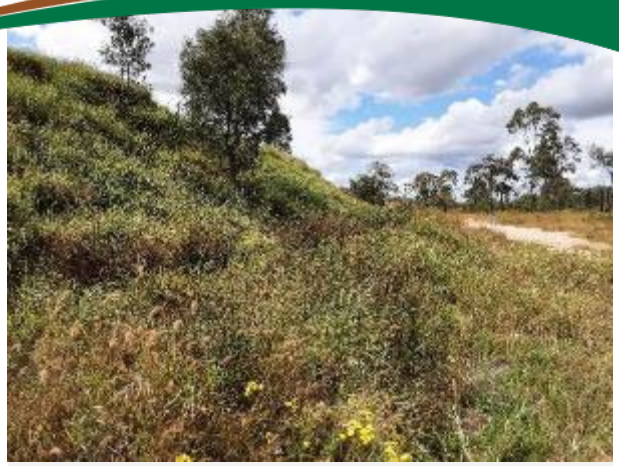




LANDFORM EVOLUTION MODELLING SIMULATIONS TO SUPPORT REHABILITATION LANDFORM DESIGN:

BLACKWATER MINE

April 2026

Whitehaven Coal Limited

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

PERTH
PO Box 5175
SOUTH LAKE WA 6164
Phone (08) 9494 2835

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

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

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

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EXECUTIVE SUMMARY

For waste landforms at Blackwater Mine (Blackwater), Landloch Pty Ltd has completed:

a) Initial WEPP runoff/erosion model simulations;
b) Derivation of parameters for the SIBERIA landform evolution model; and
c) Landform evolution simulations for 3-D waste landforms provided by Whitehaven.

Erodibility data for materials considered in WEPP simulations were sourced from previous erodibility studies that assessed Blackwater materials and from direct measurement of materials from Blackwater, and included heavy clay soil, light clay soil, and fresh Permian waste.

WEPP simulations were carried out for slope geometries that included 500 m long slopes at 30% gradient, 750 m long slopes at 20% gradient 1,000 m long slopes at 15% gradient, and 1,000 m long slopes at 10% gradient. Each of these slope geometries were sheeted with light clay soil with vegetation groundcover levels of 0–90%, heavy clay soil with vegetation groundcover levels of 0–90%, and fresh Permian waste with vegetation groundcover levels of 0–30%.

In deriving and applying SIBERIA parameters, it was assumed that:

- Heavy clay soil with vegetation groundcover levels of 70% will be used for outward-facing slopes with 15% gradient on:
  - Mimosa/Besgrove;
  - Deep Creek; and
  - Stewarton/Tannyfoil.
- Light clay soil with vegetation groundcover levels of 50% will be used for outward-facing slopes with 15% gradient on:
  - South Ballamoo;
  - Togara/North Marshmead;
  - South Marshmead;
  - Kennedy; and
  - Comet Downs East.
- Fresh Permian spoil with vegetation groundcover levels of 30% will be used for inward-facing (low wall) slopes with 30% gradient on:
  - Mimosa/Besgrove;
  - Deep Creek;
  - Stewarton/Tannyfoil;
  - South Ballamoo;
  - Togara/North Marshmead;
  - South Marshmead;
  - Kennedy; and
  - Comet Downs East.

SIBERIA landform evolution model simulations indicate that the Blackwater landforms generally have a low tendency to promote ongoing rill and gully erosion provided the correct gradients, surface materials, and the target levels of vegetation groundcover are achieved.

At a vegetation groundcover level of 70%, the heavy clay-covered slopes with lower gradients (≤15%) on Mimosa/Besgrove, Deep Creek, and Stewarton/Tannyfoil are not prone to significant levels of gully erosion. The exception is the steeper-gradient creek diversion area in the south of the landform. Improvement in the erosion performance could be achieved by refinement of the landform surface in these sections to achieve a gradient consistent with the majority of the landform surface that is not prone to gully erosion. Further, erosion resistance of the steeper-gradient zone in the south of the landform could be increased by addition of rock armour onto the steeper-gradient slopes.

At a vegetation groundcover level of 50%, the light clay-covered slopes with lower gradients (≤15%) on Kenmar, Togara/North Marshmead, South Marshmead, Kennedy, and Comet Downs East are not prone to significant levels of gully erosion.

At a vegetation groundcover level of 30%, the Permian spoil-covered slopes with steeper gradients (>15%) on Mimosa/Besgrove, Deep Creek, Stewarton/Tannyfoil, Togara/North Marshmead, and Comet Downs East are not prone to significant erosion. For South Ballamoo, South Marshmead, and Kennedy, the Permian spoil-covered slopes with steeper gradients (>15%) also have a low tendency for gully erosion, though the depth of gullies that are predicted are deeper than the other landforms. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use. Alternatively, slopes of lower gradient could be adopted to reduce erosion potential in these areas.

The average annual erosion rates for both the vegetated soil and vegetated soil-rock mixture (1:2 soil:rock mixture) surfaces are predicted to reduce through time. This indicates that the landforms are predicted to trend towards increased erosional stability through time, and that the gullies that may be present are predicted to reduce in activity through time. The long-term erosion rates for both the vegetated soil and vegetated Permian waste surfaces are predicted to reach a steady long-term annual erosion rate that has a low tendency to promote ongoing rill and gully erosion.

The model outputs have assumed the use of a heavy or light clay soil or a fresh Permian waste as the surface material. Clay soils were found to be the dominant soils across Blackwater. Fresh Permian spoil is also likely available for use in the creation of a soil-rock mixture (at a ratio of 1:2 soil:fresh Permian spoil). Weathered Permian and Tertiary materials were found to be unsuitable as a primary growth media. They should not be used to create a soil-rock mixture for use in rehabilitation. They can be used as a secondary growth media.

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1 INTRODUCTION

1.1 Overview

Landloch Pty Ltd (Landloch) has been engaged by Whitehaven Coal Limited (Whitehaven) to carry out SIBERIA landform evolution modelling for the rehabilitation landform design at the Blackwater Coal Mine (Blackwater). The SIBERIA landform evolution modelling results are to support the revision of the Progressive Rehabilitation and Closure Plan (PRC Plan) for Blackwater. The third revision of the rehabilitation design is referred to 'BWM PRCP Rev3 LF4.4' in this report, as supplied on 10 March 2026

This report outlines the SIBERIA landform evolution modelling methods and provides the modelling results, including erosion statistics and visualisations.

1.2 Objectives of landform design

The key consideration for rehabilitation landform design is to demonstrate that the landforms can be expected to be erosionally stable over the long term, while supporting the target Post Mining Land Use (PMLU). As part of that assessment, this study reports:

- Materials to be used in landform rehabilitation and their erodibility;
- WEPP erosion modelling outputs that considered the interactions between 2-D landform slope profile geometry, material erodibility, rainfall depths and erosivity, and vegetation groundcover levels to identify profile geometries that achieve acceptable erosion rates over a 100-year period; and
- Landform evolution simulations using the SIBERIA landform evolution model (LEM) to assess erosional stability of the 3-D rehabilitation landform design over a period of 300 years. The 3-D design was developed using the 2-D erosion modelling results.

1.3 Post mining land use

The PMLU for the Blackwater rehabilitation landform included cattle grazing and woodland habitat. The cattle grazing PMLU is adopted for slopes with gradients ≤15% and rehabilitation surfaces used in the LEM include vegetated soils. The woodland habitat PMLU is adopted for slopes with gradients >15% and rehabilitation surfaces used in the LEM include a vegetated surface containing a soil-waste rock mixture (1:2 soil:rock).

2 BACKGROUND

2.1 Materials

2.1.1 Soils

Broad soils mapping is available from QLD Globe[1]. Two broad soil groups exist at Blackwater, friable earths (e.g. vertosols and dermosols) and duplex soils (e.g. sodosols and chromosols).

Several more detailed soil surveys of Blackwater occurred between 1986 and 2013 (Environmental Services CSR Coal Division 1986; Mark Evans and Associates 1988; Land Reclamation Services 1997; B.R. Emmerton 1999; Groundwork Environmental Management Services 2001, 2022; SKM 2013). The data from these surveys were integrated to produce a map of soils across Blackwater (Landloch 2023a). Soil groups found within the Blackwater mining area included vertosols, dermosols, chromosols, and sodosols, consistent with the broadscale mapping. Vertosols and dermosols are the dominant soils in the northern portion of Blackwater and in a small area in the south. The southern portion of Blackwater is dominated by chromosols and sodosols.

The soil resource available for rehabilitation is predominantly situated within existing soil stockpiles. Physical and chemical characterisation of 83 soil stockpiles at Blackwater has been completed (Landloch 2023a).

Clay soils account for 75% of samples assessed across the Blackwater soil stockpiles and are evenly distributed across the mine. Generally, the clay soil samples have similar properties, but occasional minor inclusions of sands and loams are noted at some stockpiles. This is likely a result of soils from minor texture contrast soil units being stripped with the more dominant clays. Both light and heavy clay textured soils exist.

Gravelly clay soils account for 15% of samples assessed across Blackwater soil stockpiles and are located within the southern portion of the mine. These soils have similar properties to the clay soils except for their higher gravel content. The gravelly clay soils are likely to be more erosion resistant than the clay soils.

Loam soils account for 10% of samples assessed across the Blackwater soil stockpiles and are located within the southern portion of the mine. These soils have a degree of variability, but due to the limited volumes present, have been grouped together.

2.1.2 Wastes (spoils)

Geochemical and physical characterisation data for the spoil materials were collated from multiple assessments previously conducted for the project and from waste characterisation data collected as part of the PRC Plan preparation (Landloch 2023a). Spoil characteristics were found to be heterogeneous within each spoil type.

[1] QLD Globe (https://qldglobe.information.qld.gov.au/) is an online portal of location-based information curated by the Queensland Government.

Therefore, spoils were categorised into three management groups that have similar characteristics:

- Fresh Permian materials;
- Weathered Permian materials; and
- Tertiary materials.

2.1.2.1 Fresh Permian spoil

Generally, fresh Permian spoil is a rocky material consisting primarily of sandstone and siltstone, with clay content in the fine fraction ranging from 20–40%, and the coarse rock fraction being up to 75% of the mass of the material. It is generally grey in colour but may vary to pale brown after some weathering. The material ranges from moderately to highly dispersive but this can occasionally be masked by the presence of saline lenses. The material is considered to have reasonable ANC potential. Figures 1 and 2 are representative of fresh Permian spoil at Blackwater. Of the spoil management groups, fresh Permian spoils are considered most suitable for placement close to the final rehabilitated surface (within the effective rooting zone) for use as a secondary growth media (i.e. under a primary growth medium).



Figure 1: Fresh Permian sandstone present at Blackwater. Large competent rock is present throughout the stockpile.



Figure 2: Rocky fresh Permian material with weathered Permian inclusion that was sampled during erodibility studies.

2.1.2.2 Weathered Permian materials

Weathered Permian spoils are the dominant spoil material at Blackwater and are highly variable in their characteristics depending on the strata location, presence of carbonaceous inclusions, and degree of weathering. Generally, weathered Permian materials have a lower (abundance), finer (sized) rock content than fresh Permian. The rock consists primarily of fragile mudstone and sandstone, with clay content in the fine fraction ranging from 15–45% and the coarse rock fraction being 30–60% of the mass of the material. It is generally pale brown to brown in colour, but colour can vary. The material ranges from moderately to highly dispersive but this can occasionally be masked by the presence of elevated salts. It is considered to have reasonable ANC potential. Figures 3 and 4 are representative of weathered Permian spoil at Blackwater.

Weathered Permian materials are considered suitable as a secondary growth media but should be capped with a suitable quality soil (as discussed in Landloch (2023a)) to prevent exposure to the final rehabilitated surface.



Figure 3 Weathered Permian spoil present at Blackwater. Weathered and partially weathered rock is present.



Figure 4: Stockpiled weathered Permian spoil present at Blackwater, containing some coarse grains.

2.1.2.3 Tertiary materials

Tertiary materials are a highly weathered material containing small portions of fragile (low durability) rock. Generally, it has a clay content above 35%, resulting in moderate to high water holding capacity. It is typically pale orange in colour. The materials are often highly saline and strongly sodic, making it prone to a hard setting surface (Figure 5). Compared to Permian materials, the weathered Tertiary material is more susceptible to slaking and dispersion.

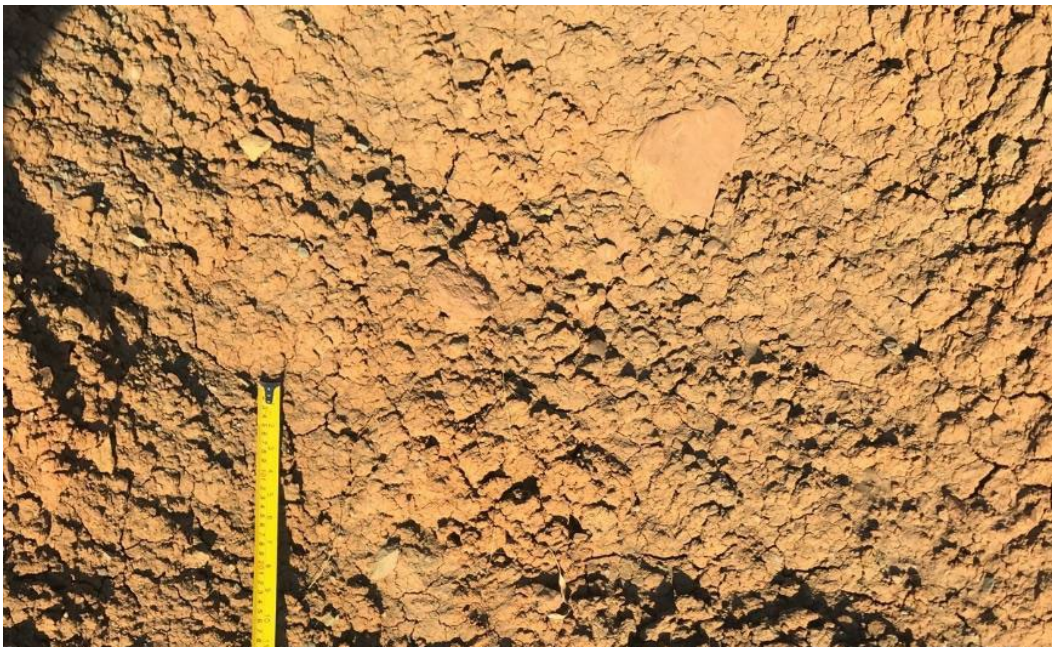


Figure 5: Hard setting Tertiary spoil stockpiled at Blackwater.

Placement of this material close to the final rehabilitated surface is not recommended on steeper gradient slopes (>15%) due to its susceptibility to erosion (including tunnel erosion). However, targeted testing may identify suitable Tertiary materials that could potentially be used to form a marginal secondary growth medium where required. Monitoring data from lower gradient (≤15%) rehabilitated slopes show that tertiary materials can be used as secondary growth media to support grazing and woodland PMLUs (Lyngco 2025a, 2025b).

2.1.3 Representativeness of materials assessed for erodibility

Landloch undertook erodibility testing of Permian spoils (Landloch 2023a, 2023b) and erodibility data for Blackwater's soils was available from Sheridan (2001). The properties of the soils and fresh Permian spoils tested for erodibility, along with a broader summary of soils and spoils reported in Landloch (2023a) are given in Table 1. Tertiary spoils (weathered sediments) were not considered further in this study because they were found to be unsuitable for use as a primary growth media and hence not present at the surface of the rehabilitated landform (Landloch 2023a).

Comparison of the soil and spoils assessed for erodibility with the broader summary of material properties show that they have:

- pH_w values (moderate to strongly alkaline) consistent with pH_w values of the materials more broadly (moderate to strongly alkaline).
- $EC_{1:5}$ values consistent with $EC_{1:5}$ values of the materials more broadly (low to moderate for soils and low to high for Permian waste).
- ECEC values consistent with ECEC values of the materials more broadly (moderate)
- Soil ESP values (non-sodic) consistent with ESP values of the soils more broadly (non-sodic to strongly sodic).
- Permian spoil ESP values (strongly sodic) consistent with ESP values of the Permian spoil more broadly (non-sodic to strongly sodic).
- Soil clay content values (41–50%) consistent with clay content values of the soils more broadly (>35%).
- Permian spoil clay content values (14–28%) consistent with clay content values of the Permian spoils more broadly (20–40%).
- Soil rock content values (commonly <20%) consistent with rock content values of the soils more broadly (10%).
- Permian spoil rock content values (up to 74%) consistent with rock content values of the spoils more broadly (>15–95%).

Based on this assessment, it was concluded that the materials assessed for erodibility are consistent with the soil and spoil materials more broadly and therefore representative of these materials.

Table 1: Summary of soil and spoil properties and properties of soil and spoils assessed for erodibility.

Analysis	Units	Summary of Material Properties (Landloch 2023a)			Materials Assessed for Erodibility		
		Clay Topsoil (Landloch 2023a)	Gravelly Clay Topsoil (Landloch 2023a)	Fresh Permian (Landloch 2023a)	Light Clay Topsoil Stockpile 93	Heavy Clay Topsoil Stockpile 291b	Fresh Permian Waste (This Study & Landloch 2023b)
pH_w	pH Units	8.0–9.0 Moderate to strongly alkaline	8.1–9.0 Moderate to strongly alkaline	8.4–9.8 Moderate to strongly alkaline	8.0 Moderately alkaline	8.6 Moderately alkaline	9.0–9.8 Strongly alkaline
$EC_{1:5}$	dS/m	<0.5 Low to moderate	<0.7 Low to moderate	<2.3 Low to high	0.4 Moderate	0.24 Low	<1.2 Low to high
ECEC	meq/100g	14–27 Moderate	12–28 Moderate	<30 Low–moderate	23 Moderate	23 Moderate	12–16 Moderate
ESP	%	3.3–14 Non-sodic to sodic	4.5–17 Non-sodic to strongly sodic	3–30 Non-sodic to strongly sodic	1.9 Non-sodic	13 Sodic	15–34 Strongly-sodic
Clay Content	%	>35	>35	20–40	41	50	14–28
Rock Content	%	<20	20–50	Up to 74	10	10	15–95

2.2 Material erodibility

An assessment of the erodibility of rocky fresh Permian spoils at Blackwater was completed (Landloch 2023b). Four (4) samples were supplied and tested (Figure 6). This erodibility data was aggregated to produce a single erodibility parameter dataset for the fresh Permian spoil.

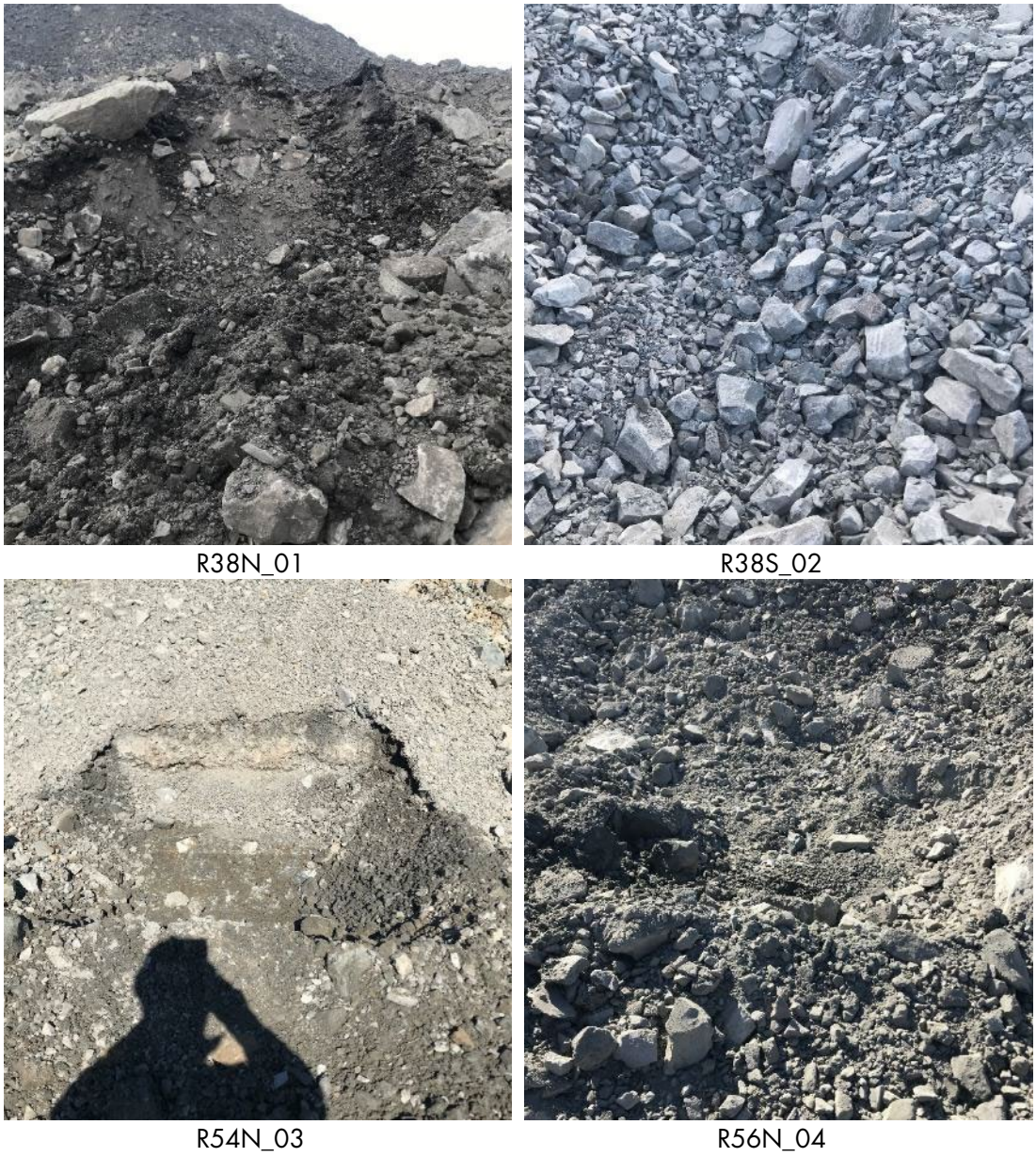


Figure 6: Photos of fresh Permian spoil samples in the field.

Given the dominance of clay soils (and the similar gravelly clay soil) at Blackwater, only the clay soils were considered further for erodibility testing. Modelling of erosionally stable slopes sheeted with clay soils would also be erosionally stable for gravelly clay soils. Hence, gravelly clay soils were not considered separately from the clay soils.

A light clay soil from Stockpile 93 (R34) and a heavy clay soil from Stockpile 291b (R34) were sourced and used for erodibility testing as part of this project. Figure 7 shows the two clay soils tested immediately after exposure to high intensity simulated rain. Erodibility data for a clay soil was also available from Sheridan (2001). These data sources were incorporated to produce an aggregated erodibility parameter dataset for the light and heavy clay soils.



Figure 7: Test plots immediately following application of simulated rain to a light clay soil from Stockpile 93 (left) and a heavy clay soil from Stockpile 291b (right).

3 WEPP 2-D EROSION SIMULATIONS

3.1 The WEPP model

WEPP was developed by the United States Department of Agriculture to predict runoff, erosion, and deposition for hillslopes akin to mine landform slopes (Flanagan and Livingston 1995). WEPP is a simulation model with a daily input time step, although shorter time steps are used by internal calculations on days when rainfall occurs. Plant and soil characteristics important to erosion processes are updated every day. When rainfall occurs, those plant and soil characteristics are considered in determining the likelihood of runoff. If runoff is predicted to occur, the model computes sediment detachment, transport, and deposition at points along the slope profile.

The erosion component of WEPP uses a steady-state sediment continuity equation as the basis for the erosion computations. Erosion in interrill areas is calculated as a function of the effective rainfall intensity and runoff rate. Erosion in rills is predicted to occur if the flow's hydraulic flow shear stress is greater than the soil's critical hydraulic flow shear stress, and when the sediment load of the flow is below its transport capacity. Deposition in rills is computed when the sediment load is greater than the capacity of the flow to transport it.

3.2 Slope geometries

WEPP runoff and erosion simulations were carried out for:

- Slopes 500 m long, at 30% gradient, surfaced with:
  - Light clay soil with vegetation groundcover levels of 0–90%;
  - Heavy clay soil with vegetation groundcover levels of 0–90%; and
  - Fresh Permian waste with vegetation groundcover levels of 0–30%.
- Slopes 750 m long, at 20% gradient, surfaced with:
  - Light clay soil with vegetation groundcover levels of 0–90%;
  - Heavy clay soil with vegetation groundcover levels of 0–90%; and
  - Fresh Permian waste with vegetation groundcover levels of 0–30%.
- Slopes 1,000 m long, at 15% gradient, surfaced with:
  - Light clay soil with vegetation groundcover levels of 0–90%; and
  - Heavy clay soil with vegetation groundcover levels of 0–90%.
- Slopes 1,000 m long, at 10% gradient, surfaced with:
  - Light clay soil with vegetation groundcover levels of 0–90%; and
  - Heavy clay soil with vegetation groundcover levels of 0–90%.

3.3 Vegetation groundcover impacts

Impacts of vegetation groundcover on infiltration rates were estimated using the relationship reported by Kato *et al.* (2009), and direct impacts of vegetation groundcover on erosion rates were estimated using Cover I factors for the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.* 1993) listed in Rosewell (1993).

Vegetation groundcover levels greater than 50–70% appear achievable on most rehabilitation carried out on Central Queensland coal mines. As a conservative approach, vegetation groundcover levels of 30% for materials of relatively low fertility (fresh Permian waste) and 50% (light clay soil) and 70% (heavy clay soil) for the more fertile soils have been applied in erosion simulations.

3.4 Climate

All simulations used a synthetic 100-year climate file prepared to match all relevant characteristics of Blackwater climate.

3.5 Soil loss targets

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

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

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

For that reason, a key priority in setting a tolerable erosion target is the prevention of significant rill or gully development. On that basis, an average annual rate of erosion of 5t/ha/y has previously been applied by Landloch on the basis that rilling is greatly reduced at this rate.

The elimination of rilling reduces the potential for channelised flow to form gullies, and experience to date with a large number of waste landforms designed by Landloch has shown that the target soil loss values adopted have achieved acceptable levels of stability to erosion.

3.6 WEPP modelling assumptions

The erosion model simulations are based on two key assumptions:

- There will be no uncontrolled discharge of runoff from landform tops onto outer slopes; and
- The assumed groundcover levels will be achieved sustainably, with those levels being set as triggers for investigation and remedial action should monitoring indicate that they are not being achieved.

In considering vegetation groundcover, this report specifically considers vegetation that is in contact with the land surface. Practically, this means a combination of grass cover and anchored (not readily moved) surface litter. Groundcover impacts do not consider rock. Where rocky materials have had erodibility measured experimentally and those parameters are used in WEPP simulations, then effects of the rock are already accounted for within the parameters used. It should be recognised there are also underlying assumptions of good rehabilitation practice such that:

- There will not be discharges of concentrated flows onto any slopes at any point of their rehabilitation;
- Slopes will not be formed with flow-concentrating profiles, e.g. variations in surface elevation such that there is cross-slope concentration of flow into consistent depressions running downslope;
- Any cross-slope ripping will be carried out strictly on the contour; and
- Soil management (including stripping, stockpiling, replacement, amendment, and fertilisation) will be carried out effectively to maximise rapid and persistent vegetation growth.

4 RESULTS OF WEPP SIMULATIONS

Simulations considered slope lengths of 500–1,000 m. The target erosion rate for modelling outward-facing slopes (light and heavy clay soil) is an average annual rate of 5 t/ha/y. The target erosion rate for modelling inward-facing slopes (low walls, fresh Permian waste) is an average annual rate of 10 t/ha/y. These rates are modelling targets only and are not necessarily suitable for determining rehabilitation success criteria. Additional data can be found in Appendix B.

4.1 Outward-facing slopes surfaced with vegetated light clay soil

For the light clay soil, long-term WEPP erosion simulations indicate that gradients of 30% would require very high vegetation groundcover levels (>70%) (Figure 8). Slopes that are 1,000 m long are predicted to be stable for a vegetation groundcover level of >50% for a 20% gradient slope (Figure 9), >50% for a 15% gradient slope (Figure 10), and >30% for a 10% gradient slope (Figure 11).

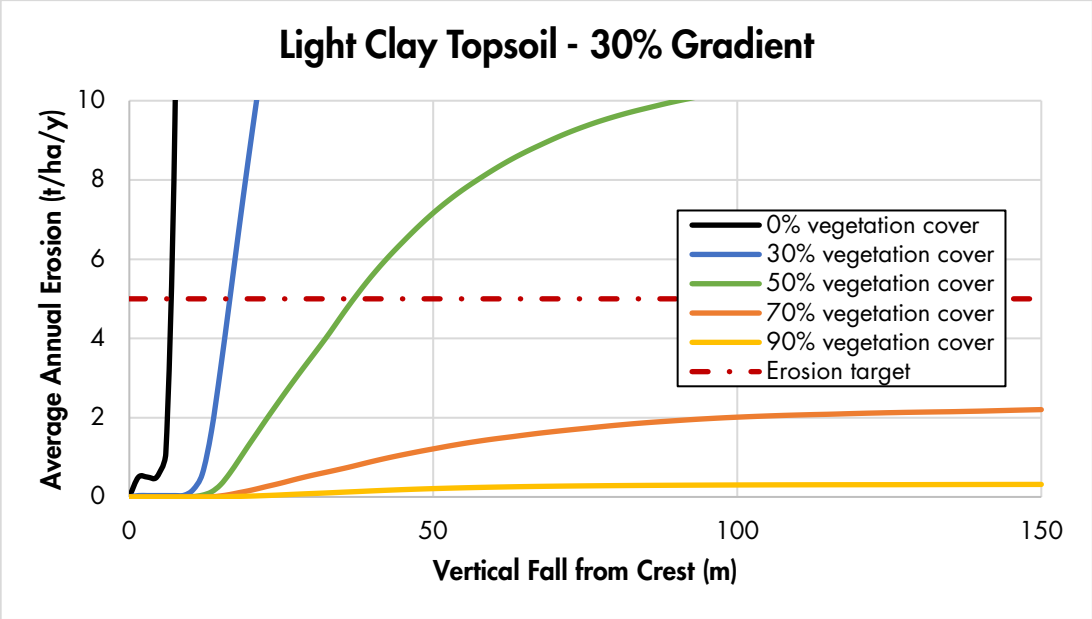


Figure 8: Predicted erosion rates on a 30% gradient outward-facing slope sheeted with light clay soil.

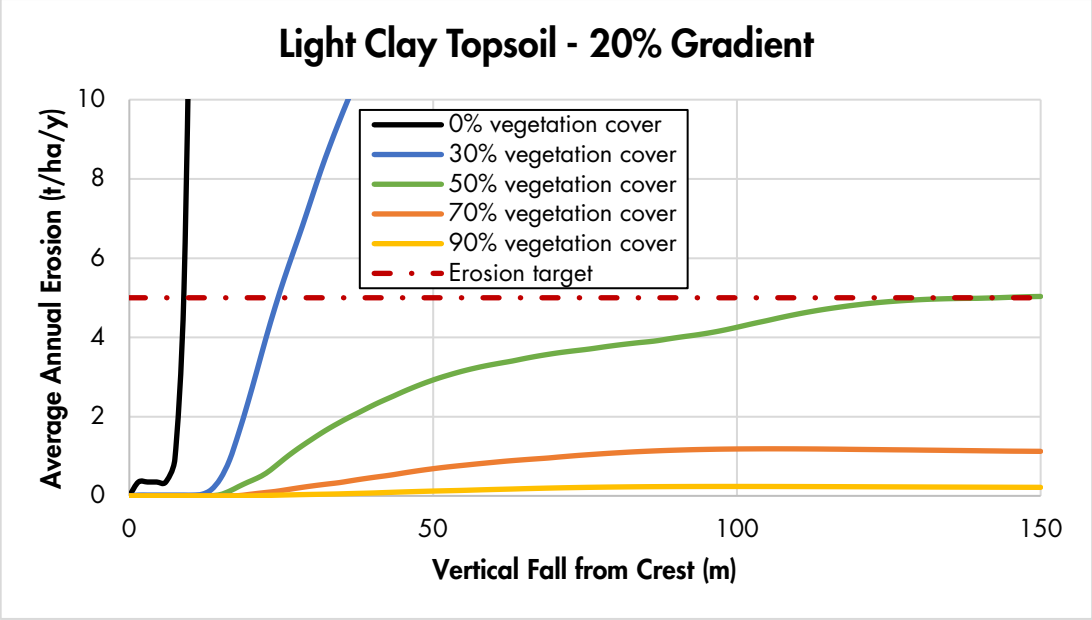


Figure 9: Predicted erosion rates on a 20% gradient outward-facing slope sheeted with light clay soil.

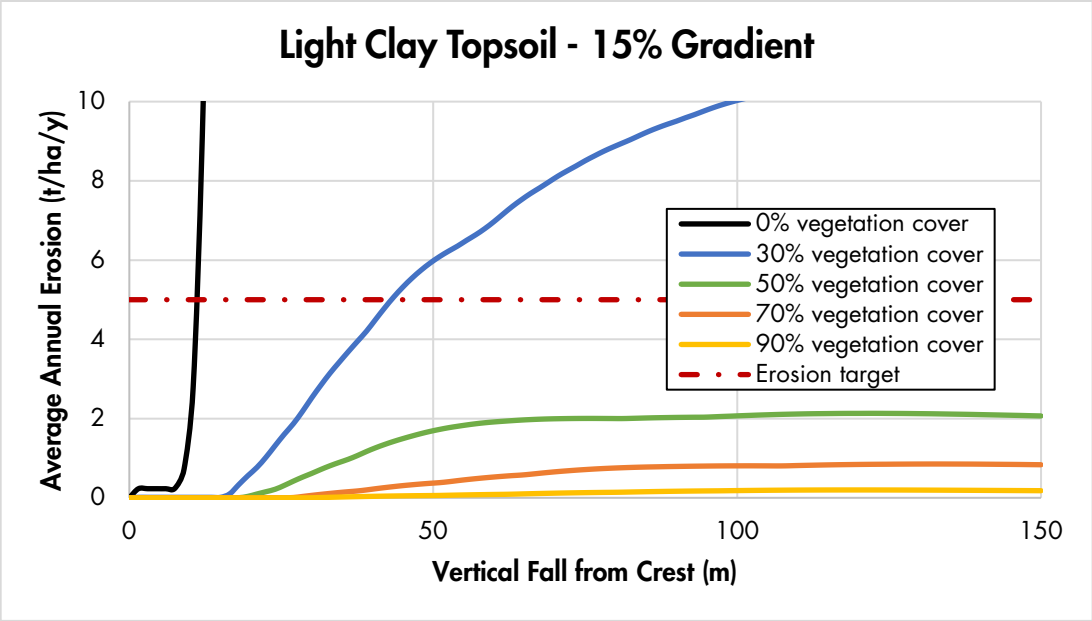


Figure 10: Predicted erosion rates on a 15% gradient outward-facing slope sheeted with light clay soil.

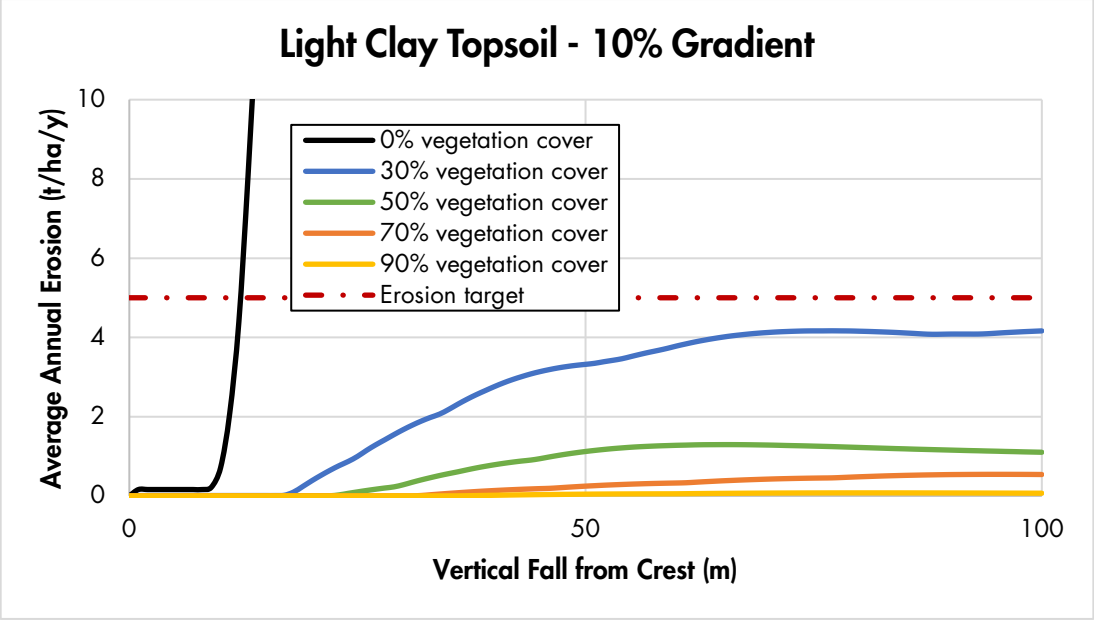


Figure 11: Predicted erosion rates on a 10% gradient outward-facing slope sheeted with light clay soil.

4.2 Outward-facing slopes surfaced with vegetated heavy clay soil

For the heavy clay soil, long-term WEPP erosion simulations indicate that gradients of 30% would require very high vegetation groundcover levels (>90%) (Figure 12). Slopes that are 1,000 m long are predicted to be stable for a vegetation groundcover level of 90% for a 20% gradient slope (Figure 13), 70% for a 15% gradient slope (Figure 14), and 70% for a 10% gradient slope (Figure 15).

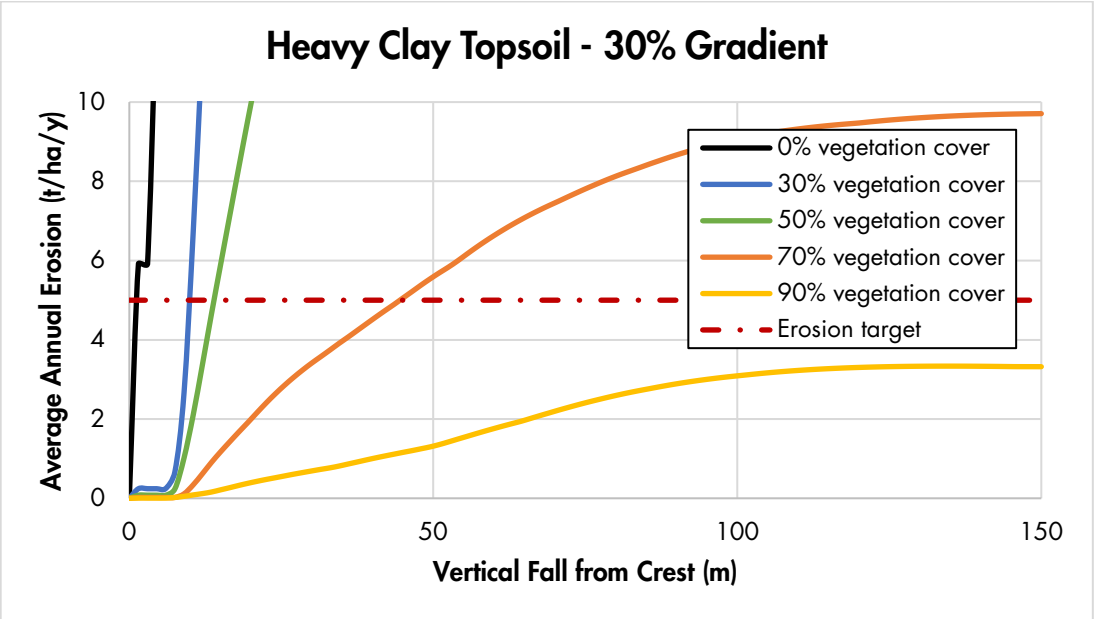


Figure 12: Predicted erosion rates on a 30% gradient outward-facing slope sheeted with heavy clay soil.

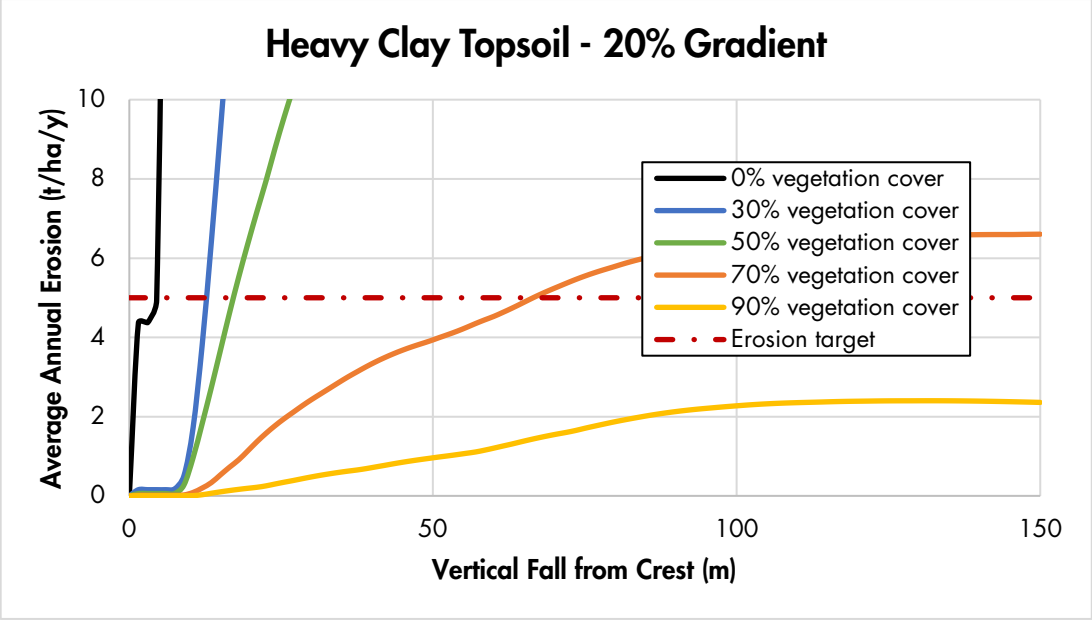


Figure 13: Predicted erosion rates on a 20% gradient outward-facing slope sheeted with heavy clay soil.

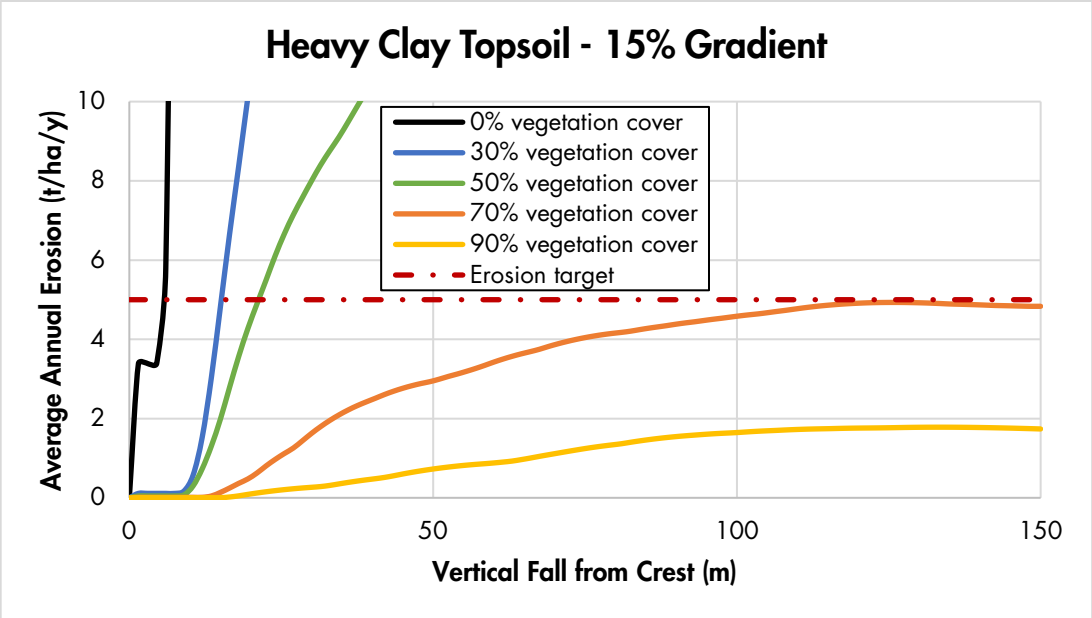


Figure 14: Predicted erosion rates on a 15% gradient outward-facing slope sheeted with heavy clay soil.

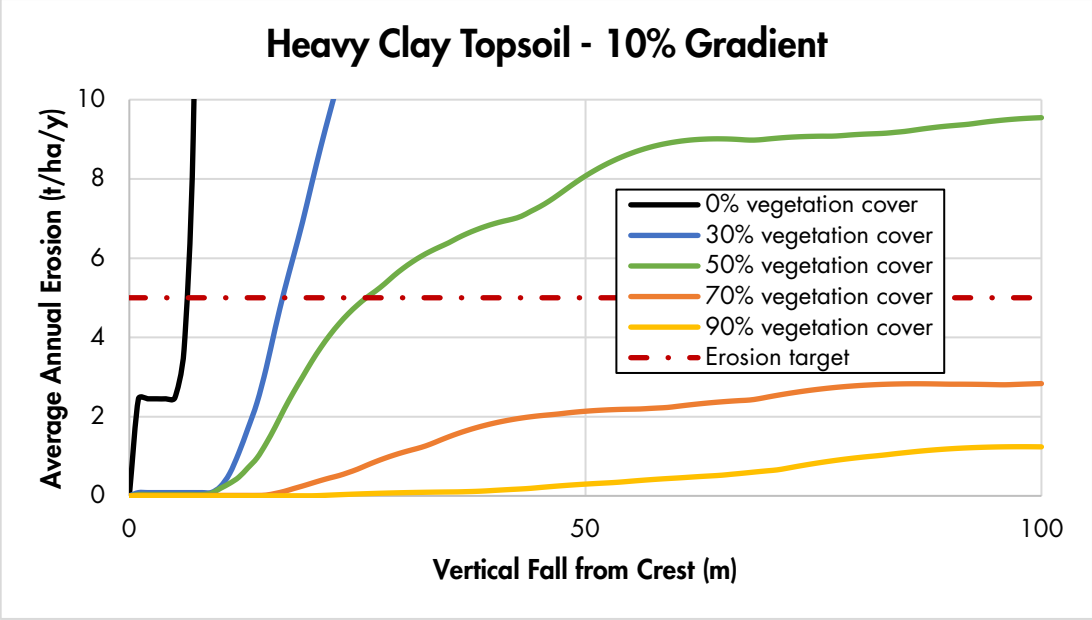


Figure 15: Predicted erosion rates on a 10% gradient outward-facing slope sheeted with heavy clay soil.

4.3 Inward-facing low walls sheeted with fresh Permian waste

For the fresh Permian waste, simulations indicate that 500 m long slopes with gradients of 30% would require vegetation groundcover levels of >30% (Figure 16). Slopes with gradients of 20% are predicted to be stable for a vegetation groundcover level of >30% (Figure 17) and slopes with gradients of 15% are predicted to be stable for a vegetation groundcover level of 0% (bare) (Figure 18).

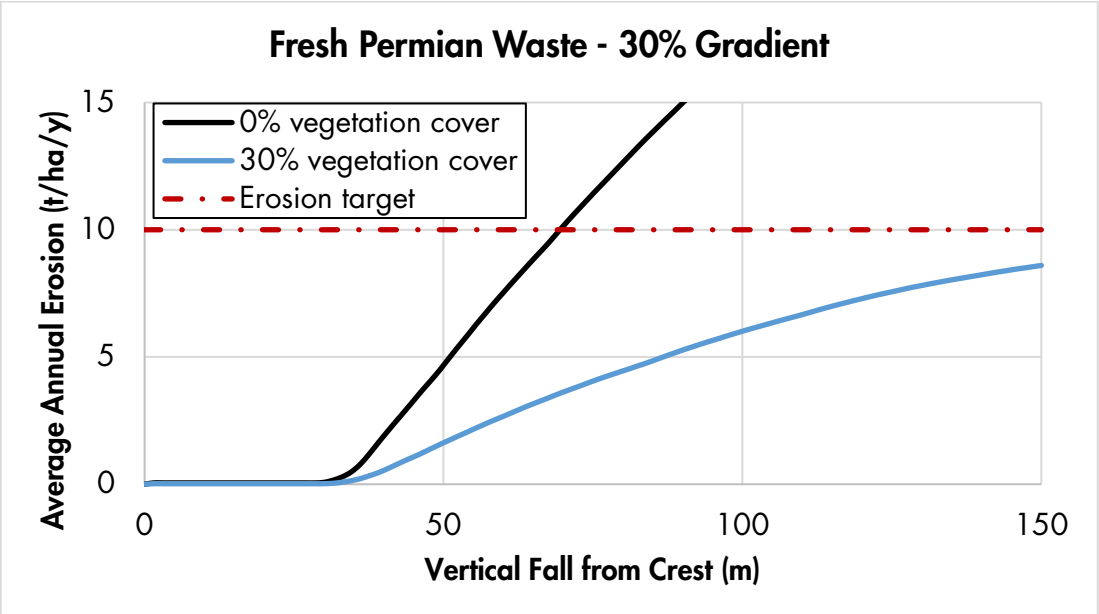


Figure 16: Predicted erosion rates on a 30% gradient inward-facing low wall slope sheeted with fresh Permian waste.

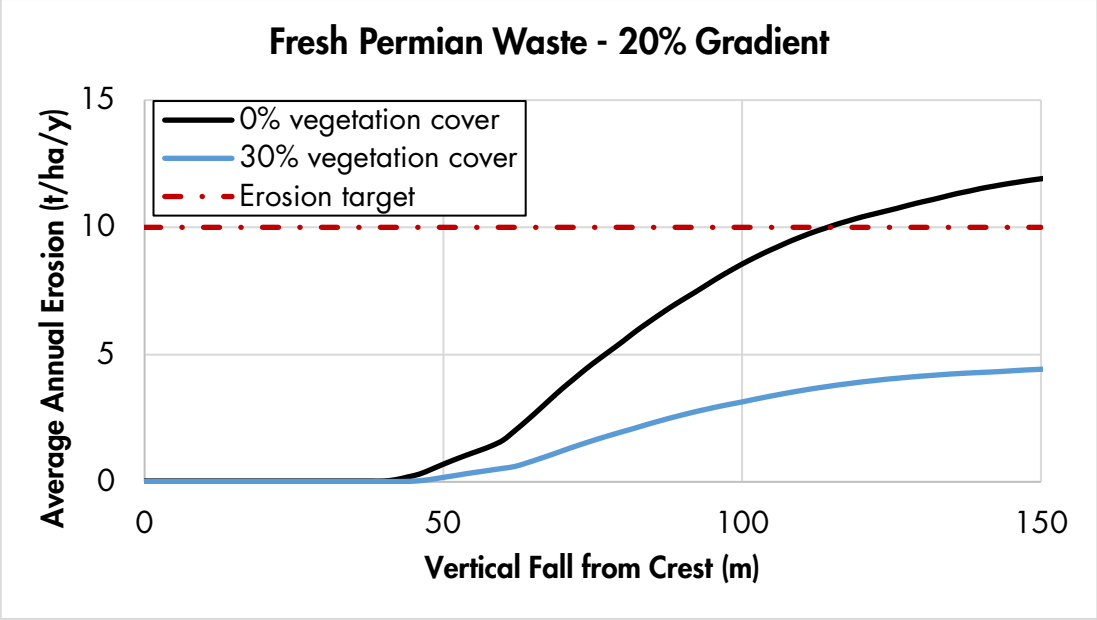


Figure 17: Predicted erosion rates on a 20% gradient inward-facing low wall slope sheeted with fresh Permian waste.

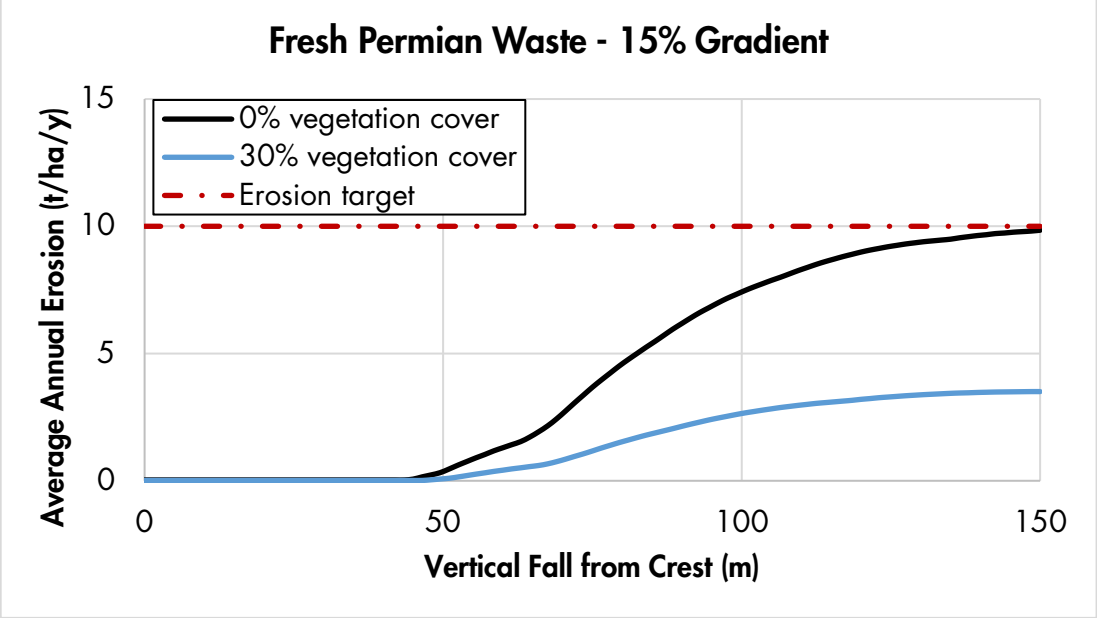


Figure 18: Predicted erosion rates on a 15% gradient inward-facing low wall slope sheeted with fresh Permian waste.

4.4 Implications for the rehabilitation landform design

Based on the erosion modelling results, it was concluded that use of vegetated clay soil and fresh Permian waste surfaces can be erosionally stable. Given this finding and the spatial distribution (different soils are available close to the different landforms) of the stockpiled soils, SIBERIA landform evolution modelling used:

- Heavy clay soil with vegetation groundcover levels of 70% for outward-facing slopes with 15% gradient on:
    - Mimosa/Besgrove;
    - Deep Creek; and
    - Stewarton/Tannyfoil.
- Light clay soil with vegetation groundcover levels of 50% for outward-facing slopes with 15% gradient on:
    - South Ballamoo;
    - Togara/North Marshmead;
    - South Marshmead;
    - Kennedy; and
    - Comet Downs East.
- Fresh Permian waste with vegetation groundcover levels of 30% for inward-facing low wall slopes with 30% gradient on:
    - Mimosa/Besgrove;
    - Deep Creek;
    - Stewarton/Tannyfoil;
    - South Ballamoo;
    - Togara/North Marshmead;
    - South Marshmead;
    - Kennedy; and
    - Comet Downs East.

5 SIBERIA 3-D LANDFORM EVOLUTION MODELLING

5.1 The SIBERIA model

The SIBERIA landform evolution model predicts the long-term, 3D development of channels and hillslopes (e.g. landform slopes) in a catchment based on runoff, erosion, and deposition.

SIBERIA has been successfully applied to explain aspects of the geomorphology of natural landforms (Willgoose 1994) and has been widely used to assess the evolution of constructed waste dumps on mine sites across Australia and overseas (Willgoose 1995; Willgoose and Riley 1993; Boggs *et al.* 2000; Hancock *et al.* 2003; Hancock and Willgoose 2004; Hancock 2004; Mengler *et al.* 2004; Hancock and Turley 2006). It has also been subjected to numerous validation studies. In general, the validation studies indicate that SIBERIA's predictions of landform evolution are reasonable provided the model is suitably parameterised (Hancock *et al.* 2000; Hancock *et al.* 2003). In one validation study (Hancock 2004) it was noted that erosion rates predicted by SIBERIA for a catchment in the Northern Territory compared favourably to erosion estimates derived using the caesium-137 method. As the two erosion assessment methods use independent input information, the reported agreement is particularly significant.

SIBERIA solves for two variables: elevation, from which slope geometries are determined, and an indicator function that determines where erosion features (channels) exist.

Changes to the predicted erosion features is governed by an activation threshold that is dependent on the runoff discharge and gradient of the slope. When the activation threshold is exceeded, an erosion feature is predicted to develop. In this way, it is possible for a modelled surface to initially have no erosion features and for rills/gullies to develop where the activation threshold is exceeded.

The rate at which rills and gullies develop is controlled by a channelisation function. SIBERIA does not directly input rainfall or material erodibility parameters. Rather, the SIBERIA input parameters define the channelisation function that is a function of both runoff and erosion (Willgoose *et al.* 1989). As a result, SIBERIA parameters are specific to both the climatic regime and the material being considered and must be derived for each specific material located within each specific climatic regime.

5.2 SIBERIA input parameters

SIBERIA predicts the long-term average change in elevation of a node (i.e. a point in the landscape) by predicting the volume of sediment lost from that node. The rate of sediment transport through a node (q_s in units of m^3/y) is determined by the equation:

$$q_s = \beta_1 \times q^{m_1} \times S^{n_1} \qquad 1)$$

where β_1 is the sediment transport rate coefficient (unitless), q is discharge (m^3/y), m_1 is the discharge exponent (unitless), S is the slope (m/m), and n_1 is the slope exponent (unitless). SIBERIA does not directly model discharge, but uses sub-grid effective parameterisation which relates discharge to the area draining through a node as:

$$q = \beta_3 \times A^{m_3} \qquad 2)$$

where β_3 is the coefficient between discharge and area (unitless), A is area (m^2), and m_3 is the exponent of the area in discharge (unitless).

To run SIBERIA, the parameters β_1, m_1, n_1, β_3, and m_3 are needed. There is interaction between all 5 parameters, with the result that an almost infinite number of parameter sets will all show the same rate of erosion, though some aspects of the pattern of erosion that is predicted will vary. Fixed values for β_3, n_1, and m_3 are adopted where possible, reducing the difficulty of deriving parameter values. If the slope to be modelled is identical to the slope for which erosion data are available for calibration, m_3 and β_3 can be taken as 1.0, and for situations where slope gradient does not affect slope erodibility, n_1 can be taken as 1.5 (Willgoose pers. comm.). This is consistent with Kirkby (1971) who suggests values ranging from 1.3–2.0 are reasonable for soils.

Therefore, two key parameters require fitting against runoff and erosion data: β_1 and m_1. Effectively, the β_1 parameter could be described as an erosion rate parameter, as it primarily controls the rate of sediment movement. The m_1 parameter could be described as primarily controlling slope length responses of erosion.

5.3 Derivation of SIBERIA parameters

To run SIBERIA, the parameters β_1, m_1, n_1, β_3, and m_3 are usually needed. However, if the slope area to be modelled is identical to the slope for which erosion data are available for calibration, m_3 and β_3 can be taken as 1.0 and a value for n_1 of 1.5 can

be adopted for situations where slope gradient does not affect slope erodibility (Willgoose, pers. comm.). Therefore, the two key parameters that require derivation are β_1 and m_1.

The β_1 parameter can be considered a "rate parameter", as it primarily controls the rate of sediment movement. The m_1 parameter can be considered as primarily controlling slope length responses. However, in practice, there is interaction between all the parameters with the result that a large number of parameter sets will all show the same rate of erosion though some aspects of the pattern of erosion that is predicted will vary. It is for this reason that, where possible, fixed values of n_1 and m_3 are adopted – thereby reducing the difficulty of deriving parameter values.

Input parameters for SIBERIA are typically derived by fitting the various model equations to time series data of runoff and erosion. To generate the necessary data, Landloch has developed method that involves:

a) Run the WEPP model to generate data sets of runoff and erosion for slopes consistent with the proposed landforms and for materials of interest using site specific climate data.
b) Analyse the WEPP output to derive the required SIBERIA input parameters.

This approach ensures that SIBERIA parameters are effectively benchmarked to the WEPP output, and thereby, effectively based on measured erodibility parameters for site materials and on site climate.

5.4 Model parameters

SIBERIA model parameters derived from WEPP simulations are shown in Table 2. As noted previously (Section 3.5.3), the vegetation groundcover levels assumed are considered conservative, with some variation to account for lower fertility of the wastes.

It should be noted that the method of deriving parameters attempts to ensure that the m_1 parameter is optimised so that SIBERIA simulations show a similar impact of slope length to that predicted by WEPP. However, because the two models use different methods to consider impacts of slope length, it is not reasonable to expect complete agreement between the two models over the full range of slope lengths considered.

Table 2: Estimated SIBERIA parameters.

Material	Vegetation Groundcover (%)	m_1	β_1	n_1
Light clay soil	50	1.1127	0.00262	1.5
Heavy clay soil	70	1.2375	0.00360	1.5
Fresh Permian waste:soil mix	30	1.5098	0.00009	1.5

5.5 Model settings

The Digital Elevation Model (DEM) modelled by SIBERIA included the landform surface meshed into the surrounding landscape. A random roughness (±10cm) was added to the DEM prior to modelling. This was done to reduce triangulation gridding artefacts from the surface of the DEM and to provide a more realistic surface for modelling (landform surfaces are not perfectly smooth). The following SIBERIA outputs were produced for each landform modelled at years 50, 100, 150, 200, 250, and 300:

- Maximum depth of gullies at each output year with gullies defined as having a minimum depth of 0.3m;
- Average erosion (t/ha/y);
- Cumulative erosion (mm) for each output year; and
- Visual outputs showing the evolved DEM over which is draped the predicted material movement (erosion and deposition).

5.6 Digital elevation model

Proposed 3-D final landform design files for Blackwater were provided by Whitehaven. The landforms modelled included:

- Mimosa/Besgrove;
- Deep Creek;
- Stewarton/Tannyfoil;
- South Ballamoo;
- Togara/North Marshmead;
- South Marshmead;
- Kennedy; and
- Comet Downs East.

Proposed 3-D rehabilitation designs (BWM PRCP Rev3 LF4.4) are shown in (Figures 19–26). These rehabilitation landforms were designed based on WEPP model results for the soils and vegetation groundcover levels that are to be applied. Different surface materials were applied based on the gradient of the landform, with purple surfaces being modelled as vegetated heavy clay soil, orange surfaces being modelled as vegetated light clay surfaces and yellow surfaces modelled as vegetated fresh Permian waste-soil mixture.

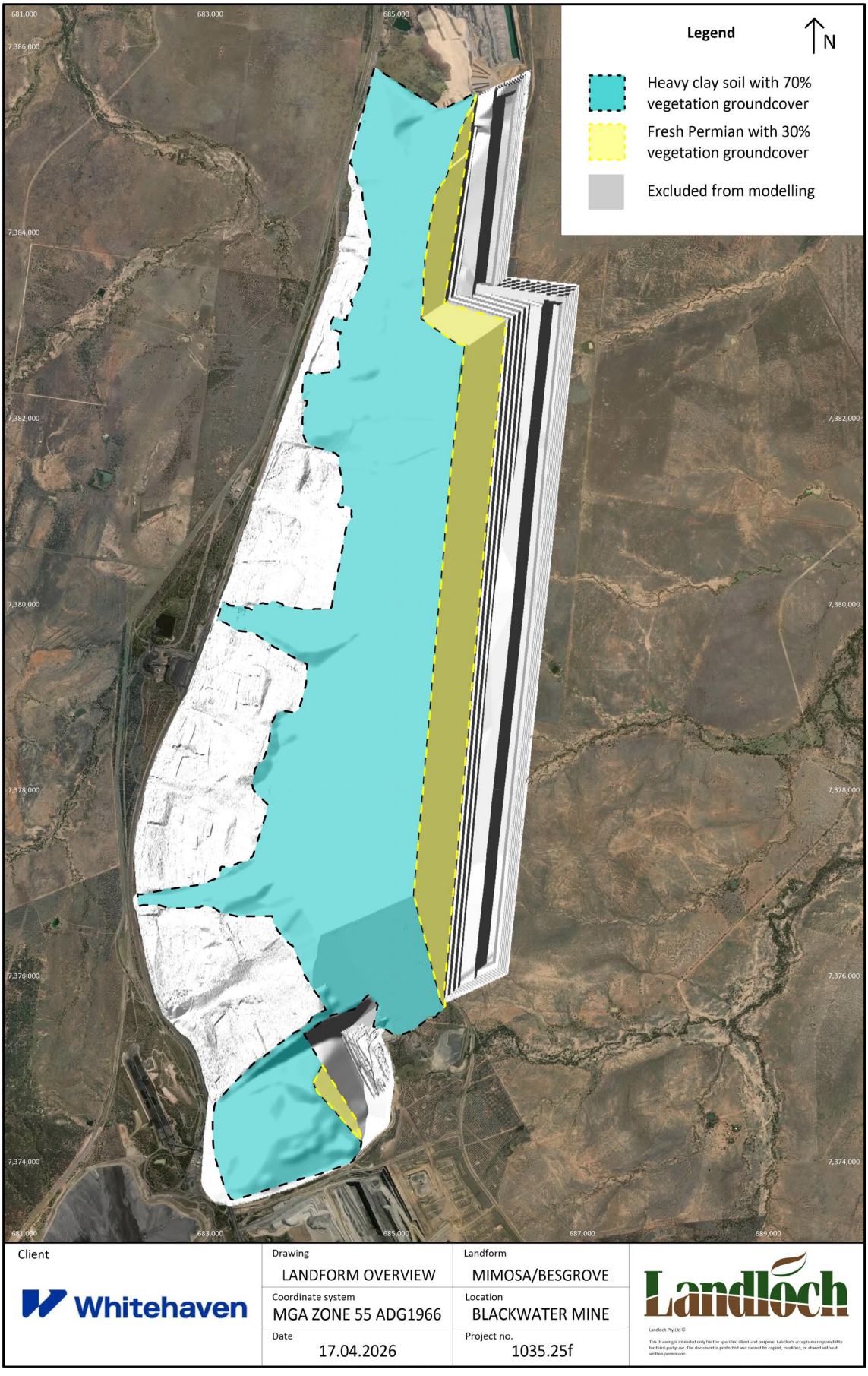


Figure 19: Mimosa/Besgrove rehabilitation landform (BWM PRCP Rev3 LF4.4).

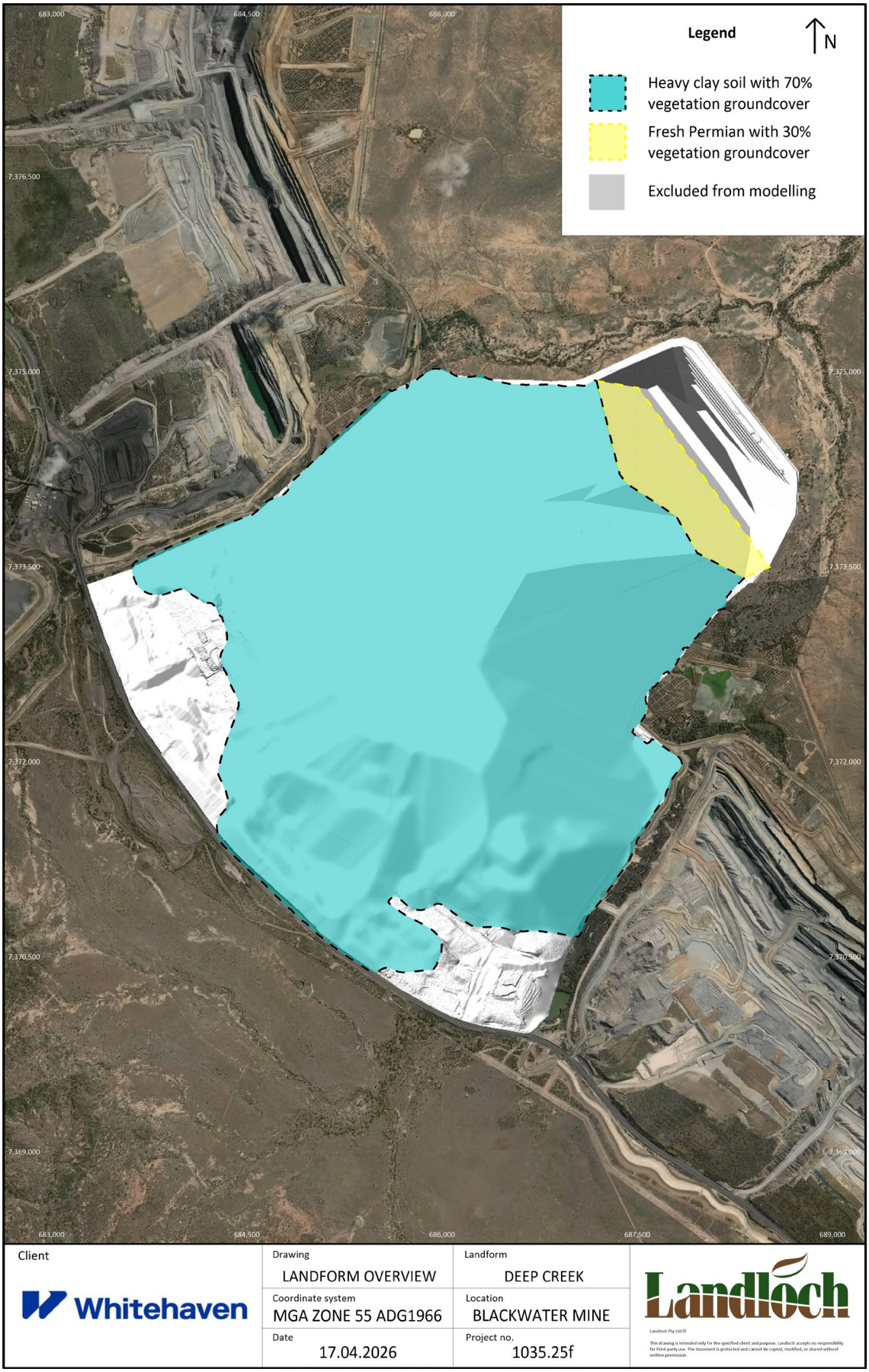


Figure 20: Deep Creek rehabilitation landform (BWM PRCP Rev3 LF4.4).

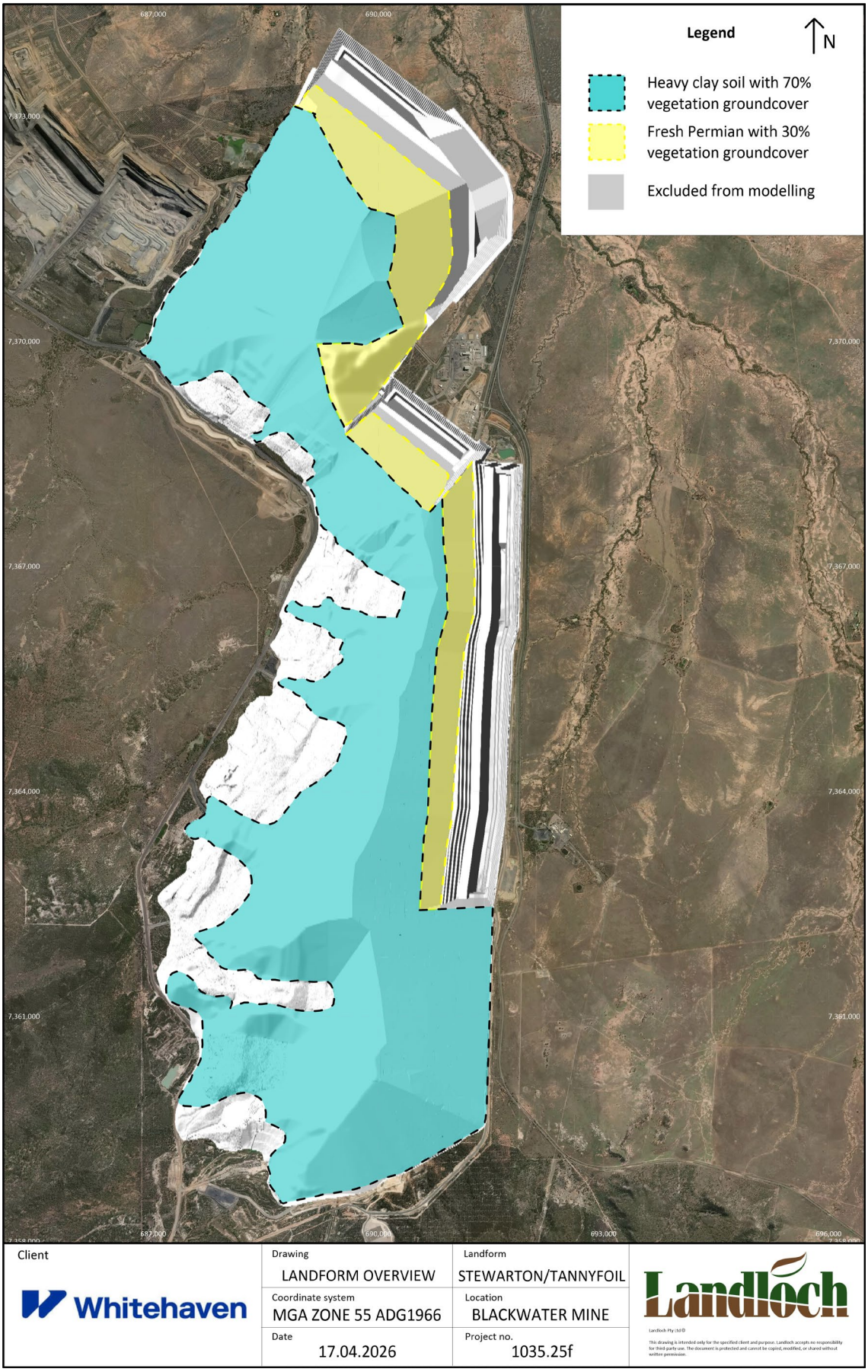


Figure 21: Stewarton/Tannyfoil rehabilitation landform (BWM PRCP Rev3 LF4.4).

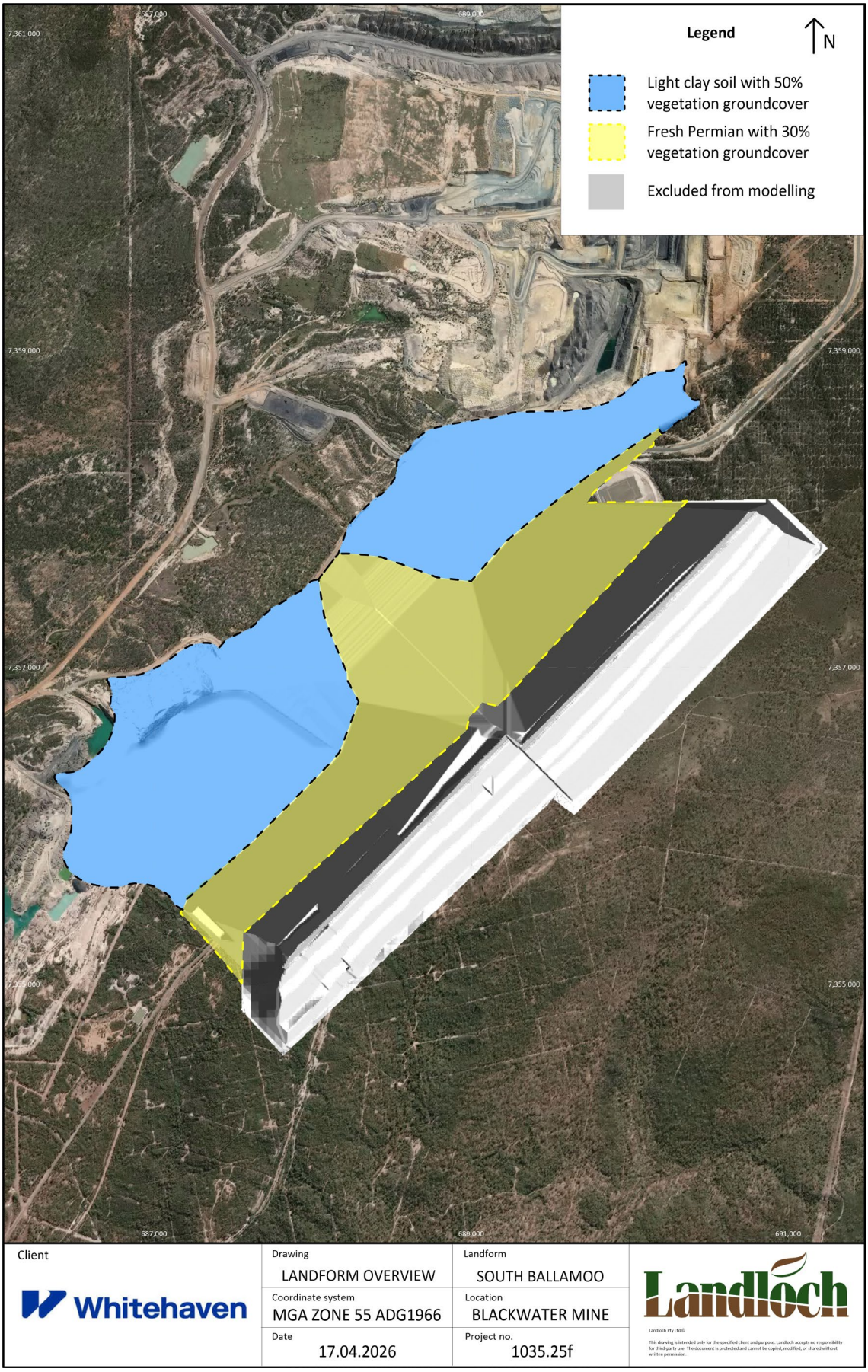


Figure 22: South Ballamoo rehabilitation landform (BWM PRCP Rev3 LF4.4).

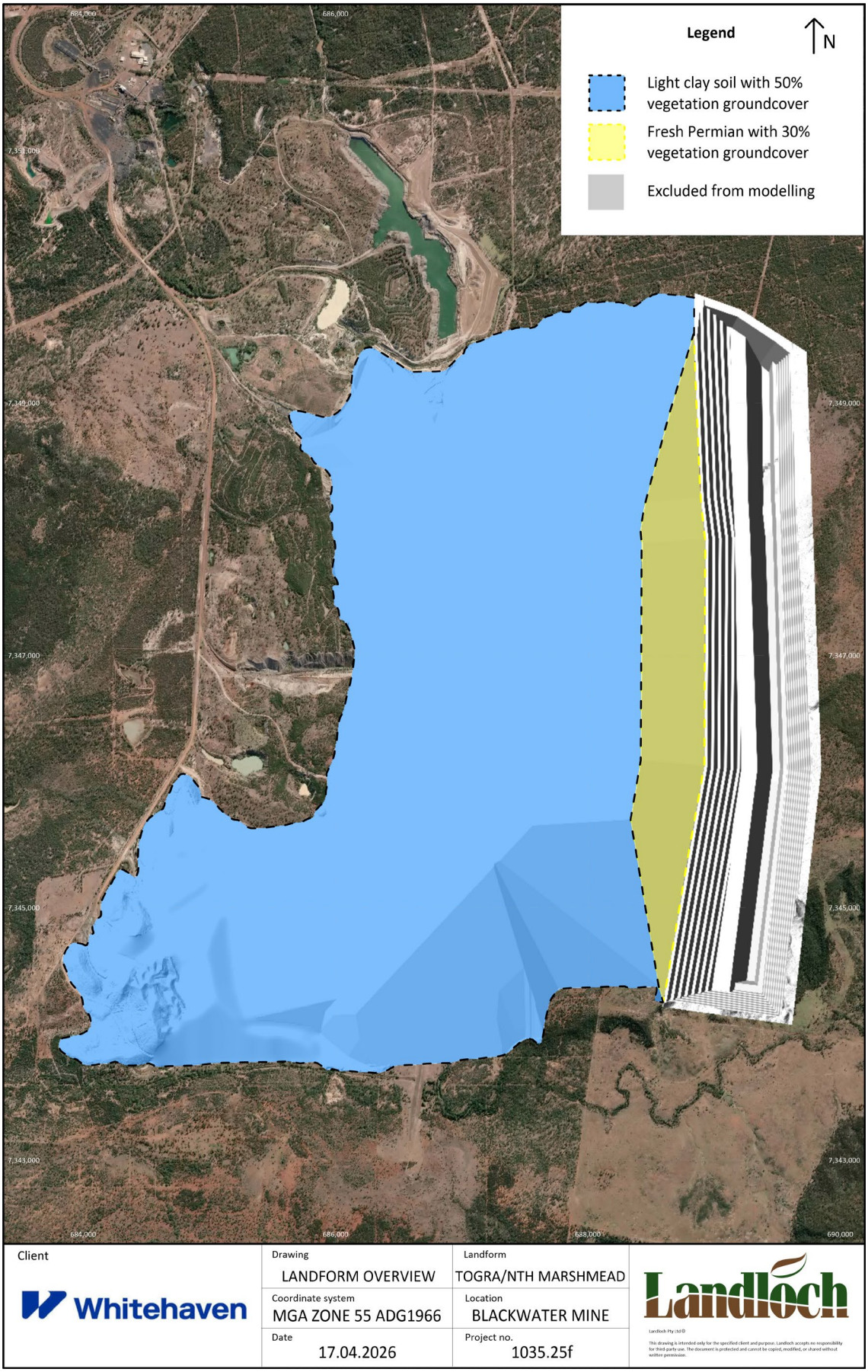


Figure 23: Togara/North Marshmead rehabilitation landform (BWM PRCP Rev3 LF4.4).



Figure 24: South Marshmead rehabilitation landform (BWM PRCP Rev3 LF4.4).

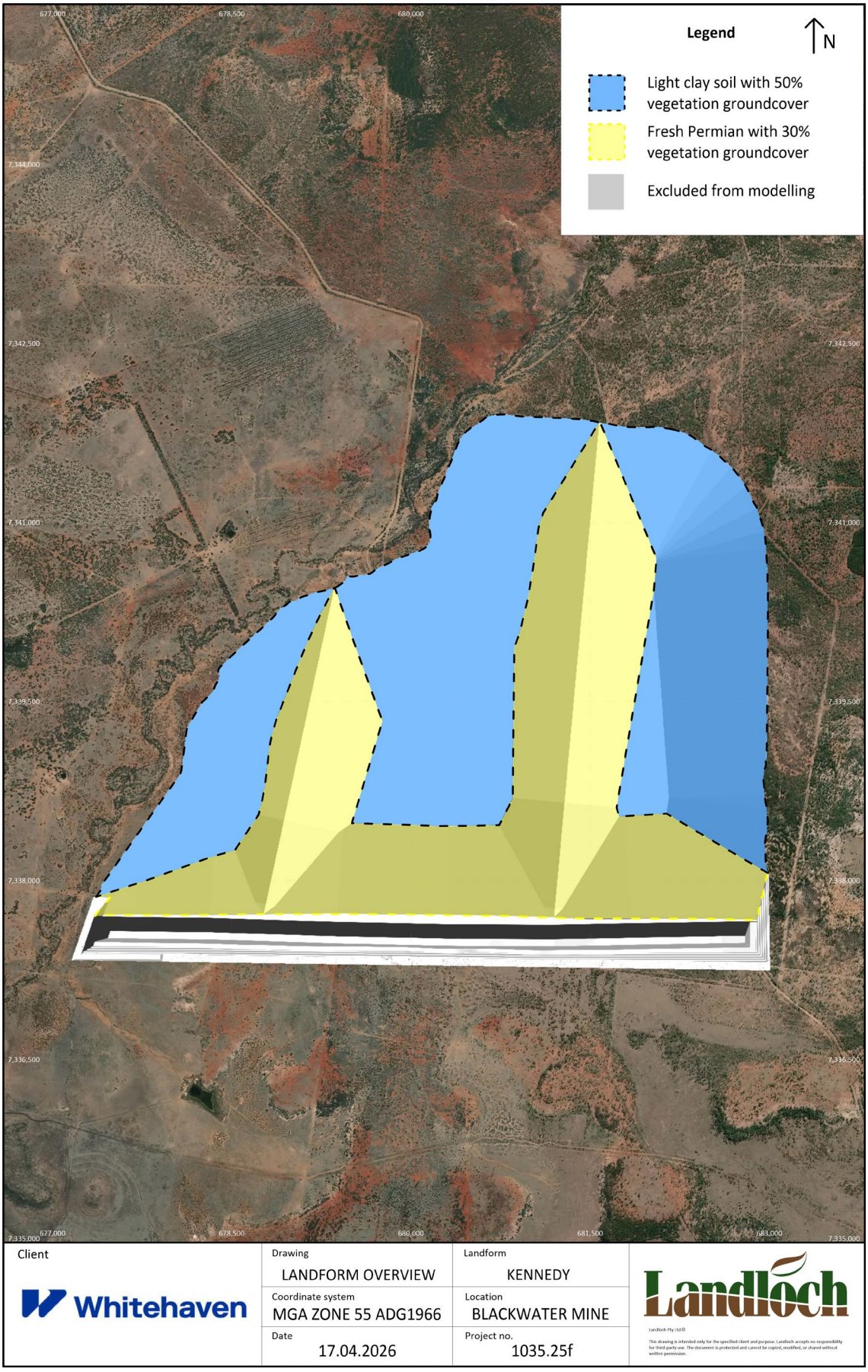


Figure 25: Kennedy rehabilitation landform (BWM PRCP Rev3 LF4.4).

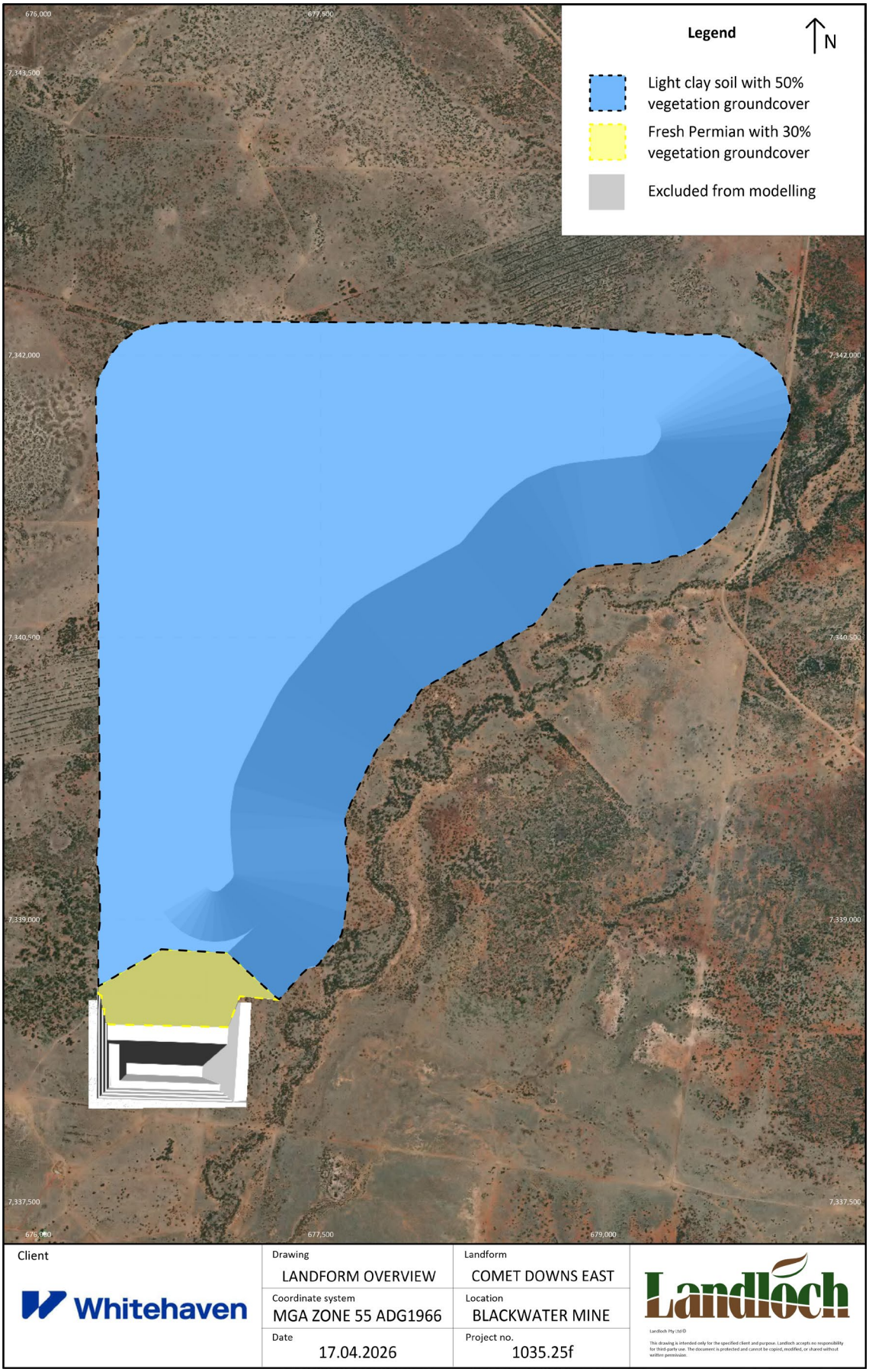


Figure 26: Comet Downs East rehabilitation landform (BWM PRCP Rev3 LF4.4).

5.7 SIBERIA modelling assumptions

The following assumptions apply to the SIBERIA modelling:

- The DEM of the existing land surface and design file for the rehabilitation landform (BWM PRCP Rev3 LF4.4) provided by Whitehaven are assumed to be accurate.
- Vegetated clay soil is applied to surfaces with gradients ≤15% and vegetated rocky fresh Permian spoil is applied to surface with gradients >15%.

These modelling assumptions valid for 2-D WEPP modelling also apply for 2-D SIBERIA modelling:

- In considering vegetation groundcover, this report specifically considers vegetation that is in contact with the land surface. Practically, this means a combination of grass cover and anchored (not readily moved) surface litter. Groundcover impacts do not consider rock. Where rocky materials have had erodibility measured experimentally and those parameters are used in WEPP simulations, then effects of the rock are already accounted for within the parameters used.
- Soil management (including stripping, stockpiling, replacement, amendment, and fertilisation) will be carried out effectively to maximise rapid and persistent vegetation growth.
- Any cross-slope ripping will be carried out strictly on the contour.

6 SIBERIA EVOLUTION MODEL RESULTS

Using input parameters derived for the vegetated clay soil and vegetated soil-rock mixture (1:2 soil:rock) applied to the landforms, SIBERIA was run for a period of 300 years, with outputs being generated at 50, 100, 200, and 300 years within the simulation period.

At each output year, visualisations of rill/gully development were produced along with a table of maximum gully depths, average annual erosion rates, and cumulative average erosion depths. These rates and depths are calculated for the steep-gradient outer slopes within the modelling domain and exclude the landform top.

Negative material movements (i.e. erosion) that exceed 0.3 m are considered gully erosion and are reported in the tables. The reported maximum gully depth is calculated as the average of the largest 1% of material movements.

Visualisations for 300 years are shown in the sections below. All visualisations (50, 100, 200, and 300 years) are provided in Appendix A.

6.1 Mimosa/Besgrove landform

Rehabilitation of the Mimosa/Besgrove landform is planned to use vegetated heavy clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 19). SIBERIA modelling has assumed a vegetation groundcover of 70%

for the outward-facing heavy clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 3 indicate that at a vegetation groundcover level of 70%, predicted erosion rates of the outward-facing slopes will be slightly higher than the target level of 5 t/ha/y (5.5 t/ha/y) after 50 years and slightly higher than the target level of 5 t/ha/y for the remainder of the simulation period (5.3 t/ha/y). If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are predicted to be below the target rate of 10 t/ha/y (4.4 t/ha/y after 300 years).

Figure 27 shows SIBERIA output after 300 years of simulation.

Table 3: Predicted erosion rates and gully depths for the Mimosa/Besgrove landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Heavy clay soil with 70% vegetation groundcover			
50	-	5.5	21
100	-	5.3	42
200	0.4	5.3	83
300	0.5	5.3	123
Fresh Permian waste with 30% vegetation groundcover			
50	-	5.0	17
100	-	4.4	31
200	-	4.3	60
300	0.4	4.4	90

The SIBERIA output predicts that the vegetated clay soil covered slopes of the Mimosa/Besgrove landform are not prone to widespread gully erosion if the surface conditions (slope gradient, material type and vegetation groundcover levels) are achieved. That said, some gully erosion is predicted to occur after 200 years for the vegetated clay soil covered slopes. Areas within the 3D landform shape that are modelled as being more prone to gully erosion are those:

- On the western and northern side of the landform that contain steeper-gradient slope sections (circled in green); and
- Within the steeper creek diversion area in the south of the landform (circled in purple).

Improvement in the erosion performance could be achieved by refinement of the landform surface in these sections to achieve a gradient consistent with the majority of the landform surface that is not prone to gully erosion. Further, erosion resistance of the steeper-gradient zone in the south of the landform could be increased by addition of rock armour onto the steeper-gradient slopes.

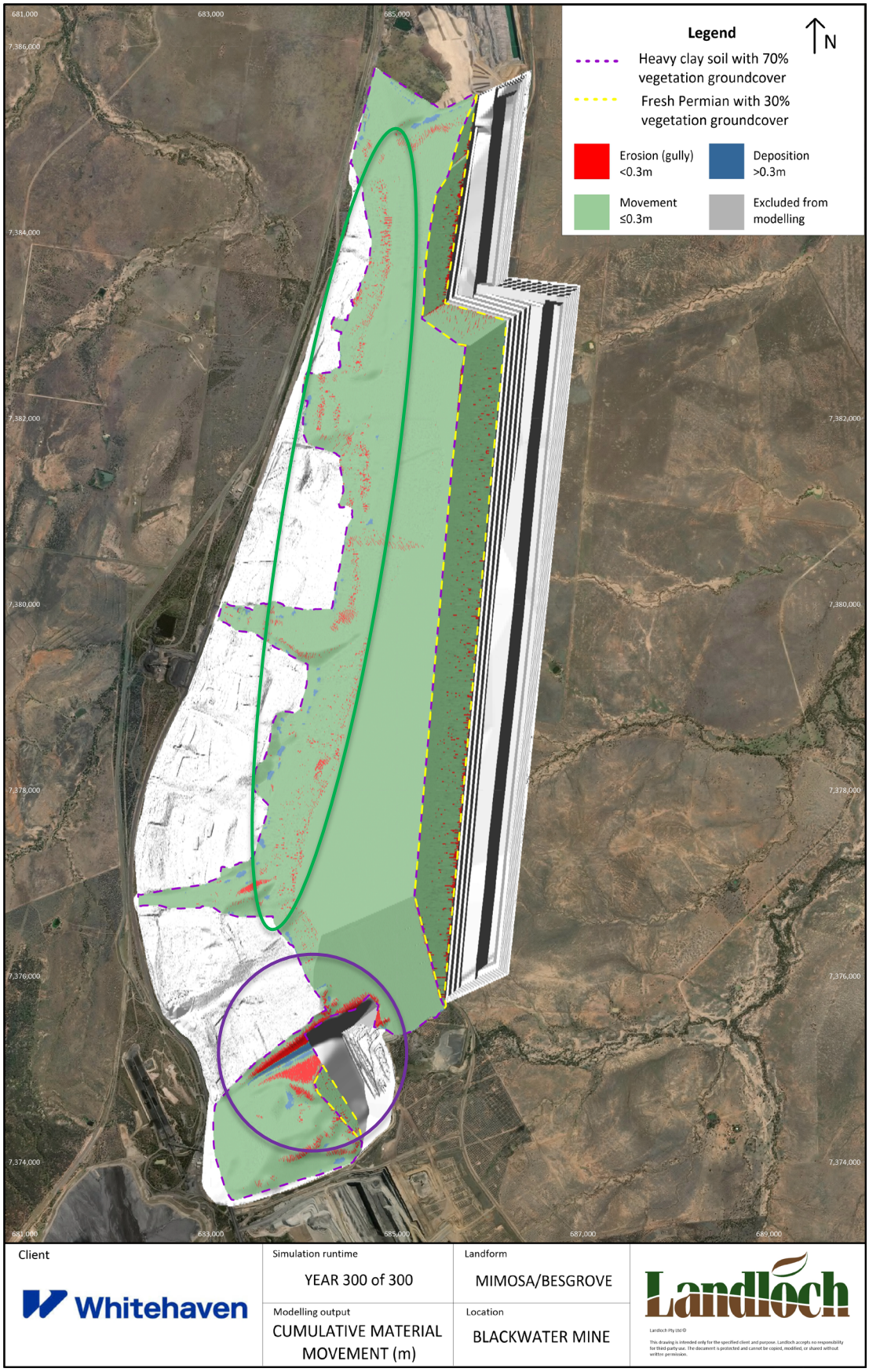


Figure 27: Predicted erosion and deposition depths of the Mimosa/Besgrove rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.2 Deep Creek landform

Rehabilitation of the Deep Creek landform is planned to use vegetated heavy clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 20). SIBERIA modelling has assumed a vegetation groundcover of 70% for the outward-facing heavy clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 4 indicate that at a vegetation groundcover level of 70%, predicted erosion rates of the outward-facing slopes will be slightly higher than the target level of 5 t/ha/y (5.5 t/ha/y) after 50 years and below the target level of 5 t/ha/y for the remainder of the simulation period (4.7–4.8 t/ha/y). If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are predicted to be below the target rate (10 t/ha/y).

Figure 28 shows SIBERIA output after 300 years of simulation.

Table 4: Predicted erosion rates and gully depths for the Deep Creek landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Heavy clay soil with 70% vegetation groundcover			
50	-	5.5	22
100	-	4.8	41
200	-	4.7	79
300	0.4	4.7	116
Fresh Permian waste with 30% vegetation groundcover			
50	-	5.5	18
100	-	4.3	33
200	-	3.7	57
300	-	3.6	81

The SIBERIA output indicates that the Deep Creek landform is not prone to widespread gully erosion if the surface conditions (gradient, material type and vegetation groundcover levels) are achieved. That said, some gully erosion is predicted to occur after 300 years for the vegetated clay soil covered slopes. Areas within the 3D landform shape that are modelled as being more prone to gully erosion are those that contain steeper slope sections. Improvement in the erosion performance could be achieved by refinement of the landform surface in these sections to achieve a gradient consistent with the majority of the landform surface that is not prone to gully erosion. Further, given the underlying secondary growth media material is likely to be the more erosion-resistant fresh Permian waste, the risk of exposing problematic (more erodible) materials and for erosion to accelerate over the long-term is considered low. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use.

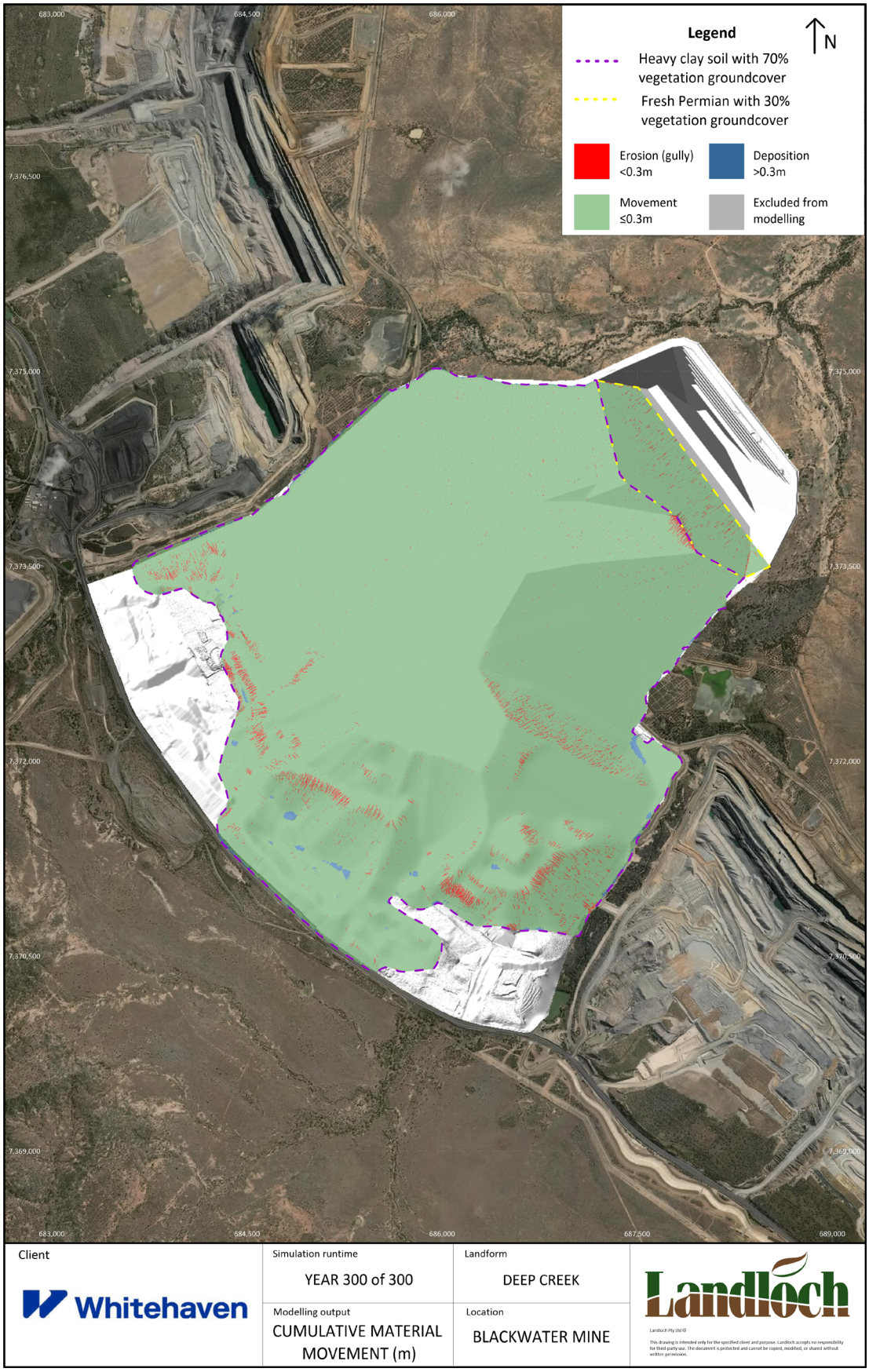


Figure 28: Predicted erosion and deposition depths of the Deep Creek rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.3 Stewarton/Tannyfoil landform

Rehabilitation of the Stewarton/Tannyfoil landform is planned to use vegetated heavy clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 21). SIBERIA modelling has assumed a vegetation groundcover of 70% for the outward-facing heavy clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 5 indicate that at a vegetation groundcover level of 70%, predicted erosion rates of the outward-facing slopes will be slightly higher than the target level of 5 t/ha/y (5.2 t/ha/y) after 50 years and below the target level of 5 t/ha/y for the remainder of the simulation period (4.7–4.8 t/ha/y). If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are predicted to be below the target rate (10 t/ha/y).

Figure 29 shows SIBERIA output after 300 years of simulation.

Table 5: Predicted erosion rates and gully depths for the Stewarton/Tannyfoil landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Heavy clay soil with 70% vegetation groundcover			
50	-	5.2	21
100	-	4.8	40
200	-	4.7	77
300	0.4	4.7	114
Fresh Permian waste with 30% vegetation groundcover			
50	-	5.8	19
100	-	4.6	35
200	0.3	4.1	62
300	0.4	4.0	89

The SIBERIA output indicates that the Stewarton/Tannyfoil landform is not prone to significant levels of gully erosion if the surface conditions (material type and vegetation groundcover levels) are achieved. Some gully erosion is predicted to occur after 300 years for the vegetated clay soil covered slopes. However, given the underlying secondary growth media material is likely to be the more erosion-resistant fresh Permian waste, the risk of exposing problematic (more erodible) materials and for erosion to accelerate over the long-term is considered low. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use. Gully erosion is not predicted to occur for the fresh Permian covered slopes, though some rilling may still occur.

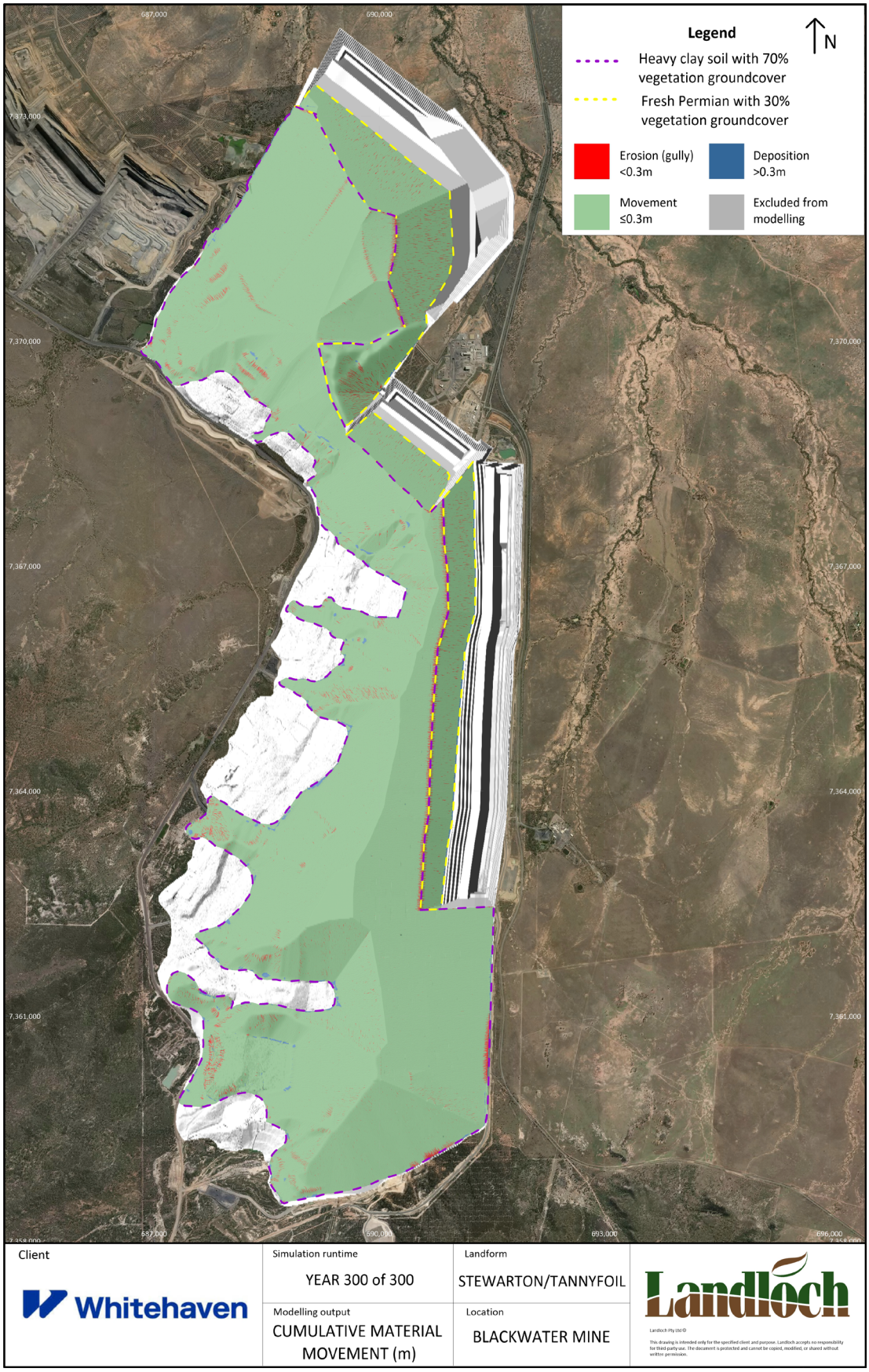


Figure 29: Predicted erosion and deposition depths of the Stewarton/Tannyfoil rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.4 South Ballamoo landform

Rehabilitation of the South Ballamoo landform is planned to use vegetated light clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 22). SIBERIA modelling has assumed a vegetation groundcover of 50% for the outward-facing light clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 6 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the outward-facing slopes are at or below the target rate (5 t/ha/y) for the simulation period. If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are predicted to be slightly higher than the target rate of 10 t/ha/y (5.7 t/ha/y) at 50 years, and below the target rate after 200 years.

Figure 30 shows SIBERIA output after 300 years of simulation.

Table 6: Predicted erosion rates and gully depths for the South Ballamoo landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Light clay soil with 50% vegetation groundcover			
50	-	5.0	25
100	-	2.6	38
200	-	1.4	53
300	-	1.0	63
Fresh Permian waste with 30% vegetation groundcover			
50	0.3	5.7	41
100	0.5	5.5	69
200	0.8	4.1	50
300	1.0	3.7	87

The SIBERIA output indicates that the South Ballamoo landform is not prone to significant levels of gully erosion if the surface conditions (gradient, material type and vegetation groundcover levels) are achieved. No gully erosion is predicted to occur within the simulation period for the vegetated clay soil covered slopes. Some gully erosion is predicted to occur after 50 years for the fresh Permian covered slopes. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use. Alternatively, slopes of lower gradient could be adopted to reduce erosion potential in these areas.

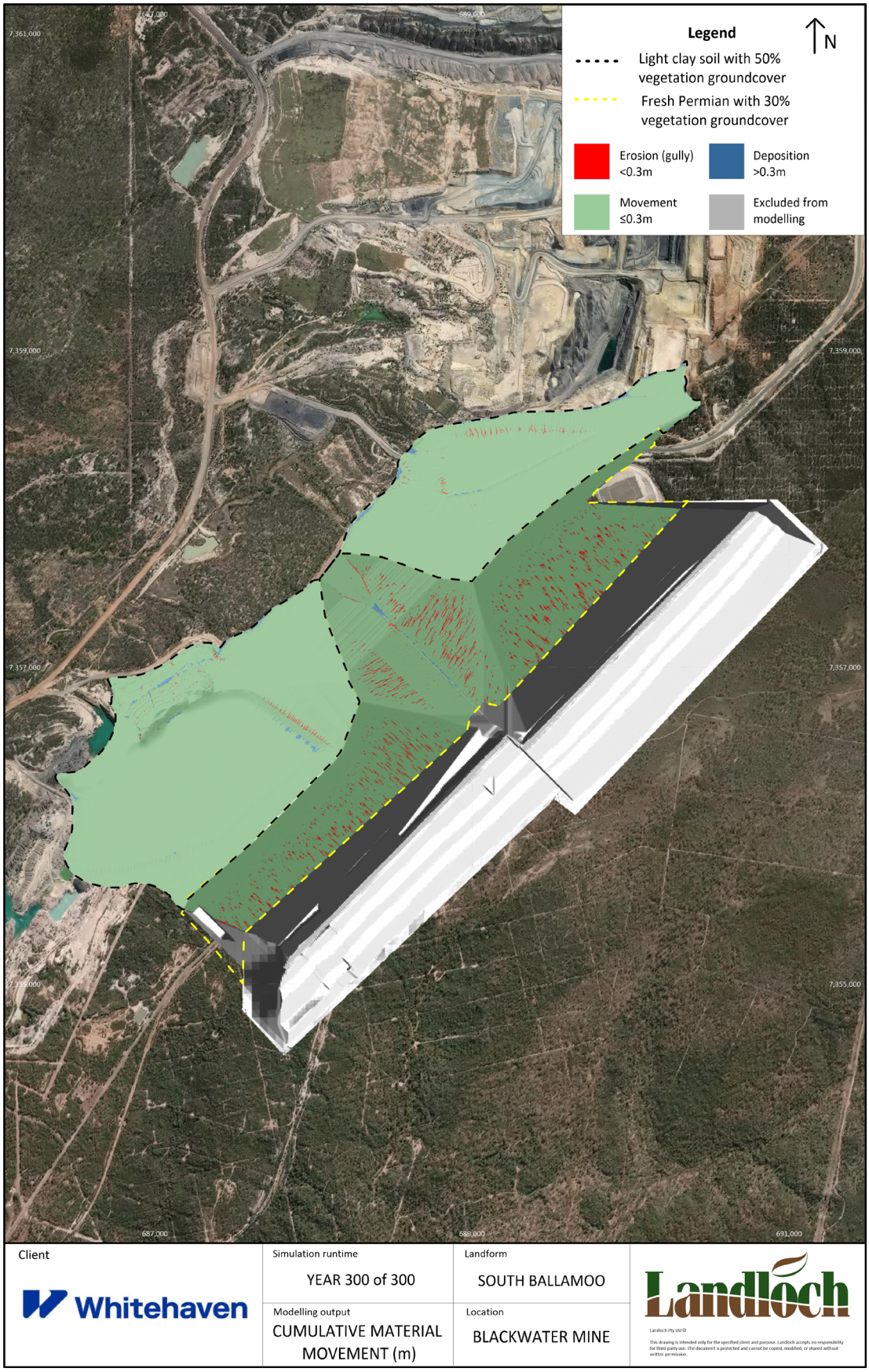


Figure 30: Predicted erosion and deposition depths of the South Ballamoo rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.5 Togara/North Marshmead landform

Rehabilitation of the Togara/North Marshmead landform is planned to use vegetated light clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 23). SIBERIA modelling has assumed a vegetation groundcover of 50% for the outward-facing light clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 7 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the outward-facing slopes are below the target rate (5 t/ha/y). If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are also predicted to be below the target rate (10 t/ha/y).

Figure 31 shows SIBERIA output after 300 years of simulation.

The SIBERIA output indicates that the Togara/North Marshmead landform is not prone to significant levels of gully erosion if the surface conditions (gradient, material type, and vegetation groundcover levels) are achieved. No gully erosion is predicted to occur within the simulation period for the vegetated clay soil covered slopes. Some gully erosion is predicted to occur after 300 years for the fresh Permian covered slopes. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use.

Table 7: Predicted erosion rates and gully depths for the Togara/North Marshmead landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Light clay soil with 50% vegetation groundcover			
50	-	2.9	14
100	-	1.9	24
200	-	1.4	37
300	-	1.2	49
Fresh Permian waste with 30% vegetation groundcover			
50	-	5.1	25
100	-	3.8	44
200	-	3.2	77
300	0.4	3.1	107

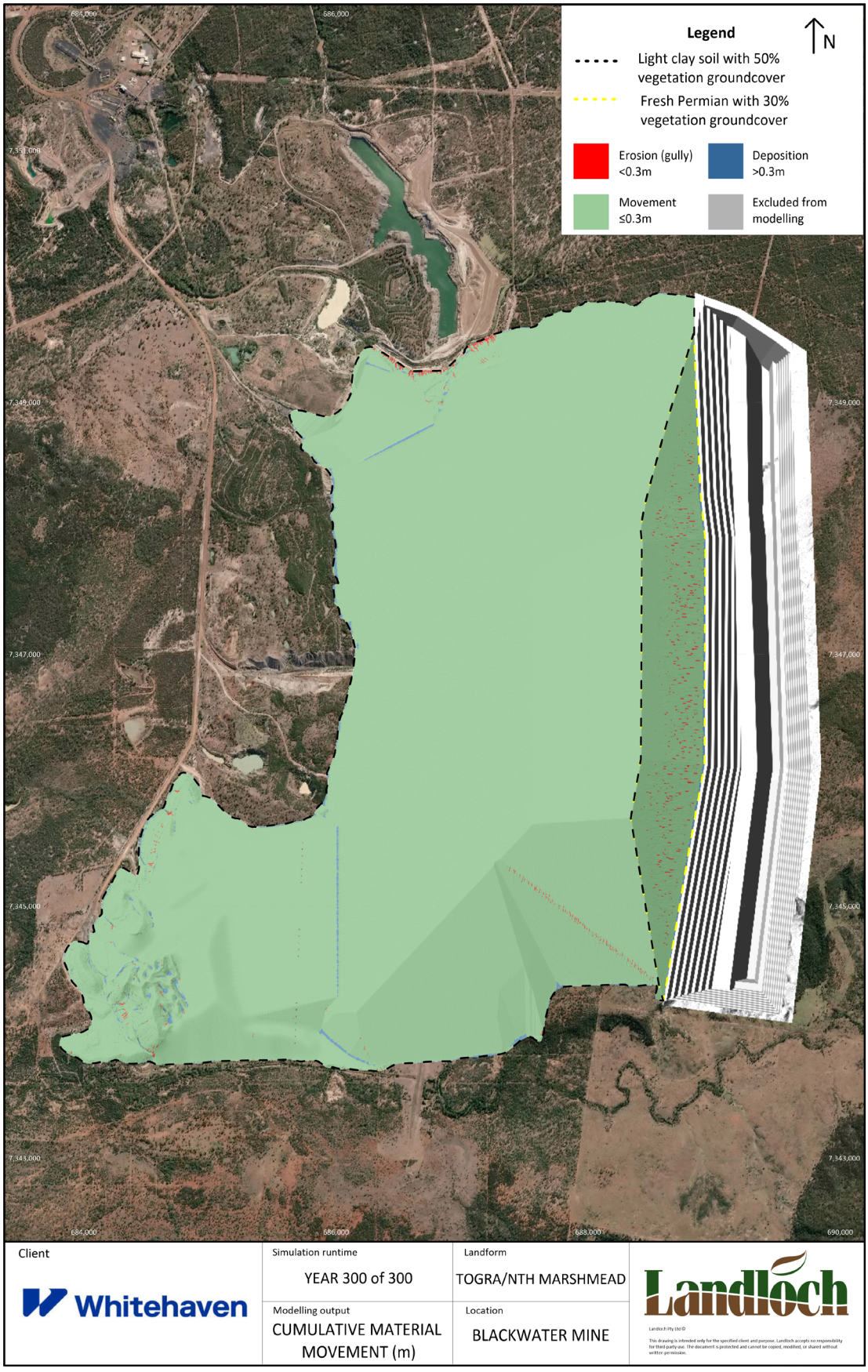


Figure 31: Predicted erosion and deposition depths of the Togara/North Marshmead rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.6 South Marshmead landform

Rehabilitation of the South Marshmead landform is planned to use vegetated light clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 24). SIBERIA modelling has assumed a vegetation groundcover of 50% for the outward-facing light clay soil surfaces and 30% for the fresh low wall Permian waste surfaces.

Predicted erosion rates shown in Table 8 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the outward-facing slopes are below the target rate (5 t/ha/y) for the simulation period. If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are also predicted to be below the target rate (10 t/ha/y).

Figure 32 shows SIBERIA output after 300 years of simulation.

The SIBERIA output indicates that the South Marshmead landform is not prone to significant levels of gully erosion if the surface conditions (gradient, material type and vegetation groundcover levels) are achieved.

No gully erosion is predicted to occur within the simulation period for the vegetated clay soil covered slopes. Some gully erosion is predicted to occur after 200 years for the fresh Permian covered slopes. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use. Alternatively, slopes of lower gradient could be adopted to reduce erosion potential in these areas.

Table 8: Predicted erosion rates and gully depths for the South Marshmead landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Light clay soil with 50% vegetation groundcover			
50	-	2.7	14
100	-	2.1	24
200	-	1.8	42
300	-	1.7	58
Fresh Permian waste with 30% vegetation groundcover			
50	-	4.9	25
100	-	3.8	43
200	0.3	3.2	75
300	0.4	3.0	105



Figure 32: Predicted erosion and deposition depths of the South Marshmead rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.7 Kennedy landform

Rehabilitation of the Kennedy landform is planned to use vegetated light clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 25). SIBERIA modelling has assumed a vegetation groundcover of 50% for the outward-facing light clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 9 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the outward-facing slopes are below the target rate (5 t/ha/y) for the simulation period. If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are also predicted to be below the target rate (10 t/ha/y).

Figure 33 shows SIBERIA output after 300 years of simulation.

The SIBERIA output indicates that the Kennedy landform is not prone to significant levels of gully erosion if the surface conditions (gradient, material type, and vegetation groundcover levels) are achieved. No gully erosion is predicted to occur within the simulation period for the vegetated clay soil covered slopes. Gully erosion is predicted to occur after 100 years for the fresh Permian covered slopes. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use. Alternatively, slopes of lower gradient could be adopted to reduce erosion potential in these areas.

Table 9: Predicted erosion rates and gully depths for the Kennedy landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Light clay soil with 50% vegetation groundcover			
50	-	3.4	17
100	-	2.6	30
200	-	2.2	52
300	-	2.2	74
Fresh Permian waste with 30% vegetation groundcover			
50	-	4.6	23
100	0.3	3.7	41
200	0.5	3.2	73
300	0.6	3.0	103

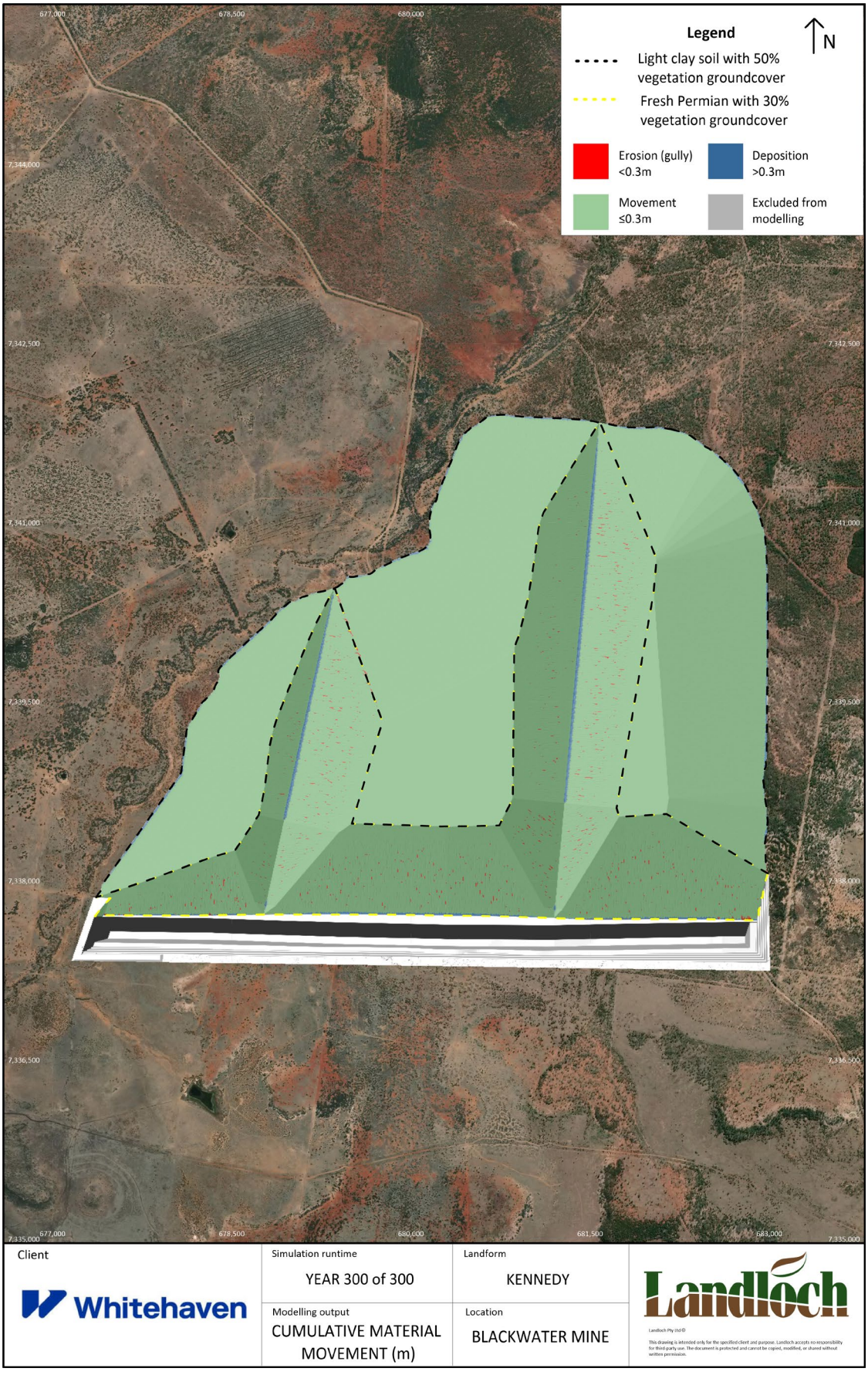


Figure 33: Predicted erosion and deposition depths of the Kennedy rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

6.8 Comet Downs East landform

Rehabilitation of the Comet Downs East landform is planned to use vegetated light clay soil on the outward-facing slopes and vegetated fresh Permian waste on the low wall slopes (Figure 26). SIBERIA modelling has assumed a vegetation groundcover of 50% for the outward-facing light clay soil surfaces and 30% for the low wall fresh Permian waste surfaces.

Predicted erosion rates shown in Table 10 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the outward-facing slopes are below the target rate (5 t/ha/y) for the simulation period. If vegetation groundcover of the low wall slopes is >30%, then slope erosion rates are predicted to be below the target rate (10 t/ha/y).

Figure 34 shows SIBERIA output after 300 years of simulation.

The SIBERIA output indicates that the Comet Downs East landform is not prone to significant levels of gully erosion if the surface conditions (material type and vegetation groundcover levels) are achieved. No gully erosion is predicted to occur within the simulation period for the vegetated clay soil covered slopes or fresh Permian covered slopes.

Table 10: Predicted erosion rates and gully depths for the Comet Downs East landform (BWM PRCP Rev3 LF4.4).

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative erosion (mm)
Light clay soil with 50% vegetation groundcover			
50	-	3.5	17
100	-	2.6	30
200	-	2.3	53
300	-	2.2	76
Fresh Permian waste with 30% vegetation groundcover			
50	-	4.5	23
100	-	3.5	40
200	-	2.9	69
300	-	2.7	96

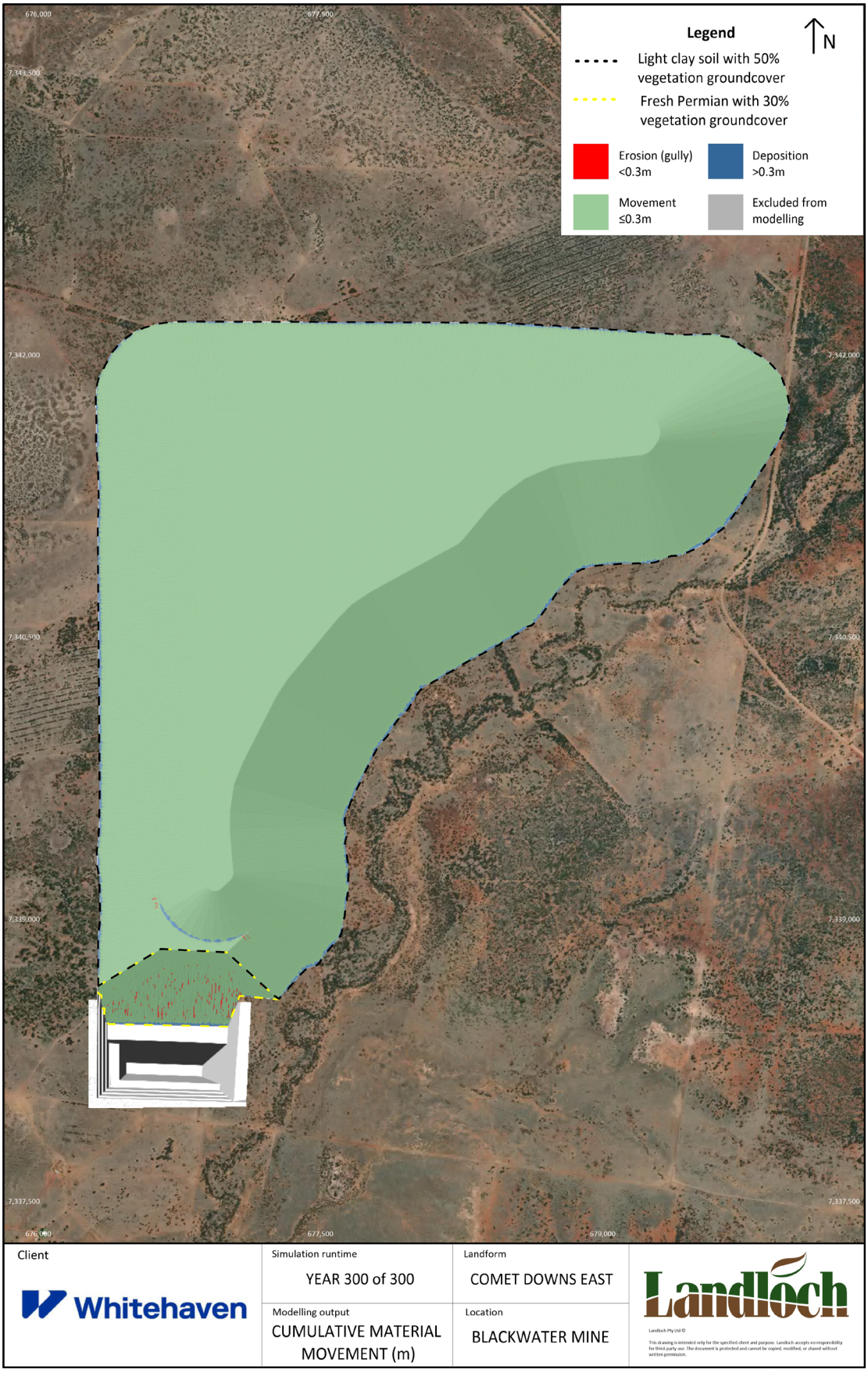


Figure 34: Predicted erosion and deposition depths of the Comet Downs East rehabilitation landform (BWM PRCP Rev3 LF4.4) after 300 years.

7 CONCLUSIONS

SIBERIA landform evolution model simulations indicate that the Blackwater landforms (as per design BWM PRCP Rev3 LF4.4) generally have a low tendency to promote ongoing rill and gully erosion provided the correct gradients, surface materials, and the target levels of vegetation groundcover are achieved.

At a vegetation groundcover level of 70%, the heavy clay-covered slopes with lower gradients (≤15%) on Mimosa/Besgrove, Deep Creek, and Stewarton/Tannyfoil are not prone to significant levels of gully erosion. The exception in the steeper-gradient creek diversion area in the south of the landform. Improvement in the erosion performance could be achieved by refinement of the landform surface in these sections to achieve a gradient consistent with the majority of the landform surface that is not prone to gully erosion. Further, erosion resistance of the steeper-gradient zone in the south of the landform could be increased by addition of rock armour onto the steeper-gradient slopes.

At a vegetation groundcover level of 50%, the light clay-covered slopes with lower gradients (≤15%) on South Ballamoo, Togara/North Marshmead, South Marshmead, Kennedy, and Comet Downs East are not prone to significant levels of gully erosion.

At a vegetation groundcover level of 30%, the fresh Permian spoil-covered slopes with steeper gradients (>15%) on Mimosa/Besgrove, Deep Creek, Stewarton/Tannyfoil, Togara/North Marshmead, and Comet Downs East are not prone to significant erosion. For South Ballamoo, South Marshmead, and Kennedy, the fresh Permian spoil-covered slopes with steeper gradients (>15%) also have a low tendency for gully erosion, though the depth of gullies that are predicted are deeper than the other landforms. Gully erosion should be monitored as part of the rehabilitation monitoring process and remediated if assessed as required by an appropriately qualified person to achieve the post-mining land use. Alternatively, slopes of lower gradient could be adopted to reduce erosion potential in these areas.

The average annual erosion rates for both the vegetated soil and vegetated soil-rock mixture surfaces are predicted to reduce through time. This indicates that the landforms are predicted to trend towards increased erosional stability through time, and that the gullies that may be present are predicted to reduce in activity through time. The long-term erosion rates for both the vegetated soil and vegetated fresh Permian waste surfaces are predicted to reach a steady long-term annual erosion rate that has a low tendency to promote ongoing rill and gully erosion.

The model outputs have assumed the use of a heavy or light clay soil or a fresh Permian waste as the surface material. Clay soils were found to be the dominant soils across Blackwater. Fresh Permian spoil is also likely available for use in the creation of a soil-rock mixture (1:2 soil:rock). Weathered Permian and Tertiary materials were found to be unsuitable as a primary growth media. They should not be used to create a soil-rock mixture for use in rehabilitation. They can be used as a secondary growth media.

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APPENDIX A: SIBERIA VISUALISATIONS

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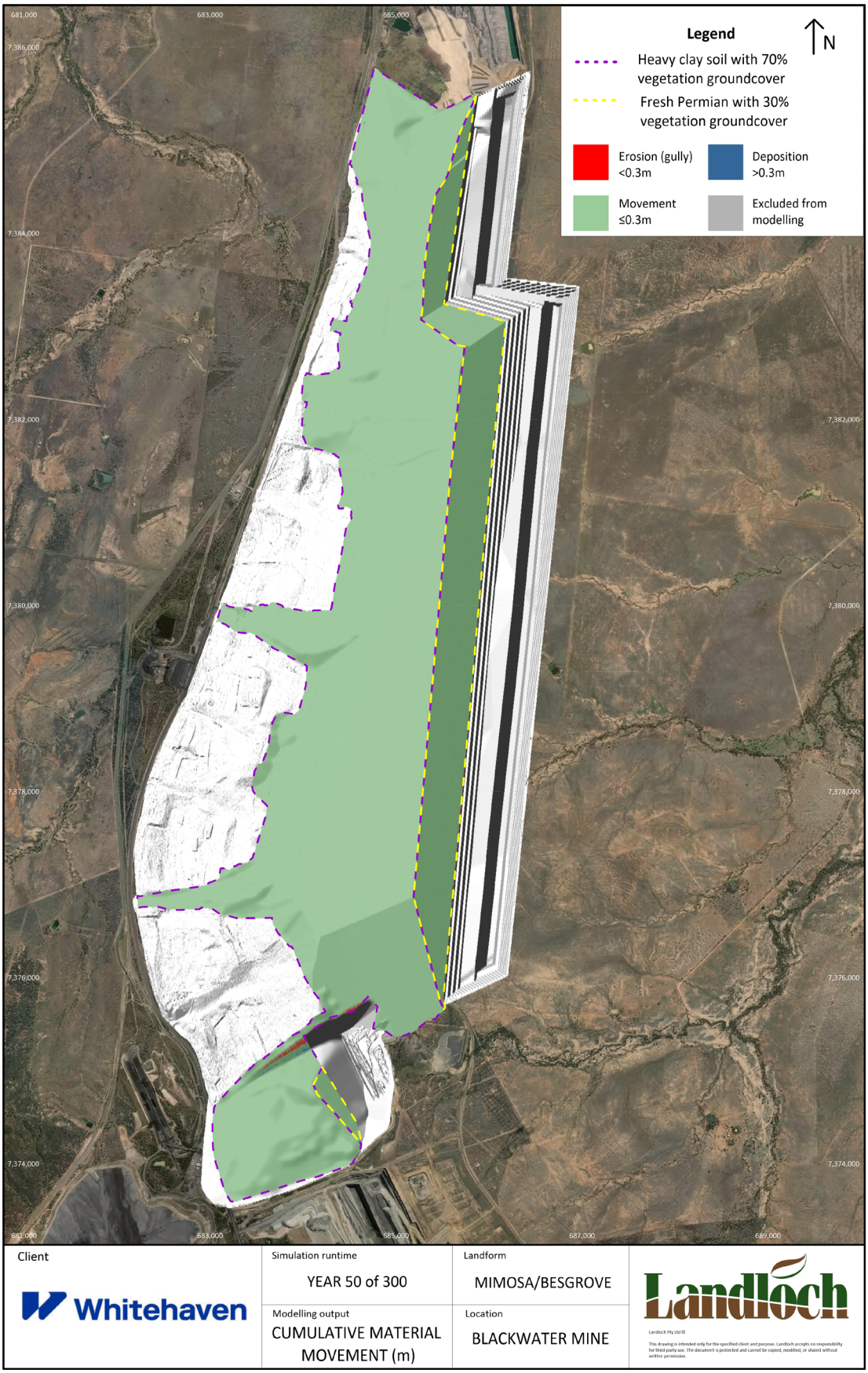


Figure A-1: Predicted erosion and deposition depths of the Mimosa/Besgrove rehabilitation landform after 50 years.

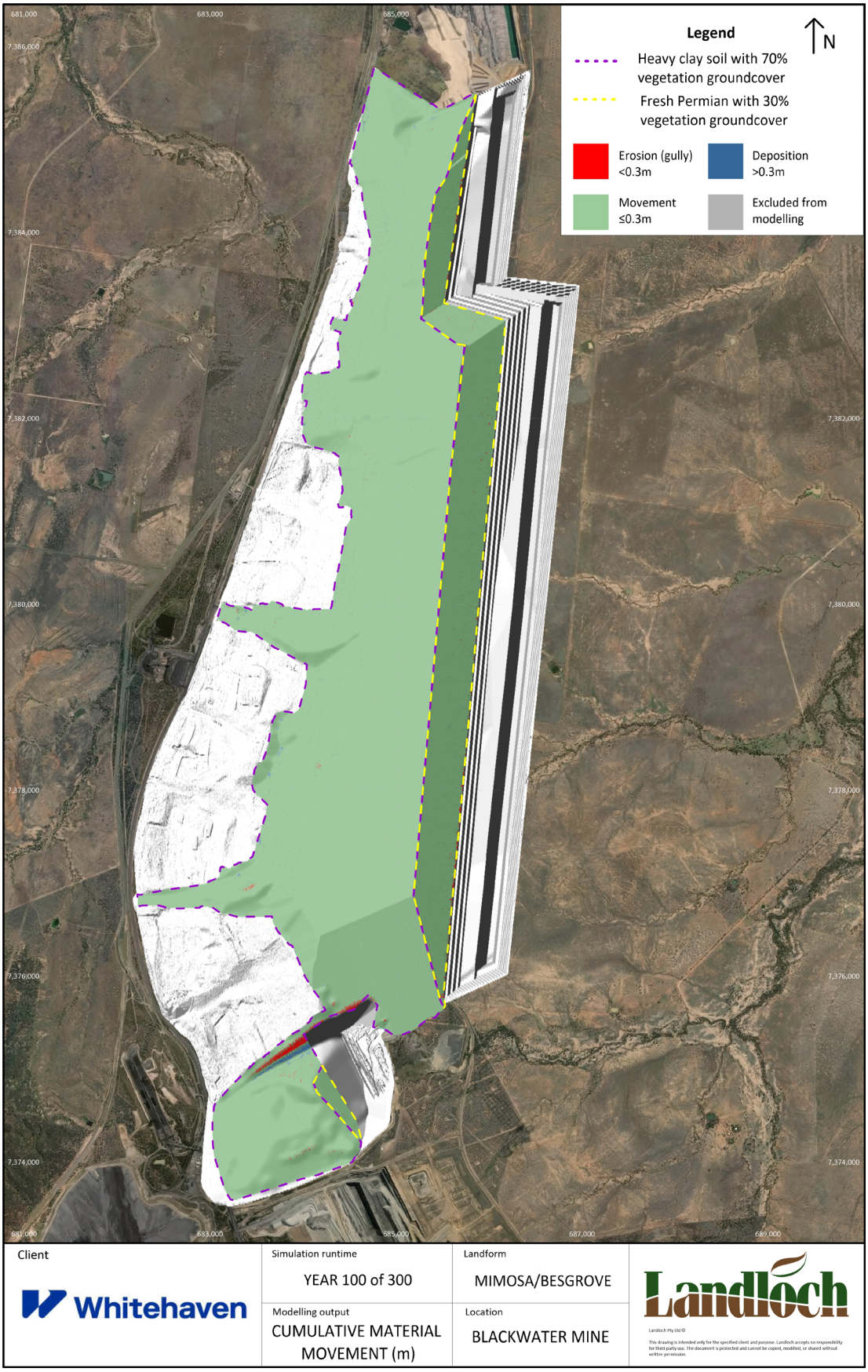


Figure A-2: Predicted erosion and deposition depths of the Mimosa/Besgrove rehabilitation landform after 100 years.

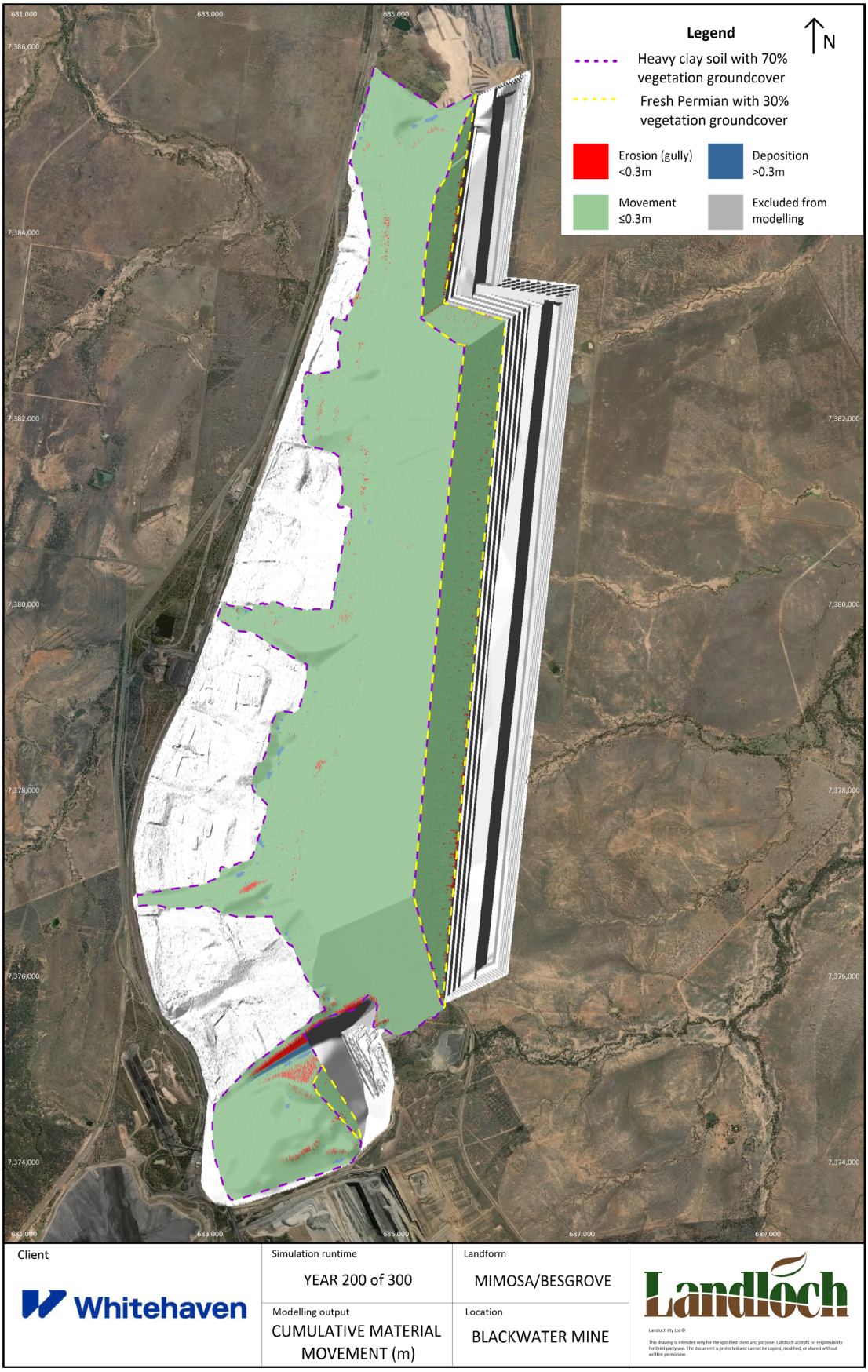


Figure A-3: Predicted erosion and deposition depths of the Mimosa/Besgrove rehabilitation landform after 200 years.

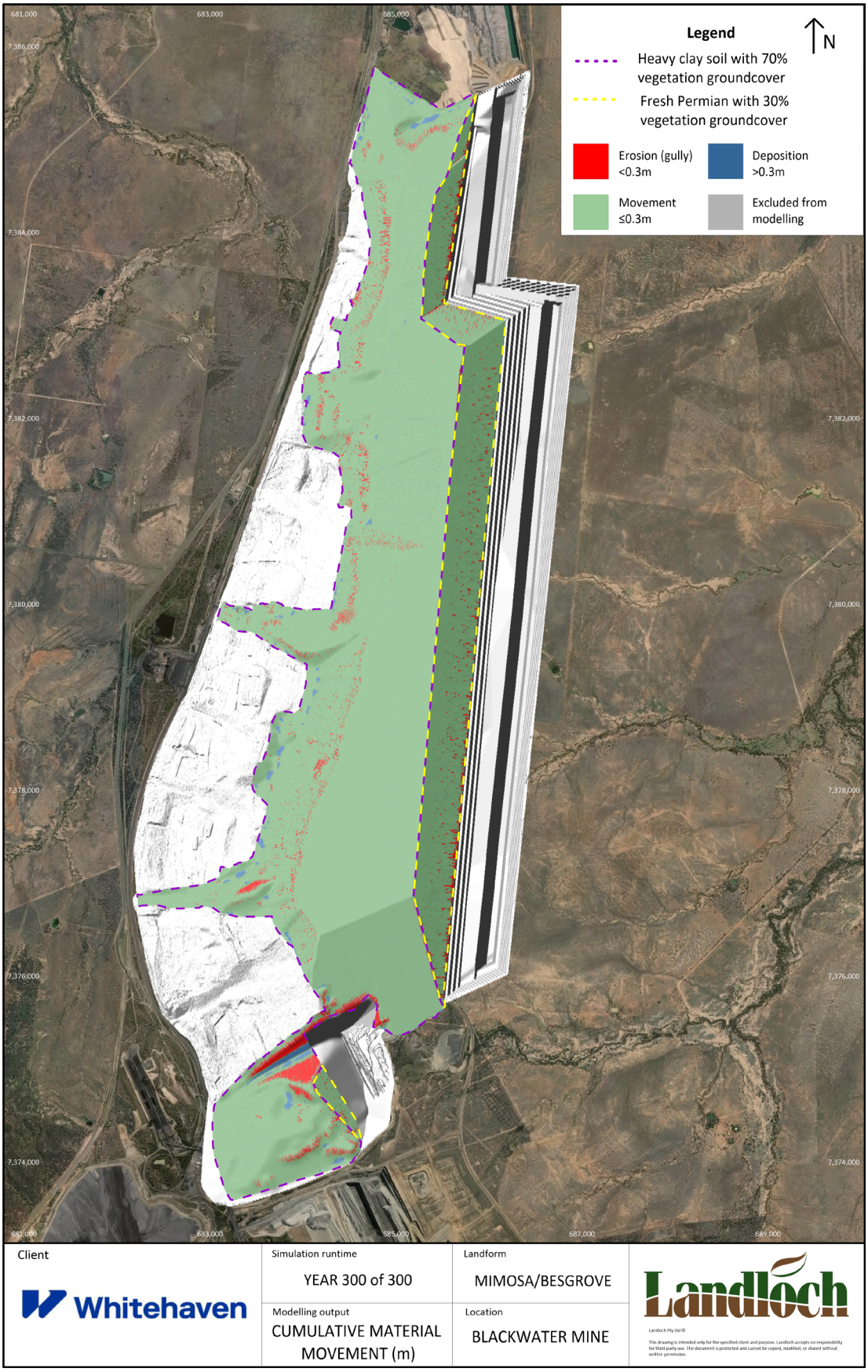


Figure A-4: Predicted erosion and deposition depths of the Mimosa/Besgrove rehabilitation landform after 300 years.

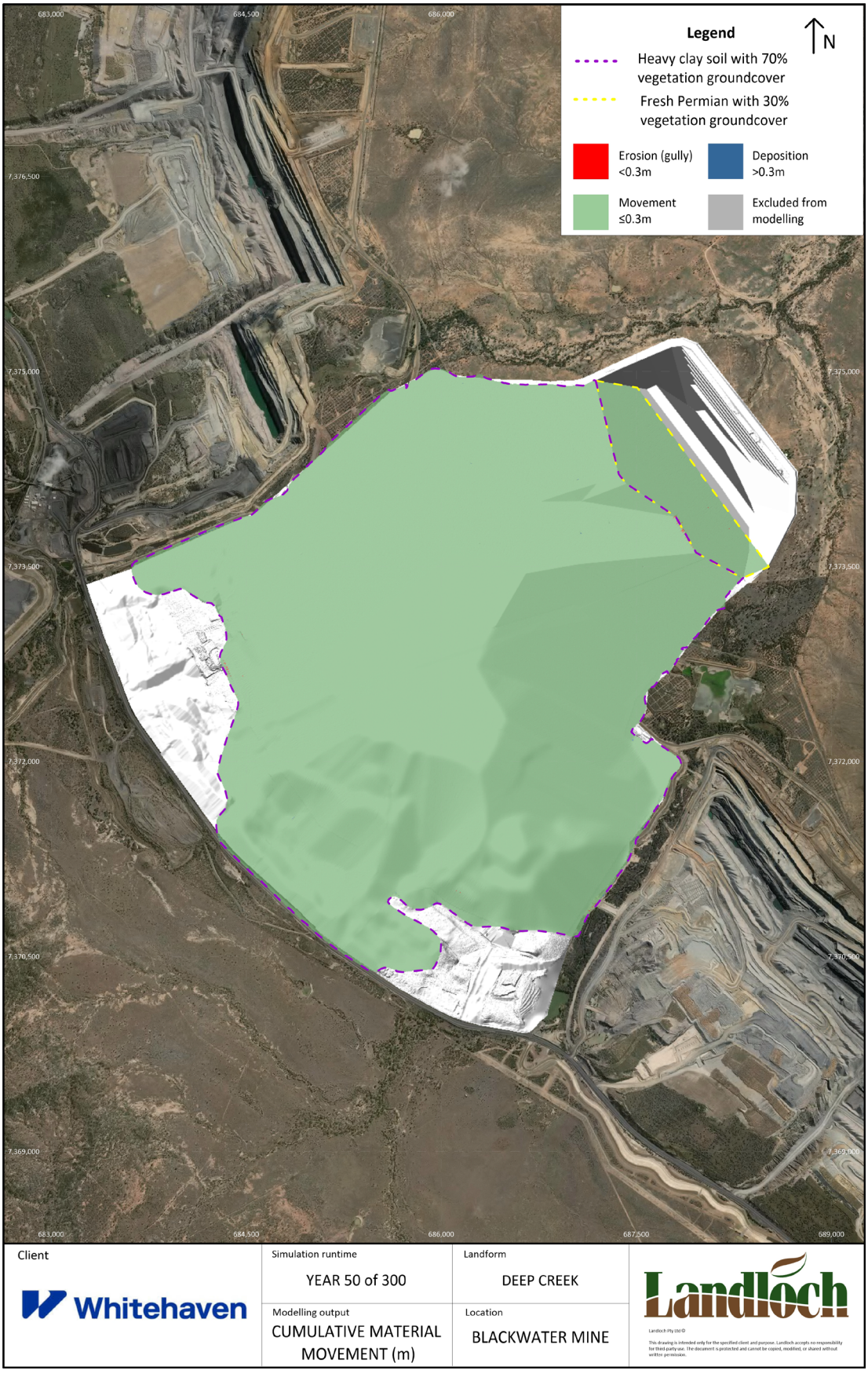


Figure A-5: Predicted erosion and deposition depths of the Deep Creek rehabilitation landform after 50 years.

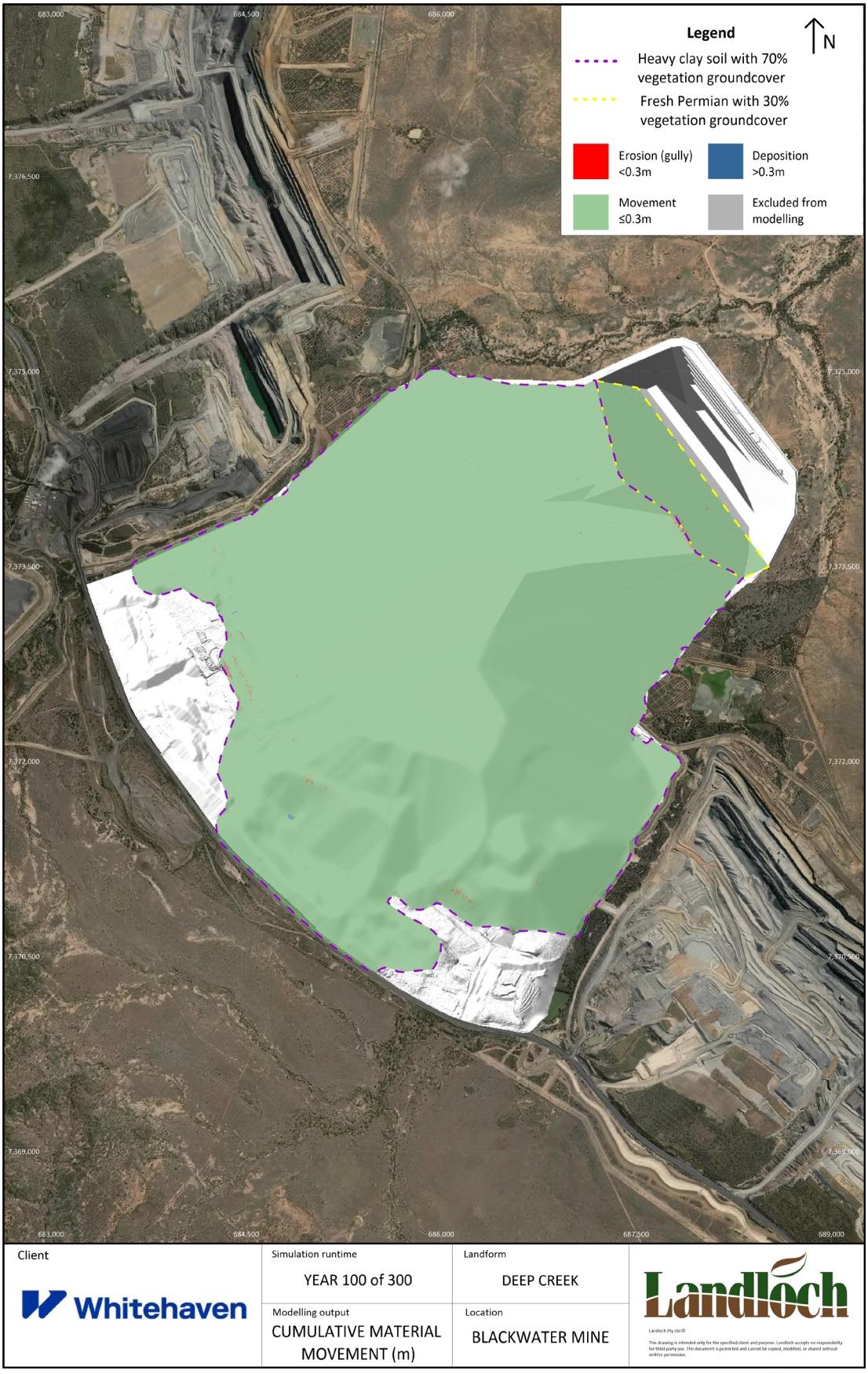


Figure A-6: Predicted erosion and deposition depths of the Deep Creek rehabilitation landform after 100 years.

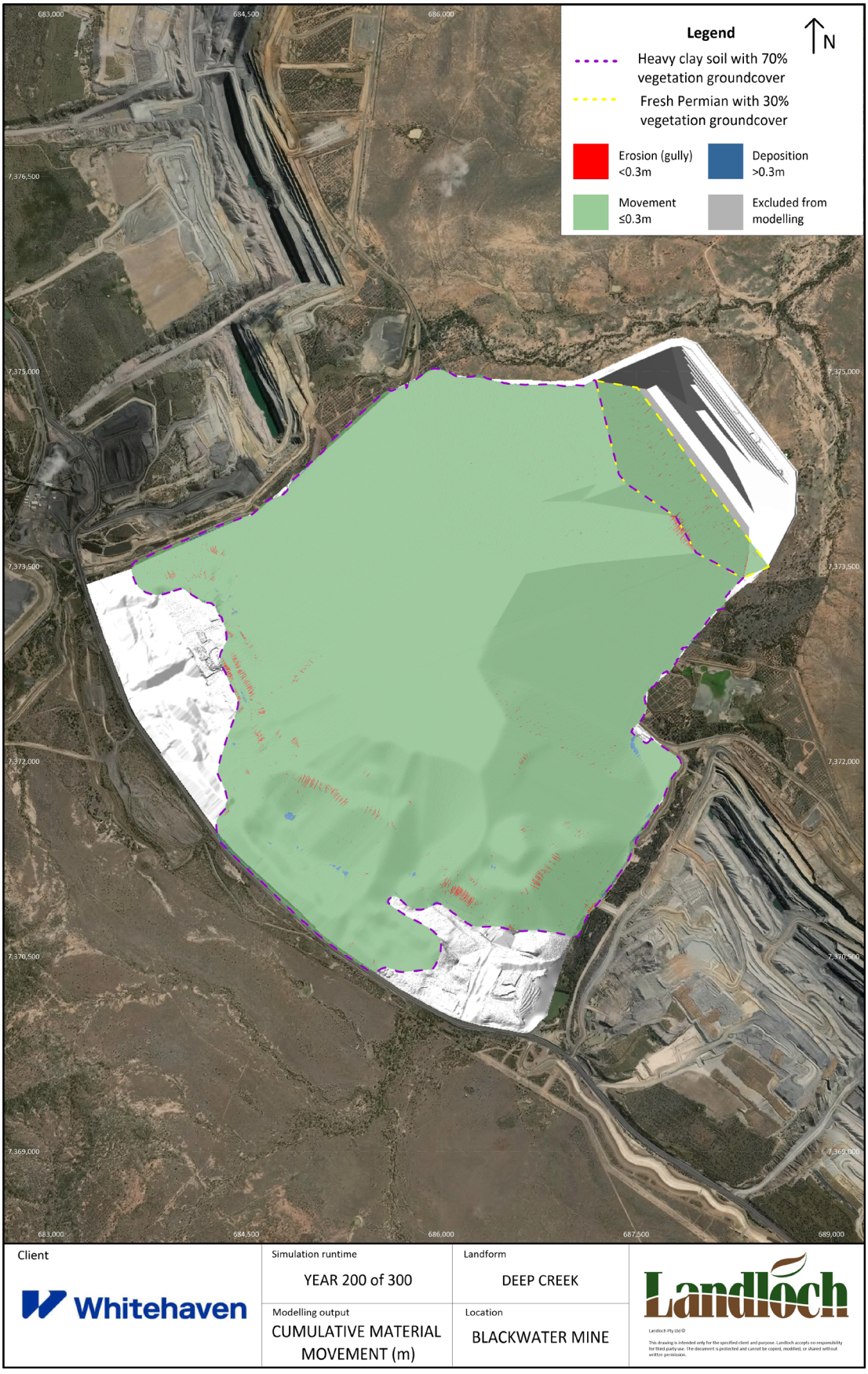


Figure A-7: Predicted erosion and deposition depths of the Deep Creek rehabilitation landform after 200 years.

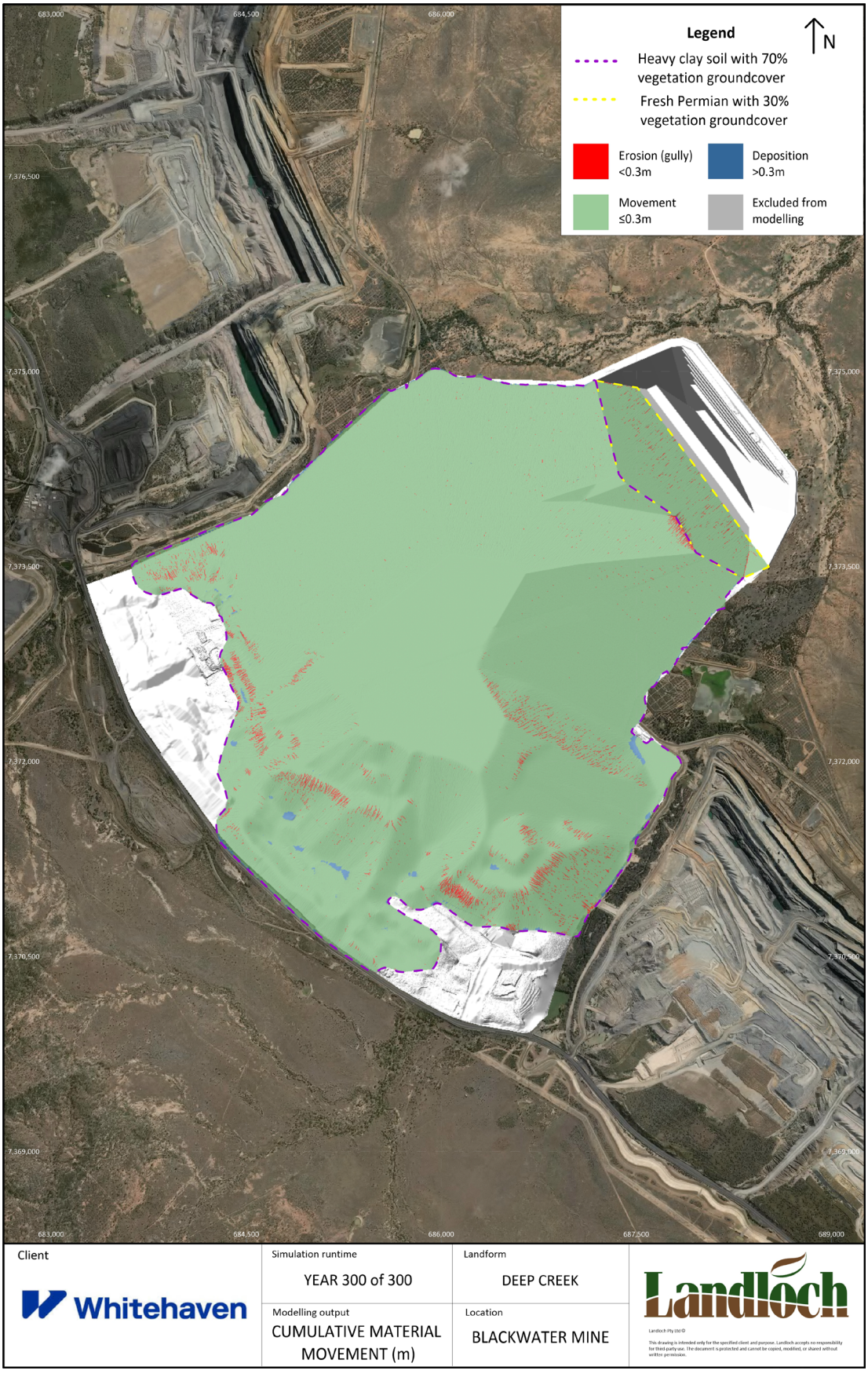


Figure A-8: Predicted erosion and deposition depths of the Deep Creek rehabilitation landform after 300 years.

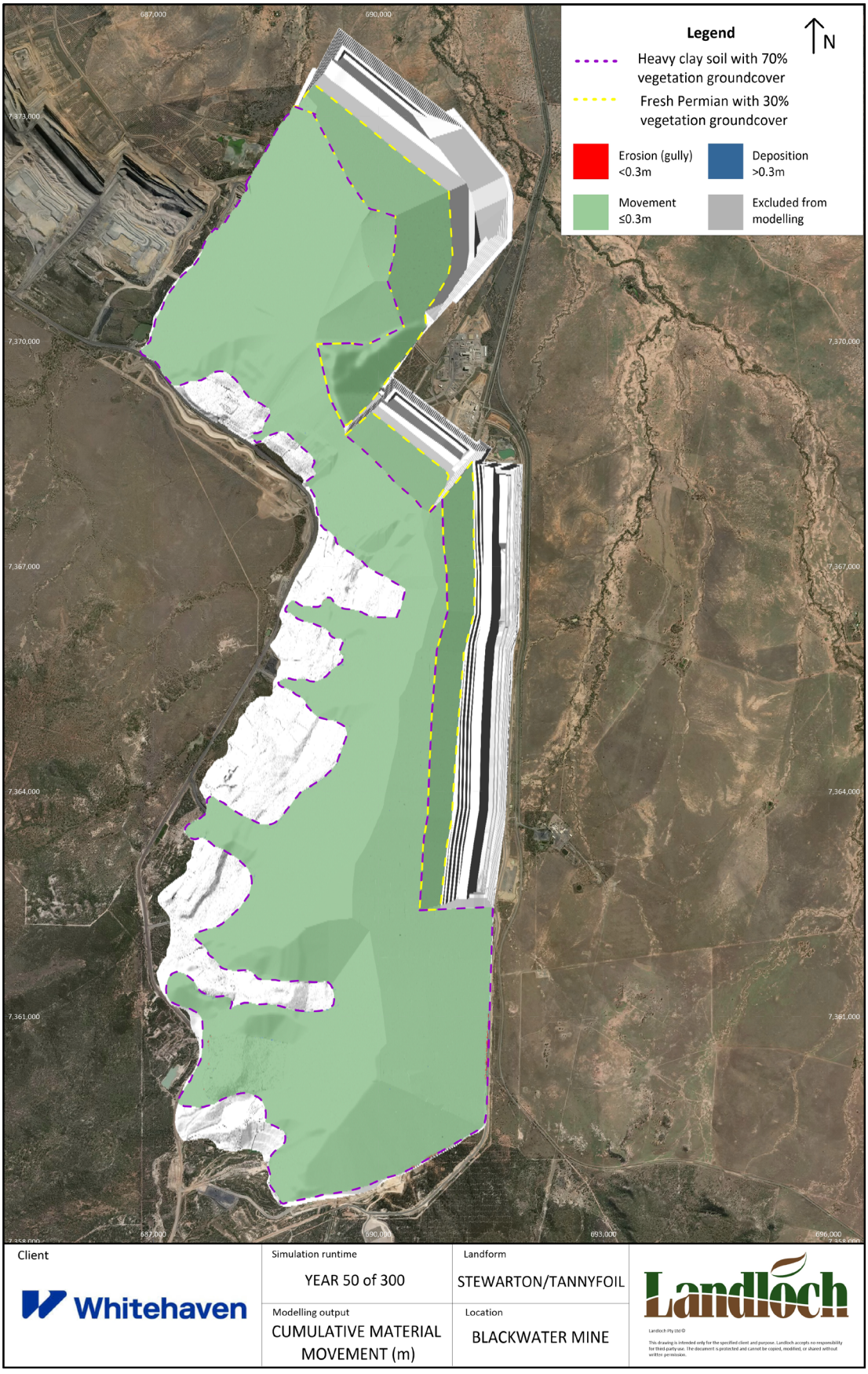


Figure A-9: Predicted erosion and deposition depths of the Stewarton/Tannyfoil rehabilitation landform after 50 years.

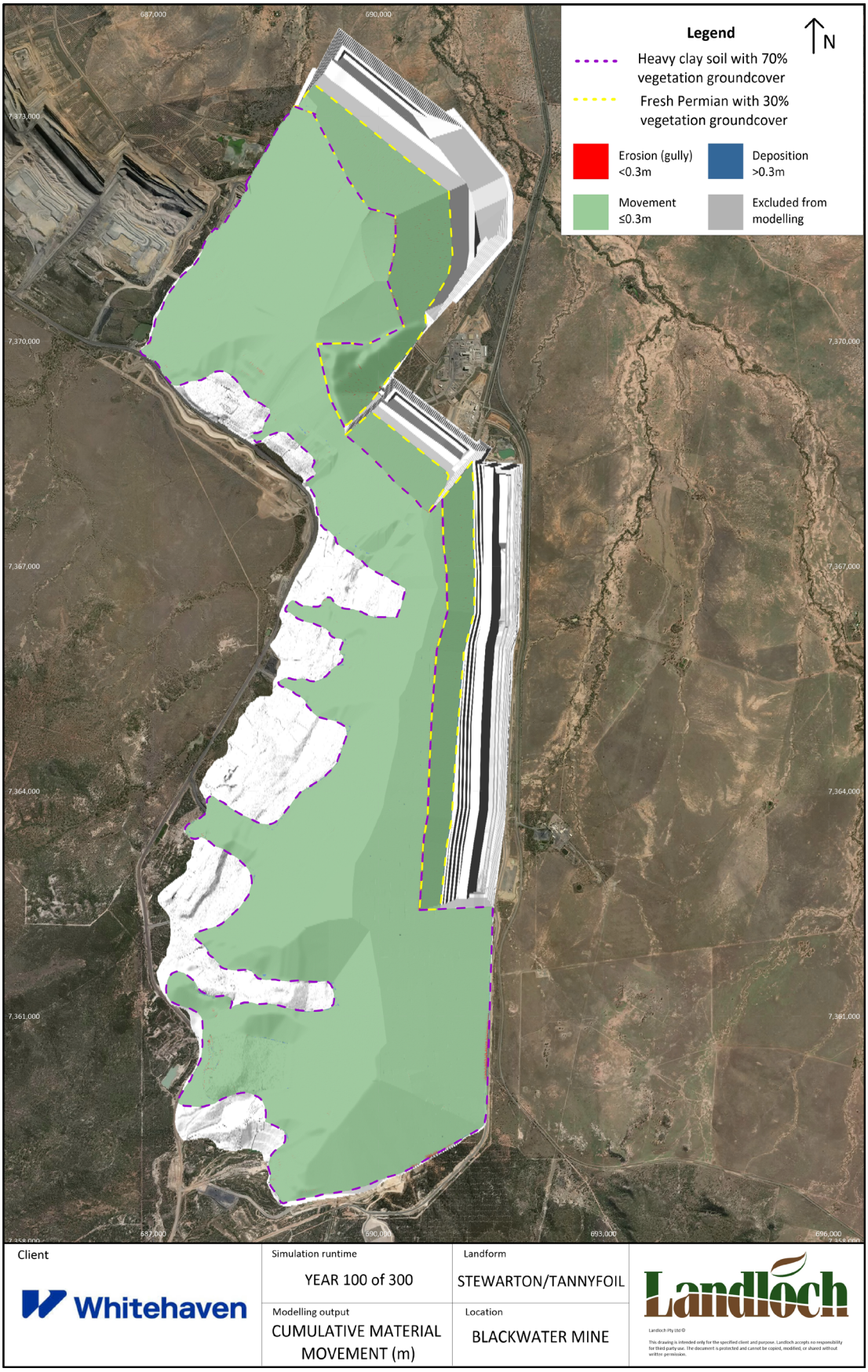


Figure A-10: Predicted erosion and deposition depths of the Stewarton/Tannyfoil rehabilitation landform after 100 years.

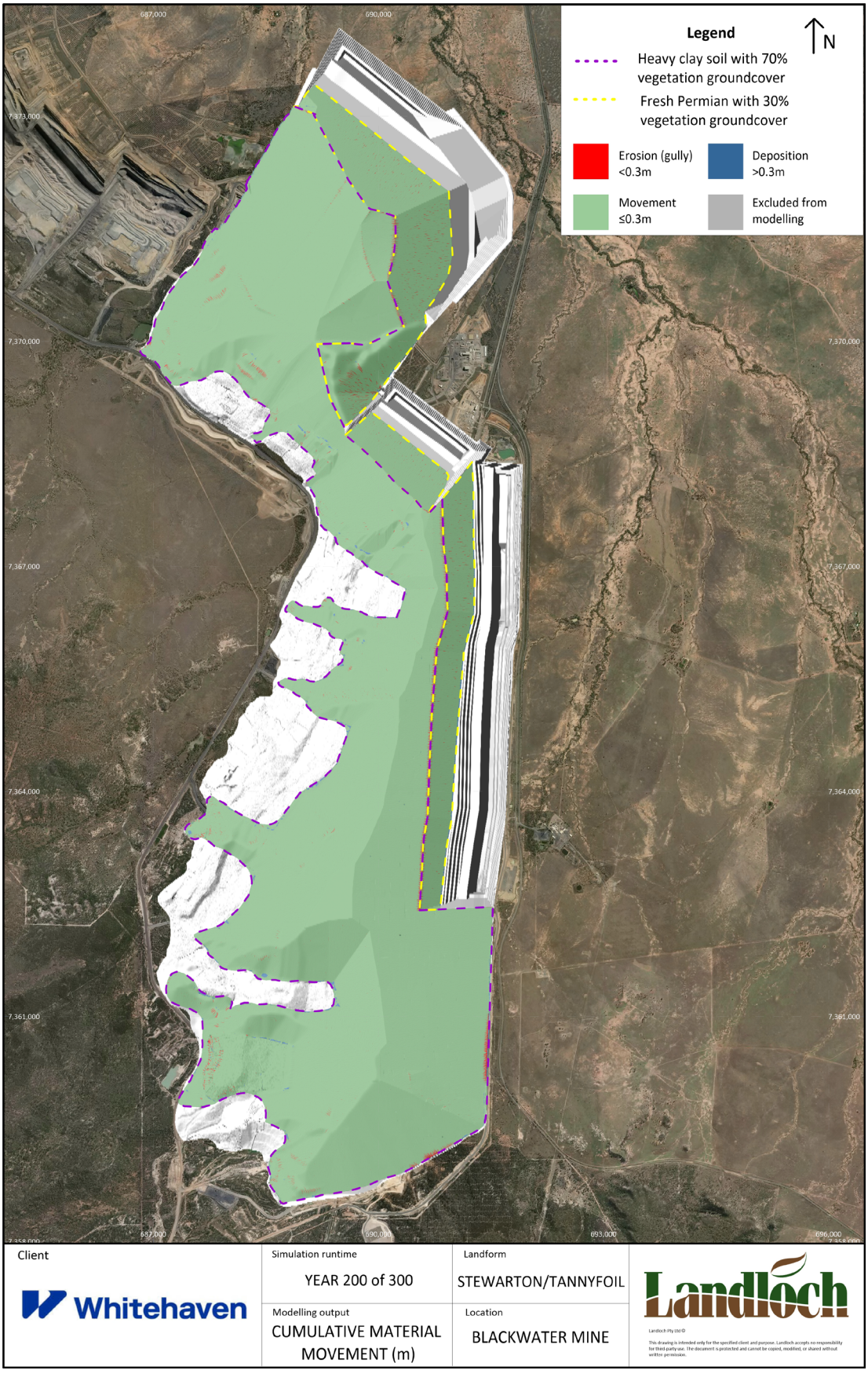


Figure A-11: Predicted erosion and deposition depths of the Stewarton/Tannyfoil rehabilitation landform after 200 years.

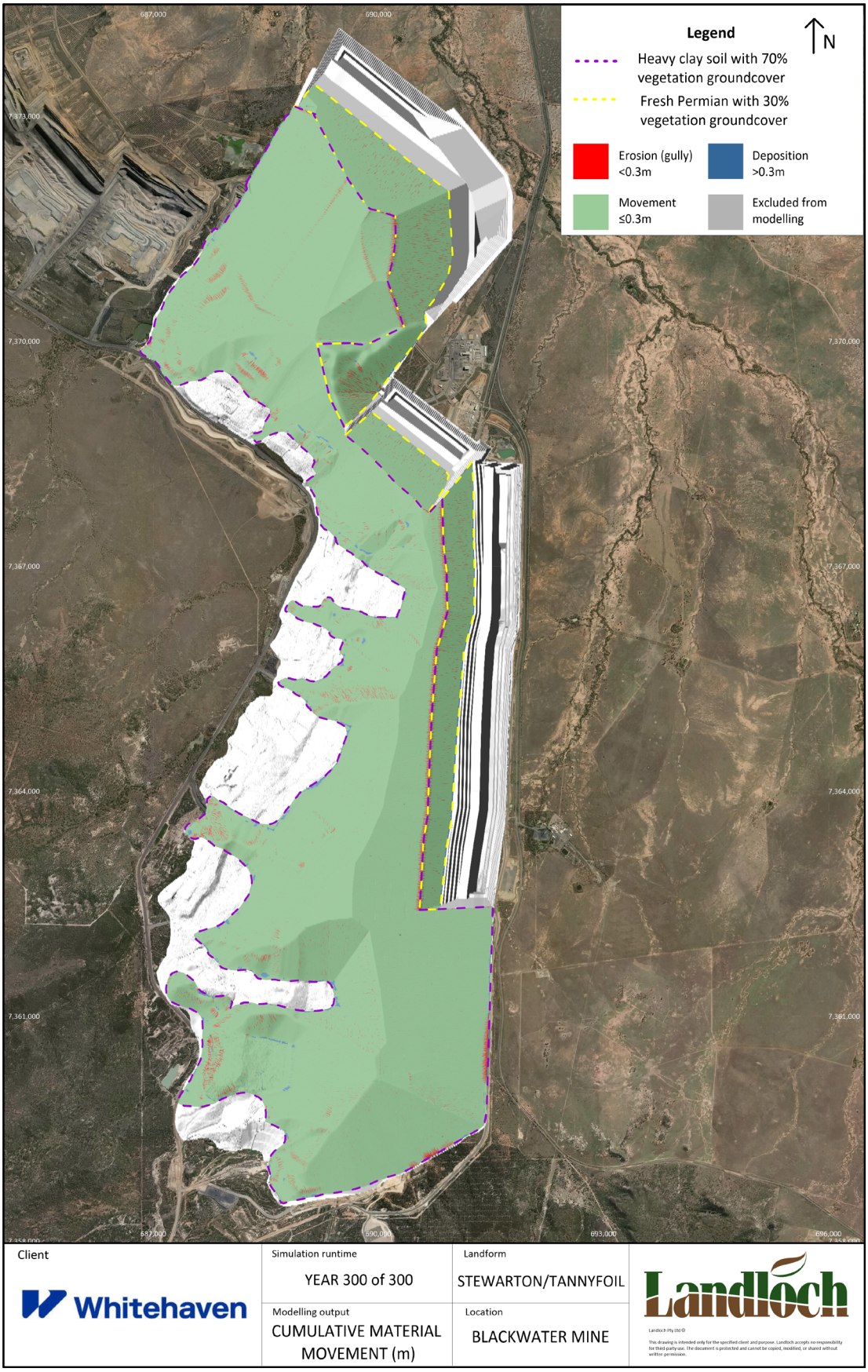


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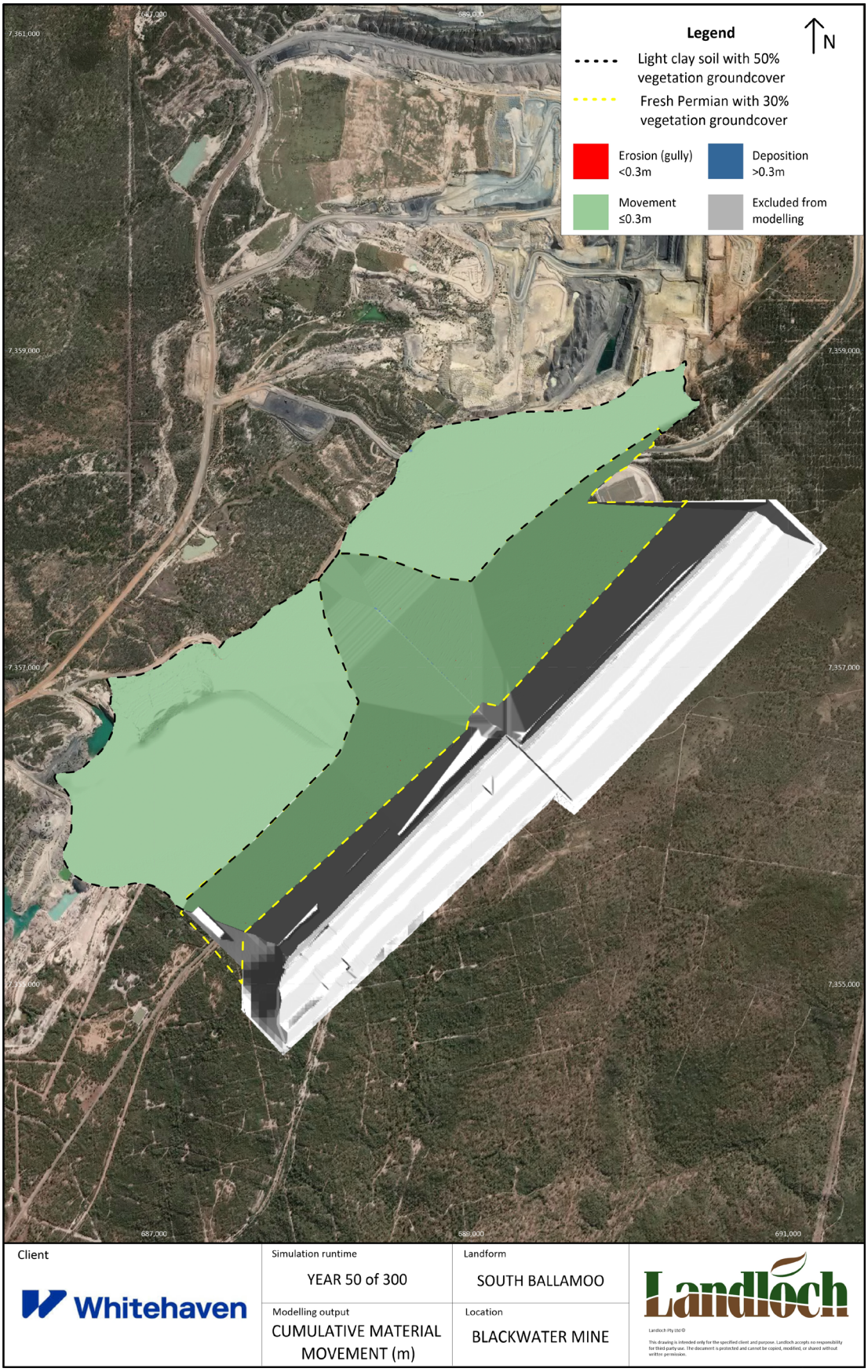


Figure A-13: Predicted erosion and deposition depths of the South Ballamoo rehabilitation landform after 50 years.

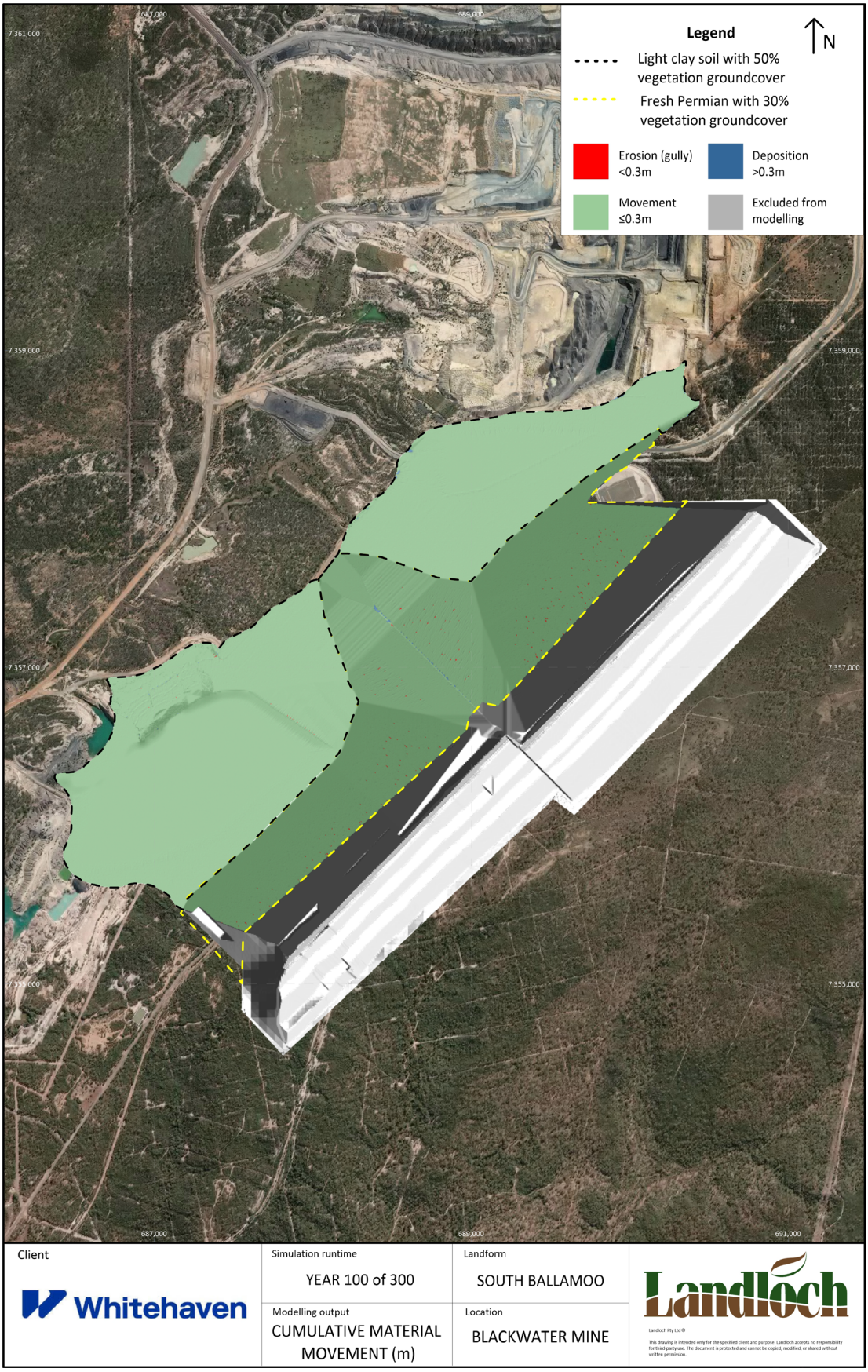


Figure A-14: Predicted erosion and deposition depths of the South Ballamoo rehabilitation landform after 100 years.



Figure A-15: Predicted erosion and deposition depths of the South Ballamoo rehabilitation landform after 200 years.

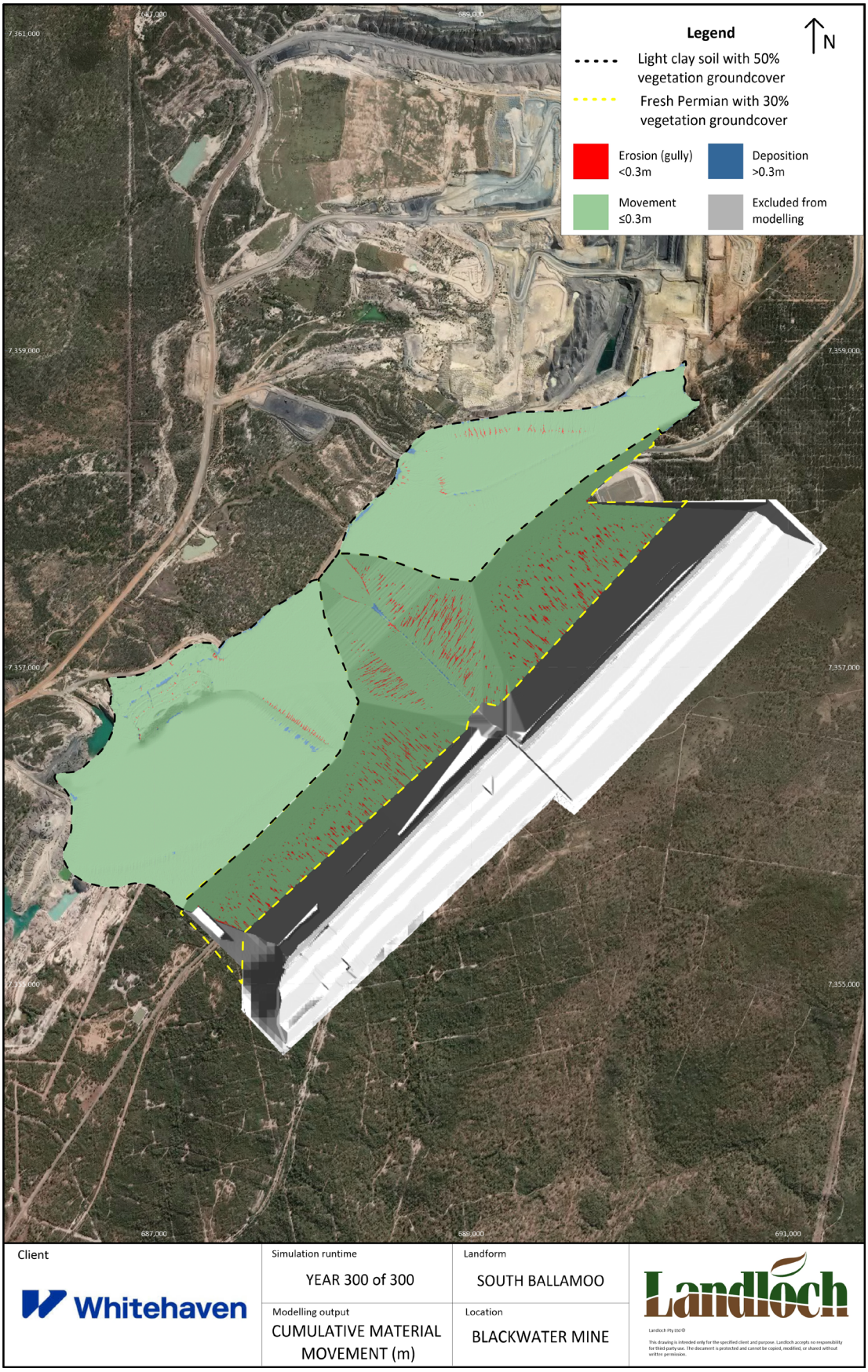


Figure A-16: Predicted erosion and deposition depths of the South Ballamoo rehabilitation landform after 300 years.

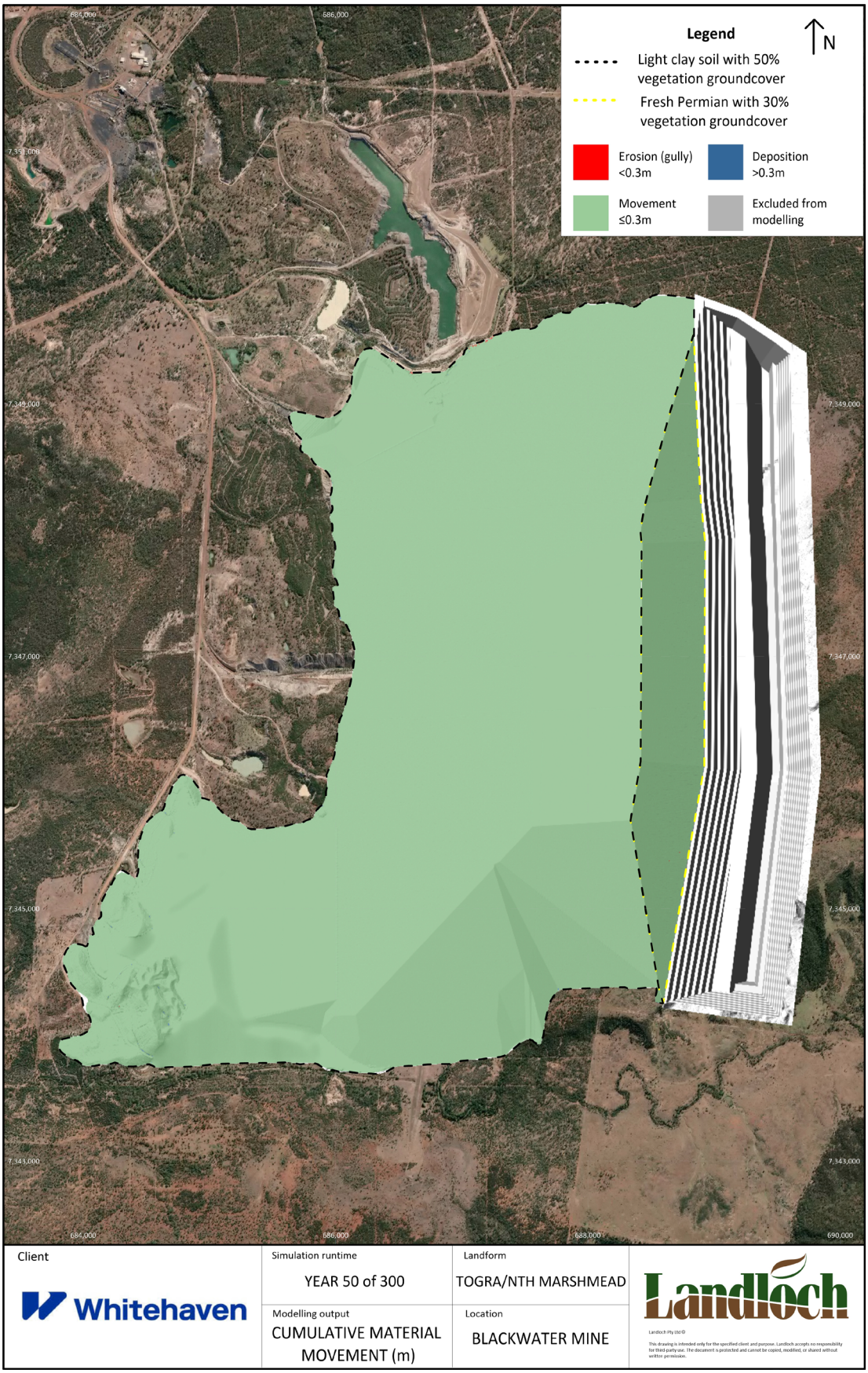


Figure A-17: Predicted erosion and deposition depths of the Togara/North Marshmead rehabilitation landform after 50 years.

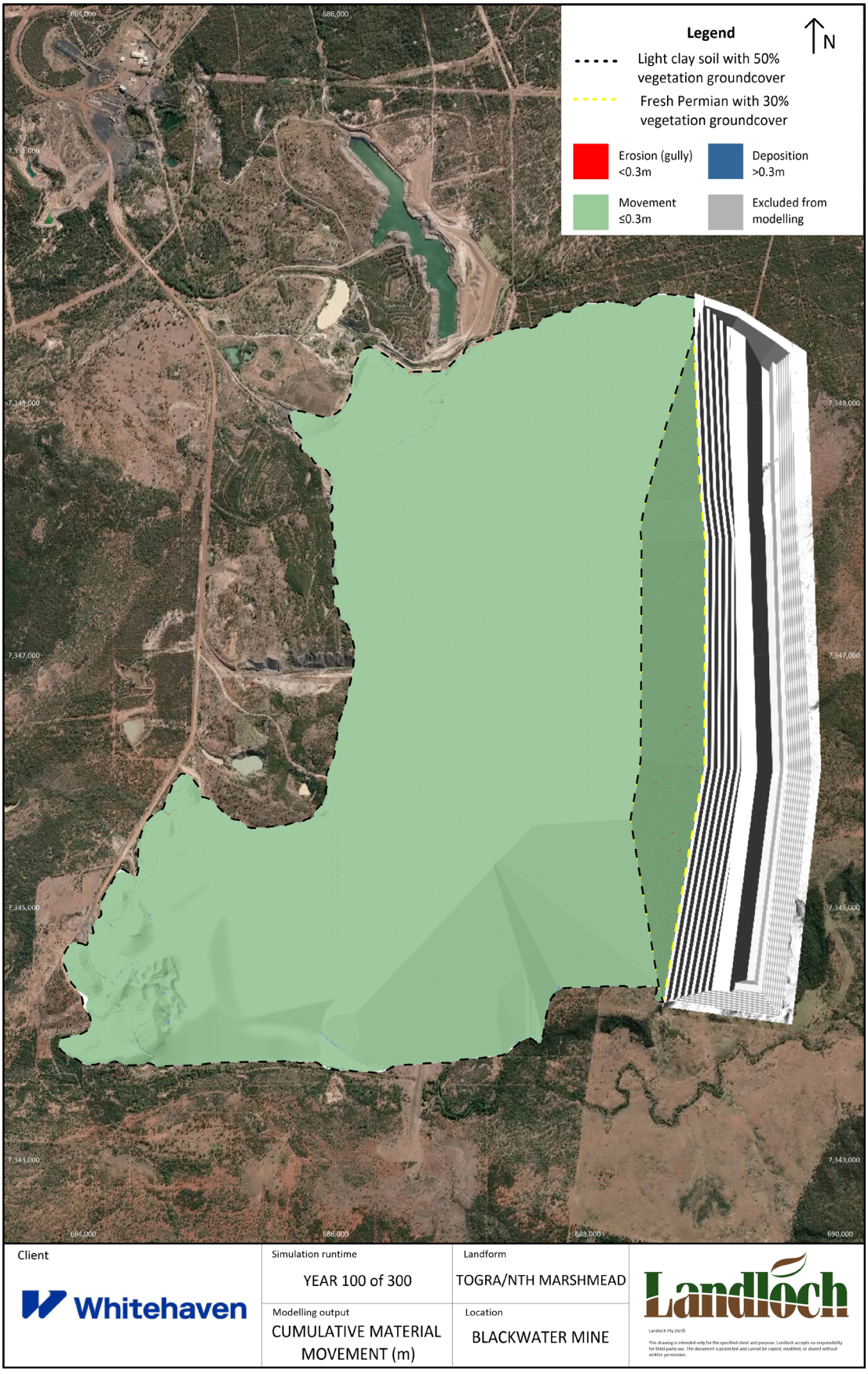


Figure A-18: Predicted erosion and deposition depths of the Togara/North Marshmead rehabilitation landform after 100 years.

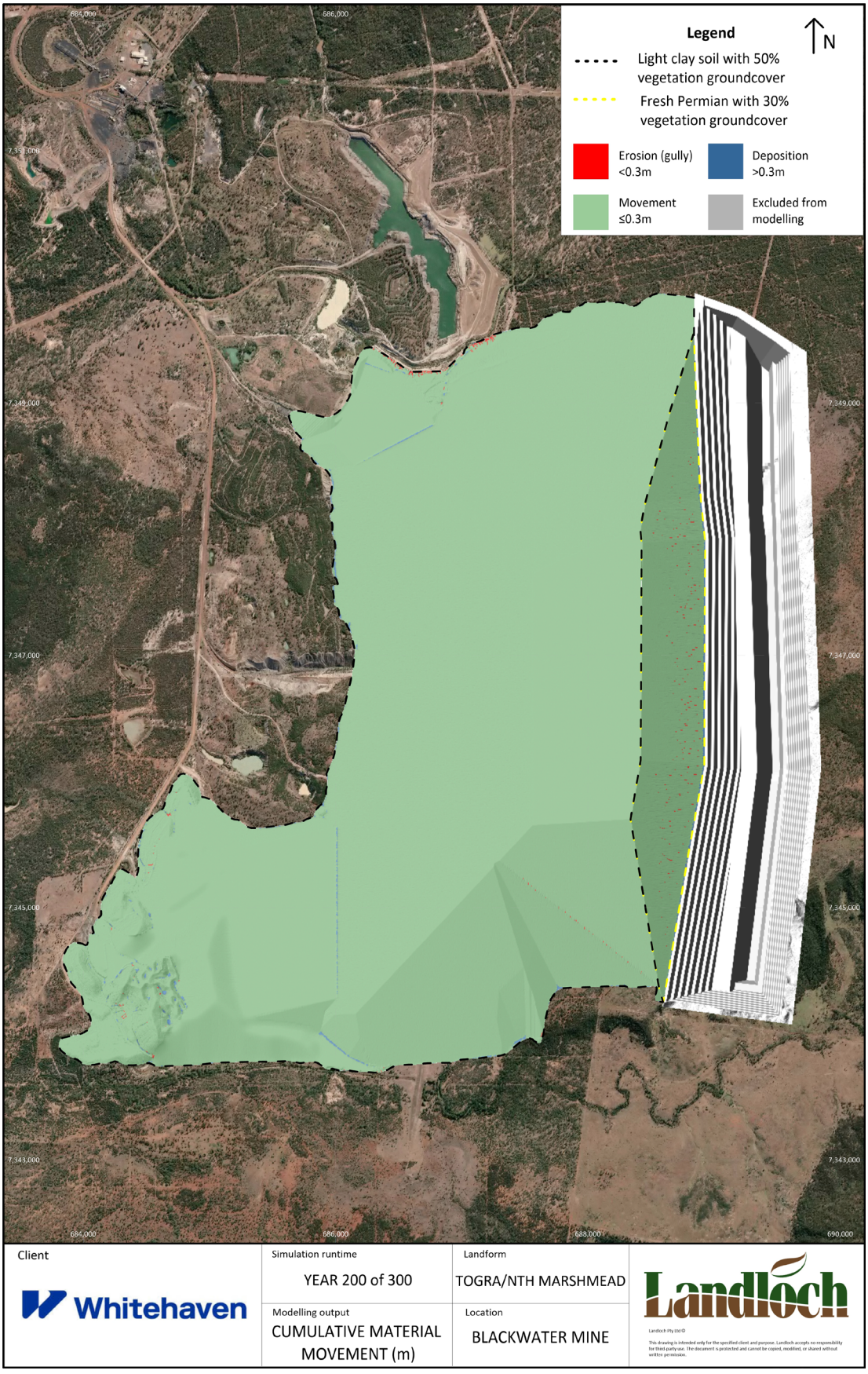


Figure A-19: Predicted erosion and deposition depths of the Togara/North Marshmead rehabilitation landform after 200 years.

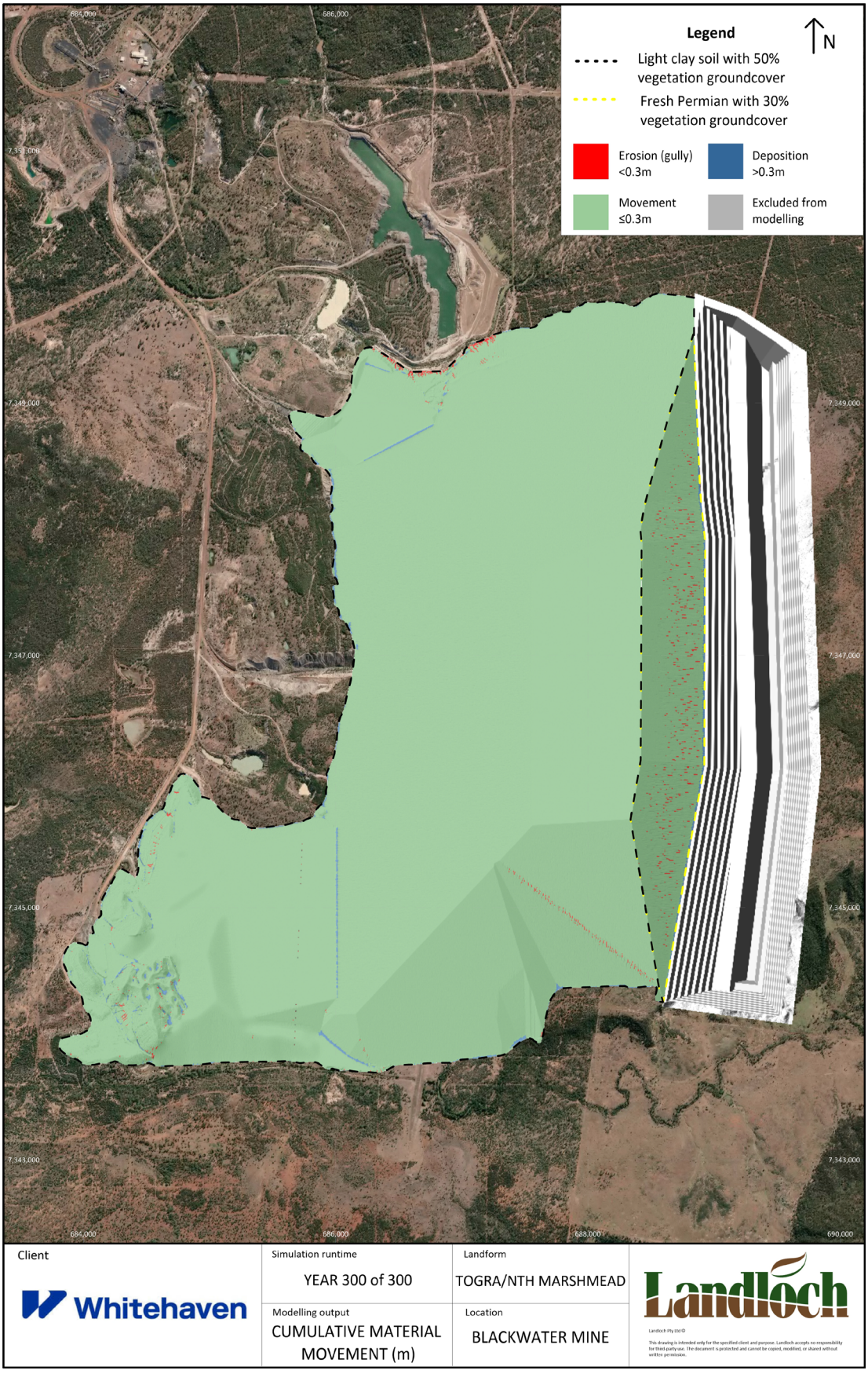


Figure A-20: Predicted erosion and deposition depths of the Togara/North Marshmead rehabilitation landform after 300 years.



Figure A-21: Predicted erosion and deposition depths of the South Marshmead rehabilitation landform after 50 years.



Figure A-22: Predicted erosion and deposition depths of the South Marshmead rehabilitation landform after 100 years.



Figure A-23: Predicted erosion and deposition depths of the South Marshmead rehabilitation landform after 200 years.



Figure A-24: Predicted erosion and deposition depths of the South Marshmead rehabilitation landform after 300 years.

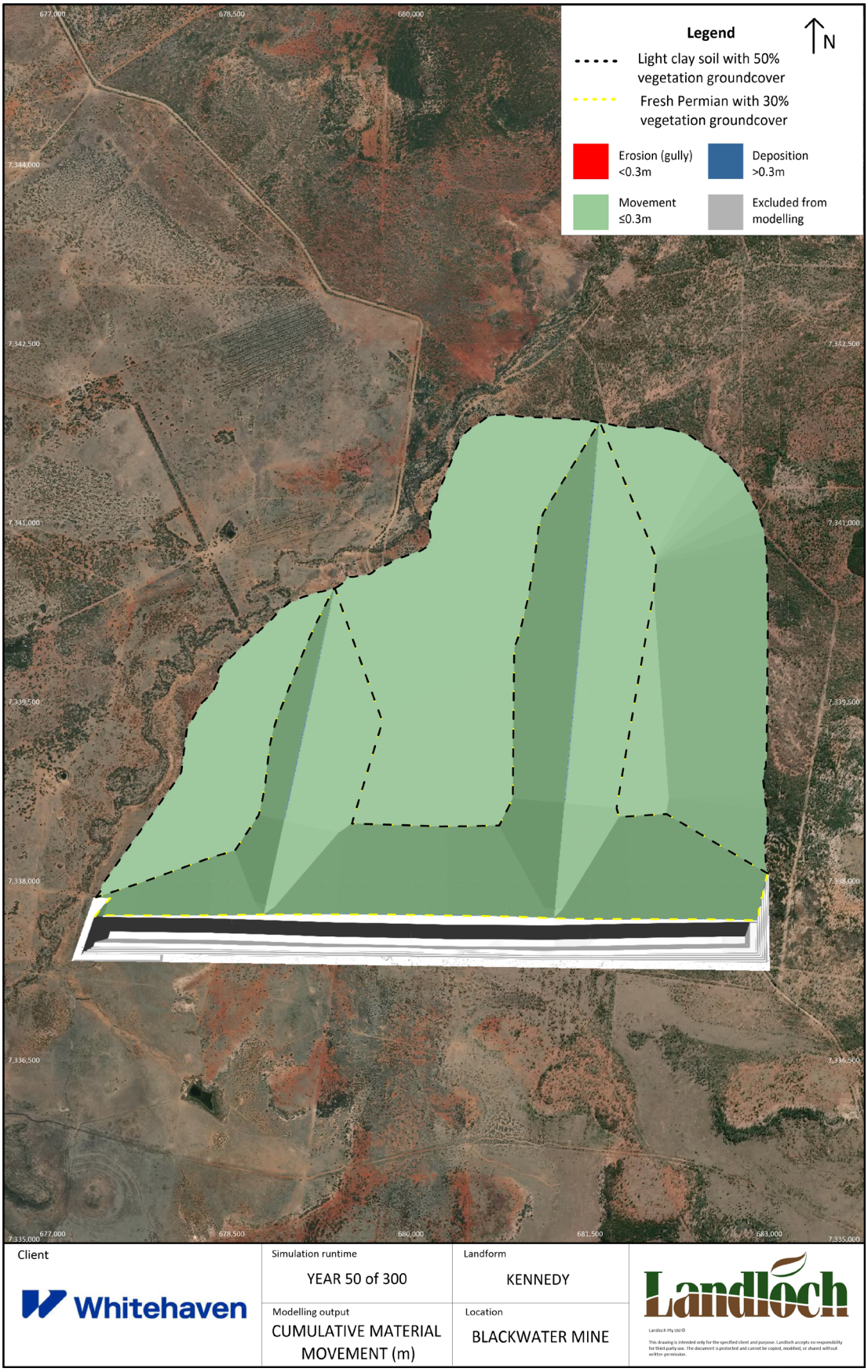


Figure A-25: Predicted erosion and deposition depths of the Kennedy rehabilitation landform after 50 years.

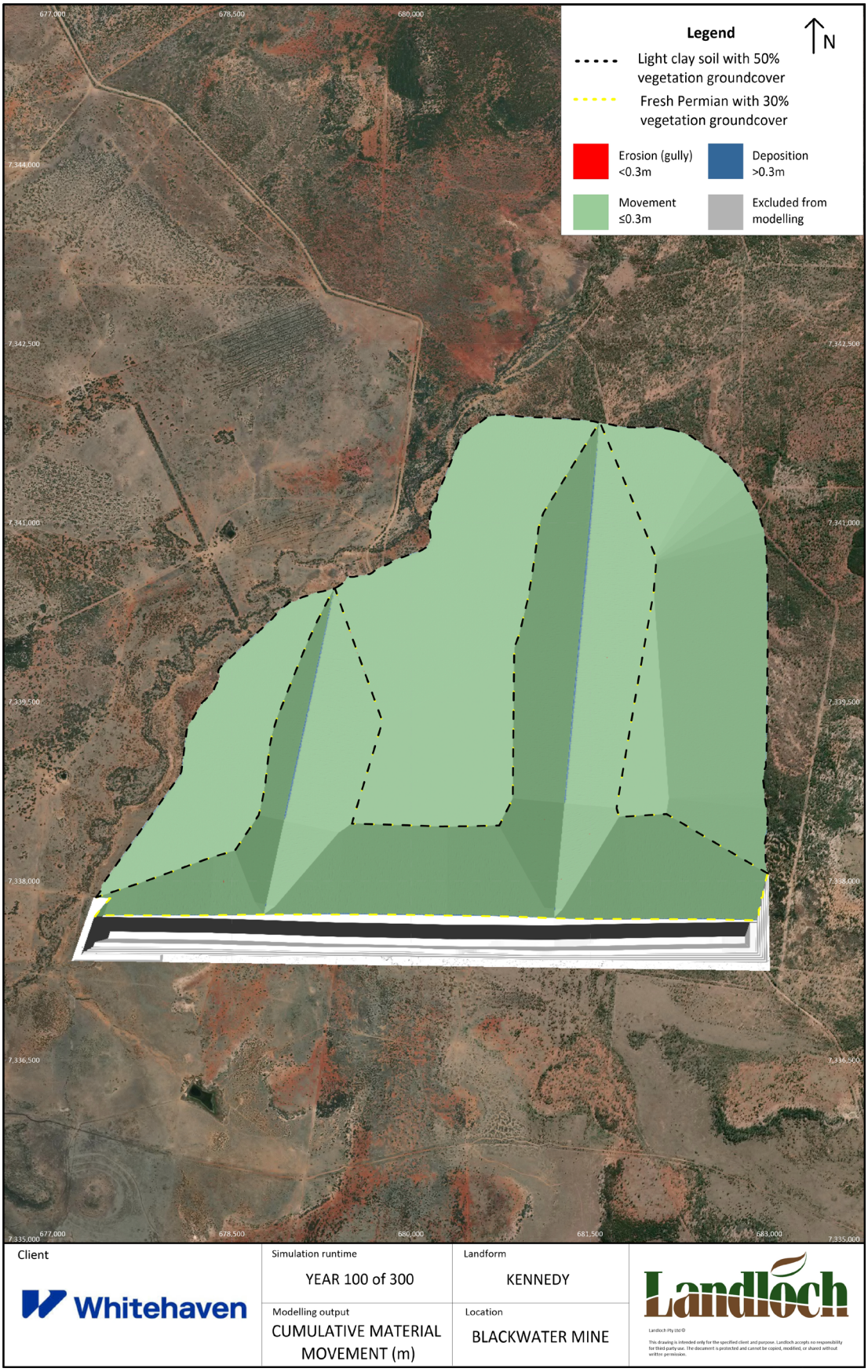


Figure A-26: Predicted erosion and deposition depths of the Kennedy rehabilitation landform after 100 years.

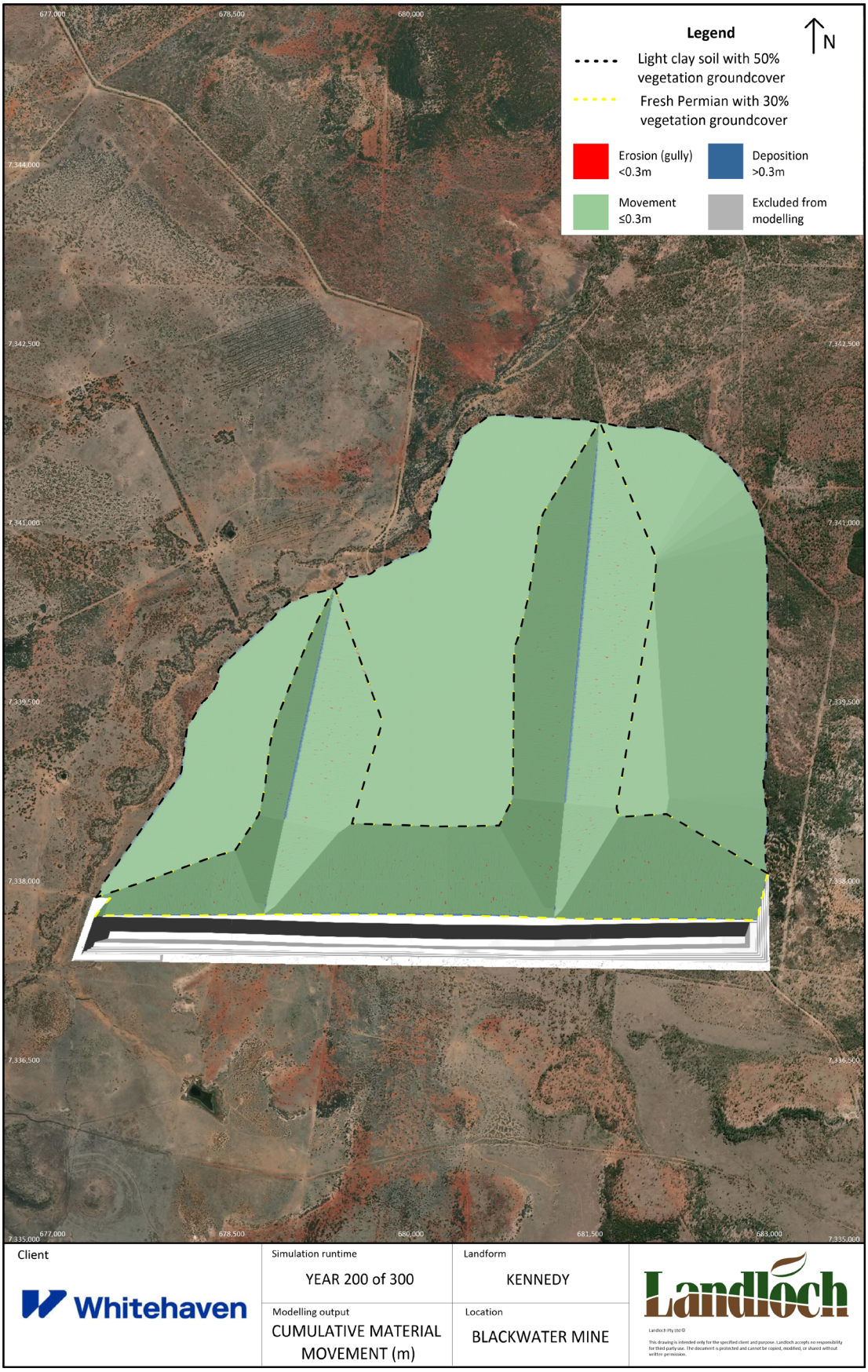


Figure A-27: Predicted erosion and deposition depths of the Kennedy rehabilitation landform after 200 years.

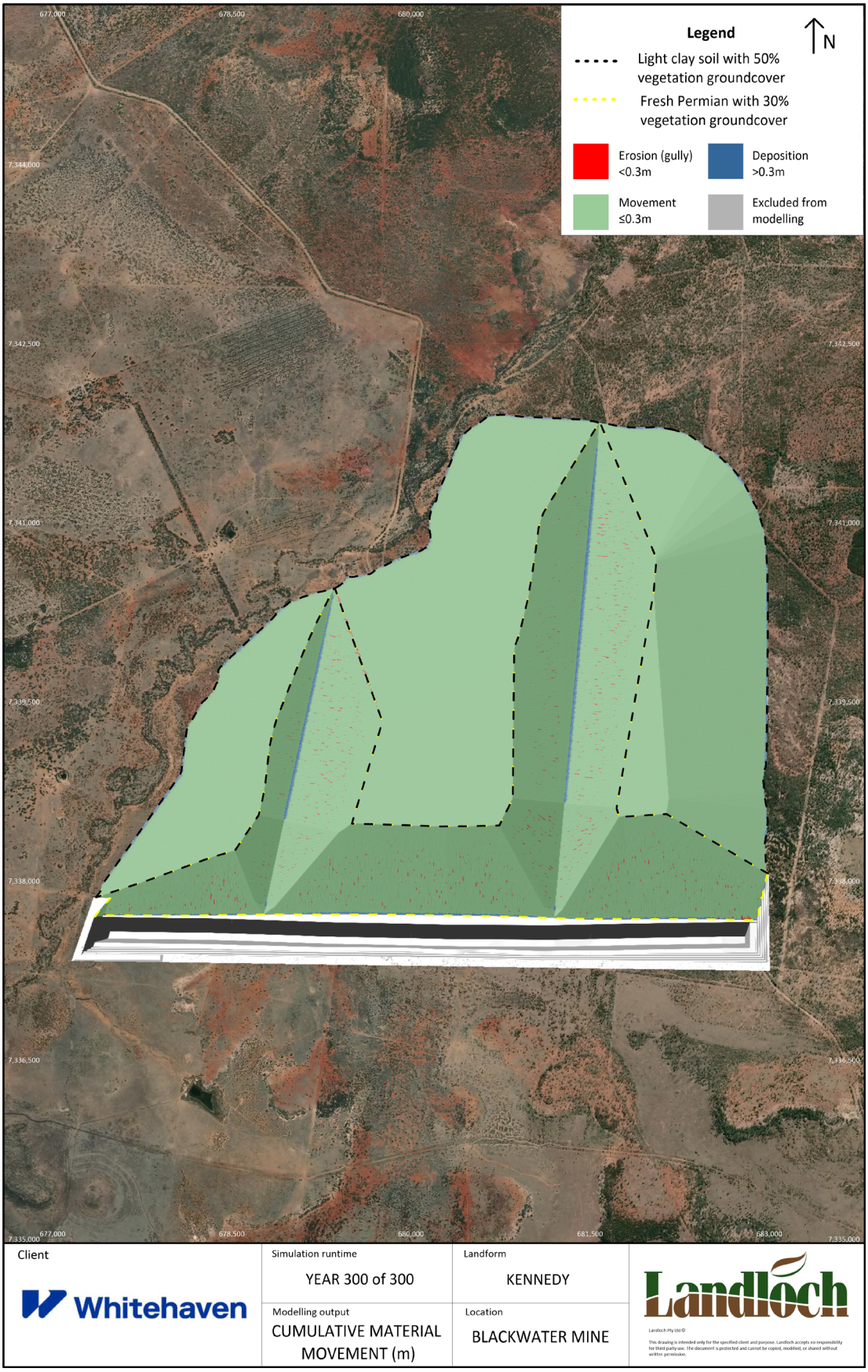


Figure A-28: Predicted erosion and deposition depths of the Kennedy rehabilitation landform after 300 years.

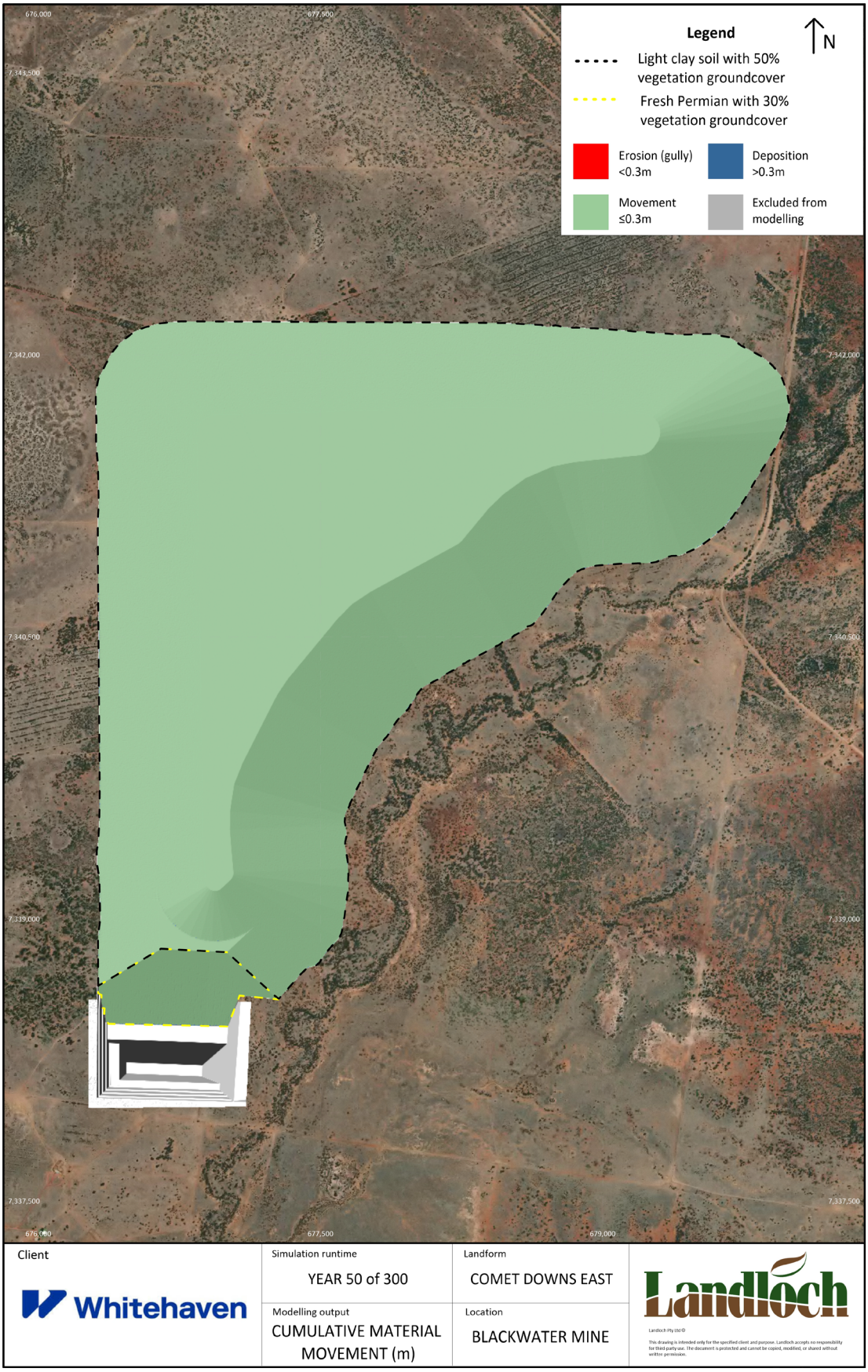


Figure A-29: Predicted erosion and deposition depths of the Comet Downs East rehabilitation landform after 50 years.

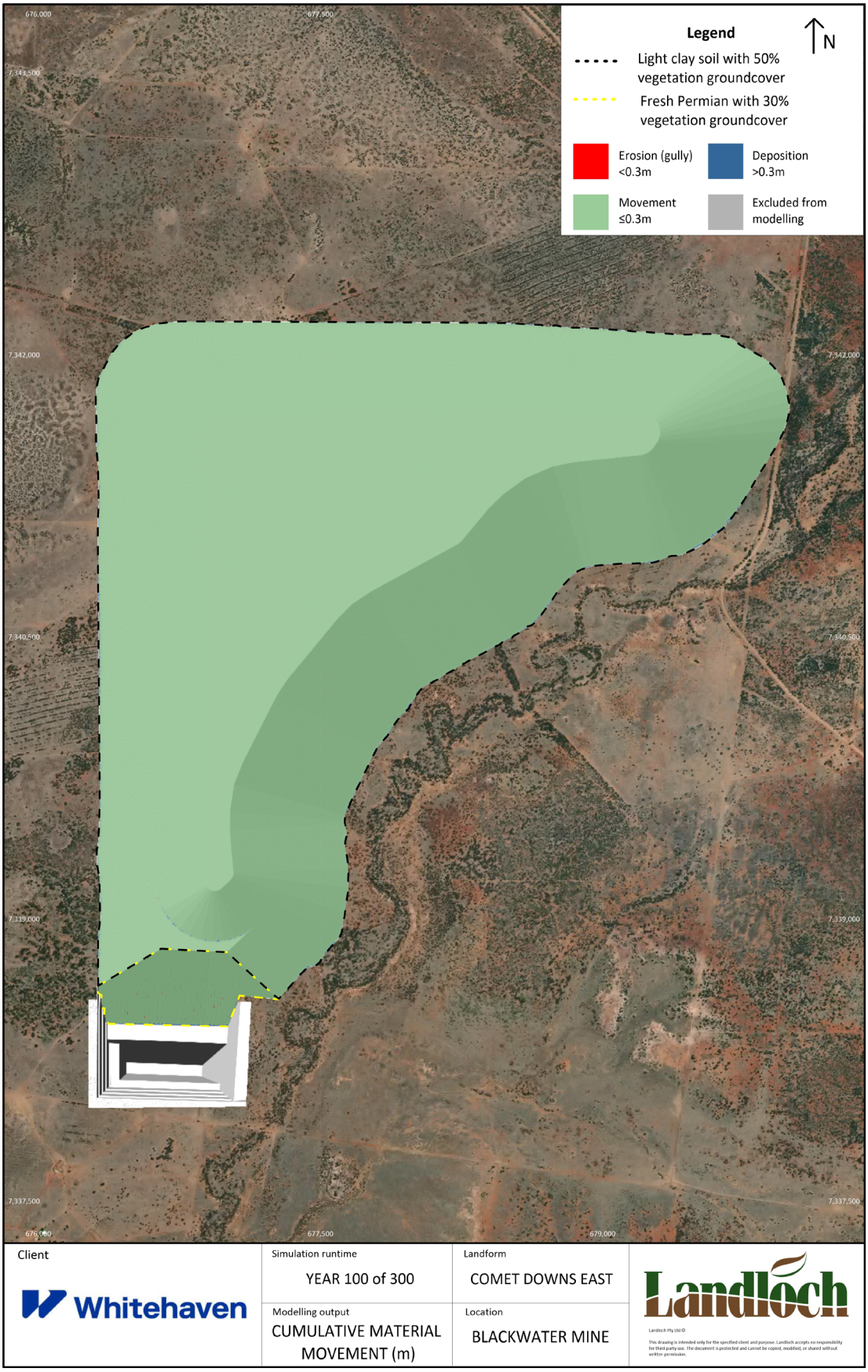


Figure A-30: Predicted erosion and deposition depths of the Comet Downs East rehabilitation landform after 100 years.

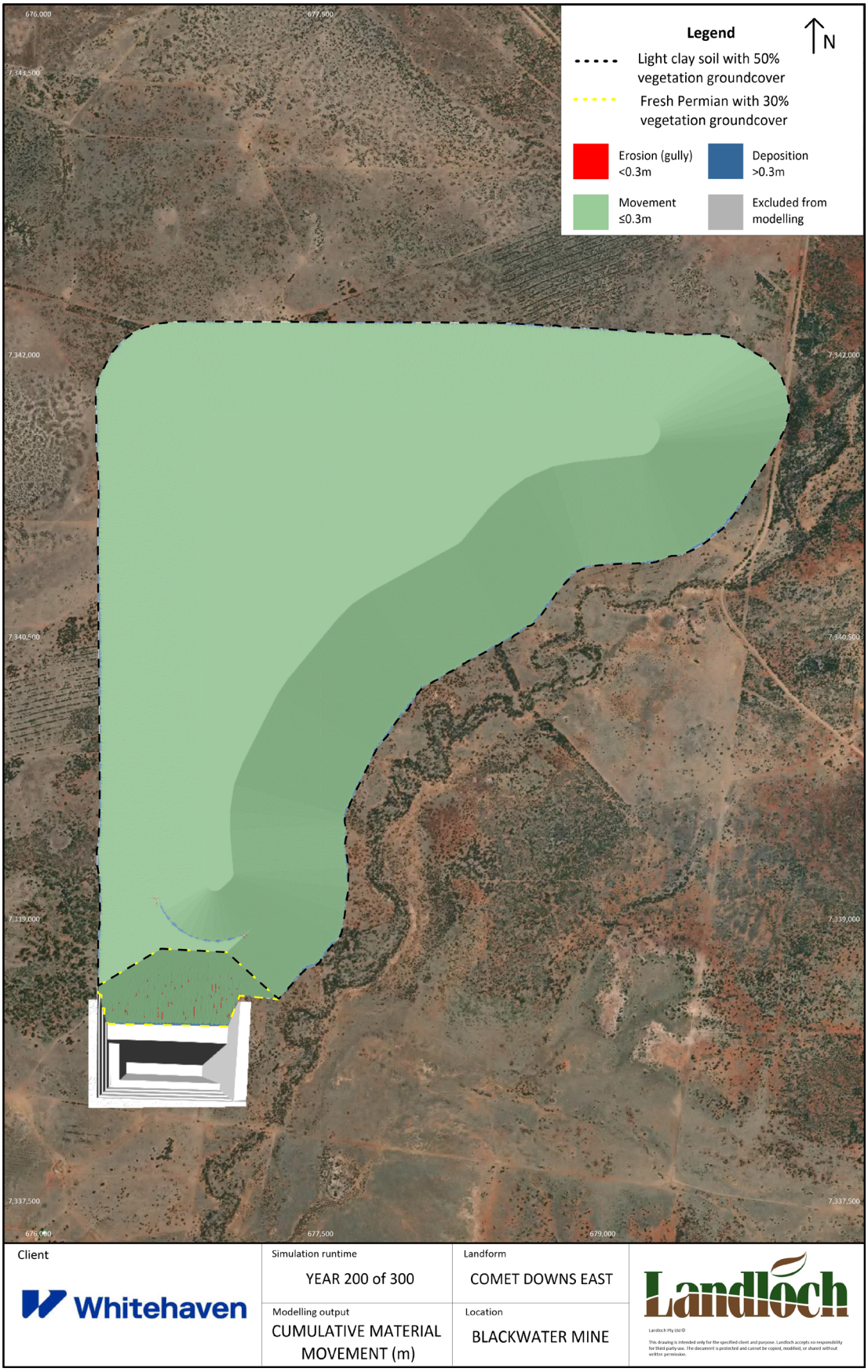


Figure A-31: Predicted erosion and deposition depths of the Comet Downs East rehabilitation landform after 200 years.

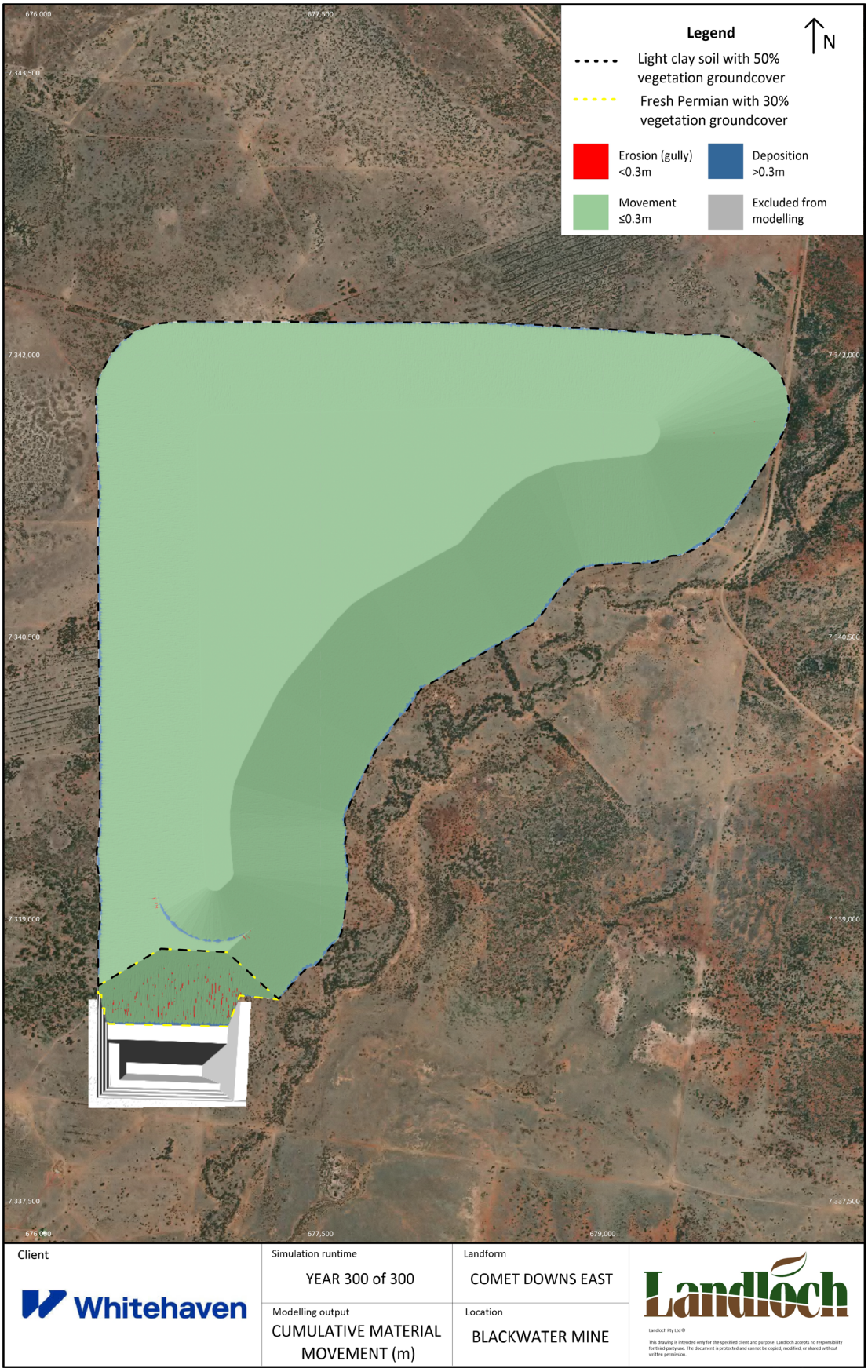


Figure A-32: Predicted erosion and deposition depths of the Comet Downs East rehabilitation landform after 300 years.

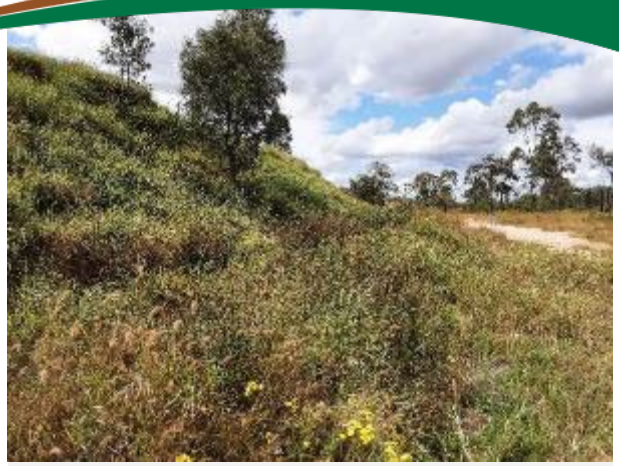
APPENDIX B: WEPP DATA TABULATION

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Material	Vegetation Groundcover (%)	Slope Gradient (%)	Average Annual Erosion (t/ha/y) For A Slope Length Of:													Max. Acceptable Length* (m)
			25	50	75	100	125	150	175	200	250	300	400	500	750	
Fresh Permian	0	15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2	3.3	-	500
		20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.7	1.6	5.5	8.6	-	500
		25	0.1	0.1	0.1	0.1	0.6	1.7	2.8	3.8	5.9	8.0	12	16	-	350
		30	0.1	0.1	0.1	0.1	1.1	3.3	5.4	7.5	11	15	21	24	-	220
	10	15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.1	3.0	-	500
		20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	1.4	5.0	7.7	-	500
		25	0.1	0.1	0.1	0.1	0.5	1.5	2.5	3.4	5.3	7.2	11	14	-	380
		30	0.1	0.1	0.1	0.1	1.1	3	4.9	6.8	10	14	19	22	-	240
	30	15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.9	-	500
		20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.5	2.0	3.1	-	500
		25	0.1	0.1	0.1	0.1	0.1	0.6	1.0	1.4	2.1	2.8	4.5	5.8	-	500
		30	0.1	0.1	0.1	0.1	0.3	1.1	1.9	2.7	4.1	5.3	7.3	8.6	-	500
Heavy Clay Topsoil	0	10	2.5	2.5	9.0	82	153	274	362	490	676	829	1012	1095	-	70
		15	3.4	28	155	429	627	914	1085	1310	1613	1831	2073	2156	-	20
		20	5.0	330	767	1193	1709	2038	2316	2613	2929	3158	3367	3451	-	20
		30	238	1245	2190	2945	3536	4004	4375	4670	5095	5375	5703	5875	-	0
	30	10	0.1	0.1	0.1	0.2	1.1	3.2	5.2	7.9	12	16	20	21	-	170
		15	0.1	0.1	0.6	4.8	8.4	14	18	23	28	33	39	40	-	100
		20	0.2	1.7	9.2	18	29	36	42	48	55	61	65	67	-	60
		30	0.7	21	43	60	74	84	92	98	108	114	122	126	-	30
	50	10	0.1	0.1	0.1	0.2	0.5	1.3	2.2	3.4	4.8	5.7	6.9	8.1	-	260
		15	0.1	0.1	0.3	2.0	3.6	5.5	6.7	8.0	9.9	12	14	15	-	140
		20	0.1	1.0	3.7	6.4	9.6	12	13	15	18	20	22	23	-	90
		30	0.2	5.9	12	17	21	24	27	29	33	35	37	38	-	40
	70	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.7	1.1	1.8	2.1	-	500
		15	0.1	0.1	0.1	0.1	0.4	0.8	1.1	1.6	2.3	2.8	3.4	4.0	-	500
		20	0.1	0.1	0.5	1.1	1.9	2.4	2.9	3.4	3.9	4.5	5.8	6.4	-	340
		25	0.1	0.1	1.4	2.2	3.1	3.8	4.3	5.0	5.9	6.6	7.7	8.3	-	200
		30	0.1	0.2	2.4	3.4	4.2	5.1	5.8	6.6	7.8	8.7	9.4	9.7	-	500

Material	Vegetation Groundcover (%)	Slope Gradient (%)	Average Annual Erosion (t/ha/y) For A Slope Length Of:													Max. Acceptable Length* (m)
			25	50	75	100	125	150	175	200	250	300	400	500	750	
Heavy Clay Topsoil	90	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	-	500
		15	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.9	1.2	-	500
		20	0.1	0.1	0.1	0.2	0.3	0.5	0.6	0.7	0.9	1.2	1.9	2.3	-	500
		30	0.1	0.2	0.5	0.7	0.9	1.2	1.4	1.8	2.4	2.9	3.3	3.3	-	500
Light Clay Topsoil	0	10	0.2	0.2	0.2	0.7	4.4	17	26	40	64	84	117	138	146	130
		15	0.2	0.2	2.8	30	51	85	108	142	187	220	260	281	303	80
		20	0.4	18	76	139	212	260	303	357	421	471	518	539	547	30
		30	9.5	149	309	442	553	641	712	768	850	904	965	995	-	0
	30	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	1.0	1.7	2.8	3.3	4.2	750
		15	0.1	0.1	0.1	0.1	0.3	1.0	1.6	2.5	3.9	5.3	7.0	8.5	10	290
		20	0.1	0.1	0.4	2.3	5.4	7.5	9.4	12	15	17	21	22	23	120
		30	0.1	3.2	12	19	24	29	33	36	40	44	47	48	-	60
	50	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.8	1.1	1.3	750
		15	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.5	1.1	1.5	1.9	2.0	2.1	750
		20	0.1	0.1	0.1	0.3	0.9	1.4	1.8	2.3	2.9	3.3	3.8	4.3	5.0	750
		30	0.1	0.3	2.0	3.5	5.1	6.4	7.5	8.3	9.4	10	11	11	-	120
	70	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	750
		15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.5	0.7	0.8	750
		20	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.5	0.7	0.8	1.1	1.2	1.2	750
		25	0.1	0.1	0.1	0.3	0.4	0.6	0.8	0.9	1.2	1.3	1.6	1.7	1.8	750
		30	0.1	0.1	0.3	0.5	0.8	1.1	1.3	1.5	1.7	1.9	2.1	2.2	-	500
	90	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	750
		15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	750
		20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	750
		30	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	-	500

* The maximum acceptable length for some combinations of material, vegetation groundcover, and slope gradient equal the maximum slope length modelled. In these cases, longer slopes may be erosionally stable, but the longest slope length modelled was reported as the maximum acceptable length.



LANDFORM EVOLUTION MODELLING SIMULATIONS TO SUPPORT TAILINGS STORAGE FACILITY DESIGN: BLACKWATER MINE

November 2025

Whitehaven Coal Limited

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

PERTH
PO Box 5175
SOUTH LAKE WA 6164
Phone (08) 9494 2835

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

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

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

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EXECUTIVE SUMMARY

Landloch has been engaged by Whitehaven Coal Limited (Whitehaven) to carry out SIBERIA landform evolution modelling for three (3) Tailings Storage Facilities (TSFs) at the Blackwater Coal Mine (Blackwater). The 3 TSFs that have been modelled are named Bottom Dam, Laleham, and NCPP.

SIBERIA LEM input parameters were previously derived for two soils present at Blackwater, heavy clay topsoil and light clay topsoil. SIBERIA LEM input parameters were derived through a process of laboratory-based erodibility testing, long-term WEPP (Water Erosion Prediction Project) runoff/erosion modelling, and analysis of 100 years of WEPP model output of daily runoff and erosion. This process is detailed as part of previous landform evolution modelling undertaken for waste landforms at Blackwater (Landloch 2024). In assigning SIBERIA parameters for each TSF, it was assumed that the topsoils and vegetation groundcover levels applied are spatially consistent with those applied in the previous landform evolution modelling work (Landloch 2024). As such, the following topsoils and vegetation groundcover levels were applied:

- Bottom Dam – Light clay topsoil with 50% vegetation cover;
- Laleham – Light clay topsoil with 50% vegetation cover; and
- NCPP – Heavy clay topsoil with vegetation groundcover levels of 70%.

SIBERIA LEM simulations indicate that the 3 proposed TSFs modelled (Bottom Dam, Laleham, and NCPP) have a low tendency for gully erosion (up to 300 years) provided the correct soils and the target levels of vegetation groundcover are achieved.

An area of increased gully erosion potential was identified in the southern section of the proposed Bottom Dam design. This increased risk is due to a steepening of the gradient in that area. This could be mitigated by further refinement of the design in this zone so that a fixed gradient is used, and a steepening gradient is avoided. Another area of increased erosion risk was identified in the northern portion of the design. However, these were model artefacts caused by imperfections in the DEM supplied. These erosion areas could be mitigated by refinement of the design input file in this zone to remove these artefacts. Once removed, the gully erosion modelled in this zone is likely to be reduced.

Some gully erosion was identified in isolated zones of the Laleham TSF. However, these were model artefacts caused by imperfections in the DEM supplied. These erosion areas could be mitigated by refinement of the design input file in these zones to remove these artefacts. Once removed, the gully erosion modelled in this zone is likely to be reduced.

The NCPP TSF design is predicted to erode at rates with a low tendency for gully erosion. However, it does erode at higher rates than either the Bottom Dam or Laleham TSFs. The increased gully erosion risk of the NCPP TSF design (relative to Bottom Dam and Laleham) is due to the use of the heavy clay topsoils and the presence of steeper-gradient outer slopes (20% rather than 15%) on some sections of the eastern side of the TSF. The increased gully erosion risk caused by the presence of steeper-gradient outer could be mitigated by further refinement of the design to lower the gradient of the outer slopes in that zone.

1 INTRODUCTION

Landloch has been engaged by Whitehaven Coal Limited (Whitehaven) to carry out SIBERIA landform evolution modelling for three (3) Tailings Storage Facilities (TSFs) at the Blackwater Coal Mine (Blackwater). The 3 TSFs that have been modelled are named:

1. Bottom Dam;
2. Laleham; and
3. NCPP.

This report briefly outlines the SIBERIA landform evolution modelling methods and provides the modelling results, including erosion statistics and visualisations.

2 MODELLING METHODS

2.1 The SIBERIA model

The SIBERIA landform evolution model predicts the long-term, 3D development of channels and hillslopes (e.g. landform batters) in a catchment based on runoff, erosion, and deposition.

SIBERIA has been successfully applied to explain aspects of the geomorphology of natural landforms (Willgoose 1994) and has been widely used to assess the evolution of constructed waste dumps on mine sites across Australia and overseas (Willgoose 1995; Willgoose and Riley 1993; Boggs *et al.* 2000; Hancock *et al.* 2003; Hancock and Willgoose 2004; Hancock 2004; Mengler *et al.* 2004; Hancock and Turley 2006). It has also been subjected to numerous validation studies. In general, the validation studies indicate that SIBERIA's predictions of landform evolution are reasonable provided the model is suitably parameterised (Hancock *et al.* 2000; Hancock *et al.* 2003). In one validation study (Hancock 2004) it was noted that erosion rates predicted by SIBERIA for a catchment in the Northern Territory compared favourably to erosion estimates derived using the caesium-137 method. As the two erosion assessment methods use independent input information, the reported agreement is particularly significant.

SIBERIA solves for two variables: elevation, from which slope geometries are determined, and an indicator function that determines where erosion features (channels) exist.

Changes to the predicted erosion features is governed by an activation threshold that is dependent on the runoff discharge and gradient of the slope. When the activation threshold is exceeded, an erosion feature is predicted to develop. In this way, it is possible for a modelled surface to initially have no erosion features and for rills/gullies to develop where the activation threshold is exceeded.

The rate at which rills and gullies develop is controlled by a channelisation function. SIBERIA does not directly input rainfall or material erodibility parameters. Rather, the SIBERIA input parameters define the channelisation function that is a function of both runoff and erosion (Willgoose *et al.* 1989). As a result, SIBERIA parameters are specific to both the climatic regime and the material being considered and must be derived for each specific material located within each specific climatic regime.

2.2 SIBERIA input parameters

SIBERIA predicts the long-term average change in elevation of a node (i.e. a point in the landscape) by predicting the volume of sediment lost from that node. The rate of sediment transport through a node (q_s in units of m^3/y) is determined by the equation:

$$q_s = \beta_1 \times q^{m_1} \times S^{n_1} \quad 1)$$

where β_1 is the sediment transport rate coefficient (unitless), q is discharge (m^3/y), m_1 is the discharge exponent (unitless), S is the slope (m/m), and n_1 is the slope exponent (unitless).

SIBERIA does not directly model discharge, but uses sub-grid effective parameterisation which relates discharge to the area draining through a node as:

$$q = \beta_3 \times A^{m_3} \quad 2)$$

where β_3 is the coefficient between discharge and area (unitless), A is area (m^2), and m_3 is the exponent of the area in discharge (unitless).

To run SIBERIA, the parameters β_1, m_1, n_1, β_3, and m_3 are needed. There is interaction between all 5 parameters, with the result that an almost infinite number of parameter sets will all show the same rate of erosion, though some aspects of the pattern of erosion that is predicted will vary. Fixed values for β_3, n_1, and m_3 are adopted where possible, reducing the difficulty of deriving parameter values. If the batter to be modelled is identical to the batter for which erosion data are available for calibration, m_3 and β_3 can be taken as 1.0, and for situations where slope gradient does not affect slope erodibility, n_1 can be taken as 1.5 (Willgoose pers. comm.). This is consistent with Kirkby (1971) who suggests values ranging from 1.3–2.0 are reasonable for soils.

Therefore, two key parameters require fitting against runoff and erosion data: β_1 and m_1. Effectively, the β_1 parameter could be described as an erosion rate parameter, as it primarily controls the rate of sediment movement. The m_1 parameter could be described as primarily controlling slope length responses of erosion.

2.3 Derivation of parameters

The β_1 and m_1 input parameters for SIBERIA are derived by fitting the SIBERIA model equations to time series data of runoff and erosion. However, in most instances, sufficient record lengths of these time series data are not available for the landforms being considered. This is particularly true for landform design planning where the landforms do not yet exist. Therefore, Landloch has developed an alternative approach for deriving the β_1 and m_1 SIBERIA input parameters:

a) Use measurements of material runoff and erosion from laboratory-based flume and rainfall simulations to derive calibrated WEPP model parameters.
b) Generate daily time-series data of runoff and erosion using WEPP set up with:
    a. Batter geometries consistent with the geometries of the landform being considered (allowing values for β_3, n_1, and m_3 to be fixed).
    b. A long-term climate sequence (100-years) that is site specific and that contains a frequent, infrequent, rare and very rare events.
c) Fit WEPP runoff and erosion output data to the SIBERIA model equations to derive values for β_1 and m_1 that are both material and site specific.

2.4 Surface soils and vegetation groundcover

SIBERIA LEM input parameters were previously derived for two soils present at Blackwater:

1. Heavy clay topsoil; and
2. Light clay topsoil.

SIBERIA LEM input parameters were derived through a process of laboratory-based erodibility testing, long-term WEPP (Water Erosion Prediction Project) runoff/erosion modelling, and analysis of 100 years of WEPP model output of daily runoff and erosion. This process is detailed as part of previous landform evolution modelling undertaken for waste landforms at Blackwater (Landloch 2024).

In assigning SIBERIA parameters for each TSF, it was assumed that the topsoils and vegetation groundcover levels applied be spatially consistent with those applied in the previous landform evolution modelling work (Landloch 2024). As such, the following topsoils and vegetation groundcover levels were applied:

- Bottom Dam – Light clay topsoil with 50% vegetation cover;
- Laleham – Light clay topsoil with 50% vegetation cover; and
- NCPP – Heavy clay topsoil with vegetation groundcover levels of 70%.

2.5 Model settings

The Digital Elevation Models (DEMs) modelled by SIBERIA included the landform surface meshed into the surrounding landscape. A random roughness (±10cm) was added to the DEMs prior to modelling. This was done to reduce triangulation gridding artefacts from the surface of the DEMs and to provide a more realistic surface for modelling (landform surfaces are not perfectly smooth).

The following SIBERIA outputs were produced for each landform modelled at years 50, 100, 150, 200, 250, and 300:

- Maximum depth of gullies at each output year with gullies defined as having a minimum depth of 0.3m;
- Average erosion (t/ha/y);
- Cumulative erosion (mm) for each output year
- Visual outputs showing the evolved DEM over which is draped the predicted material movement (erosion and deposition).

2.6 Modelling assumptions

The following assumptions apply to the SIBERIA modelling:

- The DEMs of the existing land surface and design files for the rehabilitation TSFs provided by Whitehaven are assumed to be accurate.
- Input parameters are based on a single material being present on the outer surface of the modelled landform. Light clay topsoil was applied to the surface

of the Bottom Dam and Laleham TSFs. Heavy clay topsoil was applied to the NCPP TSF.

- In considering vegetation groundcover this report specifically considers contact cover of vegetation on the soil surface. Practically, this means a combination of grass cover and anchored (not readily moved) surface litter.
- Vegetation groundcover levels for the light clay topsoil was 50%. Vegetation groundcover levels for the heavy clay topsoil was 70%.
- These vegetation groundcover levels are rapidly achieved and maintained in the long-term. It is assumed that soil management (including stripping, stockpiling, replacement, amendment, and fertilisation) will be carried out effectively to maximise early and continuing plant growth.
- During construction:
    - Batter slopes will not be formed with flow-concentrating profiles (e.g. variations in surface elevation such that there is cross-slope concentration of flow into consistent depressions running downslope).
    - Any cross-slope ripping will be carried out strictly on the contour.

3 SIBERIA MODEL SETUP

3.1 SIBERIA parameters

The SIBERIA model parameters used are shown in Table 1. These parameters were originally reported by Landloch (2024).

Table 1: Estimated SIBERIA parameters.

Material	Vegetation Groundcover (%)	m_1	β_1	n_1
Light clay topsoil	50	1.1127	0.00262	1.5
Heavy clay topsoil	70	1.2375	0.00360	1.5

3.2 Digital elevation models

Proposed 3D rehabilitation design files for the Bottom Dam, Laleham, and NCPP TSFs were provided to Landloch by Whitehaven (Figures 1–3). These rehabilitation landforms were designed based on WEPP model runoff/erosion results for the soils and vegetation groundcover levels that are to be applied.

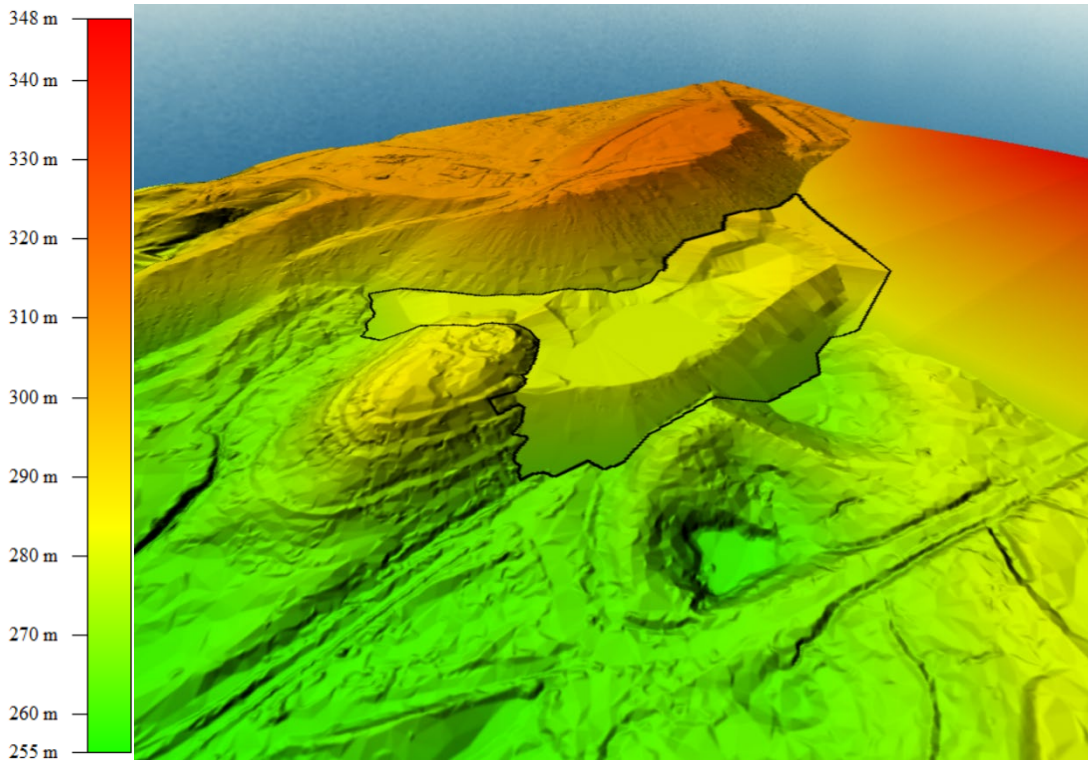


Figure 1: Digital elevation model of the Bottom Dam TSF. The black line shows the modelling domain considered within the SIBERIA LEM.

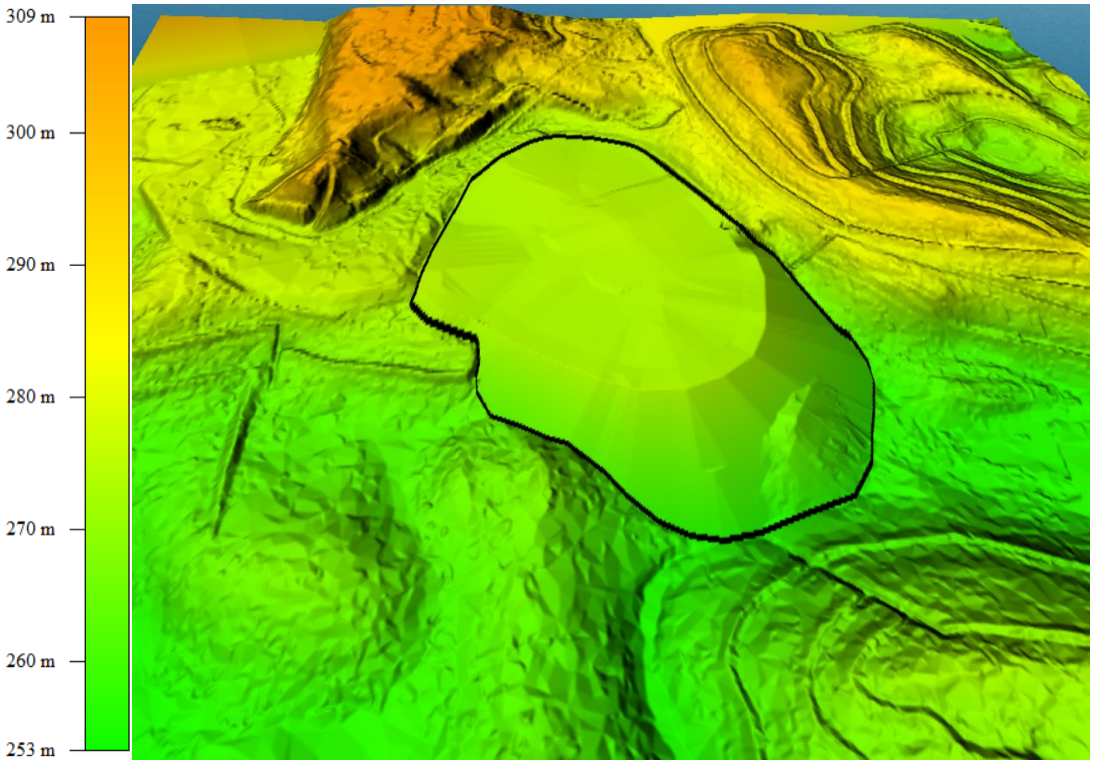


Figure 2: Digital elevation model of the Laleham TSF. The black line shows the modelling domain considered within the SIBERIA LEM.

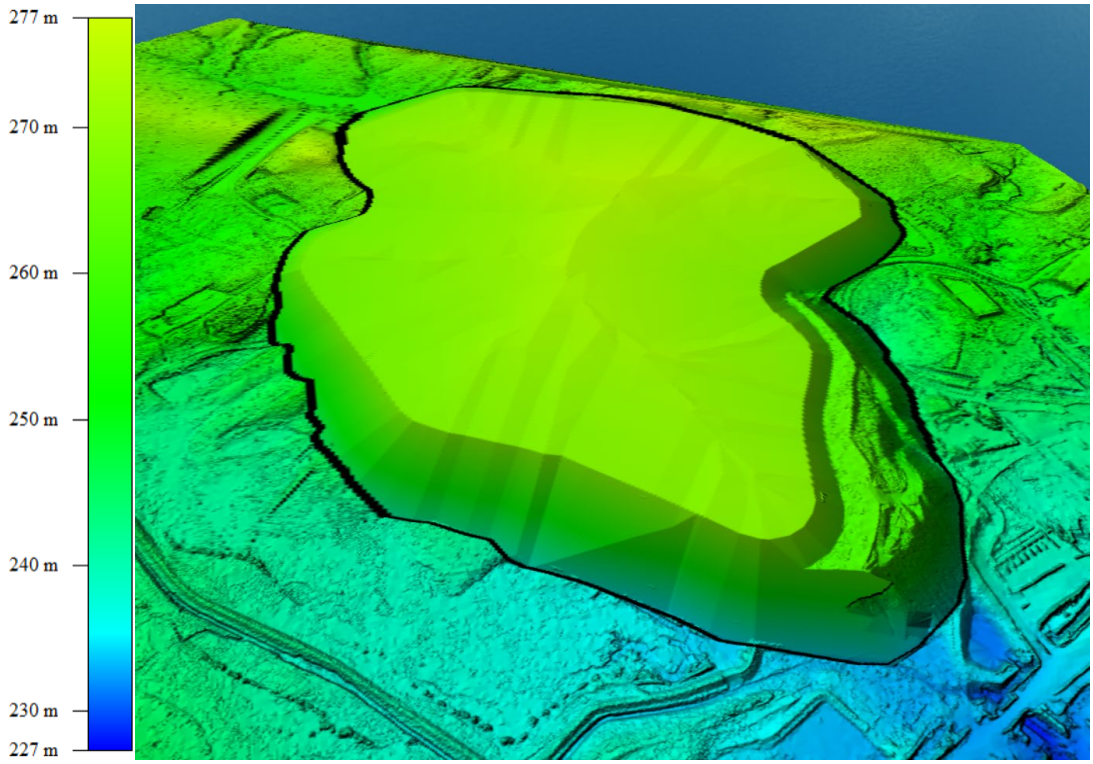


Figure 3: Digital elevation model of the NCPP TSF. The black line shows the modelling domain considered within the SIBERIA LEM.

4 SIBERIA LEM OUPUTS

Using input parameters derived for the soils and vegetation groundcover to be applied to the landforms, the SIBERIA LEM was run for a period of 300 years, with outputs being generated at 50, 100, 200, and 300 years within the simulation period.

At each output year, visualisations of rill/gully development were produced along with a table of maximum gully depths, average annual erosion rates, and cumulative average erosion depths. These rates and depths are calculated for the steep-gradient outer slopes within the modelling domain and exclude the low gradient landform top or berm areas (if they exist).

Negative material movements (i.e. erosion) that exceed 0.3m are considered gully erosion and are reported in the tables. The reported maximum gully depth is calculated as the average of the largest 1% of material movements.

Visualisations for 300 years are shown in the sections below. However, all visualisations (50, 100, 200, and 300 years) are provided in Appendix A.

4.1 Bottom Dam

Rehabilitation of the Bottom Dam TSF is planned to use light clay topsoil with 50% vegetation groundcover. The results shown in Table 2 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the steep-gradient outer slopes are low. The maximum gully depth after 300 years is predicted to be 0.4m (that is gullying is largely absent). The SIBERIA output indicates that the Bottom Dam rehabilitation design is not prone to significant levels of gully erosion if the surface conditions (material type and vegetation groundcover levels) are achieved.

Figure 4 shows SIBERIA output after 300 years of simulation. Some gully erosion is predicted to occur in the northern section of the TSF (circled in purple). This is due to a converging topography in that area. This could be mitigated by further refinement of the design input file in this zone so that a fixed gradient is used, and a steepening gradient is avoided.

Table 2: Predicted erosion rates and gully depths for the Bottom Dam TSF.

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative average erosion (mm)
Light clay topsoil with 50% vegetation groundcover			
50	-	0.5	3
100	-	0.4	5
200	0.3	0.4	10
300	0.4	0.3	14

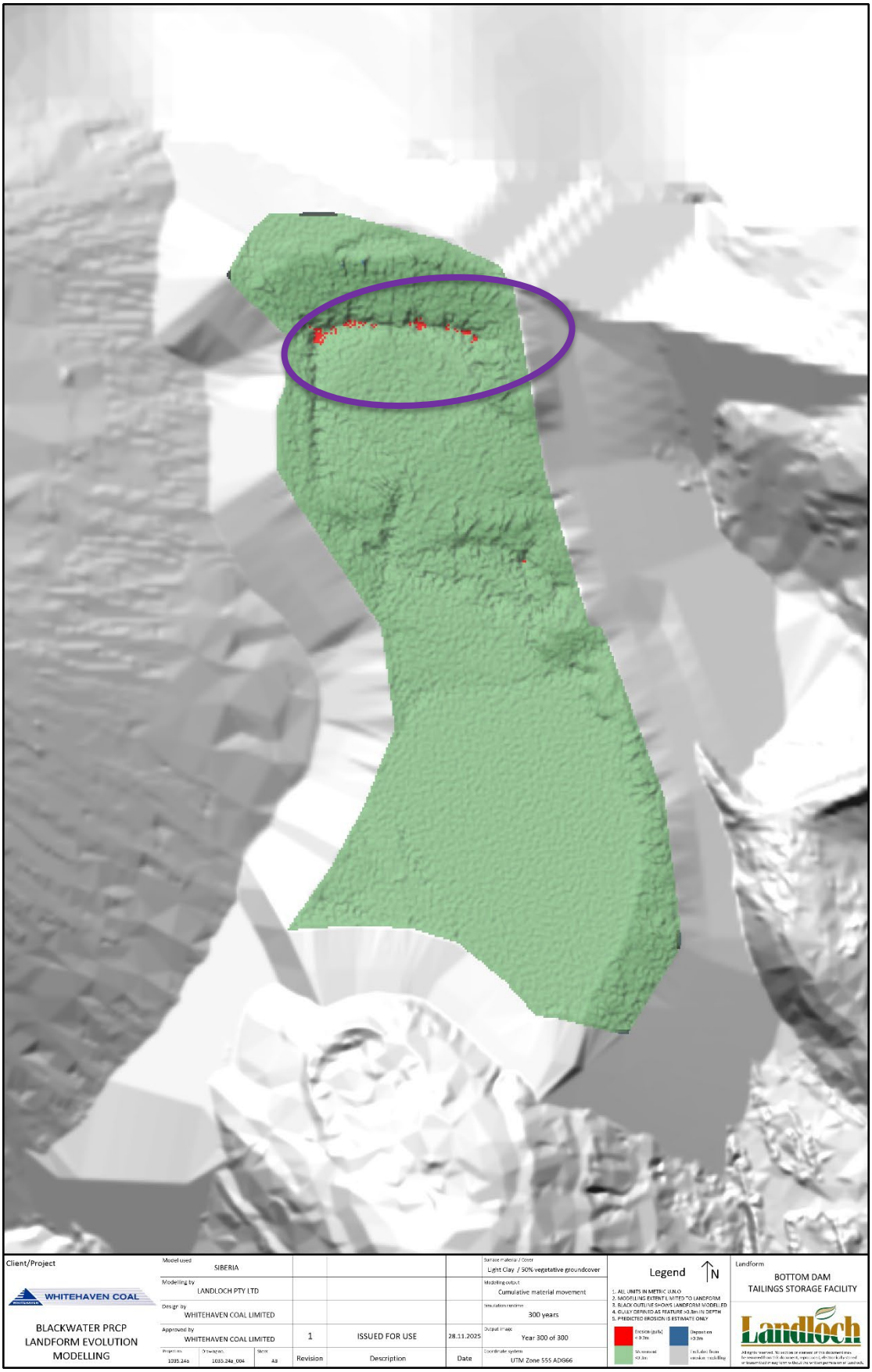


Figure 4: Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 300 years.

4.2 Laleham

Rehabilitation of the Laleham TSF is planned to use light clay topsoil with 50% vegetation groundcover. The results shown in Table 3 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the steep-gradient outer slopes are low. The maximum gully depth after 300 years is predicted to be <0.3m (that is gullying is absent). The SIBERIA output indicates that the Laleham rehabilitation design is not prone to significant levels of gully erosion if the surface conditions (material type and vegetation groundcover levels) are achieved.

Figure 5 shows SIBERIA output after 300 years of simulation. Some gully erosion is predicted to occur in isolated zones of the TSF (circled in yellow). These are model artefacts caused by imperfections in the DEM supplied (i.e. artificial elevation differences resulting from triangulation and/or gridding of the data). These erosion areas could be mitigated by refinement of the design input file in these zones to remove these artefacts. Once removed, the gully erosion modelled in this zone is likely to be reduced.

Table 3: Predicted erosion rates and gully depths for the Laleham TSF.

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative average erosion (mm)
Light clay topsoil with 50% vegetation groundcover			
50	-	1.4	9
100	-	1.4	18
200	-	1.4	34
300	-	1.3	51



Figure 5: Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 300 years.

4.3 NCPP

Rehabilitation of the NCPP TSF is planned to use heavy clay topsoil with 70% vegetation groundcover. The results shown in Table 4 indicate that at a vegetation groundcover level of 50%, predicted erosion rates of the steep-gradient outer slopes are low. The maximum gully depth after 300 years is predicted to be 0.6m.

The SIBERIA output indicates that the NCPP rehabilitation design is not prone to significant levels of gully erosion if the surface conditions (material type and vegetation groundcover levels) are achieved. However, it is more prone to erosion than either the Laleham or Bottom Dam TSF designs.

Figure 6 shows SIBERIA output after 300 years of simulation. The increased gully erosion risk of the NCPP TSF design (relative to Bottom Dam and Laleham) is due to:

1. The heavy clay topsoil being more erodible than the light clay topsoil, with gullies being triggered by the discharge of runoff generated on the lower-gradient TSF upper surface onto the steeper-gradient outer slopes; and
2. The presence of steeper-gradient outer slopes (20% rather than 15%) on sections of the eastern side of the TSF circled in yellow.

The increased gully erosion risk caused by the presence of steeper-gradient outer slopes (20% rather than 15%) on sections of the eastern side of the TSF could be mitigated by refinement of the design input file to lower the gradient of the outer slopes in that zone.

Table 4: Predicted erosion rates and gully depths for the NCPP TSF.

Simulation year	Maximum gully depth (m)	Average annual erosion (t/ha/y)	Cumulative average erosion (mm)
Heavy clay topsoil with 70% vegetation groundcover			
50	-	4.4	27
100	0.3	4.2	54
200	0.4	4.1	105
300	0.6	4.0	154

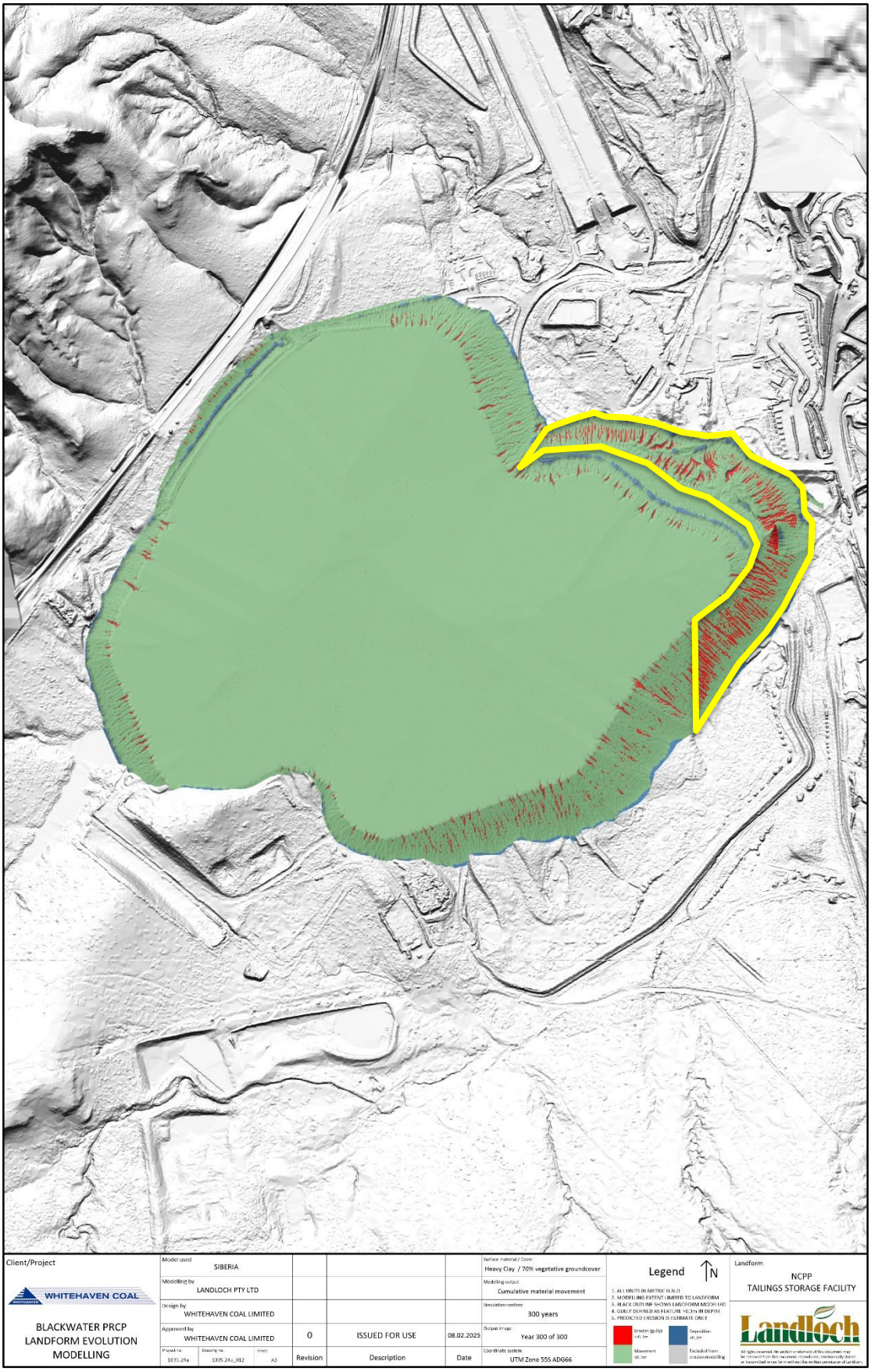


Figure 6: Predicted erosion and deposition depths of the NCPP TSF rehabilitation landform after 300 years.

5 CONCLUSIONS

SIBERIA LEM simulations indicate that the 3 proposed TSFs modelled (Bottom Dam, Laleham, and NCPP) have a low tendency for gully erosion (up to 300 years) provided the correct soils and the target levels of vegetation groundcover are achieved.

An area of increased gully erosion potential was identified in the southern section of the proposed Bottom Dam design. This increased risk is due to a steepening of the gradient in that area. This could be mitigated by refinement of the design input file in this zone so that a fixed gradient is used, and a steepening gradient is avoided. Another area of increased erosion risk was identified in the northern portion of the design. However, these were model artefacts caused by imperfections in the DEM supplied. These erosion areas could be mitigated by refinement of the design input file in this zone to remove these artefacts. Once removed, the gully erosion modelled in this zone is likely to be reduced.

Some gully erosion was identified in isolated zones of the Laleham TSF. However, these were model artefacts caused by imperfections in the DEM supplied. These erosion areas could be mitigated by refinement of the design input file in these zones to remove these artefacts. Once removed, the gully erosion modelled in this zone is likely to be reduced.

The NCPP TSF design is predicted to erode at rates with a low tendency for gully erosion. However, it does erode at higher rates than either the Bottom Dam or Laleham TSFs. The increased gully erosion risk of the NCPP TSF design (relative to Bottom Dam and Laleham) is due to the use of the heavy clay topsoils and the presence of steeper-gradient outer slopes (20% rather than 15%) on some sections of the eastern side of the TSF. The increased gully erosion risk caused by the presence of steeper-gradient outer could be mitigated by refinement of the design to lower the gradient of the outer slopes in that zone.

The model output has assumed the use of either a vegetated light clay or vegetated heavy clay soils as the surface material. These soils were found to be the dominant soils across Blackwater mine. However, if alternative growth media (e.g. different soil types, ameliorated subsoils, or manufactured growth media, etc.) are identified in the future and are to be used as part of rehabilitation, this modelling should be performed again using these alternatives.

The modelling has been completed to assess the performance of the rehabilitated TSFs with respect to erosional stability. While the landforms are predicted to have a low tendency for gully erosion, there is insufficient data to set site-specific erosion criteria. Whitehaven have committed to the establishment of site-specific erosion criteria that will be informed by site measurements of erosion from rehabilitated landforms.

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APPENDIX A: SIBERIA VISUALISATIONS

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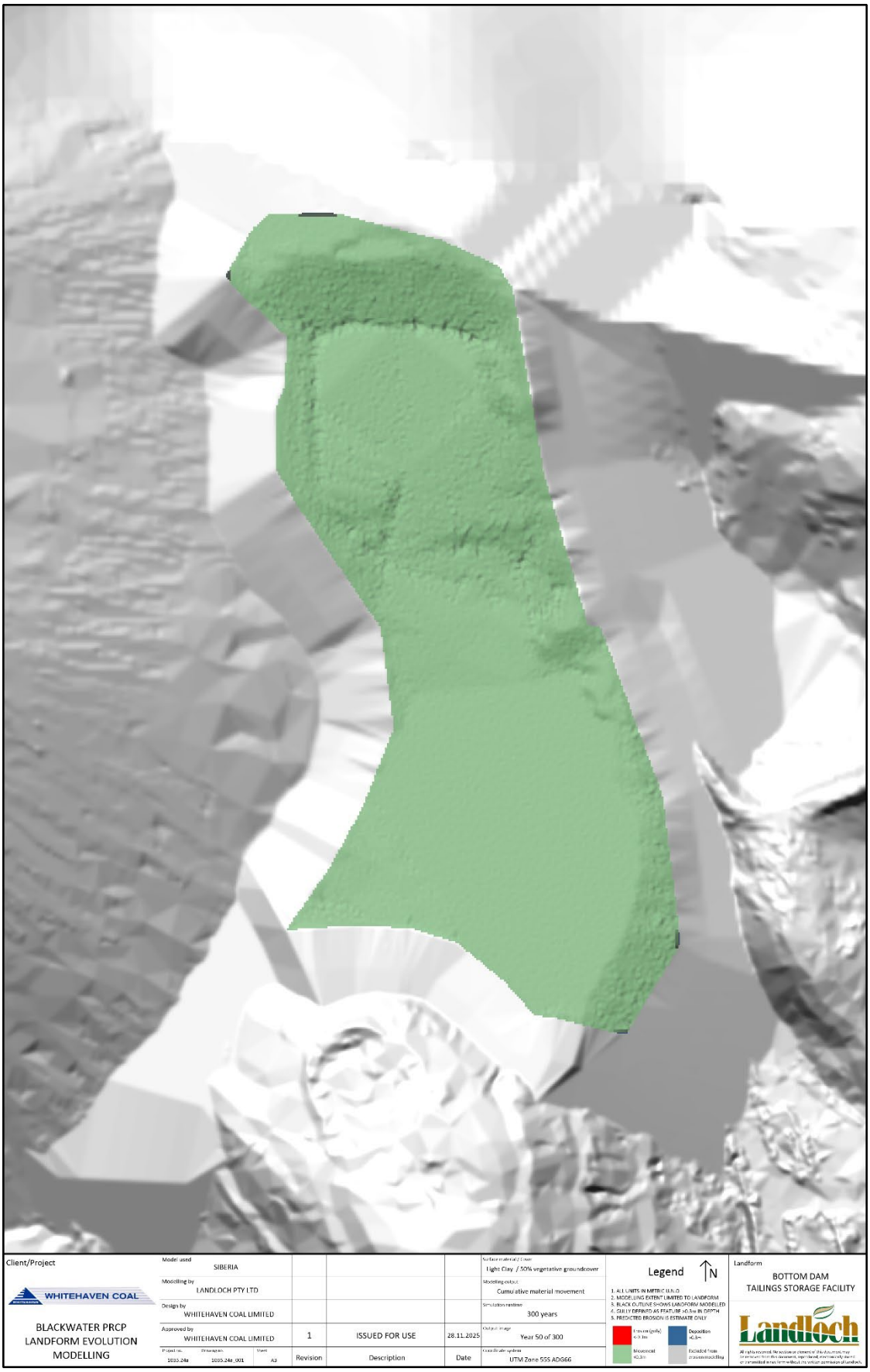


Figure A-1: Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 50 years.

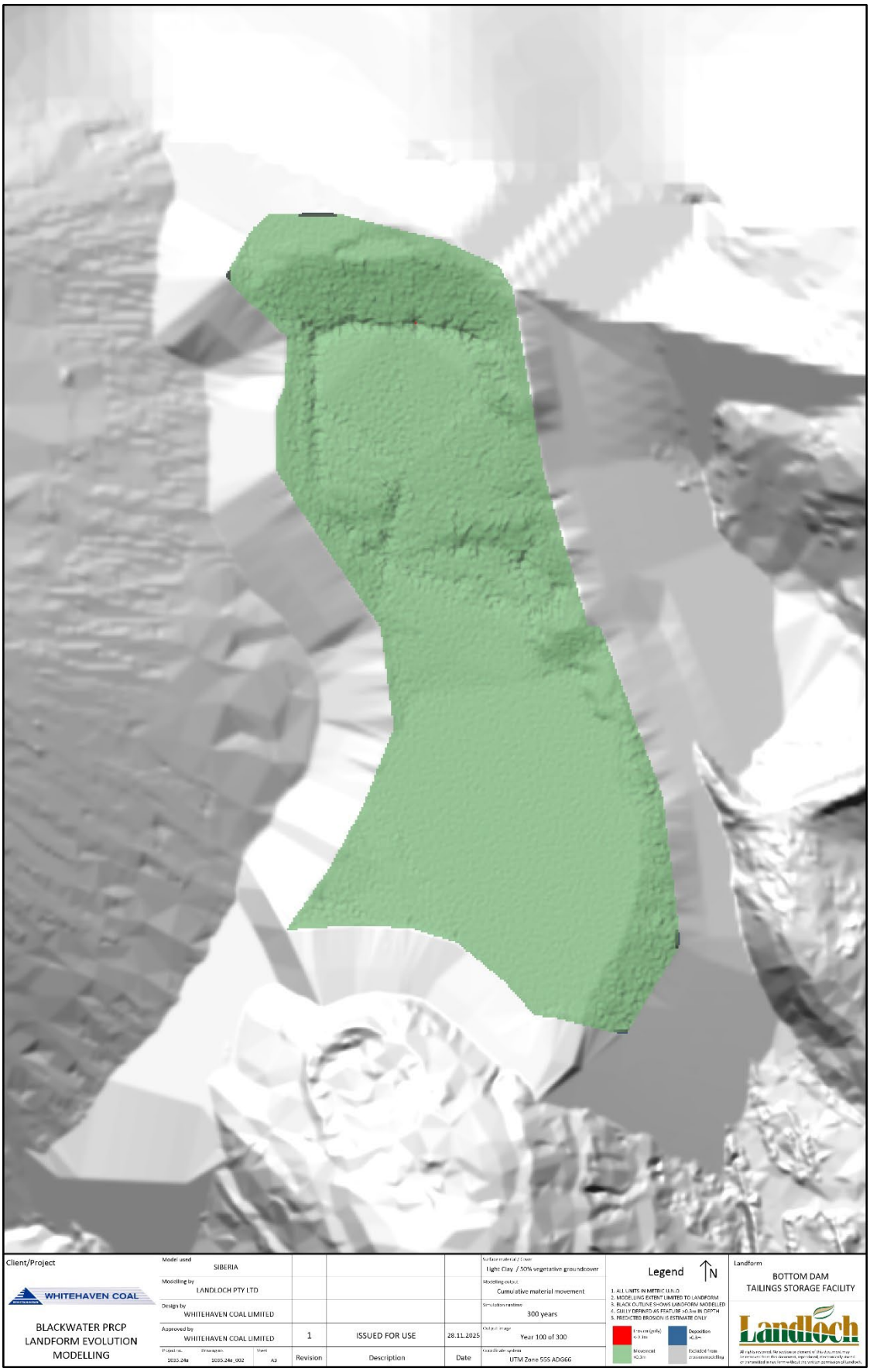


Figure A-2: Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 100 years.

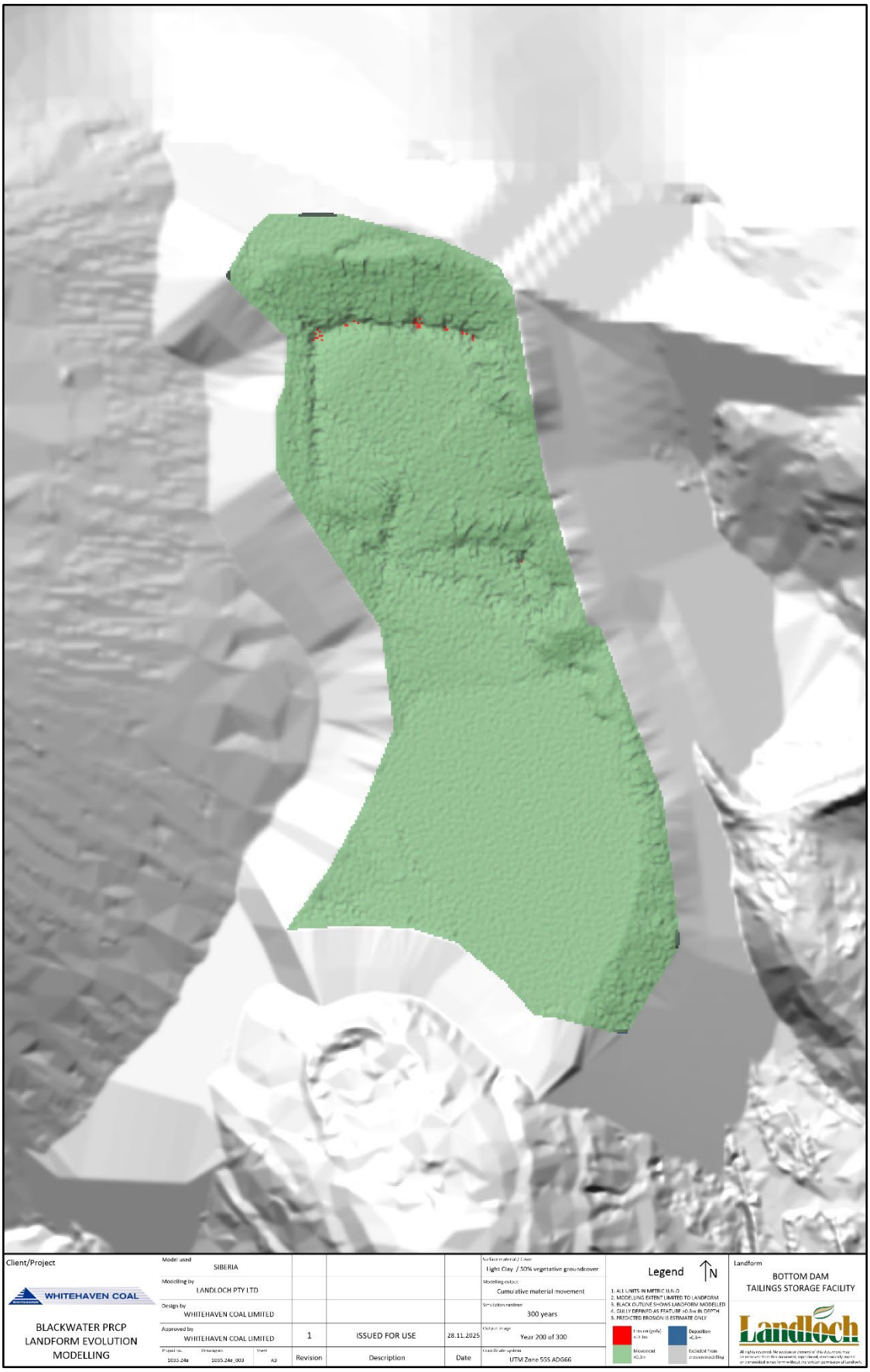


Figure A-3: Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 200 years.

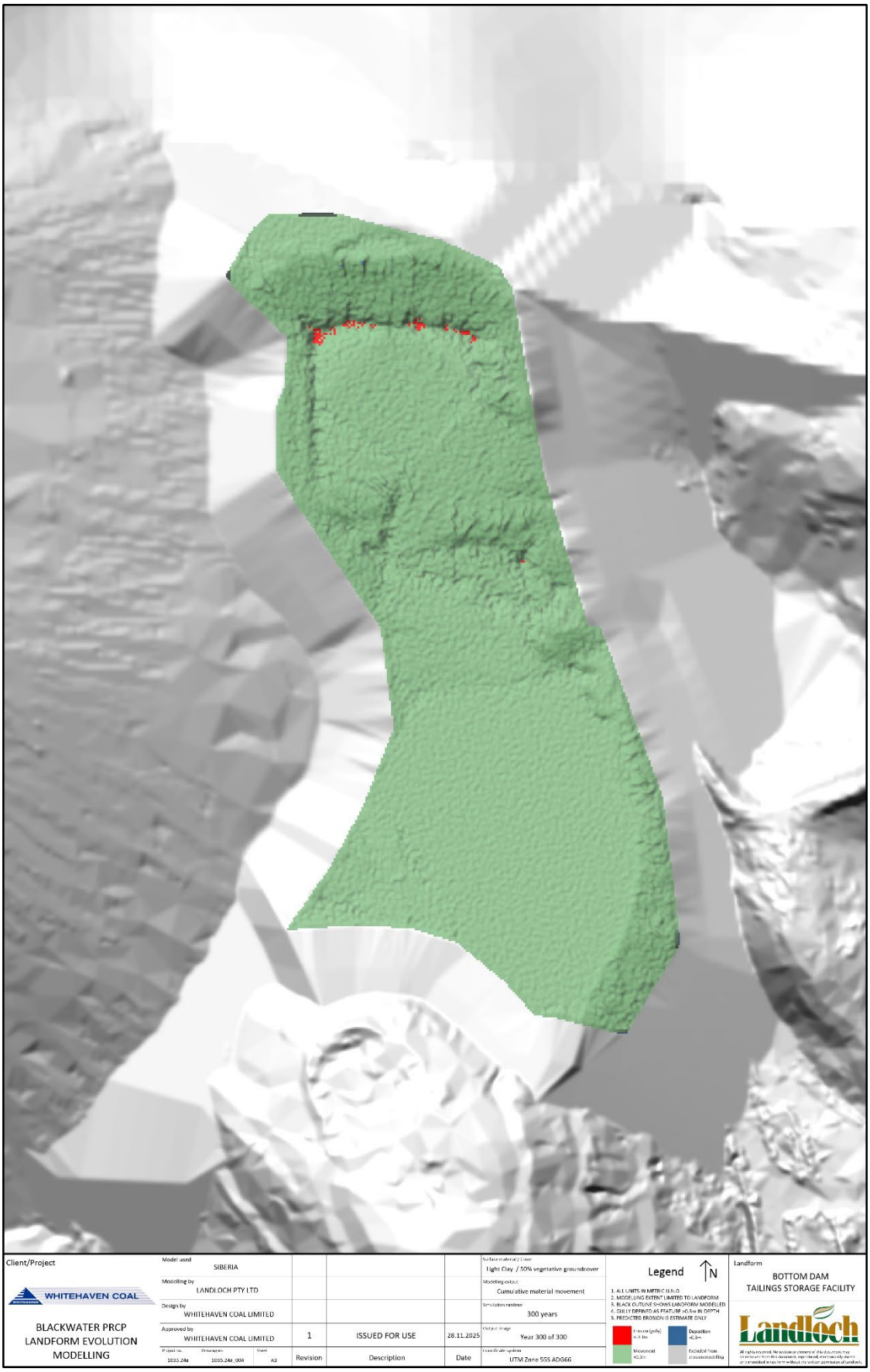


Figure A-4: Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 300 years.

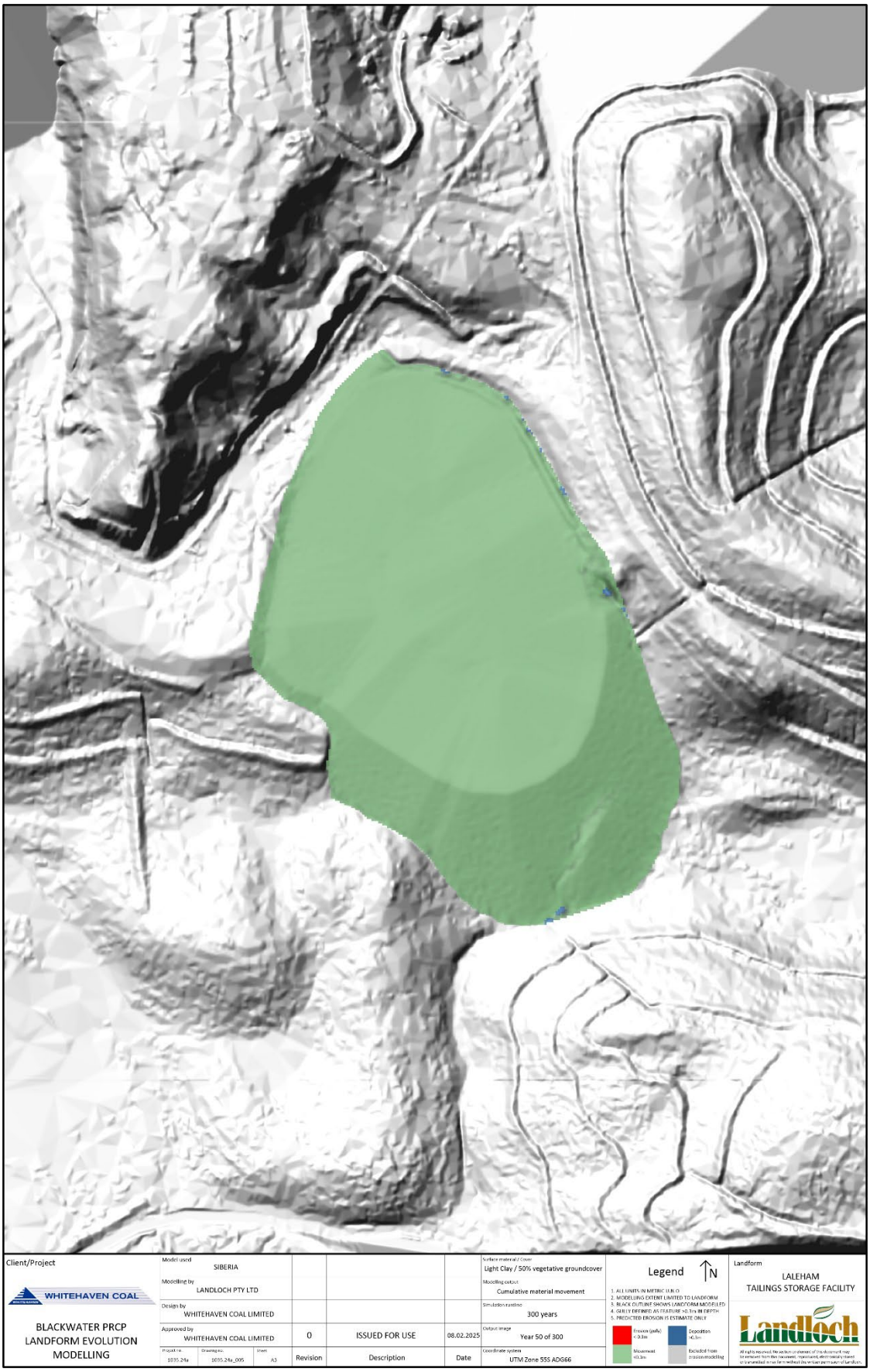


Figure A-5: Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 50 years.

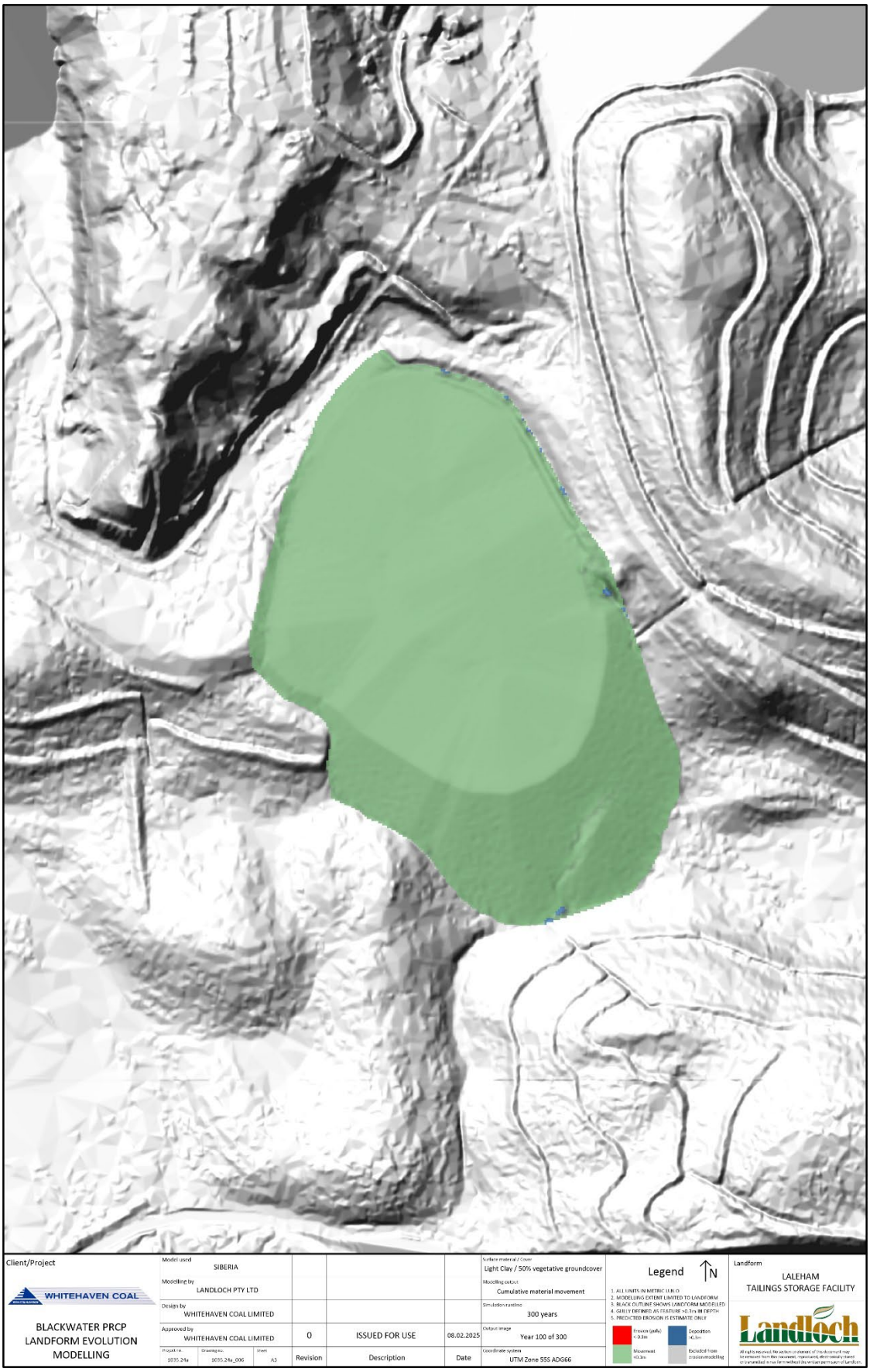


Figure A-6: Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 100 years.

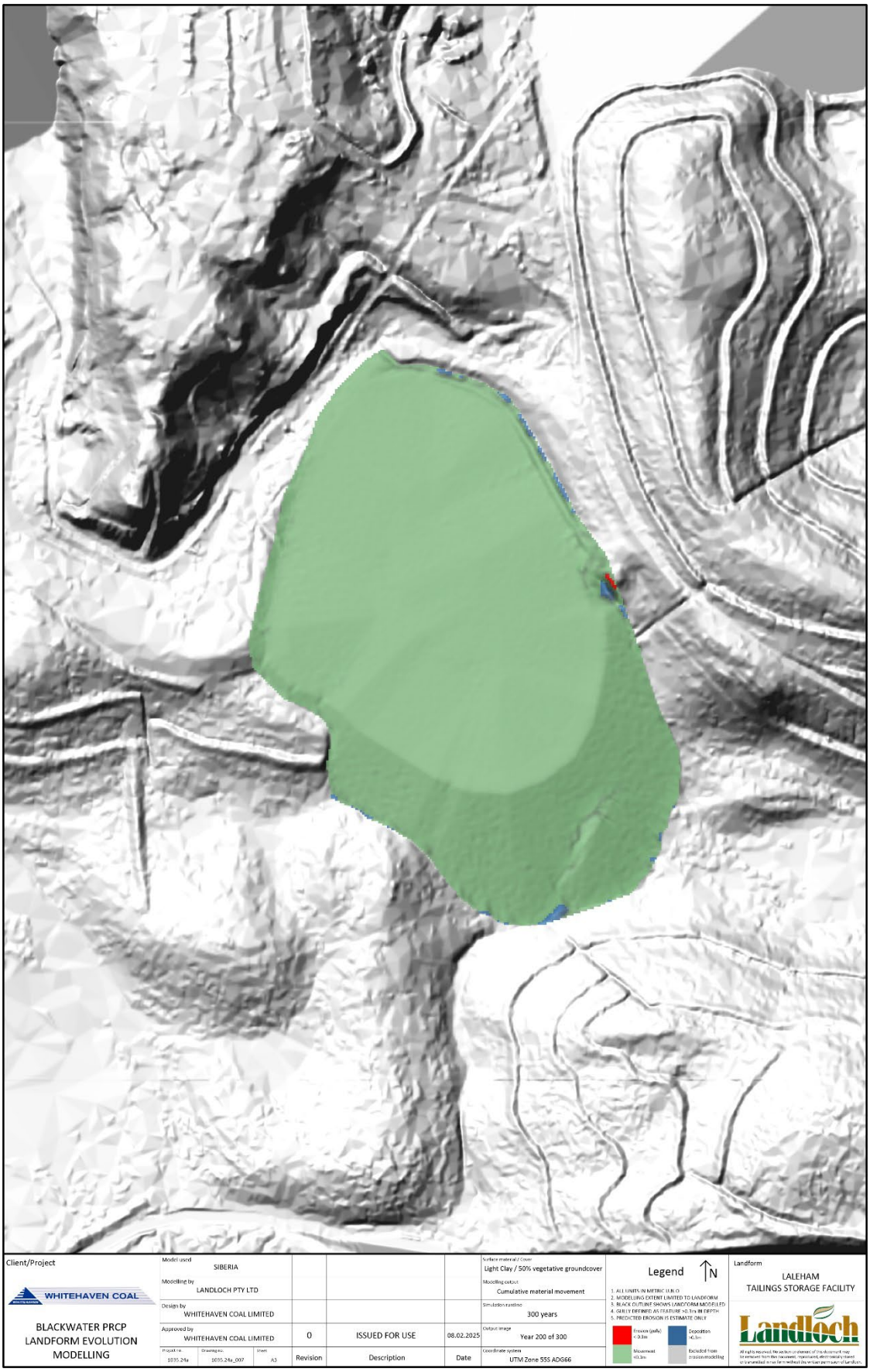


Figure A-7: Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 200 years.

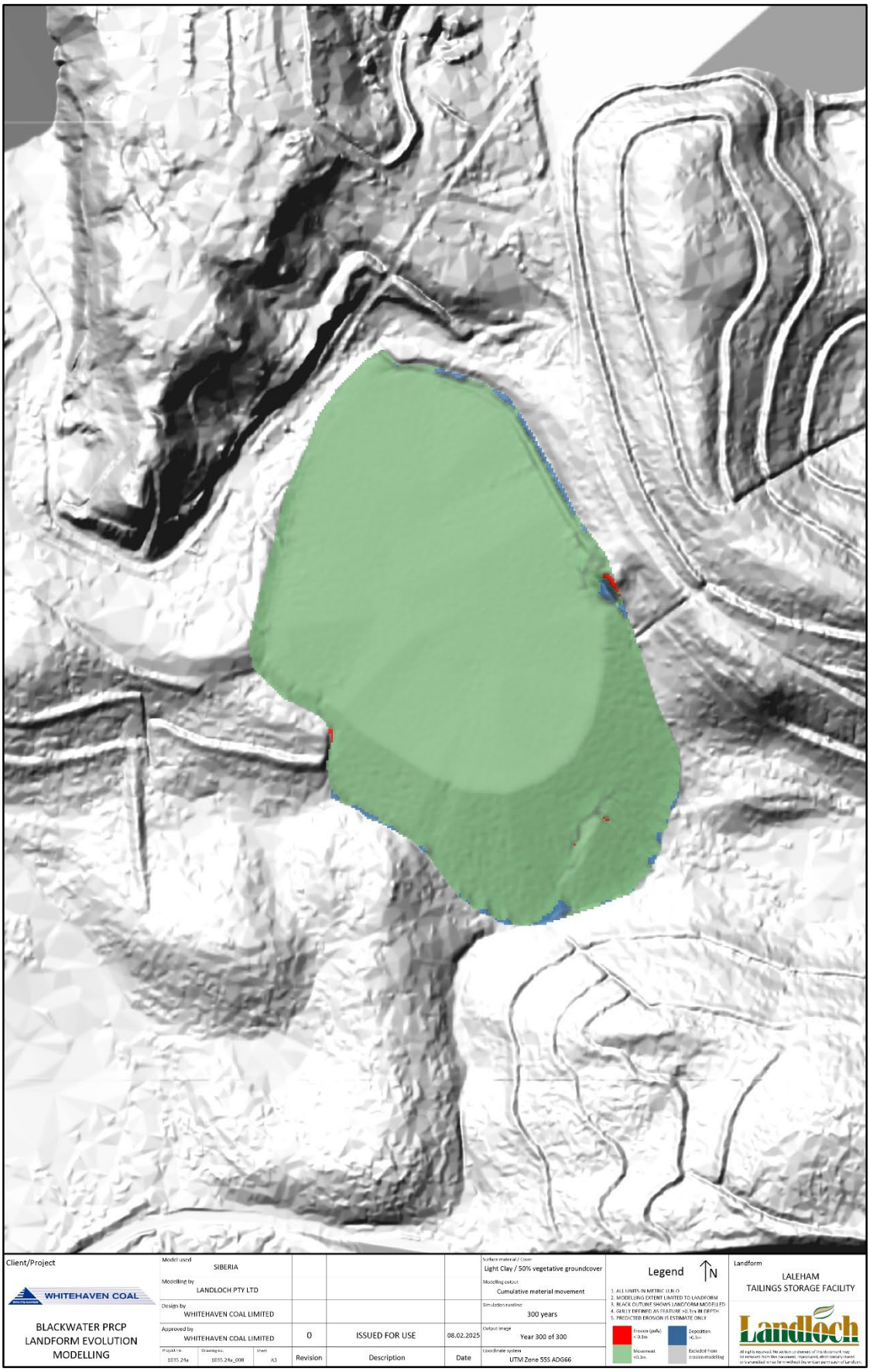


Figure A-8: Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 300 years.



Figure A-9: Predicted erosion and deposition depths of the NCPP TSF rehabilitation landform after 50 years.



Figure A-10: Predicted erosion and deposition depths of the NCPP TSF rehabilitation landform after 100 years.



Figure A-11: Predicted erosion and deposition depths of the NCPP TSF rehabilitation landform after 200 years.



Figure A-12: Predicted erosion and deposition depths of the NCPP TSF rehabilitation landform after 300 years.