1]	Stems[2] /m²	Ground Foliage Cover (%)[1]	Mulch Cover[3]		Bare Ground (%)		
								%	Depth (mm)			
1	• Broadcast seeding with preferred seed mix including native grasses, ground cover, shrubs, • Fire excluded	Prior to end of dry season	Start of wet season	0	≥40	0	0	0	0	≤60	≥40	0.22
			Mid-wet season	0	≥75	>0.25	0	≥2.5	≥1	≤25	≥75	0.03
			End of wet season	≥1	≥95	≥0.5	≥1	≥5	≥2	≤5	≥95	0.001
2	• Ground cover and shrub growth started (seedlings germinated) • Native annual grass cover 100%, now dying off • Perennial native grasses seedlings germinated • Infill planting with additional native shrub tubestock • A1 horizon meets soil specifications • Fire excluded	NA	End of dry season	≥1	≥75	≥0.5	≥1	≥25	≥5	≤5	≥95	0.001
			End of wet season	≥5	≥95	≥2	≥5	≥75	≥5	≤5	≥95	0.001
3	• Ground cover and shrub growth progressing (some flowering and seeding) • Native annual grass cover 5% • Perennial native grasses progressing (flowering and seeding) • Infill with broadcast grass and tubestock shrub as required	NA	End of dry season	≥7.5	≥75	≥2	≥7.5	≥90	≥10	≤5	≥95	0.001
			End of wet season	≥10%	≥95	≥2	≥20%	≥75%	≥20	≤5	≥95	0.001

Year	Soil Cover Description	Construction Complete By	Monitoring and Success Criteria								Total Cover %	C Factor (IECA, 2008)
			Time of Year	Shrub Foliage Cover (%)[1]	Grass Foliage Cover (%)[1]	Stems[2] /m[2]	Ground Foliage Cover (%)[1]	Mulch Cover[3]		Bare Ground (%)		
								%	Depth (mm)			
	• A1 horizon meets soil specifications • Fire excluded											
4	• Shrub growth progressing (flowering and seeding, some secondary regeneration) • Native annual grass cover 0% • Perennial native grasses reached maturity (secondary regeneration) • Ground cover reached maturity (flowering and seeding, some secondary regeneration) • Infill with broadcast grass and tubestock shrub as required • A1 horizon meets soil specifications • Fire excluded	NA	End of dry season	≥10	≥75	≥2	≥10	≥95	≥20	≤5	≥95	0.001
			End of wet season	≥20%	≥95%	≥2	≥20%	≥95	≥40	≤5	≥95	0.001
5	• Second generation of shrub growth reached maturity • Second generation of perennial native grasses seedlings • Second generation of ground cover seedlings • Infill with broadcast grass and tubestock shrub as required	NA	End of dry season	≥20	≥75	≥1	≥10	≥95	≥40	≤5	≥95	0.005
			End of wet season	≥50%	≥95%	≥1	≥20%	≥95	≥50	≤5	≥95	0.005

Year	Soil Cover Description	Construction Complete By	Monitoring and Success Criteria								Total Cover %	C Factor (IECA, 2008)
			Time of Year	Shrub Foliage Cover (%)[1]	Grass Foliage Cover (%)[1]	Stems[2] /m^2	Ground Foliage Cover (%)[1]	Mulch Cover[3]		Bare Ground (%)		
								%	Depth (mm)			
	• A1 horizon meets soil specifications • Fire excluded											
10	• Mature shrub layer • Mature perennial native grasses • Mature ground layer • >75 mm native mulch layer • A1 horizon meets soil specifications • Controlled fire introduced	NA	End of dry season	≥25	≥60	≥0.5	≥15	0	0	≤20	≥80	0.04
			End of wet season	≥50%	≥95%	≥0.5	≥20%	≥5	≥2	≤5	≥95	0.005
50	• Mature shrub layer • Mature perennial native grasses • Mature ground layer • >75 mm native mulch layer • A1 horizon meets soil specifications • Controlled fire	NA	End of dry season	≥25	≥60	≥0.5	≥15	0	0	≤20	≥80	0.04
			End of wet season	≥50%	≥95%	≥0.5	≥20%	≥5	≥2	≤5	≥95	0.005
100	• Mature shrub layer • Mature perennial native grasses • Mature ground layer • >75 mm native mulch layer • A1 horizon meets soil specifications	NA	End of dry season	≥25	≥60	≥0.5	≥15	0	0	≤20	≥80	0.04
			End of wet season	≥50%	≥95%	≥0.5	≥20%	≥5	≥2	≤5	≥95	0.005

Year	Soil Cover Description	Construction Complete By	Monitoring and Success Criteria								Total Cover %	C Factor (IECA, 2008)
			Time of Year	Shrub Foliage Cover (%)[1]	Grass Foliage Cover (%)[1]	Stems[2] /m²	Ground Foliage Cover (%)[1]	Mulch Cover[3]		Bare Ground (%)		
								%	Depth (mm)			
	• Controlled fire											
500	• Mature shrub layer • Mature perennial native grasses • Mature ground layer • >75 mm native mulch layer • A1 horizon meets soil specifications • Controlled fire	NA	End of dry season	≥25	≥60	≥0.5	≥15	0	0	≤20	≥80	0.04
			End of wet season	≥50%	≥95%	≥0.5	≥20%	≥5	≥2	≤5	≥95	0.005

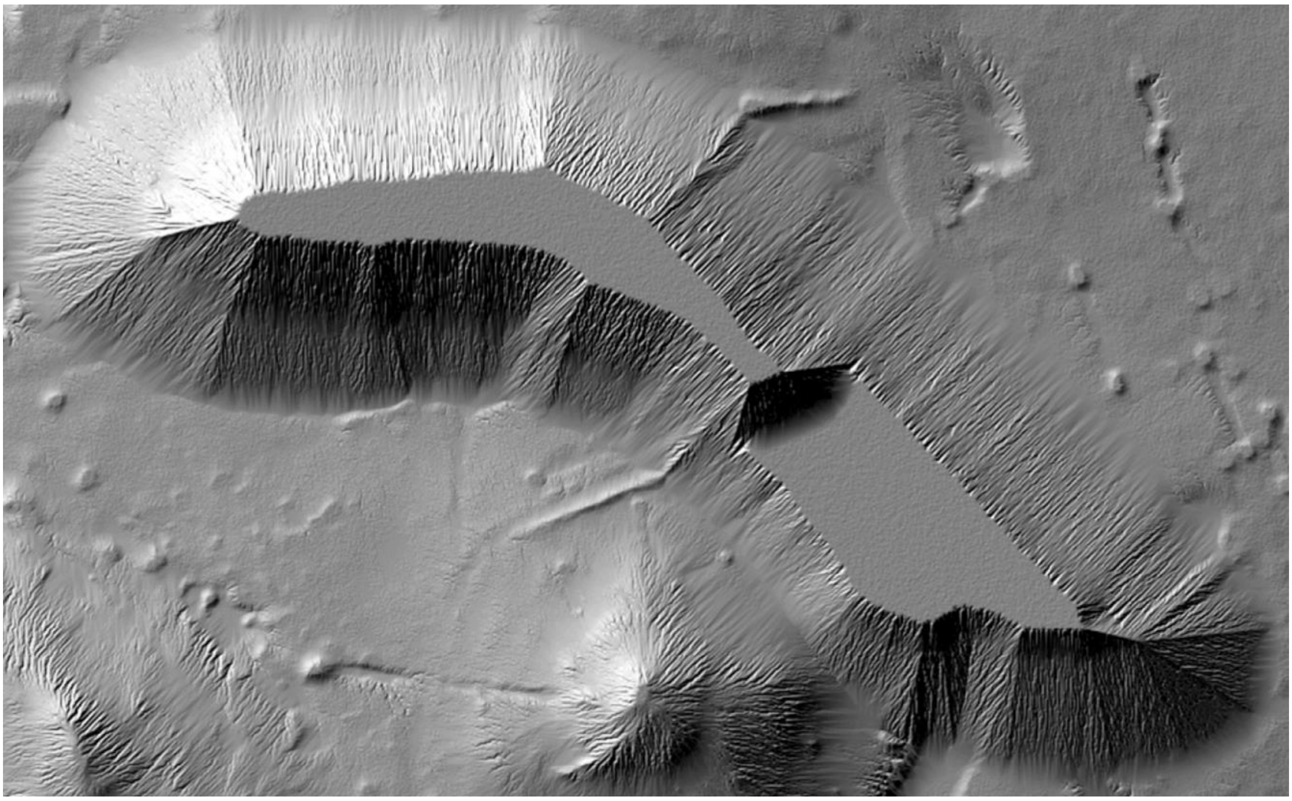
Notes:
1 Foliage cover includes live and dead standing vegetative material
2 Individual stems of shrubs only
3 Mulch cover includes and live or dead material that has detached from a plant and is laying on the ground

APPENDIX D

Stage 1 Hillshades and Erosion Colour Maps

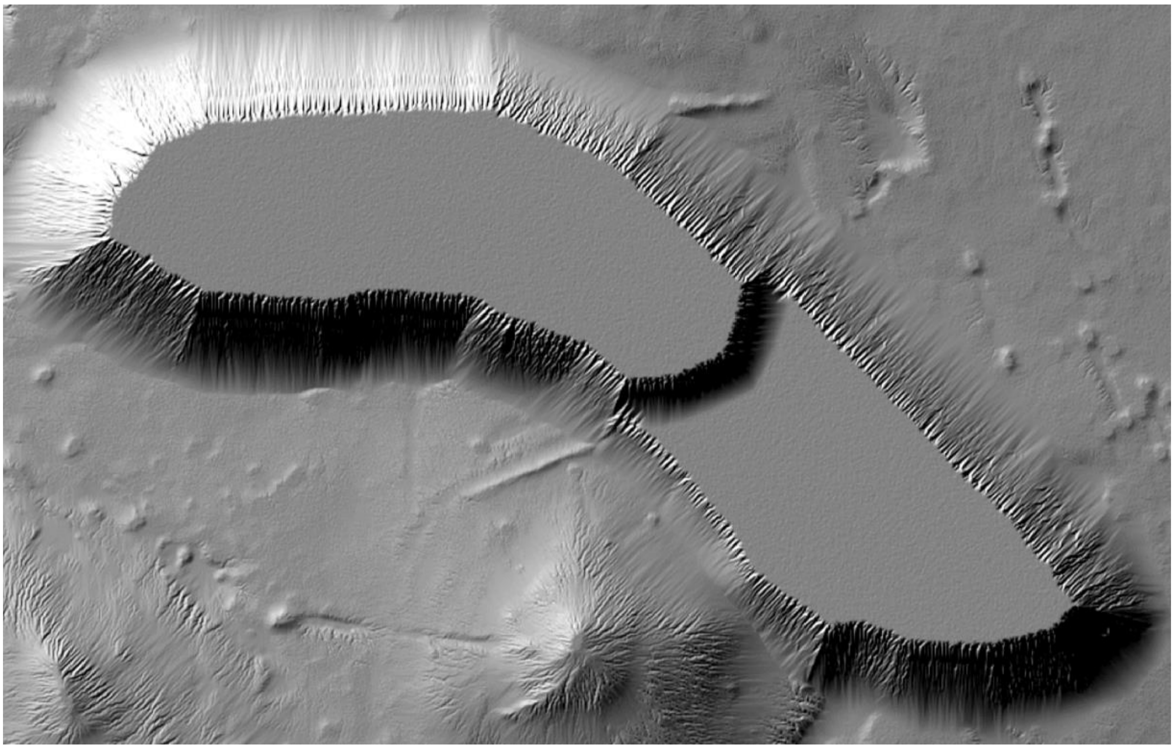
In general, the following can be observed:

- Predicted erosion profiles at 0, 200 and 500 years, showing increasing erosion depth with time.
- The majority of soil loss in all scenarios is evidenced in the -0.00 to -0.25 m bracket, where 47%, 33% and 35% of the EWSF area correspond to the low, medium and high slopes. Similarly, the deposition bracket of 0.00 to 0.25 m contains the larger portion of soil deposition at the WSF’s toe.
- The colour maps for all scenarios show that deep erosion depths i.e. >1m are around 1%, 12% and 14% of total site area for the low, medium and high dual slopes, respectively.

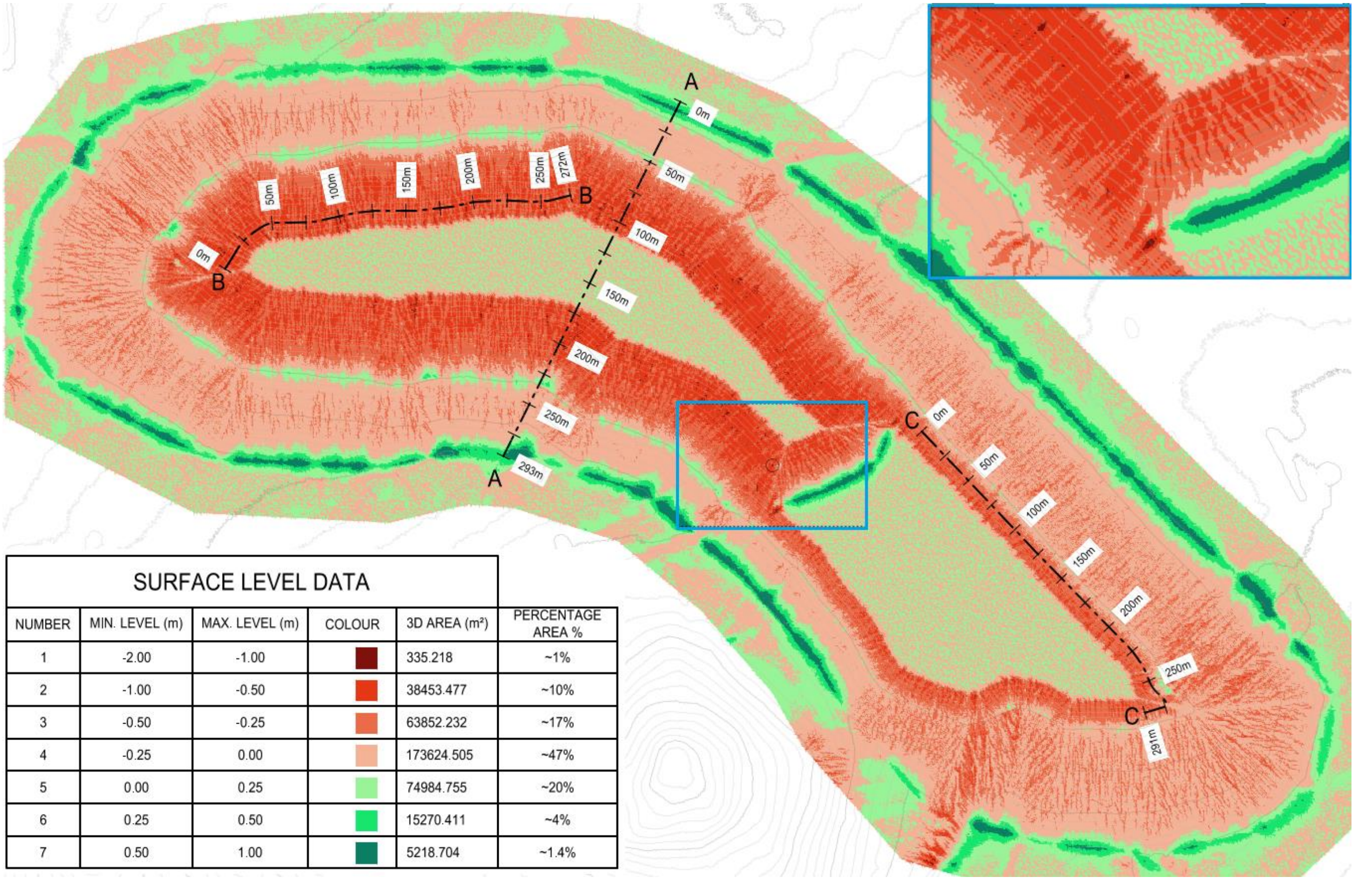


Stage 1 EWSF Hillshade After 500 Years, 9°-14° Dual-slope

Stage 1, EWSF Hillshade After 500 Years, 16°-22° Dual-slope

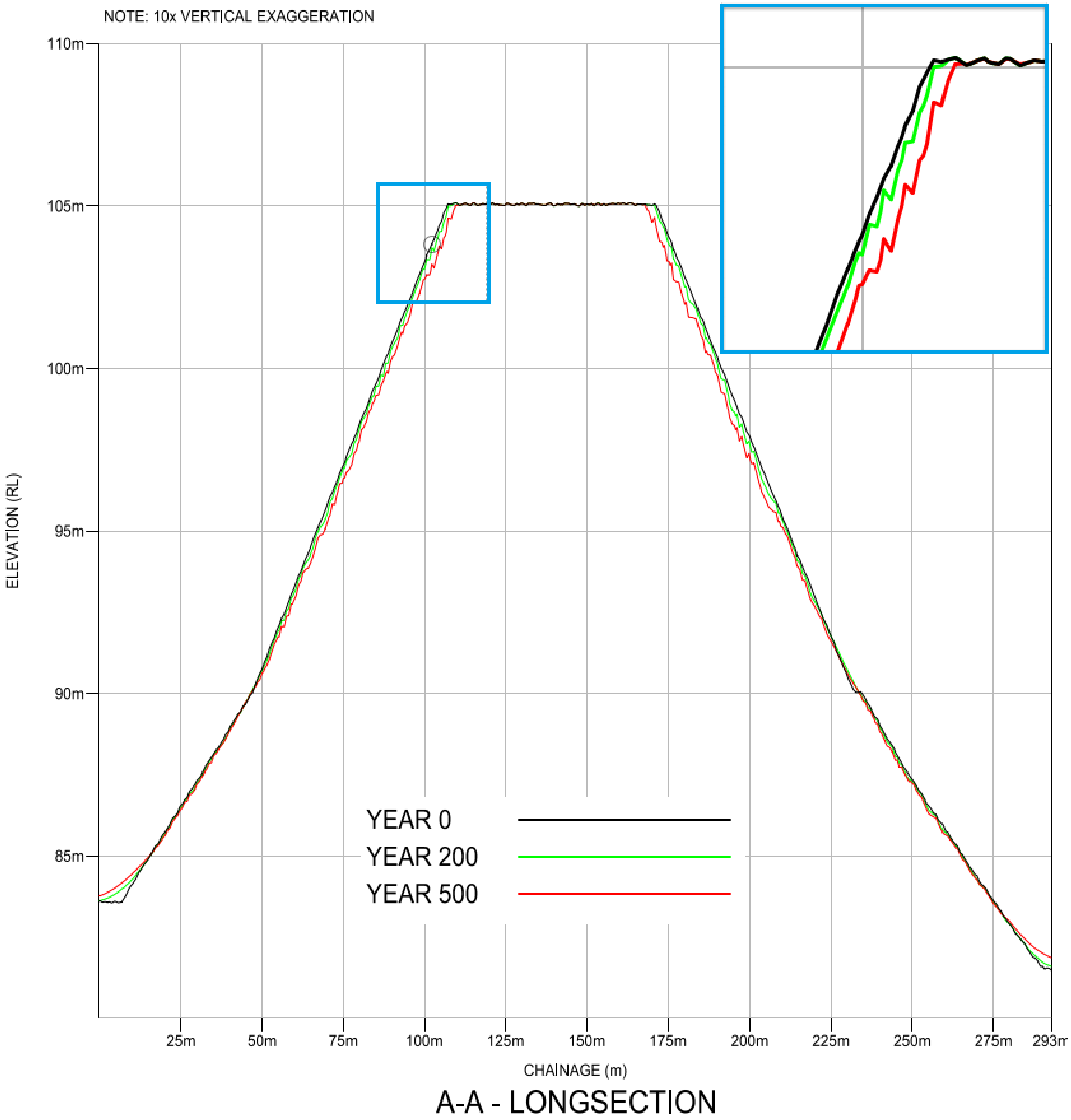


Stage 1, EWSF Hillshade After 500 Years, 18°-25° Dual-slope

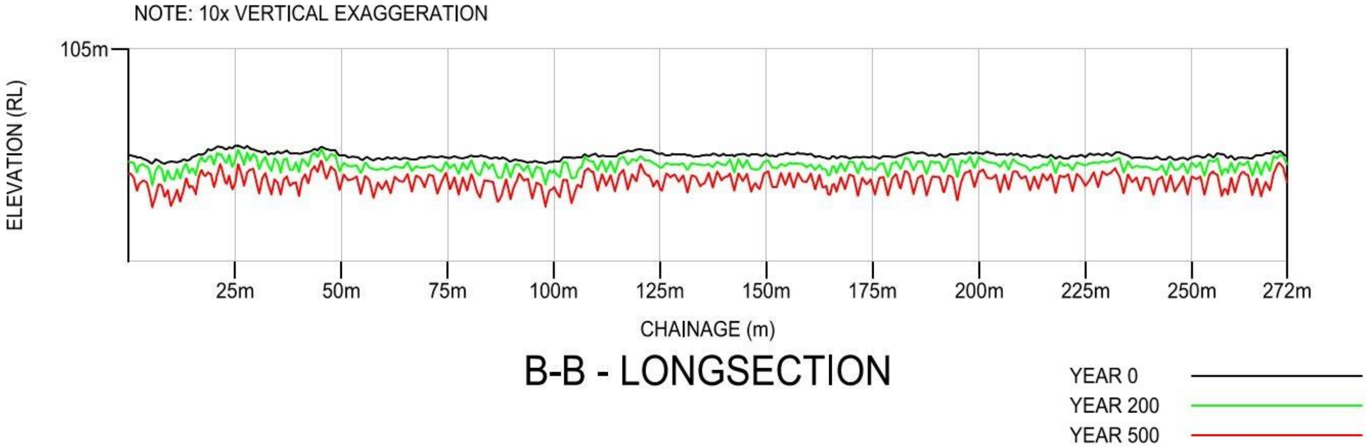


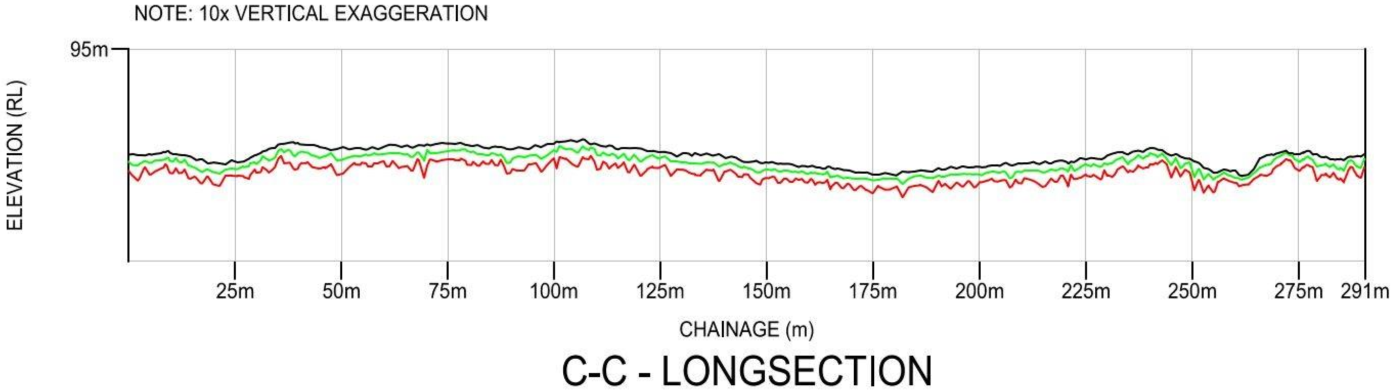
SURFACE LEVEL DATA					
NUMBER	MIN. LEVEL (m)	MAX. LEVEL (m)	COLOUR	3D AREA (m²)	PERCENTAGE AREA %
1	-2.00	-1.00		335.218	~1%
2	-1.00	-0.50		38453.477	~10%
3	-0.50	-0.25		63852.232	~17%
4	-0.25	0.00		173624.505	~47%
5	0.00	0.25		74984.755	~20%
6	0.25	0.50		15270.411	~4%
7	0.50	1.00		5218.704	~1.4%

Stage 1, Soil Loss Map, Bare Soil, 500-year Scenario, EWSF, 9°-14° Dual-slope

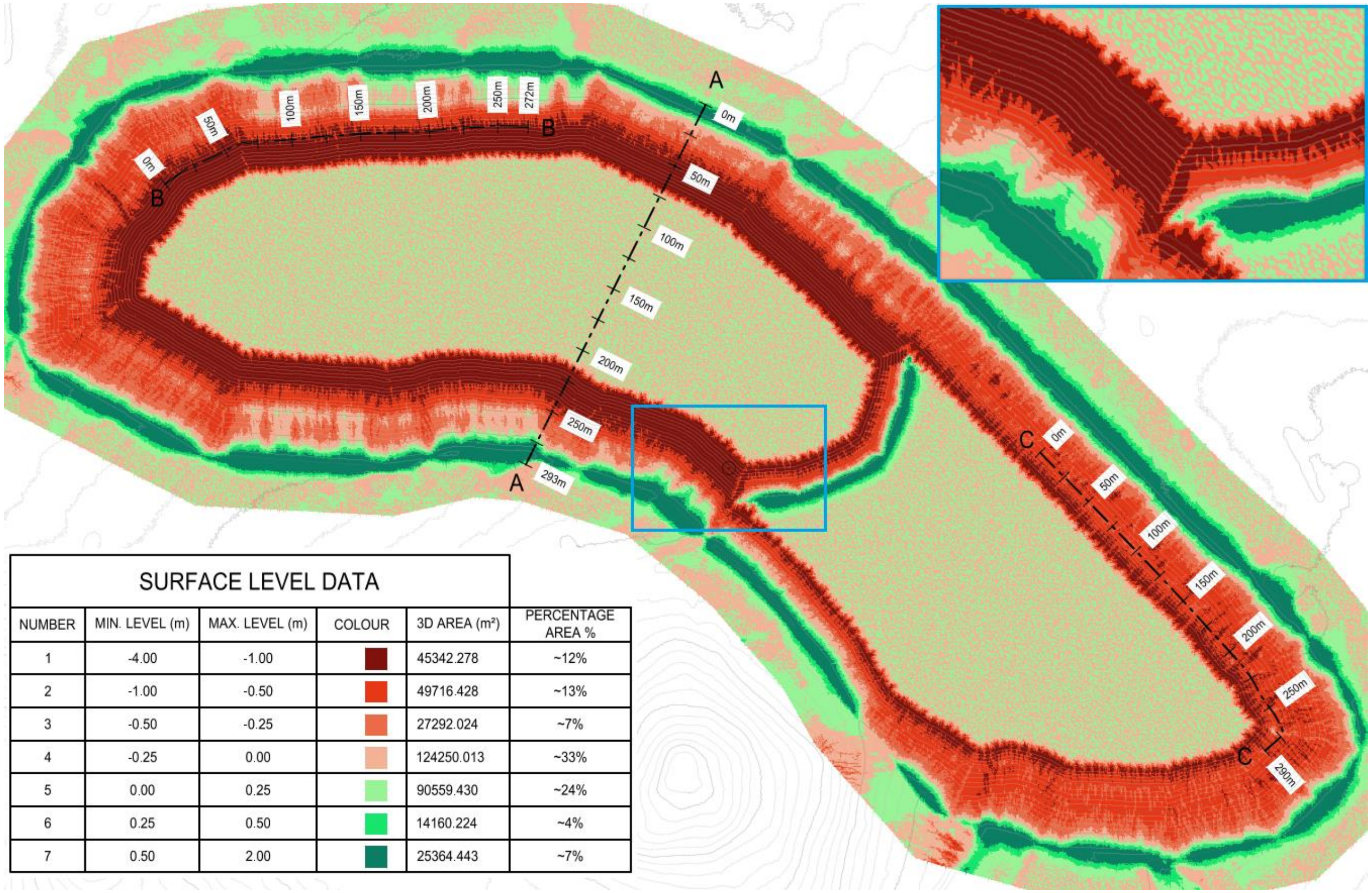


Stage 1, Cross Section A, 9°-14° Dual-slope, EWSF





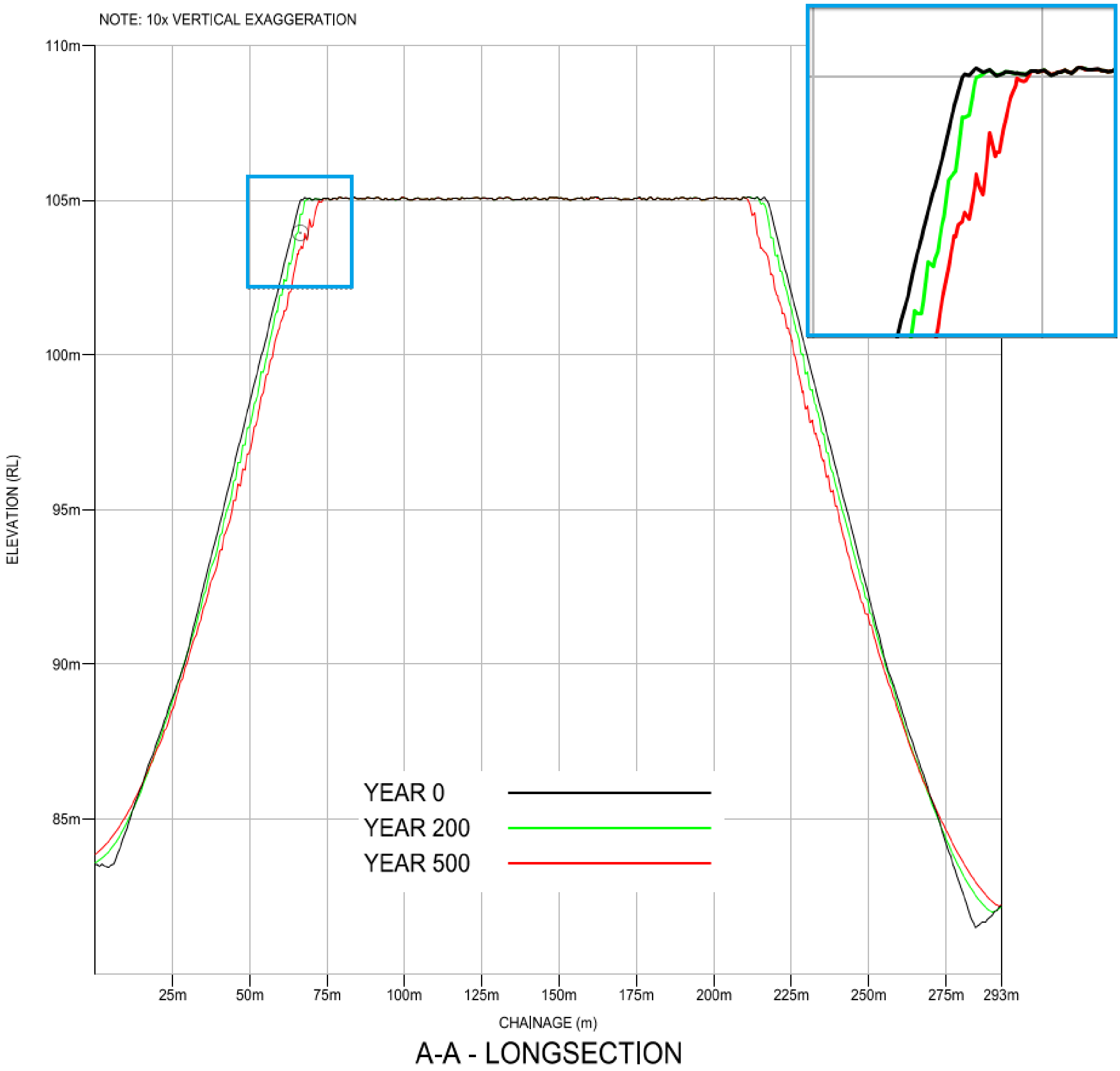
Stage 1, Cross Sections B and C, 9°-14° Dual-slope, EWSF



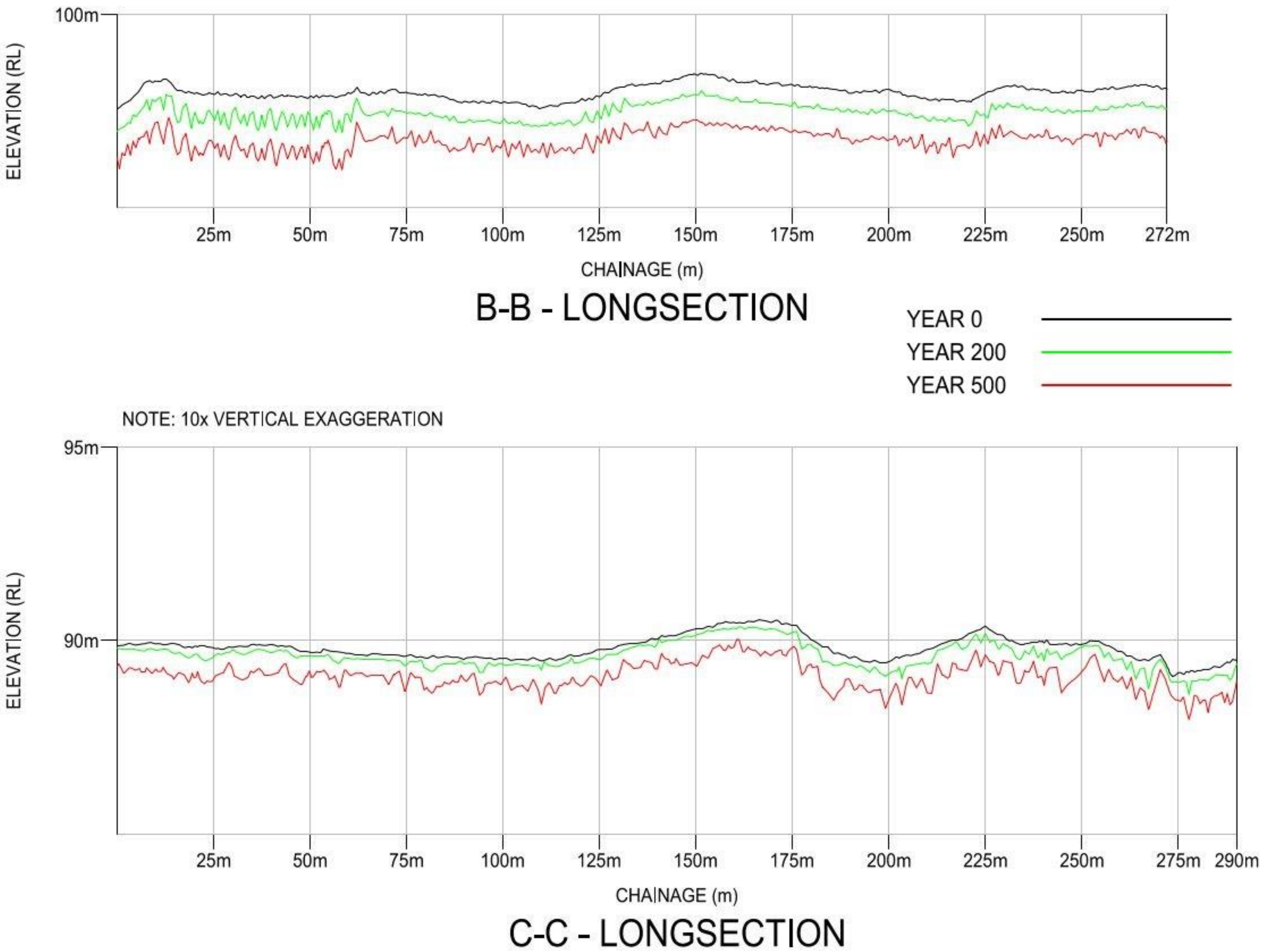
SURFACE LEVEL DATA

NUMBER	MIN. LEVEL (m)	MAX. LEVEL (m)	COLOUR	3D AREA (m²)	PERCENTAGE AREA %
1	-4.00	-1.00		45342.278	~12%
2	-1.00	-0.50		49716.428	~13%
3	-0.50	-0.25		27292.024	~7%
4	-0.25	0.00		124250.013	~33%
5	0.00	0.25		90559.430	~24%
6	0.25	0.50		14160.224	~4%
7	0.50	2.00		25364.443	~7%

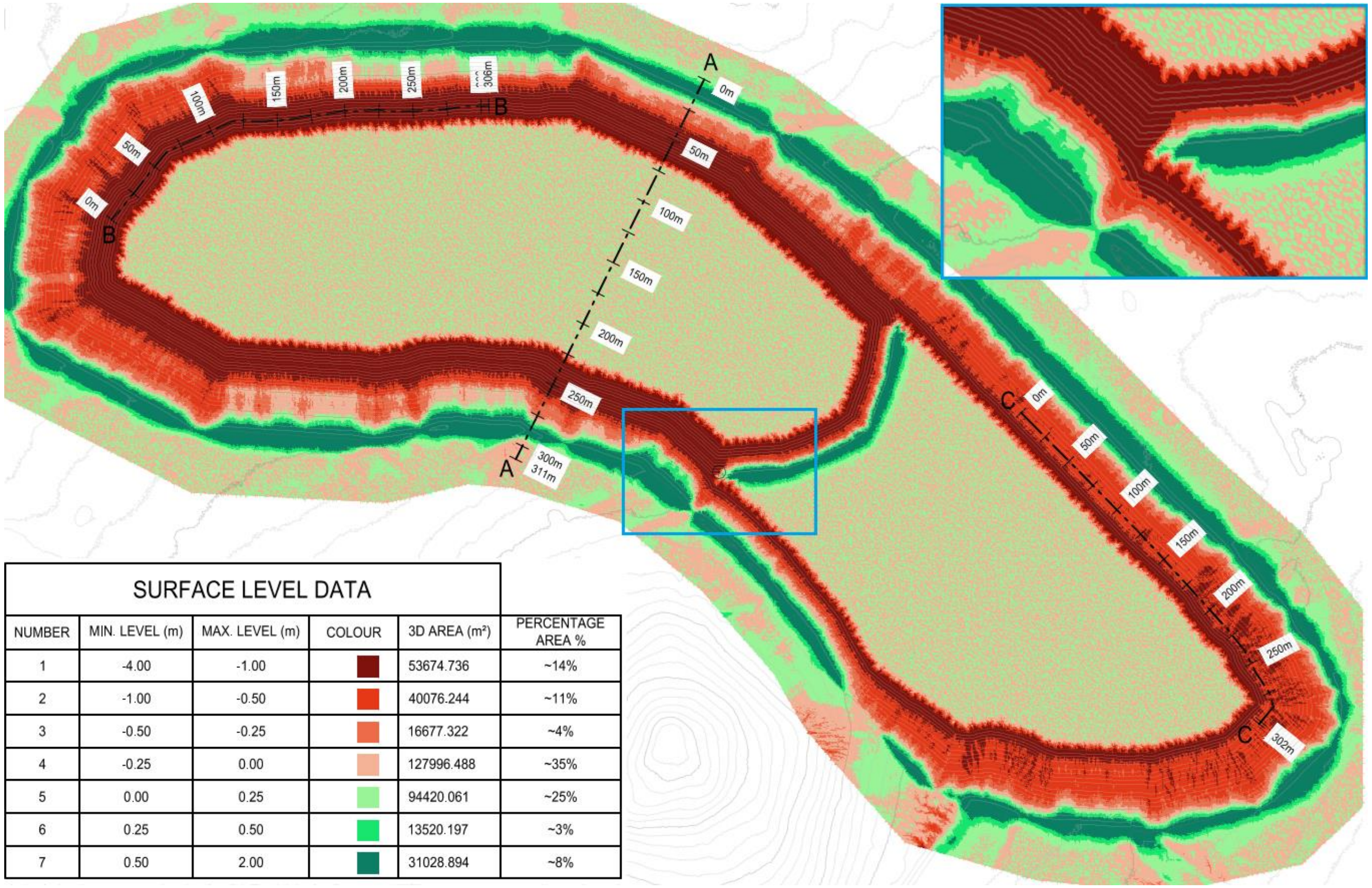
Stage 1, Soil Loss Map, Bare Soil, 500-year Scenario, EWSF, 16°- 22° Dual-slope



Stage 1, Cross Section A, 16°- 22° Dual-slope, EWSF



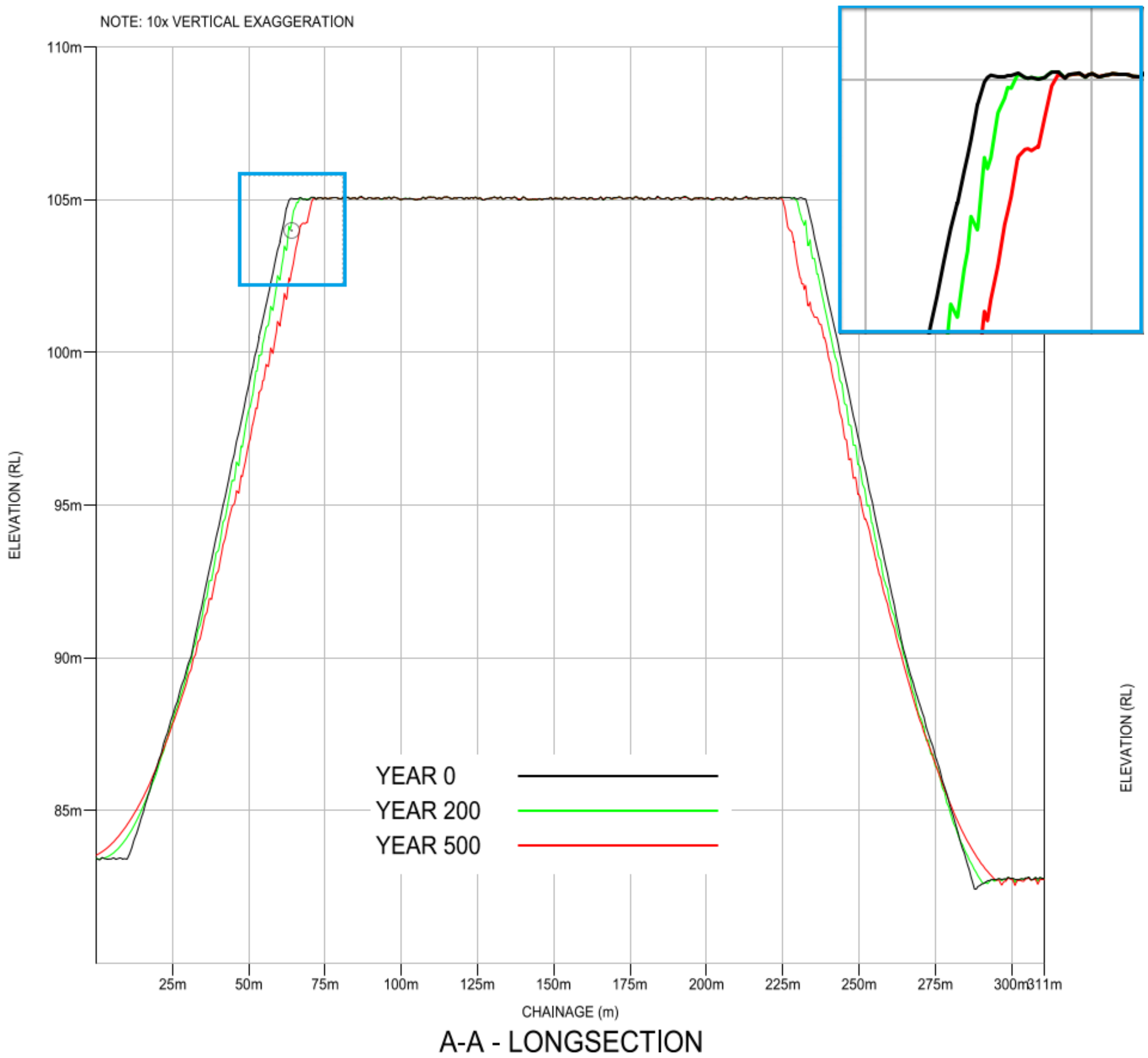
Stage 1, Cross Sections B and C, 16°- 22° Dual-slope, EWSF



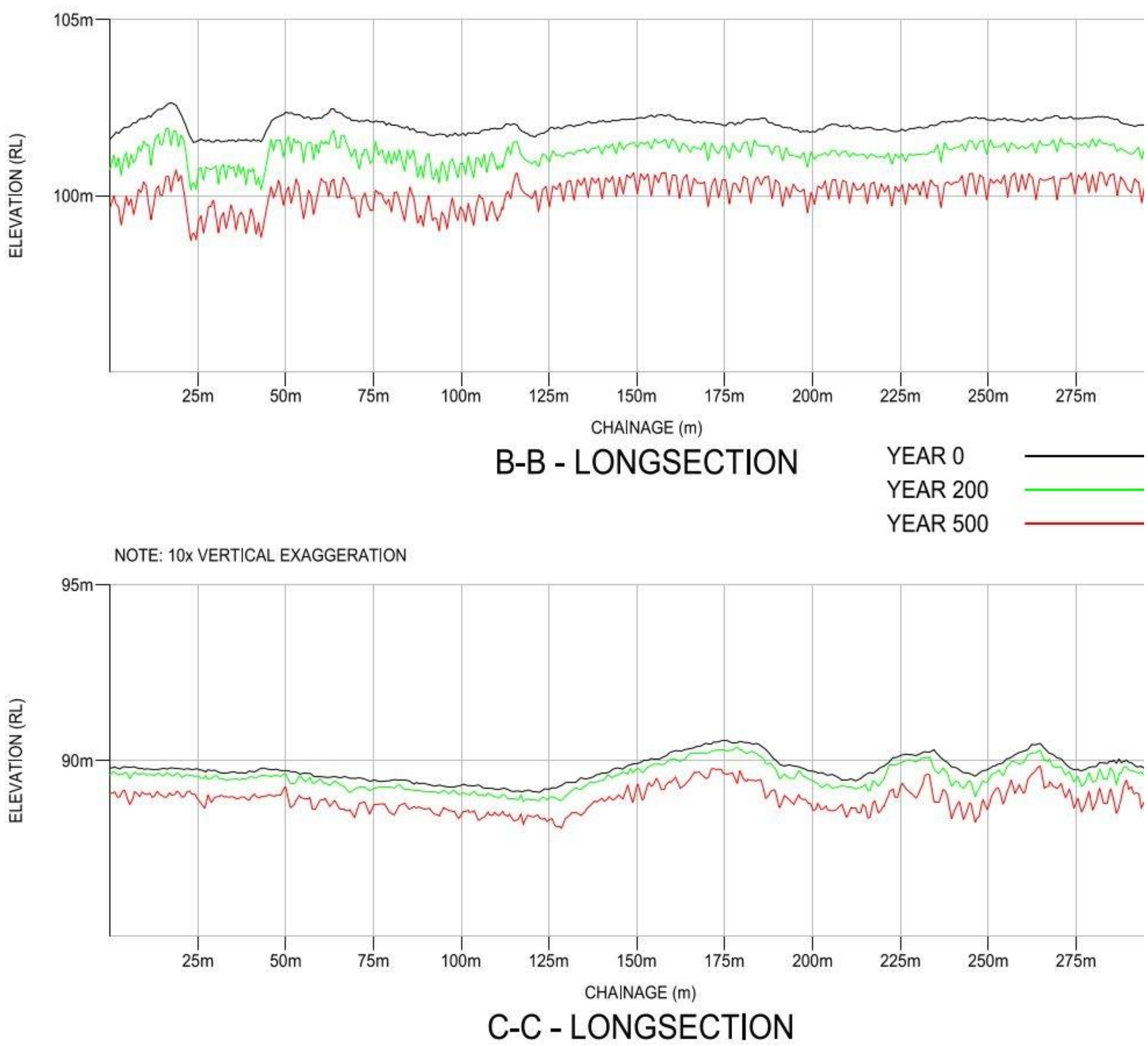
SURFACE LEVEL DATA

NUMBER	MIN. LEVEL (m)	MAX. LEVEL (m)	COLOUR	3D AREA (m²)	PERCENTAGE AREA %
1	-4.00	-1.00		53674.736	~14%
2	-1.00	-0.50		40076.244	~11%
3	-0.50	-0.25		16677.322	~4%
4	-0.25	0.00		127996.488	~35%
5	0.00	0.25		94420.061	~25%
6	0.25	0.50		13520.197	~3%
7	0.50	2.00		31028.894	~8%

Stage 1, Soil Loss Map, Bare Soil, 500-year Scenario, EWSF, 18°- 25° Dual-slope



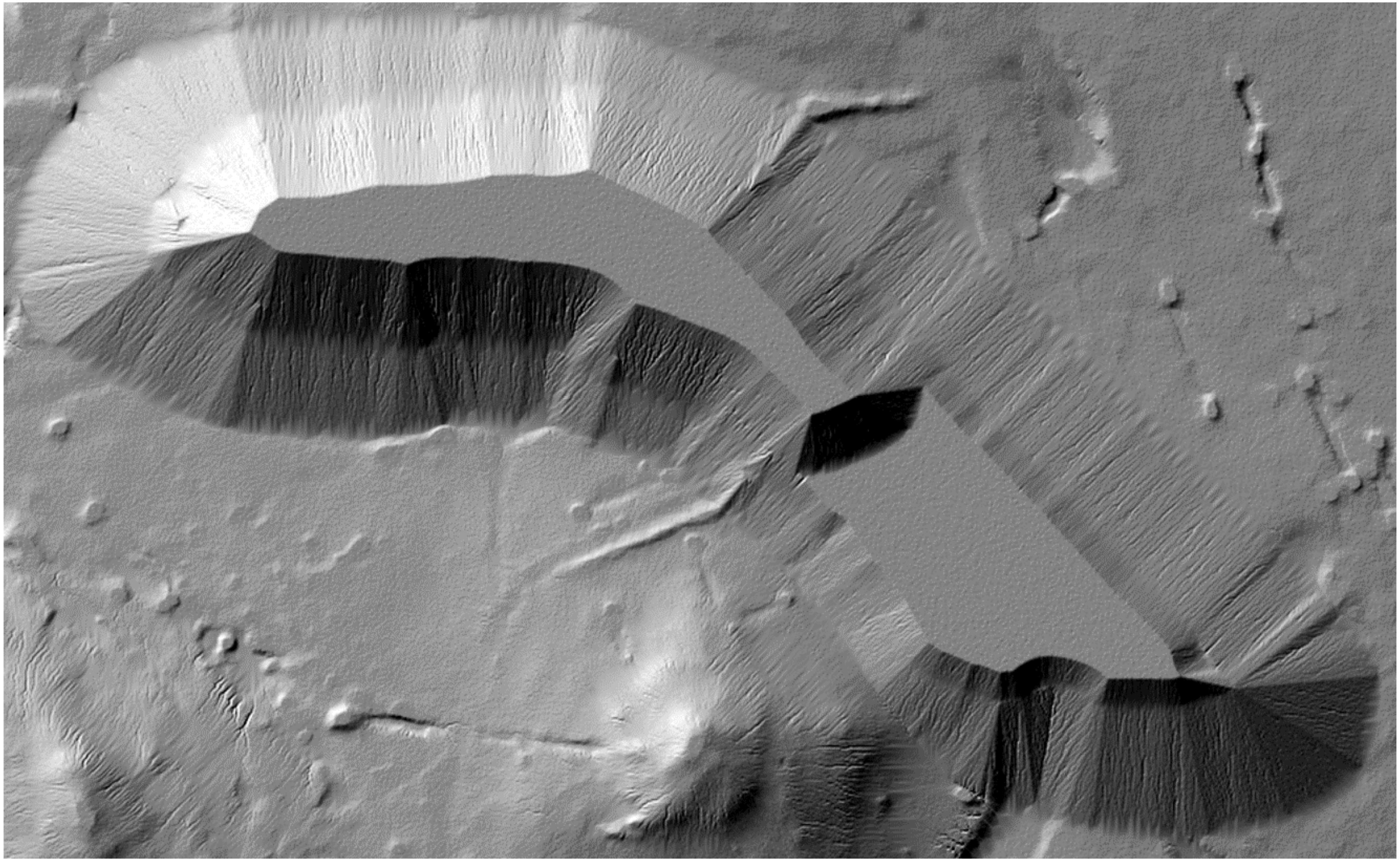
Stage 1, Cross Section A, 18°- 25° Dual-Slope, EWSF



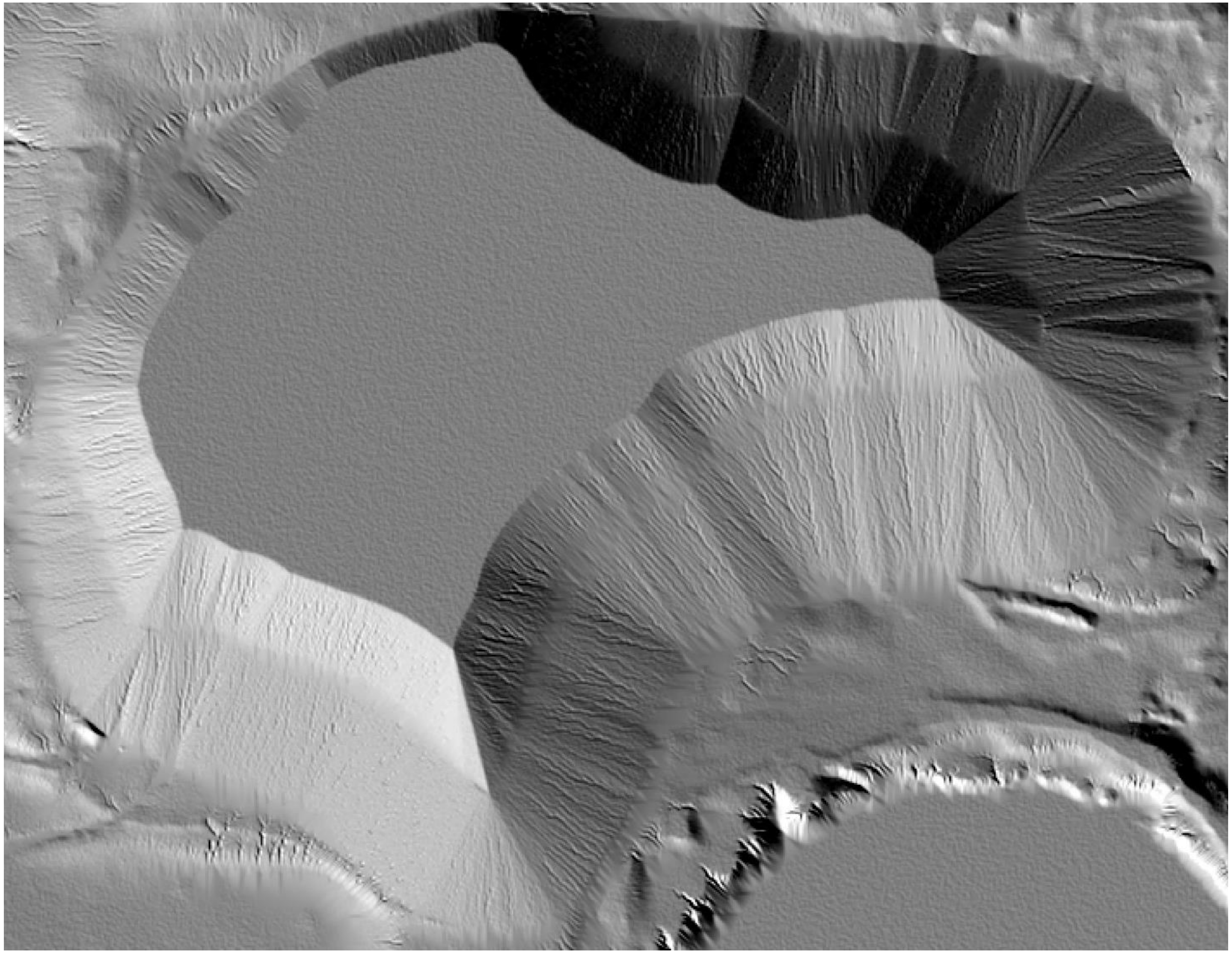
Stage 1, Cross Section B and C, 18°- 25° Dual-Slope, EWSF

APPENDIX E

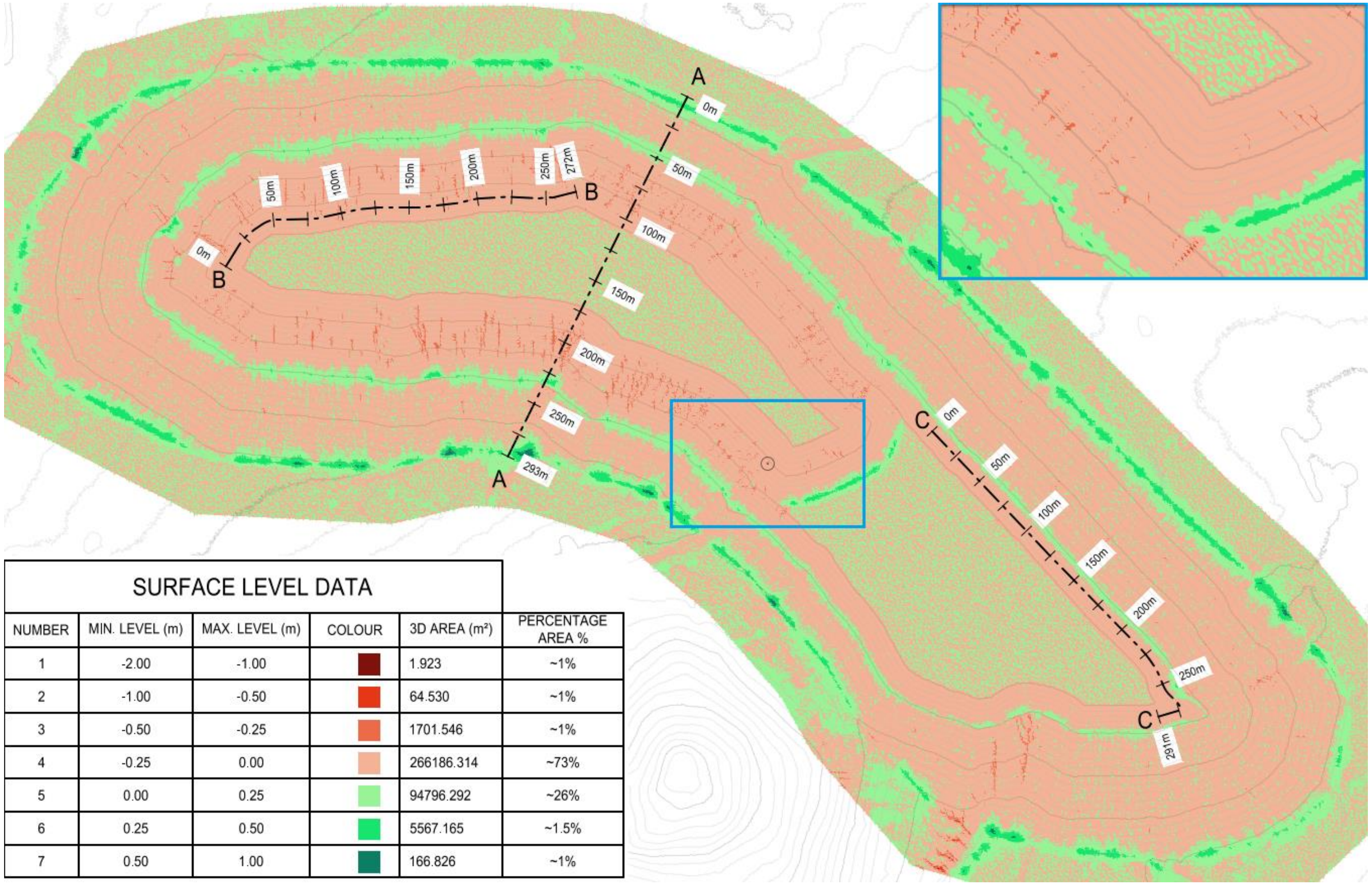
Stage 2 Hillshades and Erosion Colour Maps



Stage 2, EWSF Hillshade After 500 Years



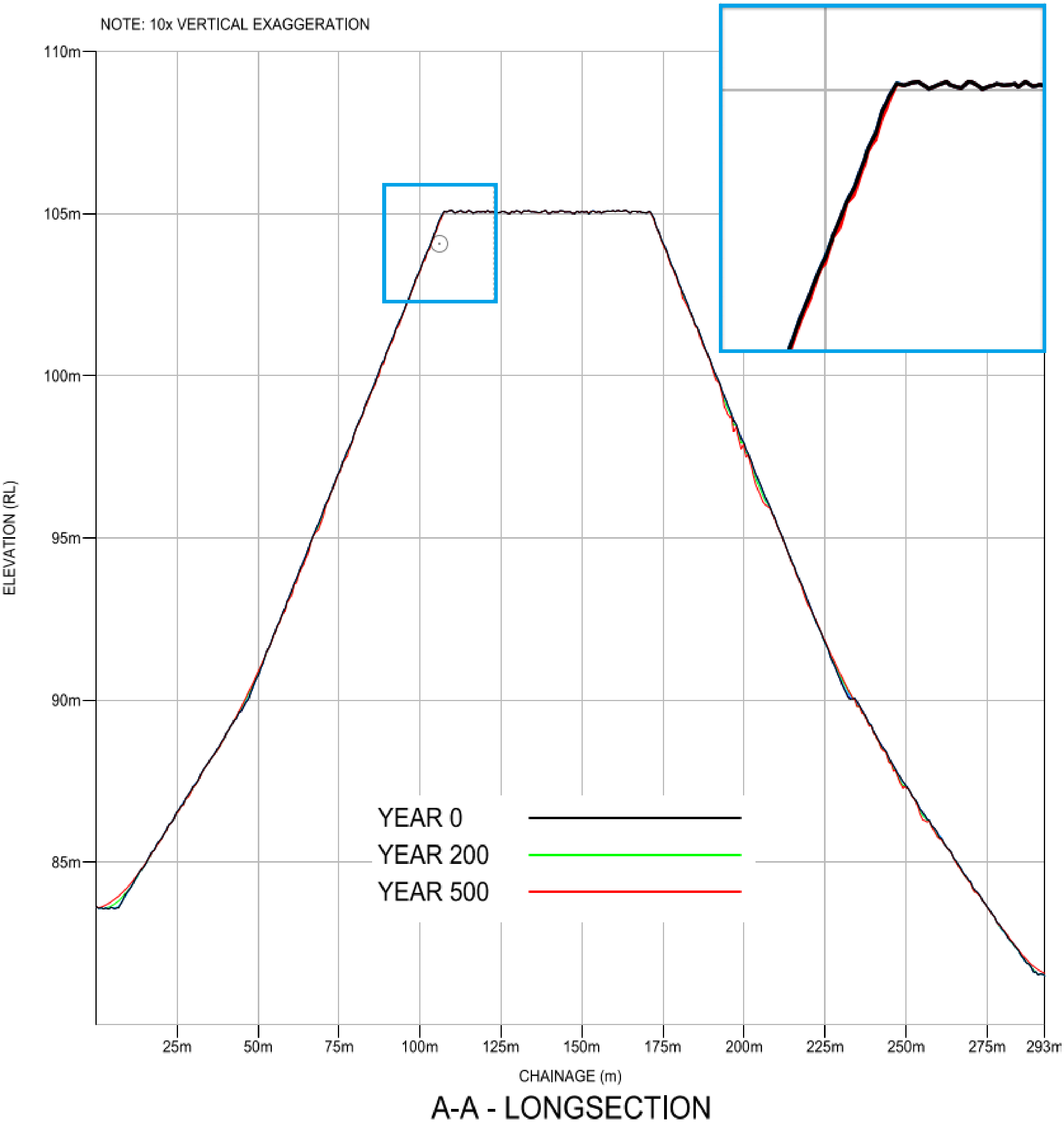
Stage 2, WWSF Hillshade After 500 Years



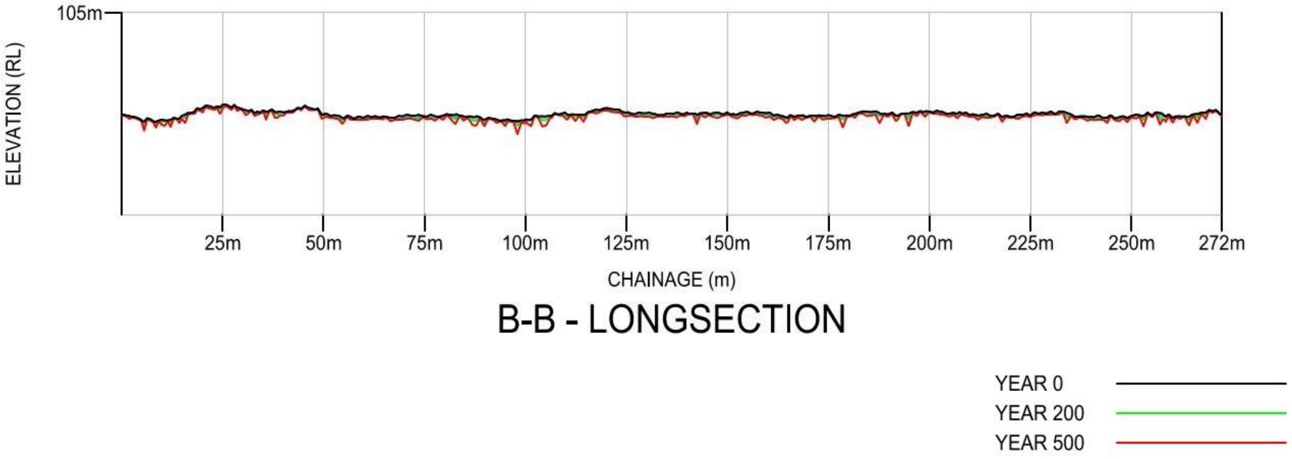
SURFACE LEVEL DATA

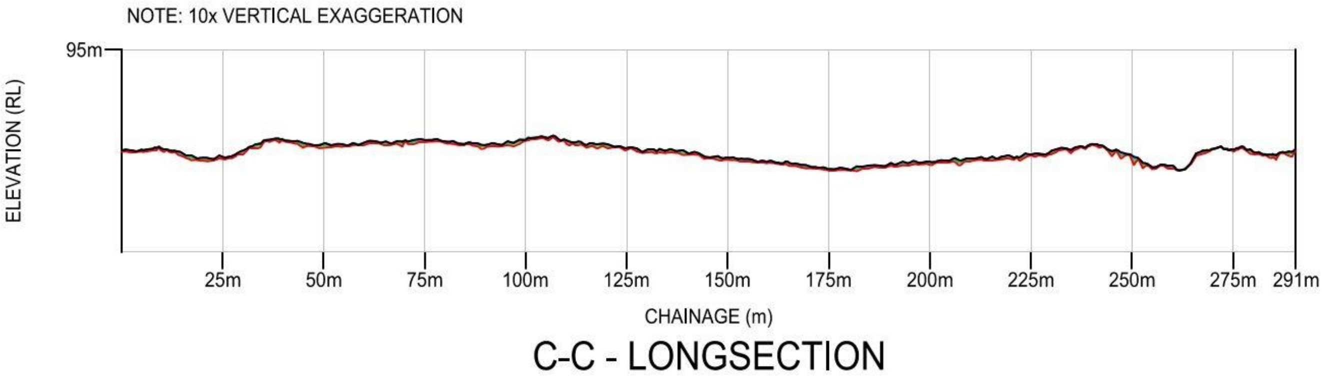
NUMBER	MIN. LEVEL (m)	MAX. LEVEL (m)	COLOUR	3D AREA (m²)	PERCENTAGE AREA %
1	-2.00	-1.00		1.923	~1%
2	-1.00	-0.50		64.530	~1%
3	-0.50	-0.25		1701.546	~1%
4	-0.25	0.00		266186.314	~73%
5	0.00	0.25		94796.292	~26%
6	0.25	0.50		5567.165	~1.5%
7	0.50	1.00		166.826	~1%

Stage 2, Soil Loss Map, Vegetated 500-year Scenario, EWSF



Stage 2, Cross Section A, EWSF



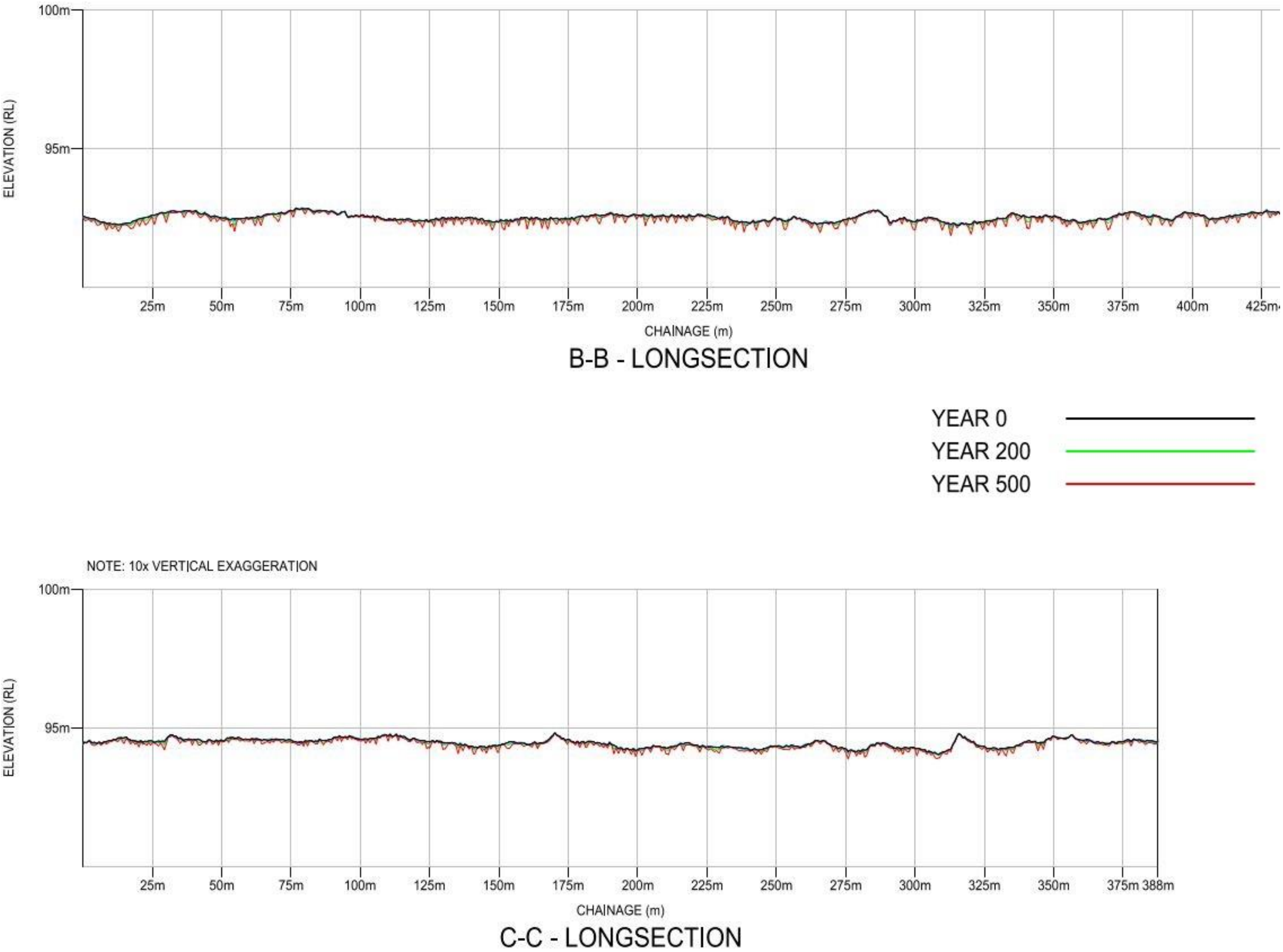


Stage 2, Cross Sections B and C, EWSF

SURFACE LEVEL DATA					
NUMBER	MIN. LEVEL (m)	MAX. LEVEL (m)	COLOUR	3D AREA (m²)	PERCENTAGE AREA %
1	-2.00	-1.00		0.000	~1%
2	-1.00	-0.50		188.841	~1%
3	-0.50	-0.25		2468.143	~1%
4	-0.25	0.00		244588.726	~75%
5	0.00	0.25		78646.050	~24%
6	0.25	0.50		3329.402	~1%
7	0.50	1.00		369.828	~1%

Stage 2, Soil Loss Map, Vegetated 500-year Scenario, WWSF

Stage 2, Cross Section A, WWSF



Stage 2, Cross Sections B and C, WWSF

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