SOILWATER CONSULTANTS

soilwater GROUP
t: +61 08 9228 3060
f: +61 08 9228 3210
a: 45 Gladstone St,
East Perth, WA 6004
e: admin@soilwatergroup.com
w: www.soilwatergroup.com

MEMO

TO:	John Ganser	COMPANY:	Lynas Kalgoorlie Pty Ltd	
FROM:	Sam Collins	PROJECT TITLE:	BY-PRODUCTS STORAGE FACILITY LEM	
DATE:	22 January 2021	PROJECT & DOCUMENT NO:	KAS-004-1-24	006
SUBJECT:	Landform Evolution Modelling for By-Products Storage Facility			

John,

This memo presents the results of landform evolution modelling (LEM) conducted for the By-Products Storage Facility (the Facility) to be developed by Lynas Kalgoorlie Pty Ltd (Lynas) in Kalgoorlie, Western Australia. The LEM was conducted on the Facility design files provided by Lynas in dxf format and was carried out to determine the long term behaviour of the landform design with respect to surface stability. The modelling will allow for any design characteristics such as slope configuration or cover material usage which may exacerbate erosion rates to be identified and the design potentially modified prior to closure. The LEM has been undertaken using a combination of watershed erosion prediction project (WEPP) and the SIBERIA landscape evolution model, both of which have been used across many different sites to model erosion patterns and landform developments over large timescales.

The scope of this study is as follows:

- Use existing data on proposed design and cover materials to parameterise the WEPP runoff and erosion model.
- Use the WEPP model to carry out 2D modelling with a standard climate sequence which includes a probable maximum precipitation (PMP) event.
- Carry out SIBERIA landform evolution modelling on the Facility design to investigate long term erosion outcomes.

Cover Material Data Summary

The cover material is proposed to be formed from the gypsum stream of the by-product from processing. The gypsum will be placed around and on top of the iron phosphate by-product in a ‘donut’ cover system used in numerous mining closure scenarios to permanently isolate problematic waste material types.

The measured physical properties of the gypsum by-product are outlined in Table 1. This material is characterised as silty clay with >80% silt + clay fraction, of which 50% of particles are between 6-8µm in diameter. It has a dry bulk density of 0.74 t/m3 (corresponding wet density 1.55 t/m3), indicating that it is highly porous with a total porosity of around 68%. The gypsum is structurally unstable and rapidly slakes when rewet, but it shows no dispersion due to its elevated salinity.

Table 1: Measured physical properties of the gypsum

Property	Unit	Value
Particle Size Distribution		
Sand (2 – 0.02µm)	%	0
Silt (0.02 – 0.002 µm)	%	60
Clay (<0.002 µm)	%	40
Bulk Density		
Wet	t/m3	1.55
Dry	t/m3	0.74
Particle Density	t/m3	2.3
Saturated permeability	m/day	0.005
Total Porosity	% v/v	68
Field Capacity	% v/v	50
Emerson Class	-	Class 6

The key chemical properties are provided in Table 2. The gypsum material is considered extremely alkaline (pH approaching 11) and it is extremely saline, with a measured electrical conductivity of close to 700 mS/m. Given the dominance of gypsum, its exchangeable Ca content is highly elevated resulting in a derived sodicity of < 4%.

Table 2: Measured chemical properties of the gypsum

Property	Unit	Value
pH (1:5)	-	10.6
EC (1:5)	mS/m	690
Sodicity (ESP)	%	<4
Organic Carbon	%	0

These properties make the gypsum material unlikely to be capable of remaining stable on a sloped closure landform surface over the long term. Therefore a second cover scenario utilising waste rock material as a stabilising agent in a 50:50 ratio with the gypsum was modelled. The waste rock material was assumed to be a competent, fresh waste rock sourced from nearby mining operations (e.g. Super pit) and either mafic or felsic in composition.

By-Product Storage Facility Closure Design

The closure design was supplied as a digital terrain model (DEM) in dxf format. Figure 1 provides an overview of the design. The closure landform has been developed to meet the following design parameters:

- Batter / berm design will be used to minimise the overall slope length and provide additional sufficient safety factors to minimise erosion and sediment loss
- Batter slope angle = 10°
- Berm width = 10 m which is backsloped to 5° to prevent overtopping of the berm during heavy rainfall event and prevent surface water ponding close to the batter crest.
- Lift height = 10 m

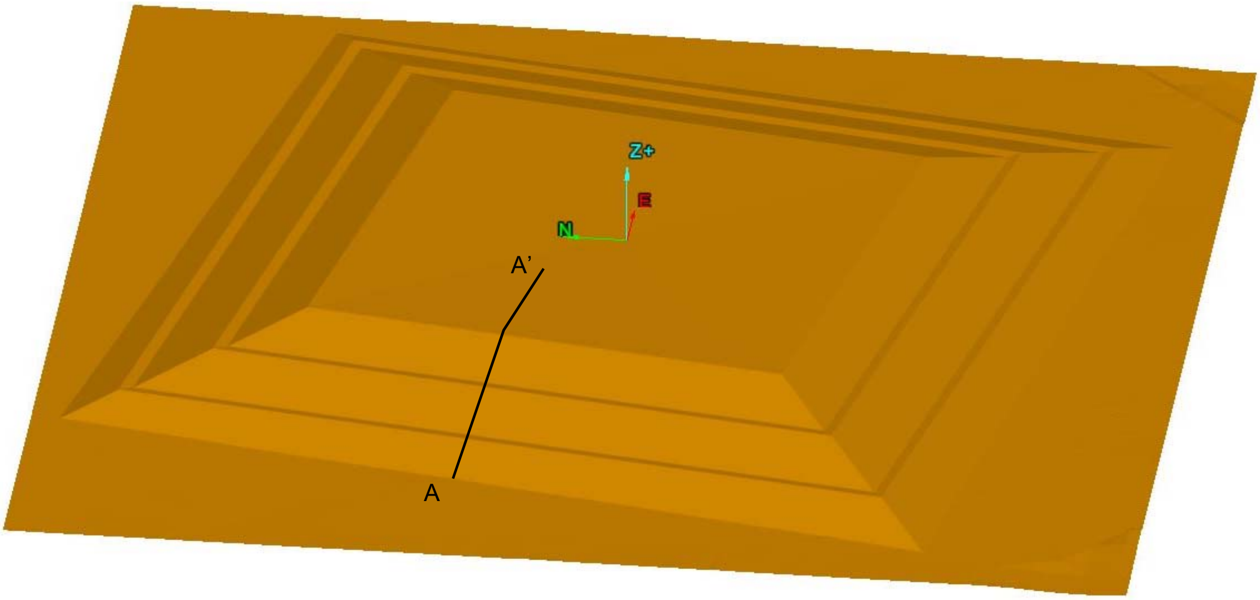


Figure 1: DEM of By-Product Storage Facility closure design

The total footprint of the closure design is approximately 62 ha and it consists of three 10 m lifts, reaching a maximum height of 390 mRL.

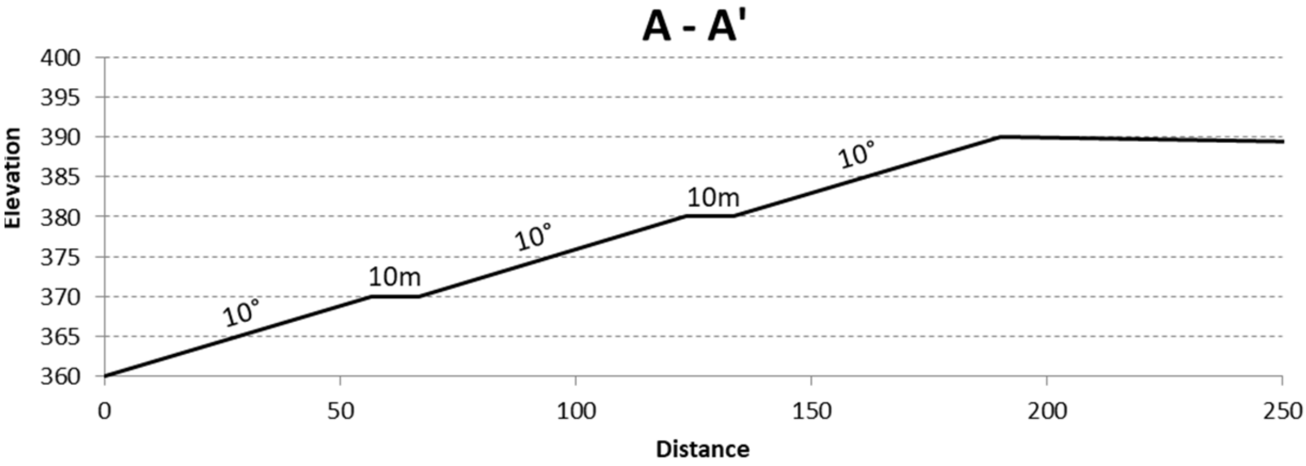


Figure 2: WRL rehabilitation design with cross section represented as A-A'

Landform Evolution Modelling Input Parameters

The determination of the response of landforms to long term erosion forces has generally been carried out using landform development models. There are several different landform development models in use however the SIBERIA model which was developed by Professor Garry Willgoose (1989) is widely accepted as the most robust and well developed example.

The SIBERIA model works to model channel network growth and elevation evolution by integrating and applying a number of erosional processes identified at small scales to a larger scale data set, in this case a gridded digital elevation model (DEM). Using the DEM a drainage direction is assigned to each grid node, with these directions then used to determine the catchment area contributing to each node. A number of equations have been developed which describe the various erosion processes.

The two processes which are central to predicting the volume of sediment lost and added to each grid node are the runoff process, modelled by;

$$Q_c = \beta_3 A^{m_3}$$

Where Q(q) is the discharge per unit width (m3/yr), and B_3 and m_3 are calibrated input parameters relating to the runoff rate and area respectively. This then feeds into the fluvial sediment transport process, modelled by;

$$q_s = \begin{cases} \beta_1 q^{m_1} S^{n_1} - q_{st} & \beta_1 q^{m_1} S^{n_1} > q_{st} \\ 0 & \beta_1 q^{m_1} S^{n_1} \le q_{st} \end{cases}$$

where S is the maximum slope (m/m) and B_1, m_1 and n_1 are calibrated input parameters. This equation holds provided q_{st} is below a critical threshold. As all of these parameters interact within the modelling process, a large number of input integers can result in the same output result. Therefore in order to simplify the calibration method m_3 and B_3 can be set to 1, with the remaining parameters then modified through repeated calibration.

Calibration Method

Where the landform area (slope angle and length) are identical to the landform area for which erosion data is available for calibration, only the fluvial sediment transport process input parameters require adjustment. As physical erosion data for the materials which will be used at the RGP are unavailable, the SIBERIA model was calibrated using a combination of two separate erosion prediction methods. The first method used to calibrate the input parameters was the Revised Universal Soil Loss Equation (RUSLE) developed by Renard et al. (1997).

The soil material properties available (particle size distribution) were used to estimate the K-factor (erodibility) whilst the rainfall specific to the site was fitted to the R-factor (erosivity) and the C factor was estimated based on gravel content and vegetation properties (e.g. litter, canopy cover).

The SIBERIA input parameters can be adjusted directly using the output from the RUSLE equation; however there is no method to introduce specific climate events such as the PMP event into the different input parameters of either SIBERIA or RUSLE. Therefore the watershed erosion prediction project (WEPP) is utilised as a secondary calibration method.

WEPP Input Parameters

The input parameters required by WEPP include particle size information (% sand, % clay), organic content, effective hydraulic conductivity (Keff), interrill erodibility (Ki), rill erodibility (Kr), and soil critical shear stress (τC). The basic physical parameters have been measured via laboratory testing with the remainder of the parameters given initial values based on experience of laboratory scale measurement of similar soil types. Basic 2D slope files simulating the batter slope of the closure design was used to calibrate the interrill and rill erodibility parameters, with the remainder staying constant. These parameters were adjusted using the results from RUSLE.

The WEPP input climate parameters were developed utilising the standard CLIGEN file (see below). The CLIGEN file was then modified to include a single probable maximum precipitation (PMP) event within the 100 yr data set.

Climate Data

A synthetic climate file was generated using the CLIGEN stochastic weather generator (Yu, 2003), and was used in the WEPP model to simulate 100 years of rainfall, runoff, and erosion for calibration purposes. Data input into CLIGEN was sourced from the Kalgoorlie Airport weather station (BOM station # 012038), which is located approximately 8 km southeast of the Facility. The following data was input to CLIGEN:

- 0.5 hourly rainfall data (from Jan 1994 to May 2019)
- 40 year data set of daily values for rainfall, maximum and minimum temperatures, and solar radiation

A comparison of the 100 year synthetic CLIGEN file and the measured data from the Kalgoorlie Airport is shown here. The comparison shows that the CLIGEN file is consistent with the 40 years of measured data from which it was generated. Figure 3 compares the frequency of 24-hour rainfall totals, indicating that larger 24-hour storms occurred slightly more frequently in the measured data than in the CIGEN file. For example the observed data shows an average 1:25 year, 24-hour event of approximately 40 mm, while the CLIGEN file includes an average event of approximately 38 mm at the same frequency.

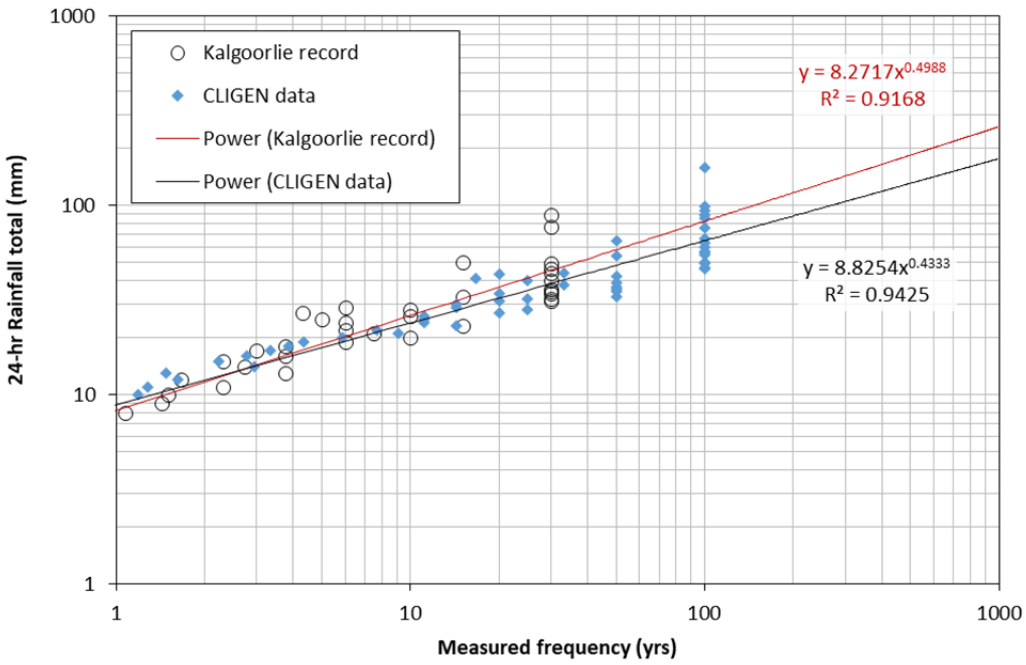


Figure 3: 24 hour frequency comparison

A comparison of the the monthly and annual rainfall depths (Figure 4, Figure 5 and Figure 6) shows that the CLIGEN file captures a similar degree of variability in rainfall depths within and between years as was observed over the last 40 year period at the Kalgoorlie BOM station.

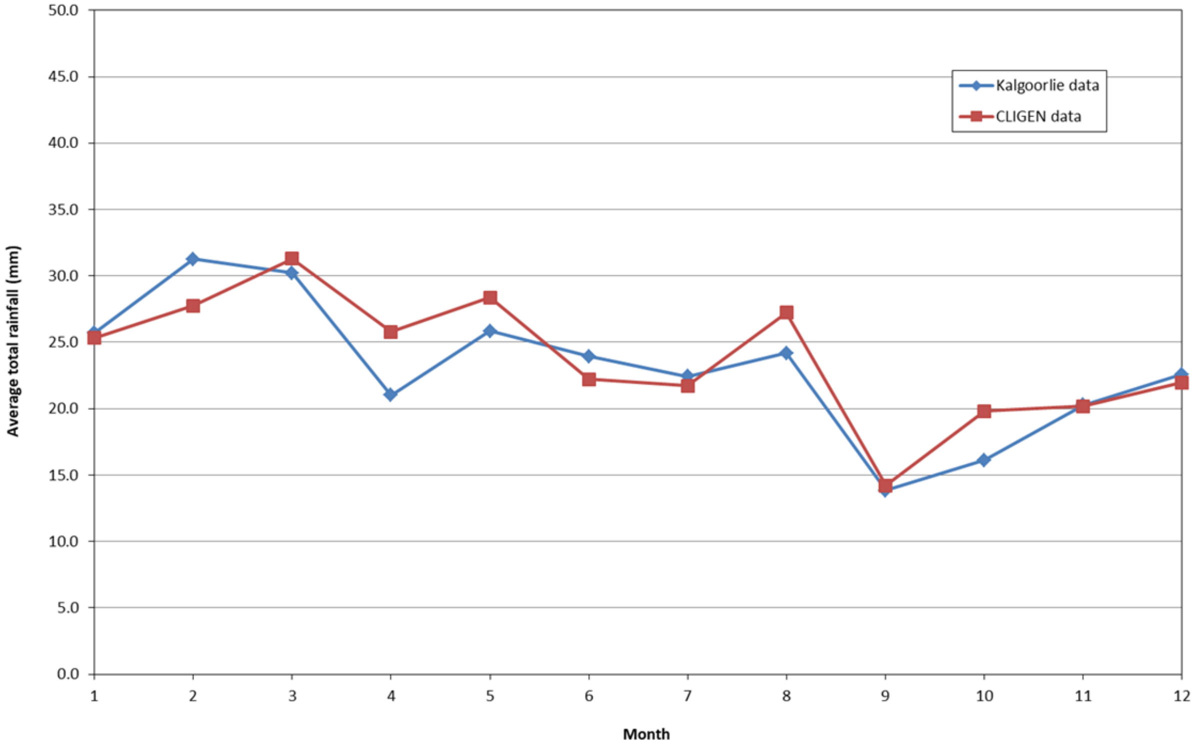


Figure 4: Monthly rainfall comparison

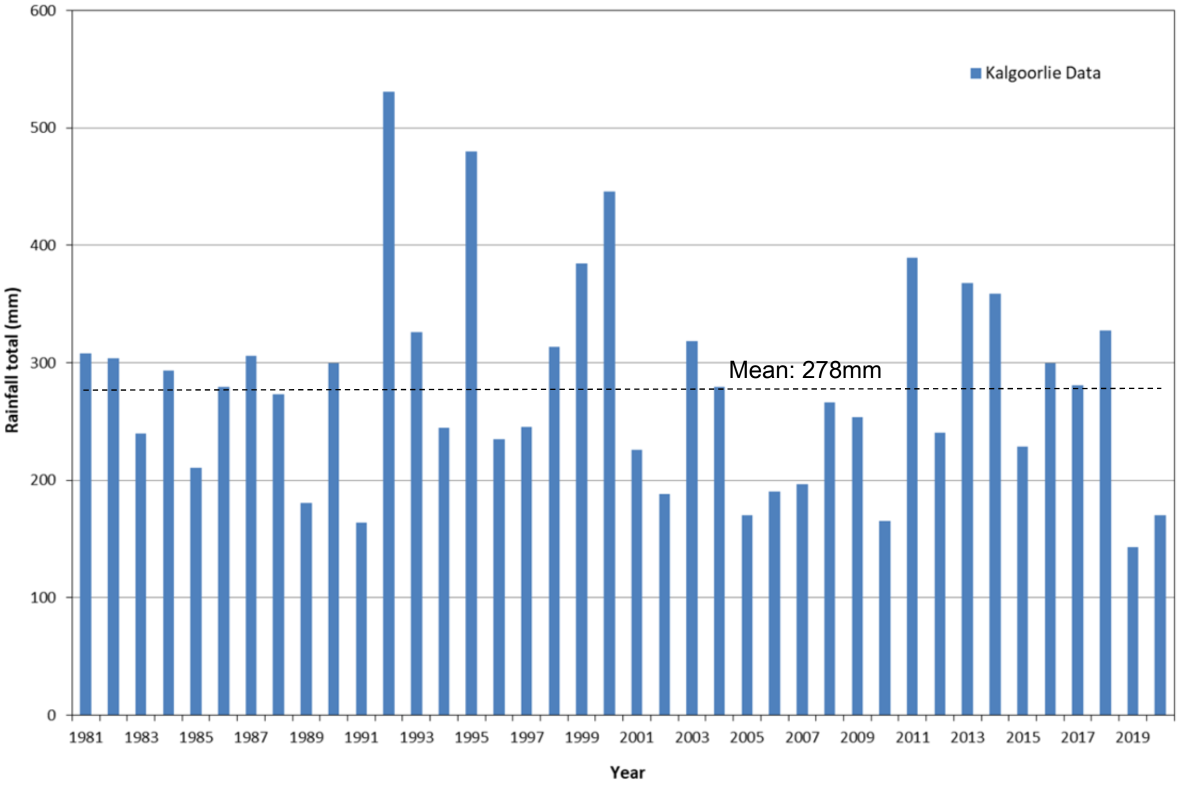


Figure 5: Annual rainfall totals for Kalgoorlie Airport station

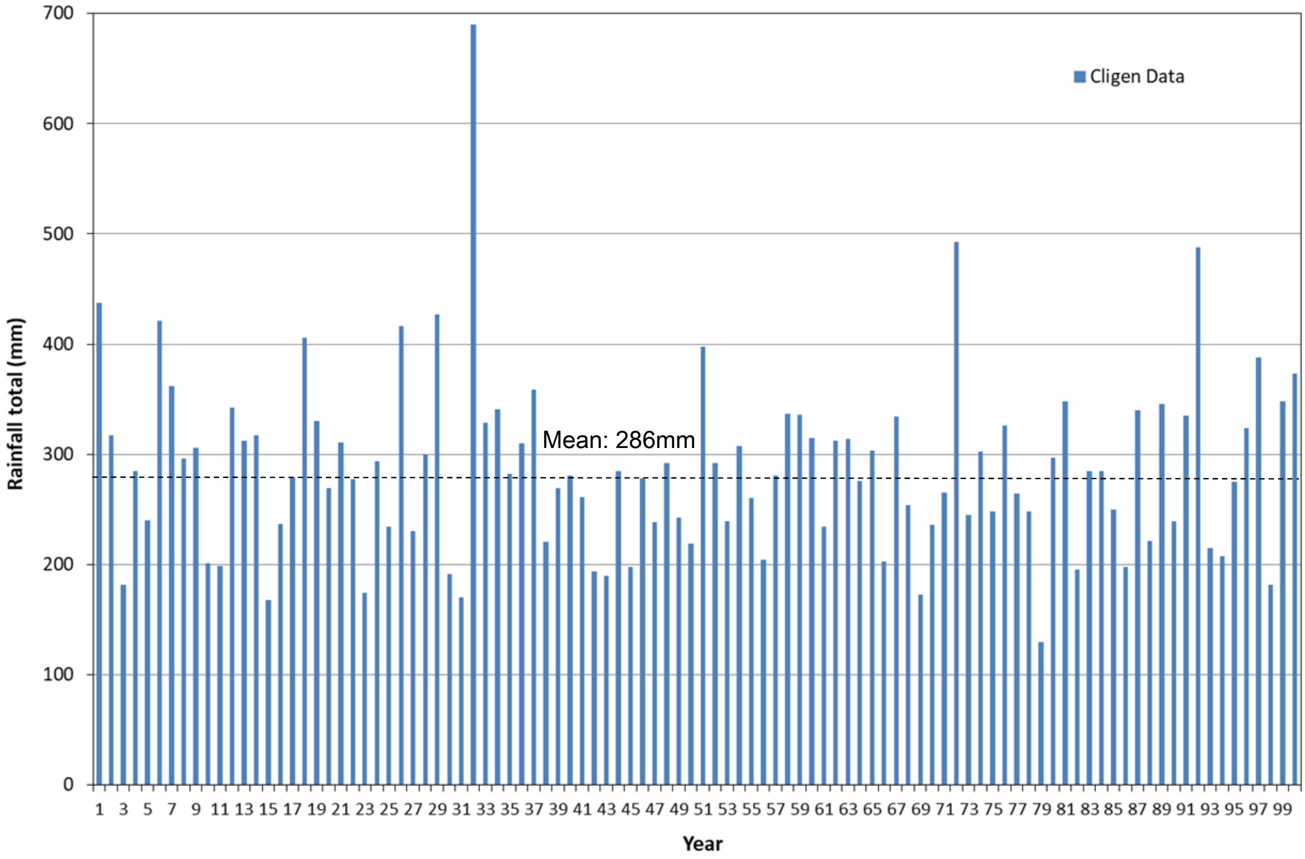


Figure 6: Annual totals from CLIGEN file including PMP event

The monthly rainfall comparison in Figure 4 indicates the CLIGEN totals generally agree within a close range to the monthly averages derived from Kalgoorlie Airport. The total rainfalls shown for both the CLIGEN file and Kalgoorlie airport data shows that the annual total rainfall depths of the CLIGEN file is slightly higher than the average of the measured data, and that year-to-year variability is similar.

PMP Calculation

The PMP is defined as the theoretical maximum precipitation for a given duration under modern meteorological conditions and was calculated using the generalised short duration method (GSDM; BOM, 2003), which is suitable for the small sized catchment of the closure landform being modelled.

Kalgoorlie is located within the intermediate zone for calculation purposes and so was given a maximum duration of 3 hours by linear interpolation. It was estimated that 20% of the catchment which would exist once the landform was built could be considered rough, with the remaining 80% considered smooth. The moisture adjustment factor for the area is 0.73.

The PMP rainfall depth was then calculated using the following equation.

$$\text{PMP depth} = (S \times D_S + R \times D_R) \times EAF \times MAF$$

Where;

- S= smooth terrain percentage (0.8,
- R = rough terrain percentage (0.2),

- D_S and D_R are initial rainfall depths read from the generated depth-duration-area curves (725 and 940 respectively),
- EAF is the elevation adjustment factor for the region (1 – no adjustment required), and
- MAF is the moisture adjustment factor for the region (0.73)

This method estimates that the PMP for a 1 square kilometre area is approximately 570 mm. This rainfall amount was randomly added to a 3-day period within the 100 yr CLIGEN data file (year 33).

Calibrated Siberia Parameters

Two separate SIBERIA parameters sets were calibrated using the combination of RUSLE and WEPP described above. These two modelling scenarios corresponded to two different surface material types. The scenarios can be summarised as:

- Gypsum material cover with no additional stabilisation and 15% vegetation cover establishment (after 5 years).
- Soil material and stable fresh waste rock (50:50 mix) with 15% cover establishment (after 5 years).

A cover establishment of 15% after 5 years (which includes leaf litter and canopy cover) is considered to represent a low end outcome for rehabilitation establishment within the region.

The addition of fresh rock to the gypsum material cover was modelled as a secondary scenario. This was modelled through modification of the soil parameter inputs in RUSLE and WEPP. Although the model calibration method, based on baseline soil particle size data, is suitable for the interrogation of conceptual design suitability, it is recommended that direct measurements in a laboratory setting are made for the different soil and rock material erodibility and surface runoff / permeability characteristics. This will allow increased confidence in the input parameters and the final modelled erosion results.

In each scenario, the landform initially underwent a 5 year model run with no cover to simulate the time required for root establishment and appreciable leaf litter etc. to develop. Following this, the output DEM was used to run a further 4,995 years of simulated erosion using the input parameters shown in Table 3.

Table 3: SIBERIA modelling input parameters

	Gypsum – no cover	Gypsum – 15% cover	Gypsum & rock – no cover	Gypsum & rock – 15% cover
B_1	0.0100	0.0125	0.0030	0.0045
m_1	1.50	1.80	1.60	1.40
n_1	2.00	2.10	1.60	1.50

Using the above parameters, modelling was undertaken over a 5,000 year time period for the closure design with the following outputs:

- Average erosion along the batter/berm area in tonnes/hectares/year and mm/year at years 250, 500 and 1,000 and 5,000.
- Depth of gully formation along the batter/berm area at years 250, 500 and 1,000 and 5,000. (minimum cut-off depth for inclusion set at 0.25m).
- Visual representation of erosion and deposition at years 250, 500 and 1,000 and 5,000.

The results of the SIBERIA modelling are summarised in Table 4. Digital elevation models created from the output of the modelling at each chosen time period are shown in the series of figures below.

Table 4: Summary of SIBERIA modelling results.

Model Scenario	Simulation Year	Average gully depth (m)	Average gully length (m)	Average erosion (t/ha/yr)	Average erosion (mm/yr)*	Cumulative erosion (m)
Gypsum	250	0.38	3.2	42.1	2.81	0.7
	500	1.12	6.5	40.1	2.67	1.4
	1,000	1.16	11	35.6	2.37	2.6
	5,000	1.26	17	24.8	1.65	9.2
Gypsum + Waste Rock	250	0.22	2.5	15.8	0.79	0.2
	500	0.86	5.1	14.2	0.71	0.4
	1,000	1.57	6.8	13.8	0.69	0.7
	5,000	3.40	8.9	13.5	0.69	3.4

*Assumed average bulk density of 2.0 t/m^3 for gypsum + waste rock

The summary of erosion statistics within Table 4 show a distinct difference between the two cover scenarios both in terms of overall erosion rates and the dominant erosion process. The gypsum only cover system displays much higher overall rates, approximately 3 times higher than the mixed cover system scenario. In contrast to this, the average gully depths calculated from the gypsum cover scenario output DEMs are generally shallower than the mixed scenarios, particularly as the model run time extends beyond 500 years.

This response is caused by the increased fluvial transport term included within the gypsum cover modelling input. This causes higher mobility and transportation rate of the surface sediment which in turn results in longer transport routes which effectively ‘smooth out’ the DEM surface. The effects of this process can be seen when looking at the visual representation of the modelling outputs. The mixed cover scenario shows significantly more surface erosion features (i.e. gullies) in comparison to the gypsum cover scenario outputs. Visually this makes it appear that the mixed cover system is experiencing higher erosion rates, however it is the higher resistance to erosion and the difference in the rate of sediment transport which cause the surface erosion features to develop.

Comparing the two scenarios across the modelling timeframe also displays significant differences in how the landform erodes. At 250 years both modelling scenarios show development of surface erosion features on the batter slopes and sediment deposition on the batter berms. The depth of sediment loss on the batter berms for the gypsum cover scenario which averages approximately 0.7m are already substantially higher than the mixed cover system at approximately 0.2m. The 500 year time step output continues this trend, with the erosion depths increasing but overall sediment movement following the same trend of erosion on the batter slopes and deposition within the batter berm areas. At 1,000 years the situation starts to diverge as the berm areas have been ‘lost’ as a landform feature due to the mass movement of sediment within the gypsum cover scenario. This results in increasing the mass transport of sediment from the landform surface to the surrounding plains. This process can be clearly seen in Figure 11 where the profile view of the 1,000 and 5,000 year outputs of the gypsum cover scenario are compared to the initial closure design. These images illustrate the loss of the batter/berm design which has been replaced by a long gently curving sinusoidal type slope.

Considering the 1,000 and 5,000 year outputs for the mixed cover system modelling scenario, it can be seen in Figure 16 that the batter berm configuration has been largely retained (strongly so at 1,000 years). This retention of the batter berm configuration results in lower erosion rates and much lower overall sediment loss to the surrounding land area.

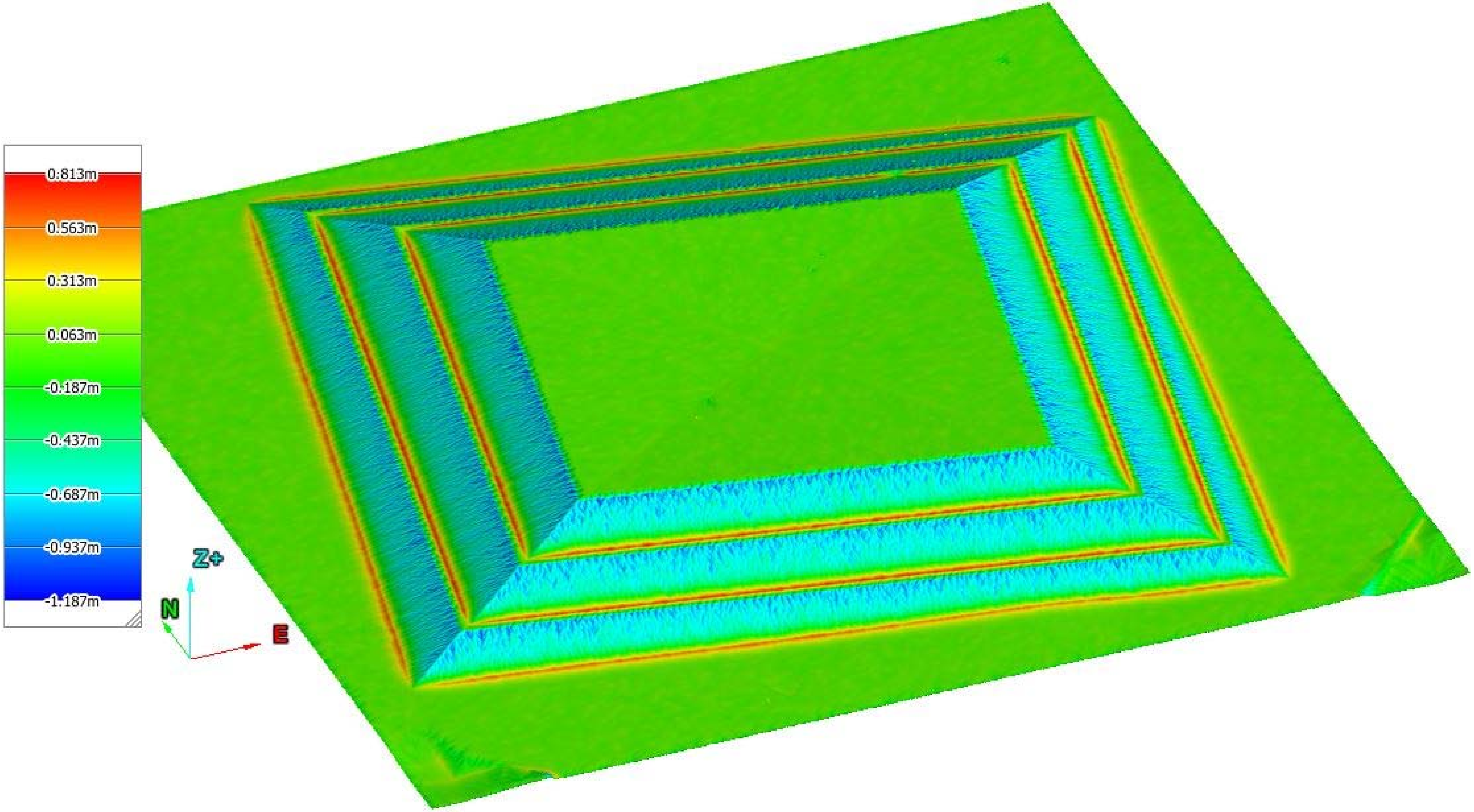


Figure 7: Gypsum cover scenario after 250 years of simulated erosion

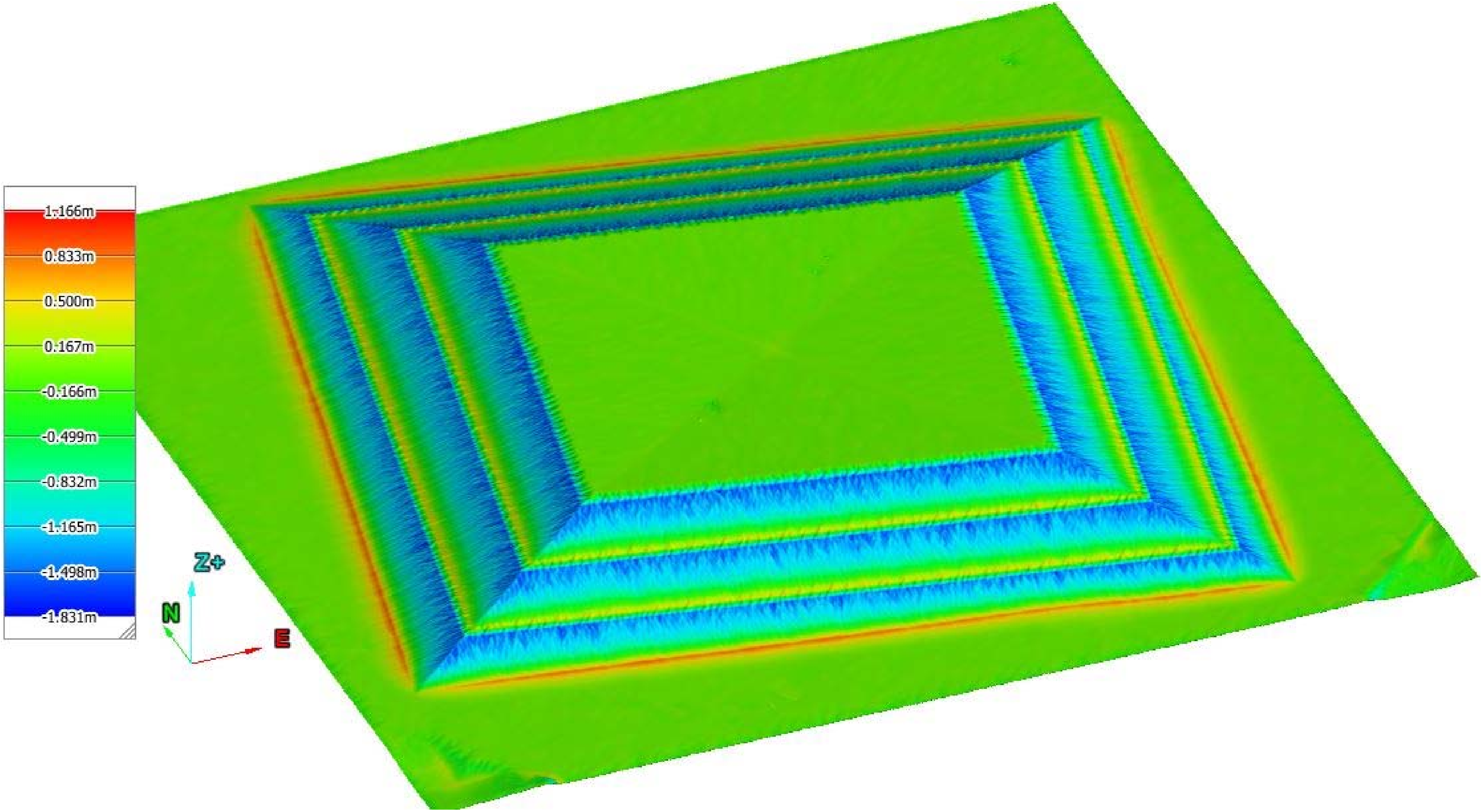


Figure 8: Gypsum cover scenario after 500 years of simulated erosion

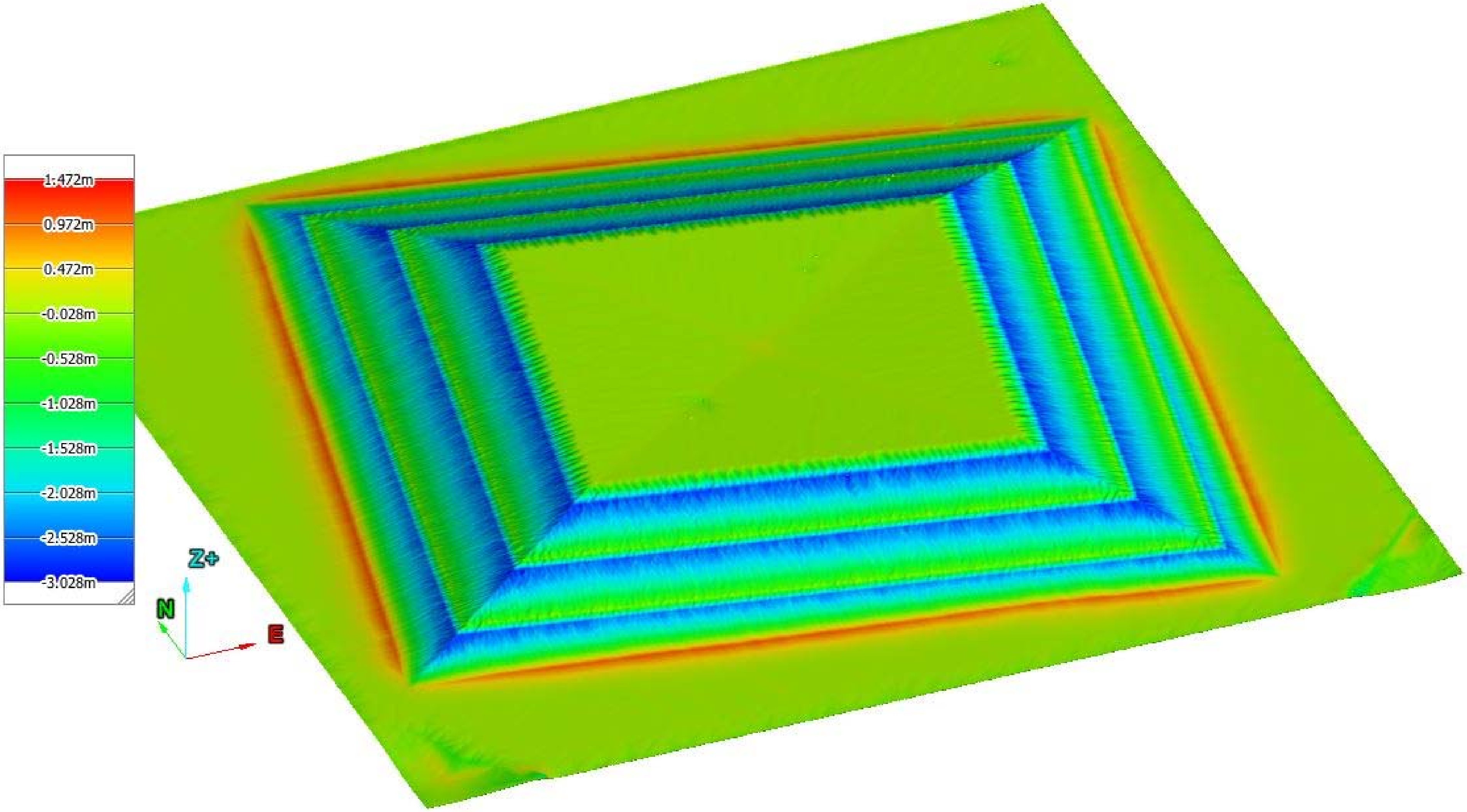


Figure 9: Gypsum cover scenario after 1,000 years of simulated erosion

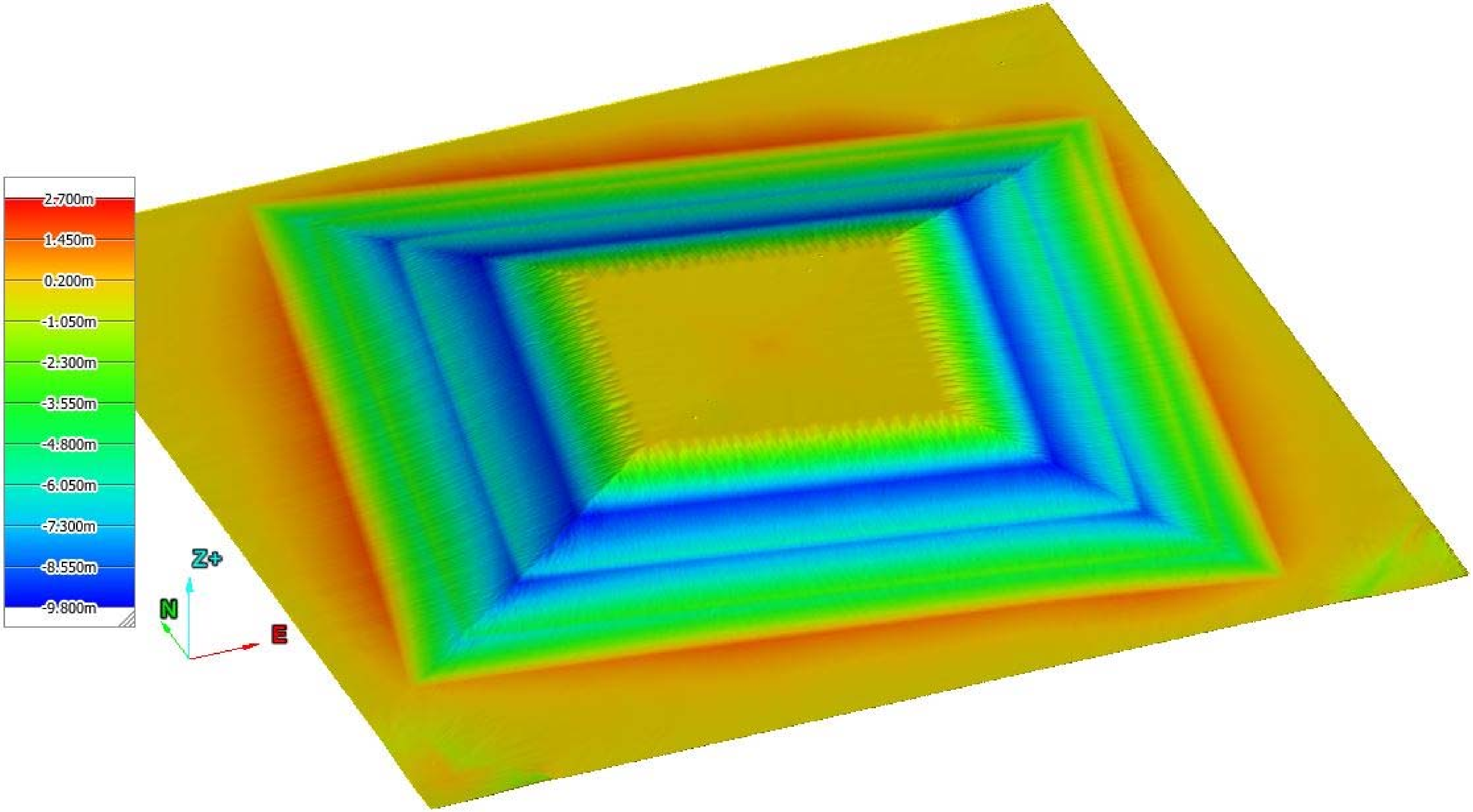
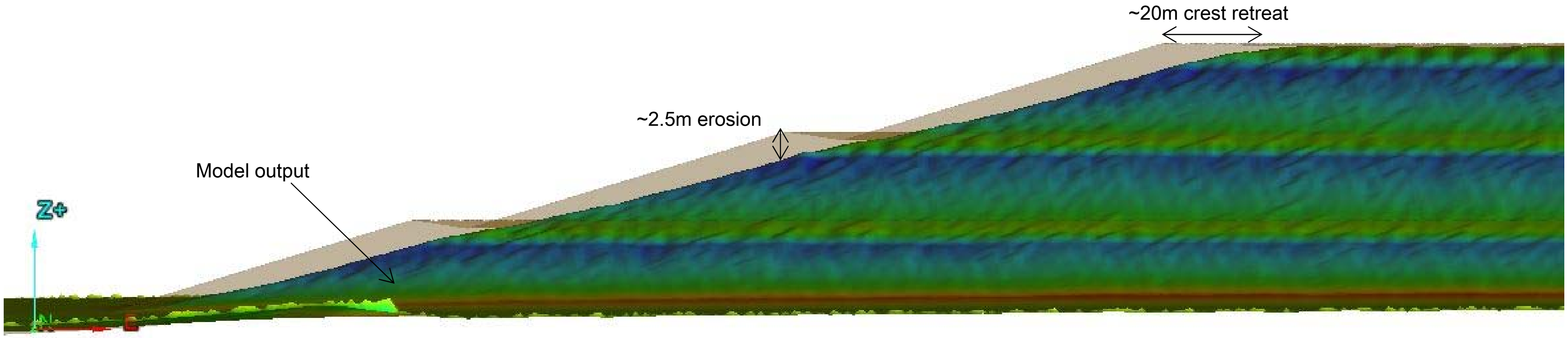


Figure 10: Gypsum cover scenario after 5,000 years of simulated erosion

1,000 year modelling output



5,000 year modelling output

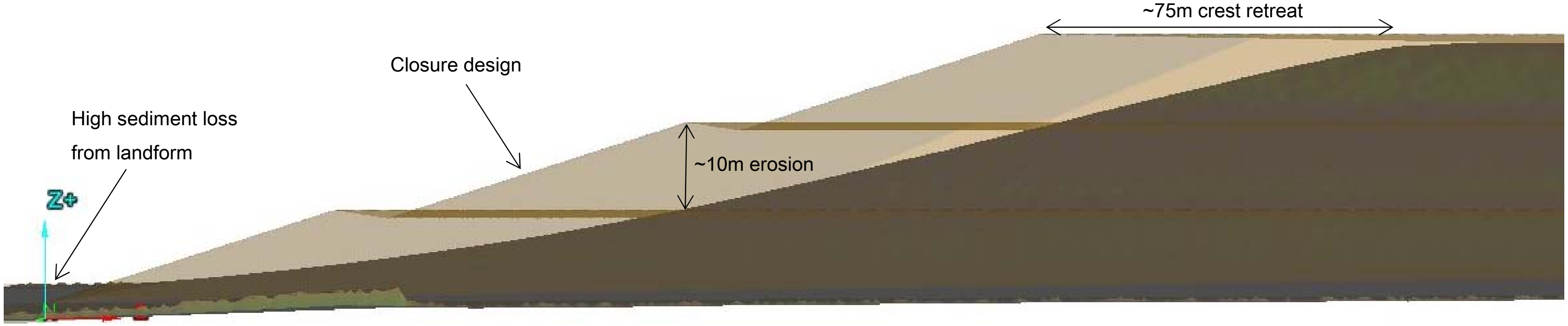


Figure 11: Comparison of gypsum cover scenario modelling outputs with initial closure design

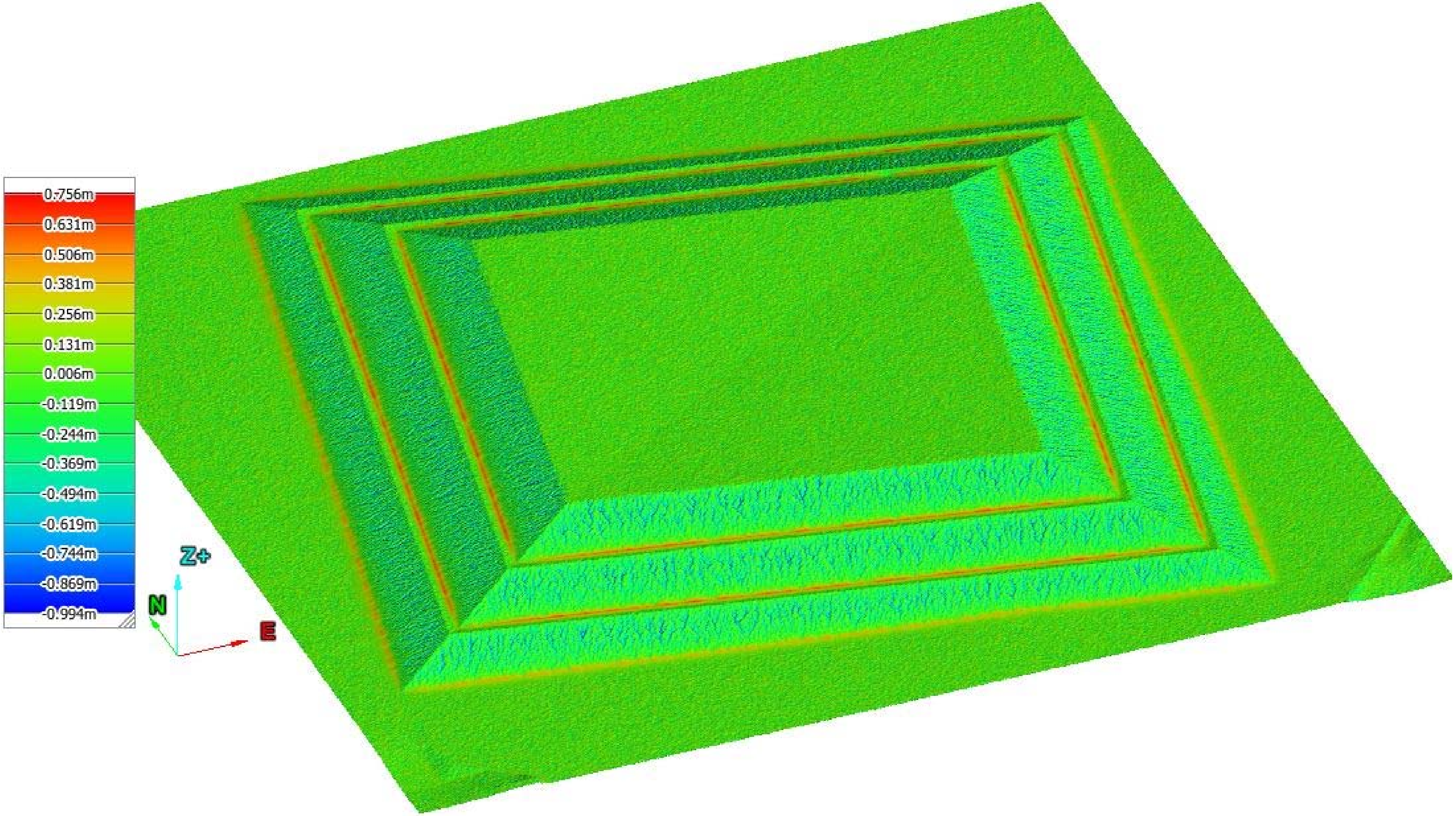


Figure 12: Gypsum and rock cover scenario after 250 years of simulated erosion

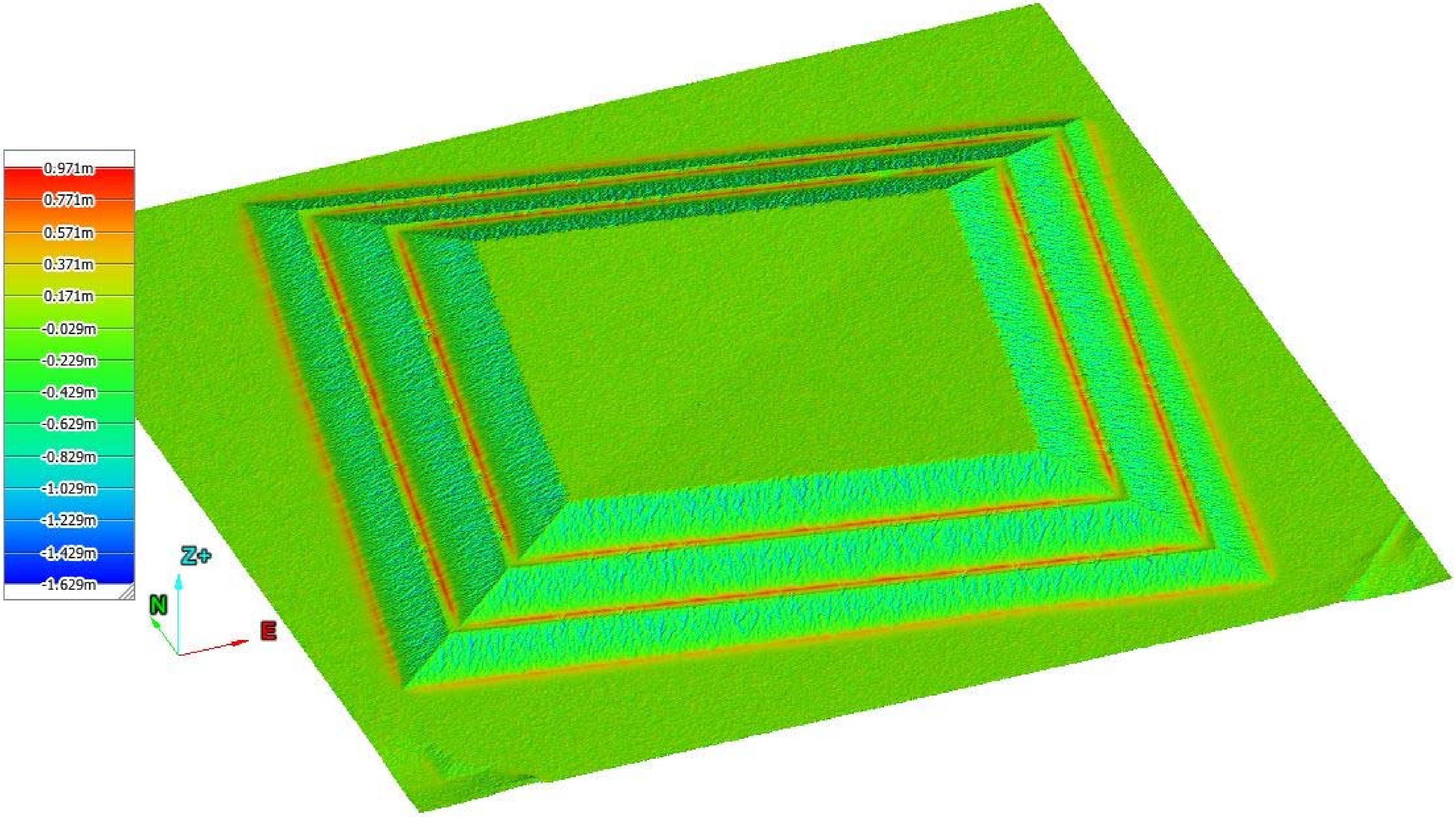


Figure 13: Gypsum and rock cover scenario after 500 years of simulated erosion

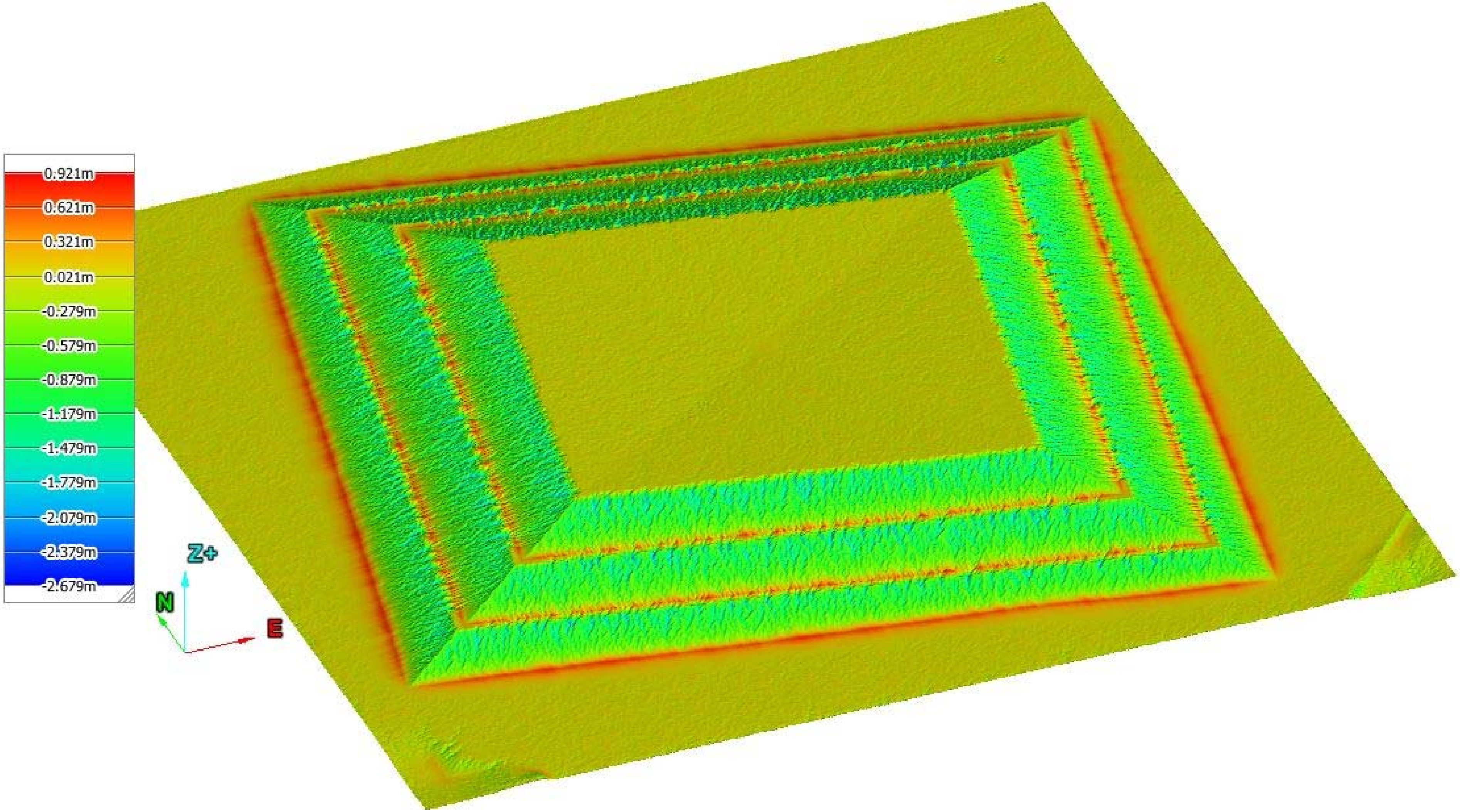


Figure 14: Gypsum and rock cover scenario after 1,000 years of simulated erosion

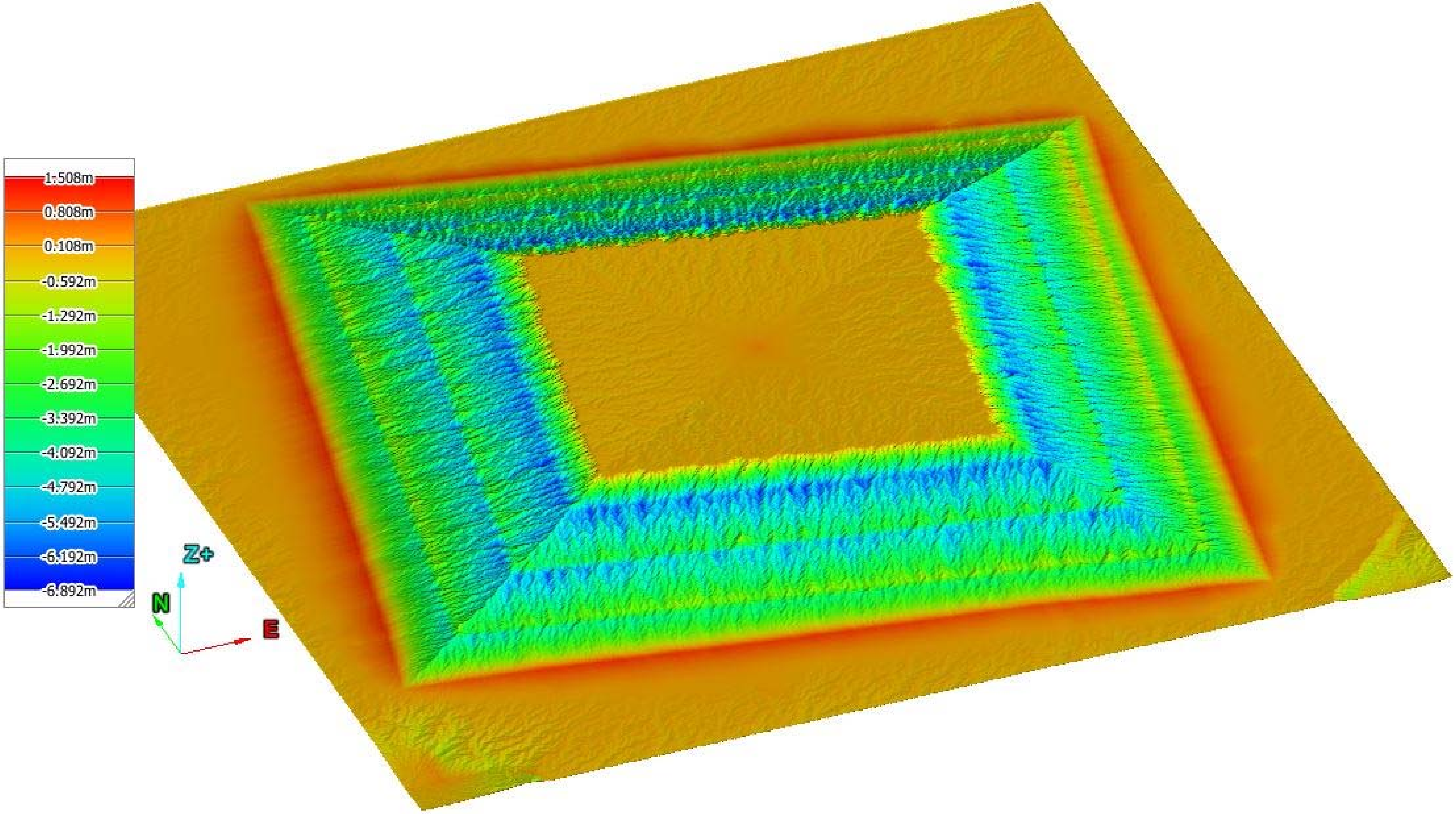
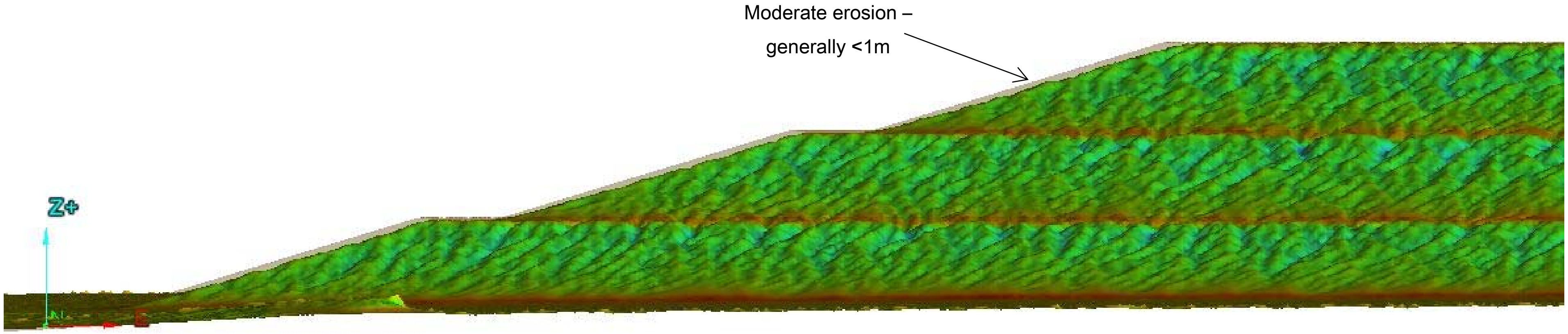


Figure 15: Gypsum and rock cover scenario after 5,000 years of simulated erosion

1,000 year modelling output



5,000 year modelling output

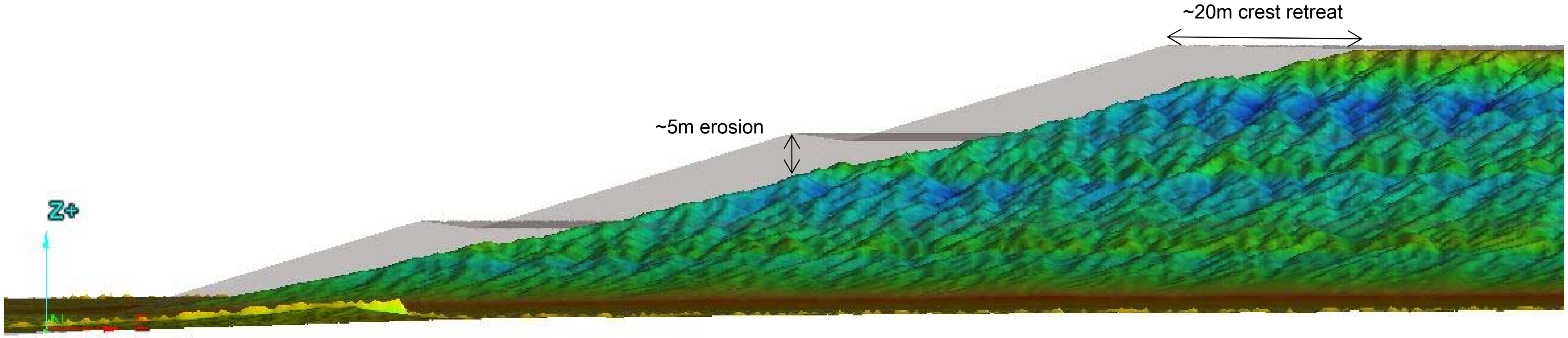


Figure 16: Comparison of gypsum and rock cover scenario modelling outputs with initial closure design

The results of LEM modelling of the two cover scenarios show that surface stability in both scenarios is not high, with large sediment movement and loss occurring over the modelled timeframe in both scenarios. The mixed cover system displayed higher resistance to erosion as would be expected, and significantly also largely retained the over batter berm design configuration over the length of the model. However neither cover scenario outcome can be considered stable over the long term for closure purposes.

Based on these outcomes the following recommendations are made:

- Carry out direct measurements of material erodibility and surface runoff / permeability characteristics in a laboratory setting for the different components of all proposed cover system(s).
- Consider different cover system materials and/or proportions to increase long term surface stability of the closure design.

Yours sincerely,

Sam Collins
Senior Scientist
Soils and Geology
m: +61 (0)427 105 200
t: +61 8 9228 3060
e: Sam.Collins@soilwatergroup.com