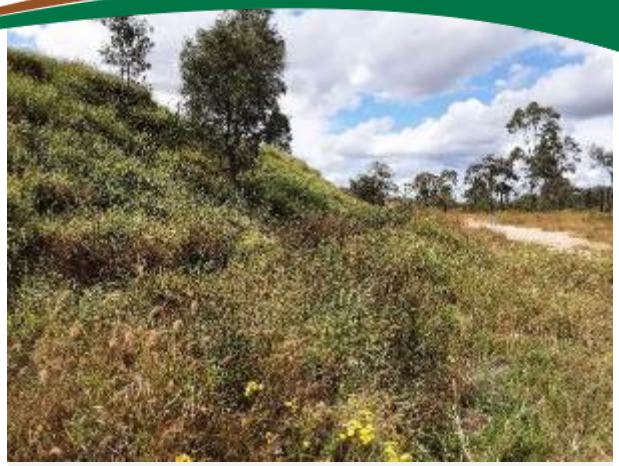


# LANDFORM EVOLUTION MODELLING SIMULATIONS TO SUPPORT TAILINGS STORAGE FACILITY DESIGN: BLACKWATER MINE

November 2025

Whitehaven Coal Limited

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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 $\beta_1$ 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 $\beta_3$ 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 $\beta_1$, $m_1$, $n_1$, $\beta_3$, 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 $\beta_3$, $n_1$, 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 $\beta_3$ 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: $\beta_1$ and $m_1$. Effectively, the $\beta_1$ 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 $\beta_1$ 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 $\beta_1$ 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 $\beta_3$, $n_1$, 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 $\beta_1$ 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 (%) | $m_1$ | $\beta_1$ | $n_1$ |
|---|---|---|---|---|
| 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.

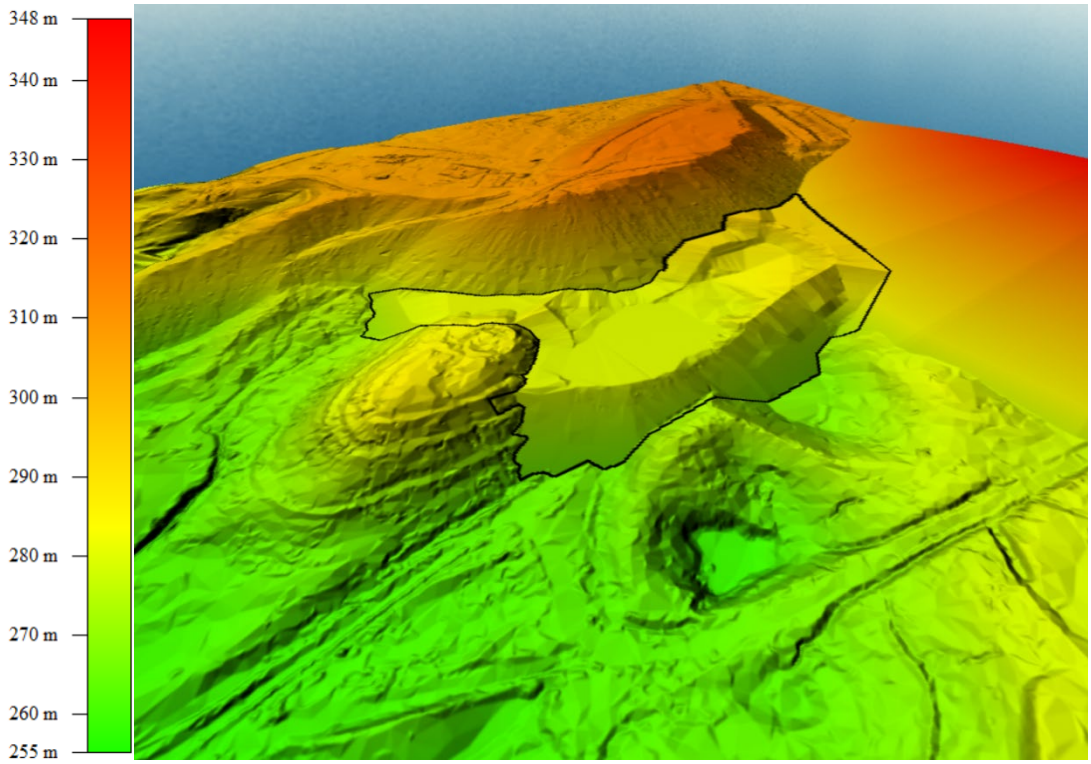



**Figure 1:** Digital elevation model of the Bottom Dam TSF. The black line shows the modelling domain considered within the SIBERIA LEM.

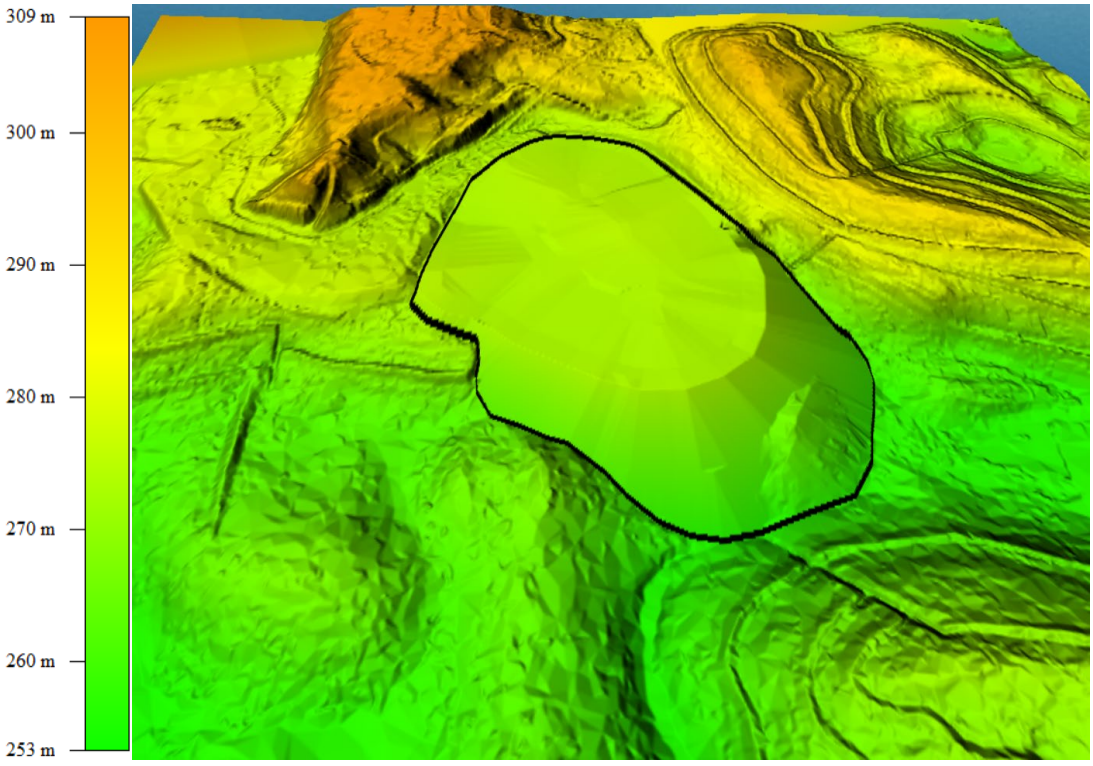



**Figure 2:** Digital elevation model of the Laleham TSF. The black line shows the modelling domain considered within the SIBERIA LEM.

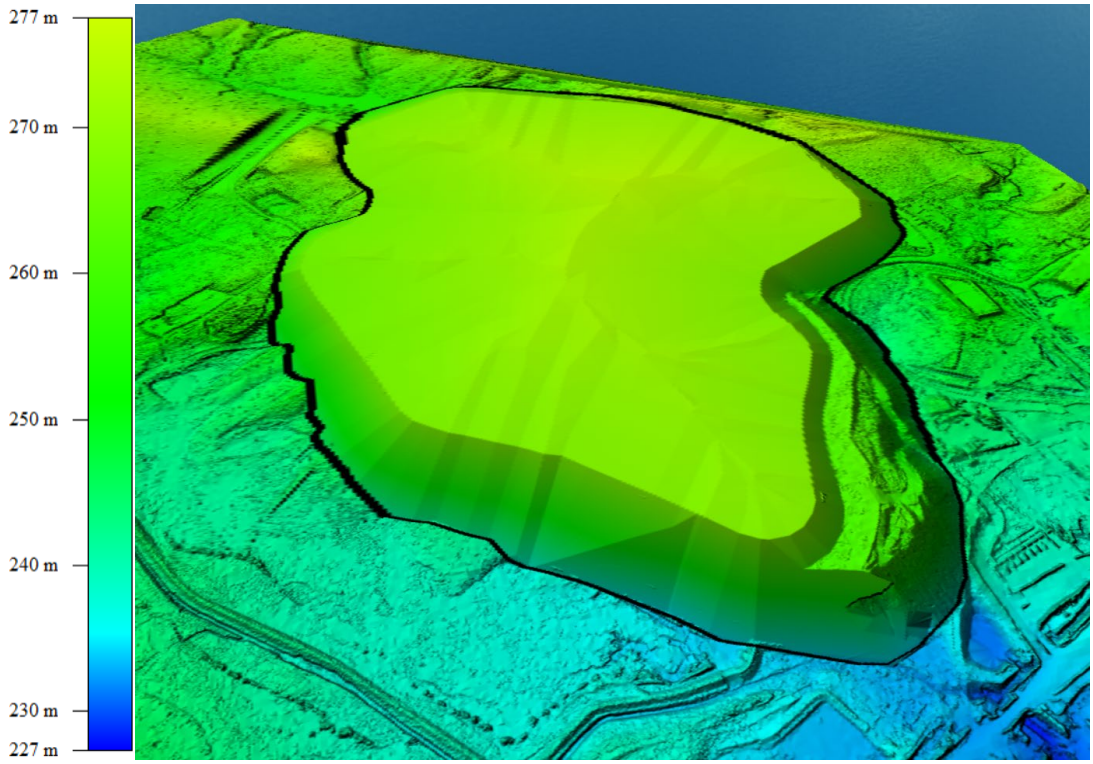



**Figure 3:** Digital elevation model of the NCPP TSF. The black line shows the modelling domain considered within the SIBERIA LEM.

# 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 |

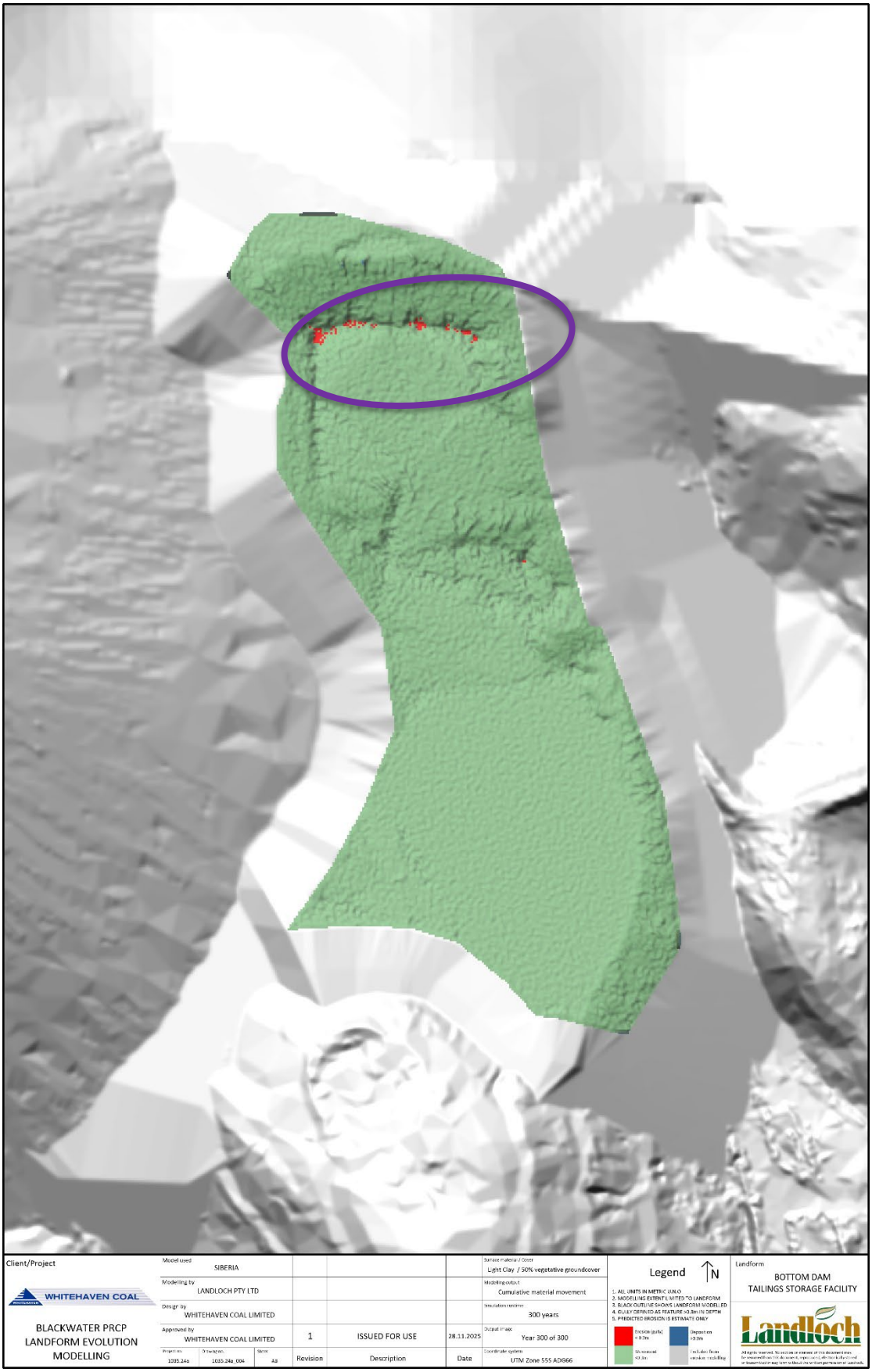



**Figure 4:** Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 300 years.

## 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 |

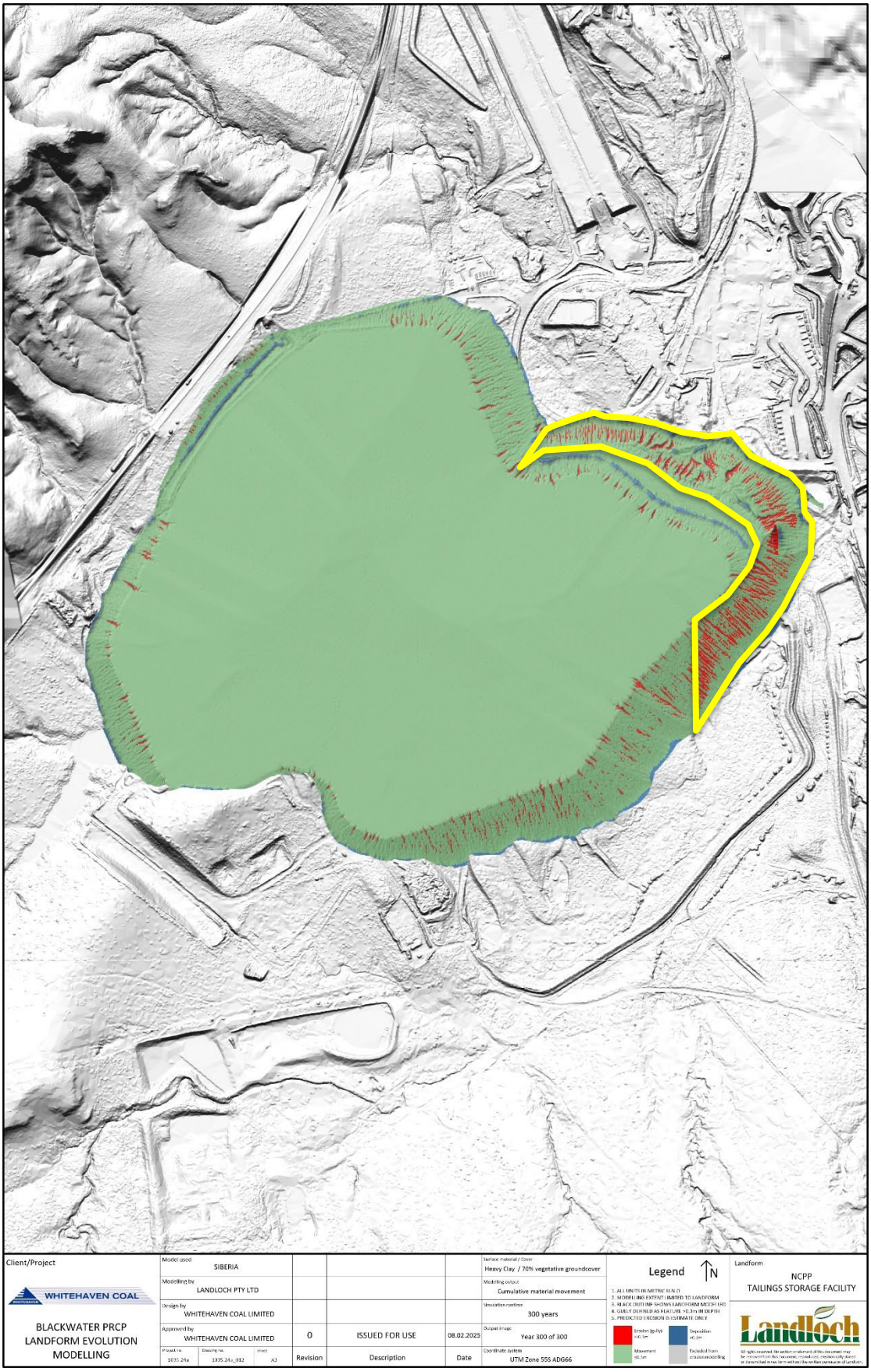



**Figure 6:** Predicted erosion and deposition depths of the NCPP TSF rehabilitation landform after 300 years.

# 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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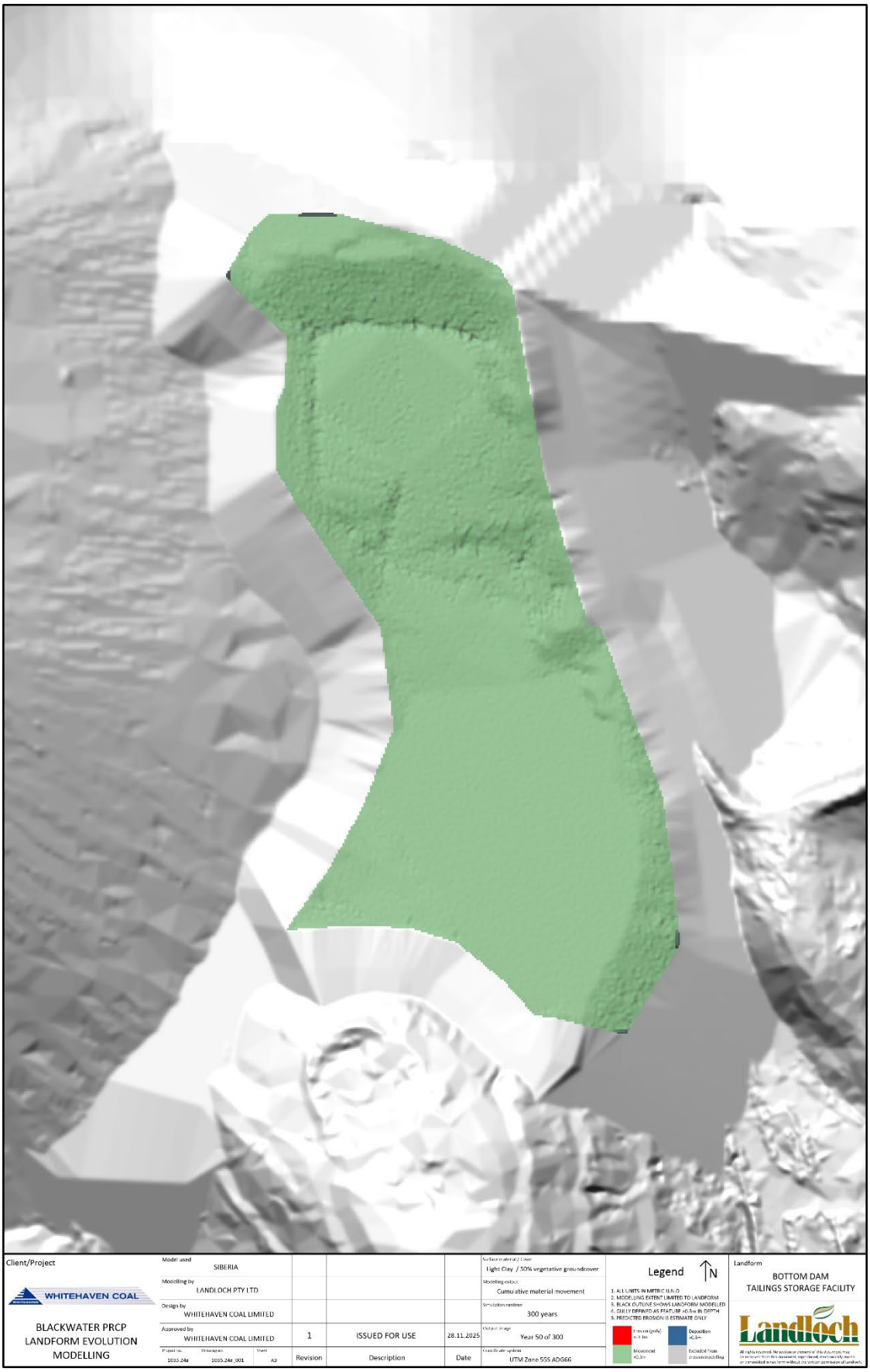



**Figure A-1:** Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 50 years.

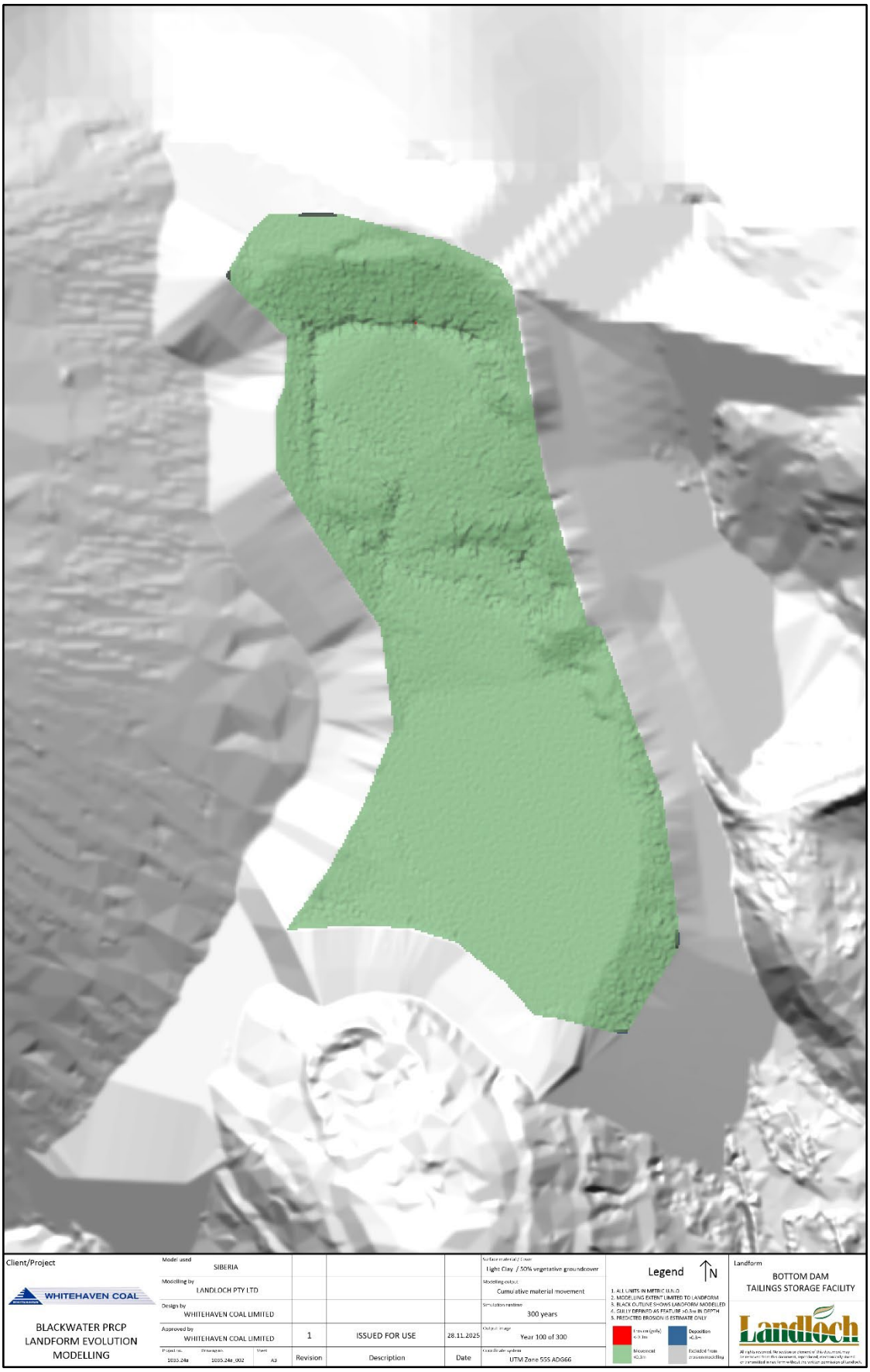



**Figure A-2:** Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 100 years.

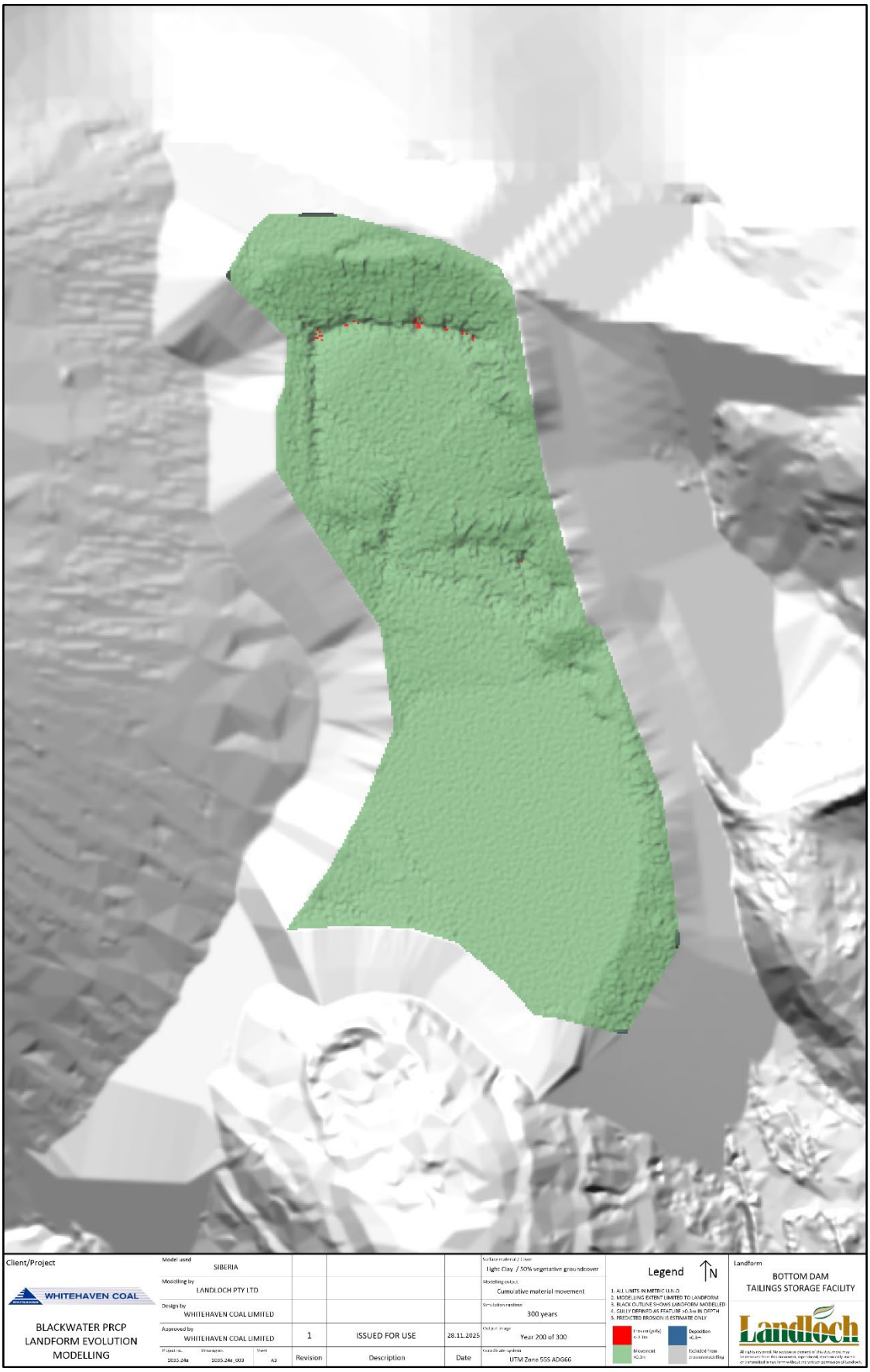



**Figure A-3:** Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 200 years.

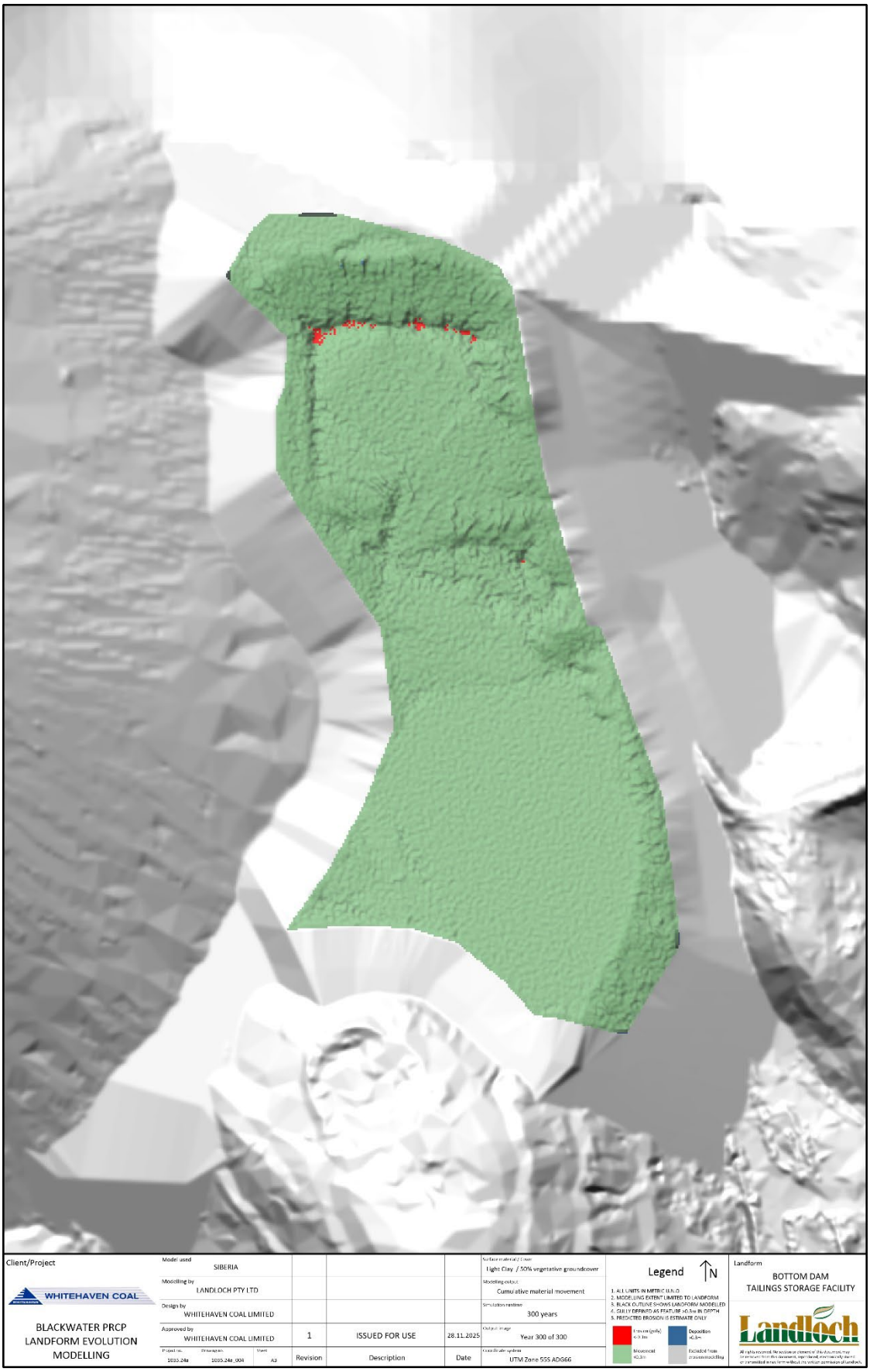



**Figure A-4:** Predicted erosion and deposition depths of the Bottom Dam TSF rehabilitation landform after 300 years.

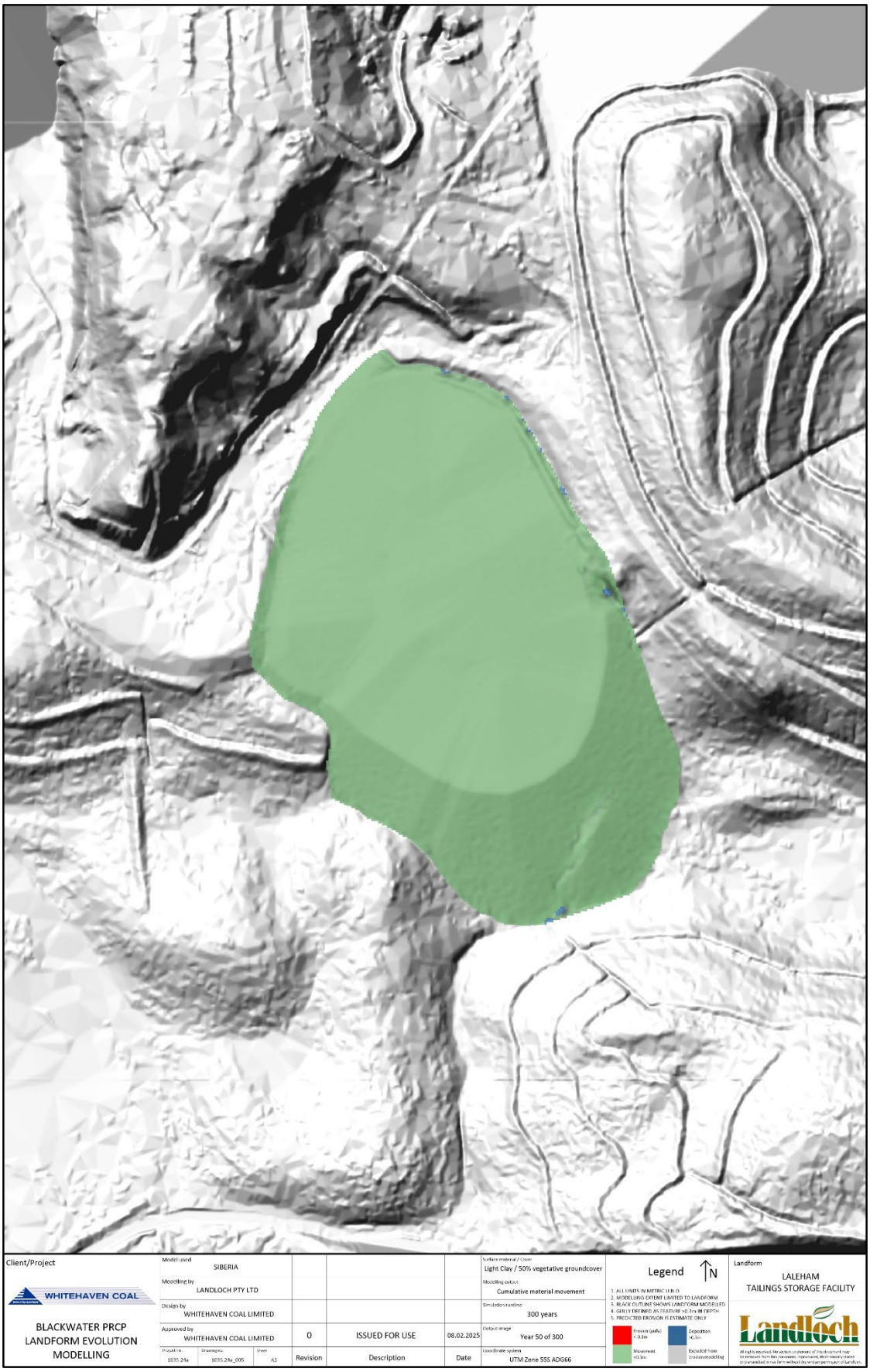



**Figure A-5:** Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 50 years.

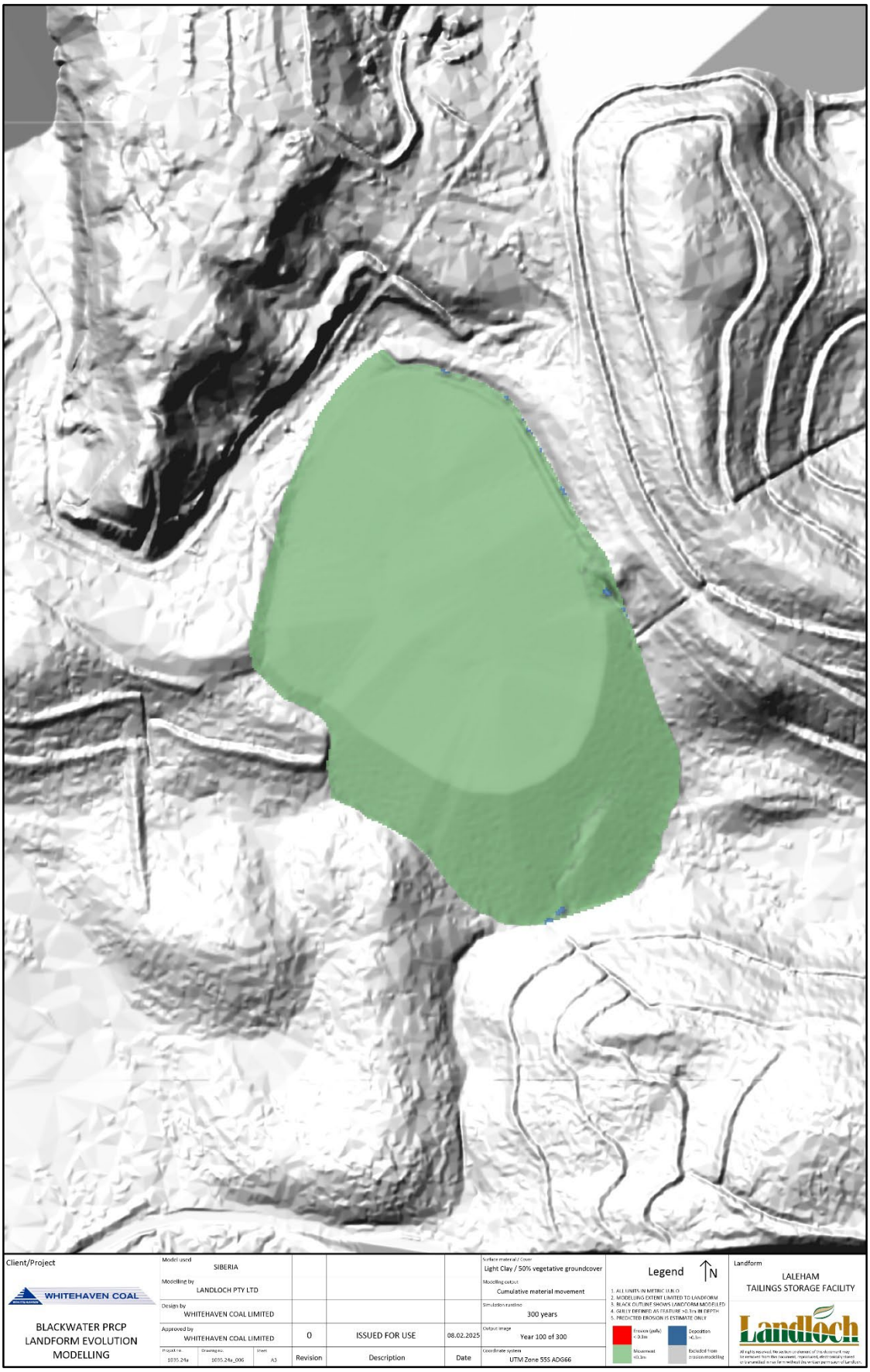



**Figure A-6:** Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 100 years.

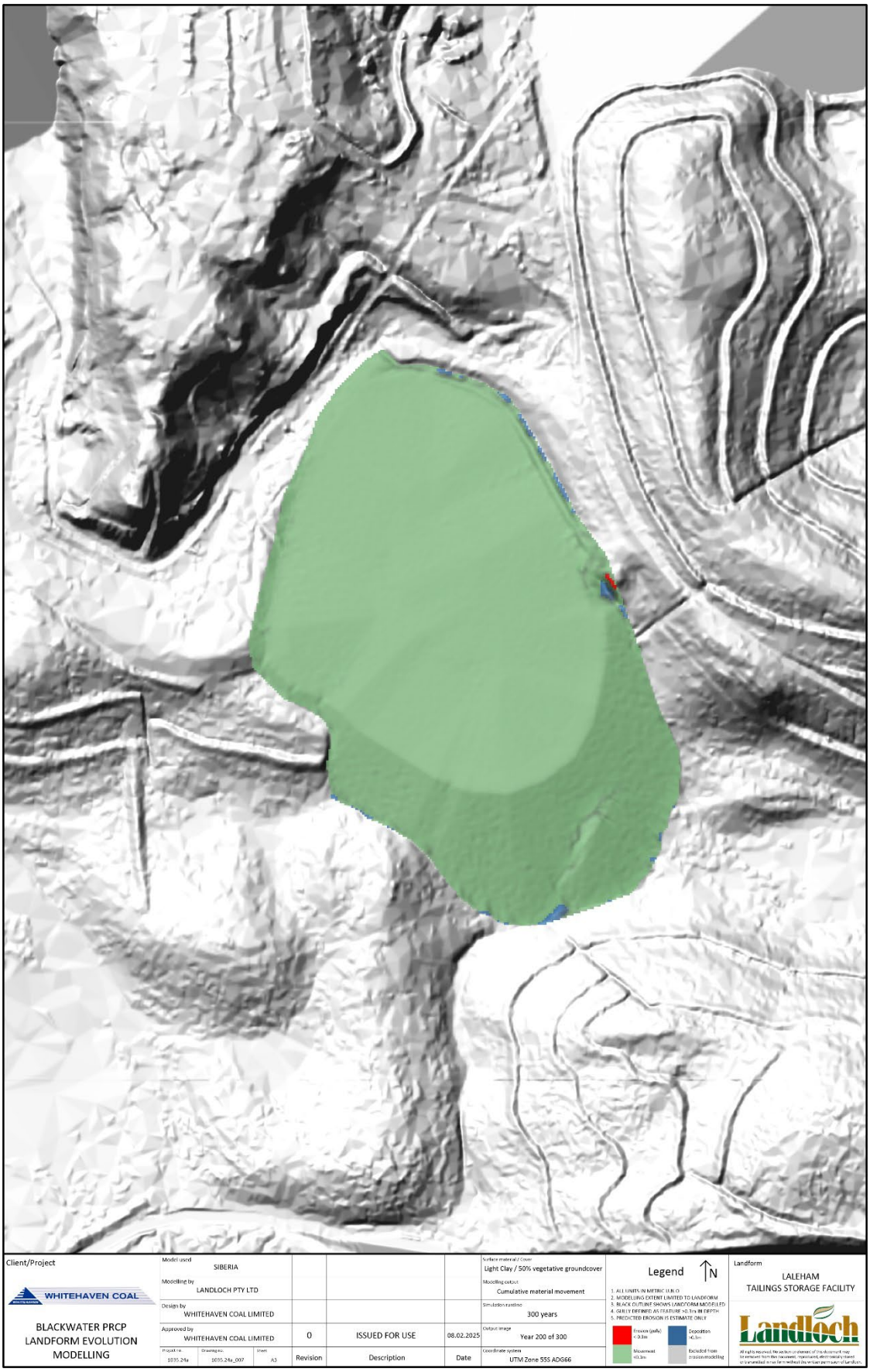



**Figure A-7:** Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 200 years.

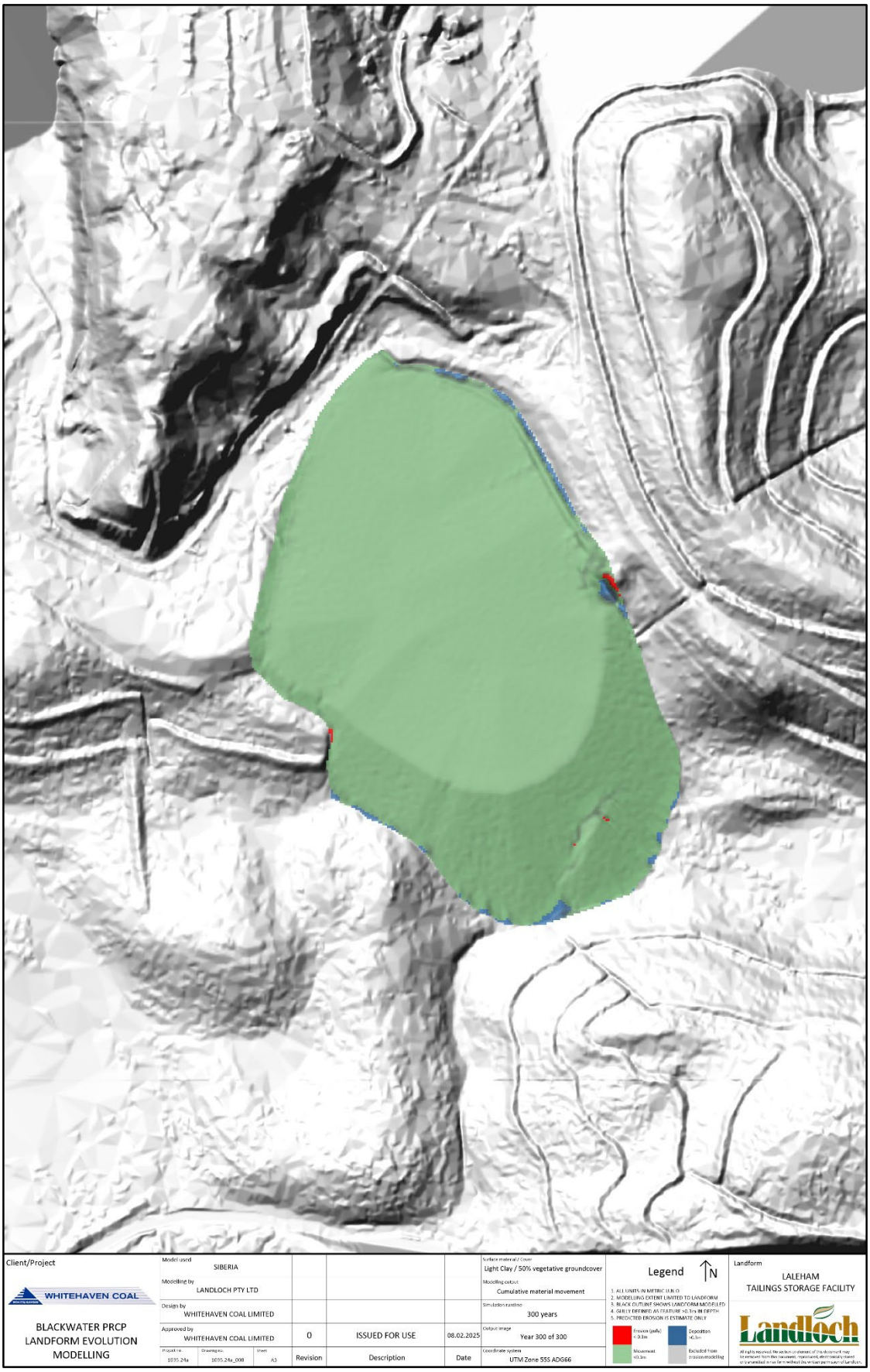



**Figure A-8:** Predicted erosion and deposition depths of the Laleham TSF rehabilitation landform after 300 years.




**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.