SOILWATER CONSULTANTS

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

MEMO

COMPANY:	Cameco Australia Pty Ltd			
FROM:	Soilwater Group	PROJECT TITLE:	Yeelirrie Uranium Project MCP	
DATE:	19/06/2015	PROJECT & DOCUMENT NO:	CAM-003-1-13	003
SUBJECT:	Landform Evolution Modelling			

1 STUDY METHODOLOGY

1.1 SAMPLE COLLECTION

Soilwater Consultants (SWC) conducted a site visit in April 2015 to inspect the surficial soil materials at the Yeelirrie Deposit, and to collect bulk samples for laboratory erosion testing. The following two soil materials were identified as being the most abundant, and likely rehabilitation materials within the disturbance areas:

- 'Surficial Clay': often (but not always) present in local-scale surface depressions, at depths of <0.5 m
- 'Surficial Loam': widespread, occurring at the surface (or just below the Surficial Clay) across the disturbance area, typically with a thickness of approximately 1.5 m. Directly overlaying the ore body (calcrete).

Approximately 100 kg of each material was collected for subsequent laboratory analysis.

1.2 EROSION TESTING

1.2.1 RAINFALL SIMULATOR

A laboratory-scale rainfall simulator (Plate 1) was used to measure the interrill (raindrop impact) erodibility of each material. The rainfall simulator was designed to apply water at an intensity of 80-100 mm/hr, with a raindrop size and spatial distribution closely resembling natural rainfall. An intensity of 100 mm/hr corresponds to a 1:20, 1:50 and 1:100 year ARI storm event of approximately 10, 15, and 20 min duration, respectively (BOM, 2015a).

Prior to testing, each material was placed into a 0.75 x 0.75 x 0.20 m container and lightly compacted to approximate the expected field conditions. The base of the container was free draining to avoid saturated conditions and air entrapment within the samples. Each material was pre-treated by sequentially wetting and drying the surface to allow natural organisation and settling of the soil particles.

The container was set at a slope angle of 5° to simulate the maximum expected proposed landform batter angle. The materials were then subjected to a simulated rainfall of approximately 90 mm/hr, and 10 samples of the resulting surface runoff were collected over a 4 hour period. Runoff volume and sediment loss in each sample were determined gravimetrically. Measurements from the rainfall simulator were used to calculate soil erodibility parameters required for the WEPP erosion model.

1.2.2 RILL EROSION MEASUREMENTS

Laboratory scale testing was completed to measure the rill erodibility (Kr) and critical shear stress (τ_C) of the materials under overland flow conditions. The rill erosion test was conducted using a 1.8 metre-long erosion flume (Plate 2). The laboratory testing was designed to expose the materials to a range of overland flow depths to simulate storm events of different sizes, and to measure the resulting sediment content in the surface runoff, generated by rill erosion.

Each material was subjected to a series of different overland flow rates, and the following measurements were made for each:

- A timed sample of the resulting surface runoff was collected. Surface flow rate and sediment loss were then determined gravimetrically.
- A measurement of surface flow velocity was made using a dye tracer method. The initial breakthrough time of the dye was measured, and the “average” flow velocity was calculated by applying a correction factor (α = 0.5) according to (Zhang *et al.*, 2010).
- Measurements of rill width were made at three standardised locations along the rill.

Rill erosion measurements were used to calculate rill erodibility parameters required for the WEPP erosion model.

1.3 EROSION MODELLING

The Watershed Erosion Prediction Project (WEPP) model (Flanagan and Livingston, 1995)was used to predict erosion rates from the range of slope angles likely to be used in the construction of the final post-mine landform (1-10%). The modelled erosion rates were then used to calibrate a SIBERIA model (Willgoose, 2005), which was subsequently used to predict how the shape of the post-mine landform would erode and evolve in the long-term (i.e. 10,000 years).

Model input values and assumptions are discussed in the following sections.

1.3.1 CLIMATE DATA

One of the key inputs to the WEPP model is a 100-year synthetic climate file, typically developed using the CLIGEN stochastic weather generator (Yu, 2003). A CLIGEN file was derived using the available climate data from the long-term climate station at Wiluna (BOM station #013021, located approximately 70 km to the north-east of the Project Area) (BOM, 2015b). The Wiluna weather data was compared with that from the long-term climate station at Yeelirrie (BOM station #012090) to ensure applicability(Figure 1 – Figure 3)

The climate data figures demonstrate that the 100-year synthetic CLIGEN file used in this investigation is generally consistent with available climate data in the region. Figure 1 depicts the frequency of 24-hour storm depths, and demonstrates that the storm intensities predicted by CLIGEN are generally consistent with the available monitoring data.

Figure 2 depicts the average monthly rainfall depth within the CLIGEN file, and shows that it generally falls within the range of monthly averages derived from on-site climate data and data from Wiluna. Figure 3 depicts annual total rainfall for both the CLIGEN file and measured data sets. It demonstrates that the annual total rainfall depths of the CLIGEN file is slightly higher than the average of the measured data, and that year-to-year variability is similar.

1.3.2 ELEVATION DATA

The WEPP model uses slope profile information to model the expected erosion and deposition rates along a unit-width of slope. Four linear slope profiles – 1%, 5%, 8%, and 10% linear slopes – were input to simulate the range of design options likely to apply to the post-mine landform. The SIBERIA model was calibrated to an equivalent set of unit slopes.

The SIBERIA model uses a digital elevation model (DEM) to predict erosion and deposition, and modifies the DEM accordingly at each time step to predict the final shape of the landform. The post-mine DEM model developed by URS for the Surface Water Study (URS, 2011) was used as the initial input DEM for SIBERIA. The DEM surface had a grid size of 100 x 100 m over the entire model domain, and was cropped to an area of approximately 92 km^2 around the post-mine landform (Figure 4). This DEM was then used to assess erosion of the landform, in context with the surrounding landscape.

1.3.3 INPUT SOIL PARAMETERS

The soil parameters required by WEPP were derived from the laboratory erosion testing. These parameters include particle size information (% sand, % clay), effective hydraulic conductivity (K_{eff}), interrill erodibility (Ki), rill erodibility (Kr), and soil critical shear stress (τ_C). K_{eff} was estimated by fitting the Green-Ampt equation (Green and Ampt, 1911) to the measured infiltration rates derived from rainfall simulator test. Ki was calculated from the inter-rill erosion rate measured in the rainfall simulator, according to (Elliott *et al.*, 1989). Kr and τ_C were determined from the shear stress (τ) and rill erosion rate (Dc) measurements collected in the laboratory erosion flume by a linear regression analysis according to the method described by (Foster, 1982) and (Elliott *et al.*, 1989). The derived parameters used in the WEPP model are summarised in Table 1

The SIBERIA model was calibrated to the 100-yr average sediment loss rate derived from WEPP, according to the model calibration methods described in Willgoose (2005). Model calibration curves are presented in Figure 5. The primary input parameter is the coefficient B_1 in the fluvial transport formula, which defines the magnitude of annual erosion by fluvial processes (rill erosion). The model is also calibrated for diffusive sediment transport (Dz) and the exponents m_1 and n_1 (exponents on discharge and slope, respectively). The calibrated parameters used in the WEPP model are summarised in

Table 2.

Table 1: Key soil parameters used in the WEPP model.

Material ID	Sand (%)	Clay (%)	K_{eff} (mm/hr)	$K_i \times 10^5$ (Kg s / m^4)	K_r (s / m)	τ_C (Pa)
Surficial Clay	53.0	35.8	1.4	4.1	0.0080	3.6
Surficial Loam	74.1	16.3	18.4	2.2	0.0206	4.7

Table 2: Key input parameters used in the SIBERIA model.

Material ID	B_1	D_Z	m_1	n_1
Surficial Clay	0.025	0.00025	1.80	2.10
Surficial Loam	0.010	0.00010	1.80	2.10

1.3.4 MANAGEMENT ASSUMPTIONS

The land management input file used in the WEPP model was designed to describe the expected conditions on the rehabilitated landform. The key features of the input management file include:

- A pre-consolidated soil surface. This means that no further settling is simulated within the model, and that the measured infiltration rates and runoff characteristics apply for the duration of the model (i.e., no further changes in these properties with time). This is reasonable because the laboratory measurements (from which the input parameters were derived) were conducted on pre-consolidated soil samples.
- No vegetation. This assumption will result in conservative (i.e. “worst-case”) erosion results, and will apply to the landform during the period prior to re-vegetation establishment. Subsequent vegetation growth will act to enhance the stability of the landform by dissipating rainfall impact energy, producing leaf litter as a ground cover, and stabilising the sub-surface and improving infiltration with root growth. The degree of stabilisation will depend on the types of vegetation used, and their rates of establishment.
- Zero initial surface cover (i.e. no woody debris or plant litter). This means that no additional surface cover was expected to be added to the soil surface to reduce erosion rates. This assumption does not have any impact on the armouring effect of the rock and gravel fraction in the soil, which was already accounted for within the laboratory-measured soil parameters.

Because the SIBERIA model is calibrated to the WEPP model results, these “worst case” management assumptions carry through to the “base case” SIBERIA model runs. As described in the following section, alternative land management scenarios have been considered, whereby vegetation and surface cover develop over time.

1.3.5 SIBERIA MODEL SCENARIOS

The following two model scenarios were developed for each of the two soil materials:

1. Base case model: Soil erodibility values, B_1 and D_Z, were kept constant throughout the entire 10,000 year modelling period. This is considered a “worst case” model scenario, as it assumes that no surface-stabilising vegetation or soil cover (e.g. cryptogam or plant material) will develop, and the soil will remain in a similar condition as it was in shortly after completion of the backfilling process.
2. Time-varying erodibility model: Soil erodibility values, B_1 and D_Z, are constant for the first 100 years of the simulation, and decrease to 1/10th of the original values thereafter. This scenario estimates the effects of vegetation and surface cover development over time, and allows for 100 years’ worth of erosion before significant vegetation re-establishment occurs.

2 LANDFORM EVOLUTION MODELLING RESULTS

2.1 BASE CASE SCENARIO

The SIBERIA model was first used to predict the shape of the rehabilitated landform after exposure to 10,000 years' worth of rainfall, based on the "base case" model scenario described previously. Two model runs were conducted, one using the surficial clay and one using the surficial loam soil as the primary cover material. The final model output, the predicted DEM at 10,000 years post-closure, is presented in Figure 6 for the surficial loam.

In general, both of the tested cover materials resulted in similar soil movement over the model period. In both cases, the majority of sediment loss was predicted to occur on the valley slopes, with a net deposition occurring in many areas of the valley floor near the rehabilitated landform. Some gullying of the backfilled profile is evident, but due to the very gentle land slopes (i.e. typically ≤0.25°, or 4 m elevation change per km), this is not widespread. Diffusive sediment transport (a.k.a. raindrop impact erosion, or inter-rill erosion) appears to be the dominant erosion mechanism. Soil losses of ≥0.5 m occurred over approximately 80% and 50% of the former TSF area for the surficial clay and surficial loam, respectively. Soil losses of ≥1.0 m occurred over approximately 40% and 20% of the former TSF area for the surficial clay and surficial loam, respectively. Soil losses of up to 2 m were predicted at some isolated locations within the former TSF area.

2.2 TIME-VARYING ERODIBILITY SCENARIO

A second set of SIBERIA model runs undertaken based on the "time-varying erodibility" model scenario described previously. Again, two model runs were conducted, one using the surficial clay and one using the surficial loam soil as the primary cover material. The final model output, the predicted DEM at 10,000 years post-closure, is presented in Figure 7 for the surficial loam. Figure 8 shows the overall change in elevation predicted for each model grid cell across the model domain.

In general, the "time-varying erodibility" model scenarios showed similar patterns of soil movement to the "base case" scenarios, although the overall volume of soil eroded was smaller. Again, the majority of sediment loss was predicted to occur on the valley slopes, with a net deposition occurring in many areas of the valley floor near the rehabilitated landform. While the degree of sediment loss within the backfilled profile was reduced from the "base case" model, more defined gullies were evident in the final landform. Gully depth within the TSF area was up to approximately 1.5 m deep in both of the modelled materials, although the extent of gullying was greater in the clay. Despite this, the majority of the soil over the rehabilitated TSF cells remained relatively in-tact, with gullying only occurring in some areas. Soil losses of <0.5 m were predicted over approximately 75-80% and 80-85% of the former TSF area for the surficial clay and surficial loam, respectively.

3 CONCLUSIONS

- Laboratory testing indicated that the surficial clay material was more erodible than the surficial loam material.
- A SIBERIA landform evolution model was calibrated using erodibility parameters derived from the laboratory testing. Two scenarios were tested, (1) "base case" = constant erosion rate over 10,000 years, and (2) "time-varying" = erodibility decreases after 100 years.
- Both scenarios indicated similar patterns of soil movement, with the majority of sediment loss predicted to occur on the valley slopes, and a net deposition occurring in many areas of the valley floor near the rehabilitated landform.

- Diffusive sediment transport appeared to dominate the “base case” scenarios, with soil losses of up to 2 m predicted at some isolated locations within the former TSF area. Soil losses of ≥1.0 m occurred over approximately 40% and 20% of the former TSF area for the surficial clay and surficial loam, respectively. Soil losses of ≥0.5 m occurred over approximately 80% and 50% of the former TSF area for the surficial clay and surficial loam, respectively.
- While the degree of sediment loss within the backfilled profile was reduced in the “time-varying erodibility” model, more defined gullies were evident in the final landform. Maximum gully depth within the TSF area was up to approximately 1.5 m deep in both of the modelled materials, although the extent of gullying was greater in the clay. Despite this, the majority of the soil over the rehabilitated TSF cells remained relatively in-tact, with gullying only occurring in isolated areas. Soil losses of <0.5 m were predicted over approximately 75-80% and 80-85% of the former TSF area for the surficial clay and surficial loam, respectively.
- The surficial loam material is expected to be far more abundant at the site than the clay material, and is thus expected to constitute the majority of the rehabilitation soil mixture. Thus, the model results for the loam are expected to be the more applicable of the two materials tested for closure planning purposes.
- The “base case” SIBERIA model scenarios are considered to be conservative estimates of soil loss, as they do not consider soil stabilising effects such as plant or cryptogam growth or litter cover that will likely become significant factors promoting stability and reducing erosion potential over the long-term. The “time-varying erodibility” model scenarios are considered to be more realistic, as they include a degree of soil stabilisation after 100 years post-closure. Whilst the time varying model is considered more realistic than the base case scenario, it is still inherently conservative as it assumes that no vegetation cover or other surface stabilising methods (e.g. contour ripping) have developed or been employed in the first 100 years post closure. Therefore actual erosion rates during the first 100 years post-closure can be expected to reduce considerably compared with modelled results.
- The erosion potential of the above scenarios results in the predicted formation of some rill erosion gullies over the TSF area after a period of 10,000 years. The predicted features are generally isolated and restricted to the outer edges of the cover system and will not have a negative impact on either the overall stability of the cover system or sediment transport downstream. As discussed, the erosion potential used in both scenarios is considered to be conservative and higher than likely erosion potential (particularly in the critical early years of revegetation establishment). Therefore, further research into likely rehabilitation establishment rates to allow further refinement of the modelled erosion potential and investigation of alternative cover designs such as the inclusion of competent rock on the surface is recommended.

Should you have any queries regarding this report, please do not hesitate to contact us.

Yours sincerely,

Joe Powers

Environmental Engineer

t: +61 8 9228 3060

e: Joe.Powers@soilwatergroup.com

References

BOM (2015a) *Rainfall IFD Data System*. Available at: http://www.bom.gov.au/hydro/has/cdirswebx/cdirswebx.shtml (accessed February 2015).

BOM (2015b) *Climate Data Online*. Available at: http://www.bom.gov.au/climate/data/ (accessed February 2015).

Elliott, W. J., Liebenow, A. M., Laflen, J. M. and Kohl, K. D. (1989) *A compendium of soil erodibility data from wepp cropland soil field erodibility experiments 1987 & 1988. Ohio State University and USDA Agricultural Research Service National Soil Erosion Research Laboratory Report.* Lafayette, Indiana, USA.

Flanagan, D. and Livingston, S. (1995) *Water erosion prediction project (WEPP) version 95.7 user summary*. In: *WEPP User Summary (Eds: Flanagan and Livingston) NSERL Report*

Foster, G. R. (1982) Modeling the erosion process. . In *Hydrologic Modeling of Small Watersheds* (ed. by Hahn, CT), pp. 295-380.

Green, H. W. and Ampt, G. A. (1911) Studies on Soil Phyics. *The Journal of Agricultural Science*, **4**, 1-24.

URS (2011) *Surface Water Study - Proposed Yeelirrie Development*. 10 March 2011. Unpublished report prepared by URS Australia for BHP Billiton Yeelirrie Development Company Pty Ltd.

Willgoose, G. (2005) *User Manual for SIBERIA, Version 8.3*. Telluric Research. Scone, NSW.

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

Zhang, G.-h., Luo, R.-t., Cao, Y., Shen, R.-c. and Zhang, X. C. (2010) Correction factor to dye-measured flow velocity under varying water and sediment discharges. *Journal of Hydrology*, **389**, 205-213.

Plate 1: Laboratory rainfall simulator

Plate 2: Laboratory erosion flume

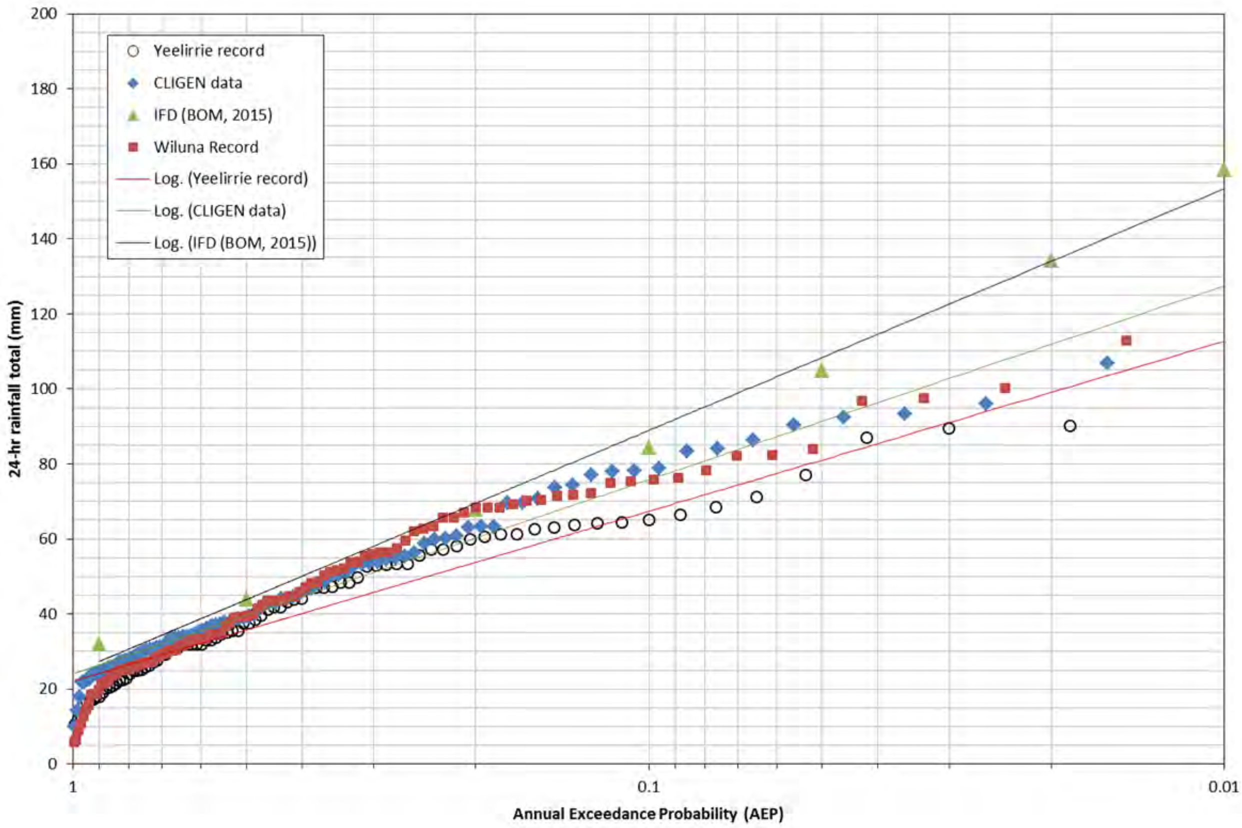

Figure 1: 24-hr rainfall frequency, CLIGEN compared to local climate record

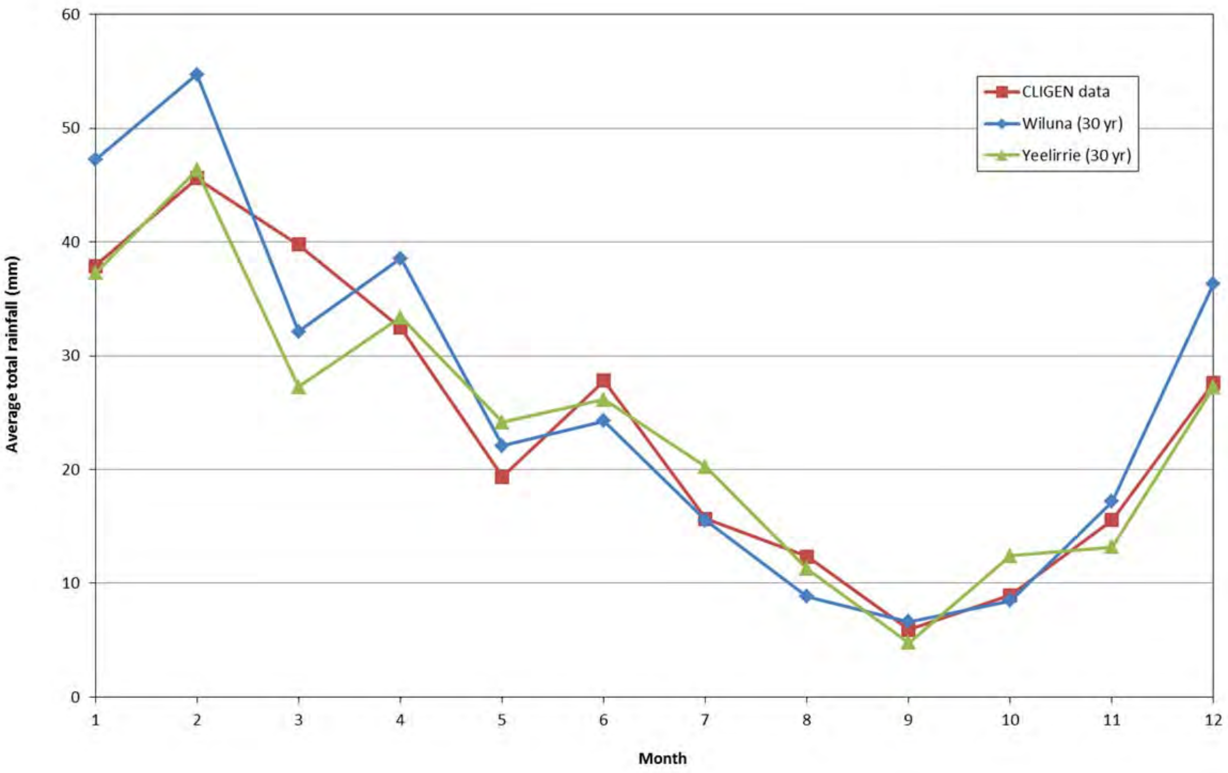

Figure 2: Average monthly total rainfall, CLIGEN compared to local climate record

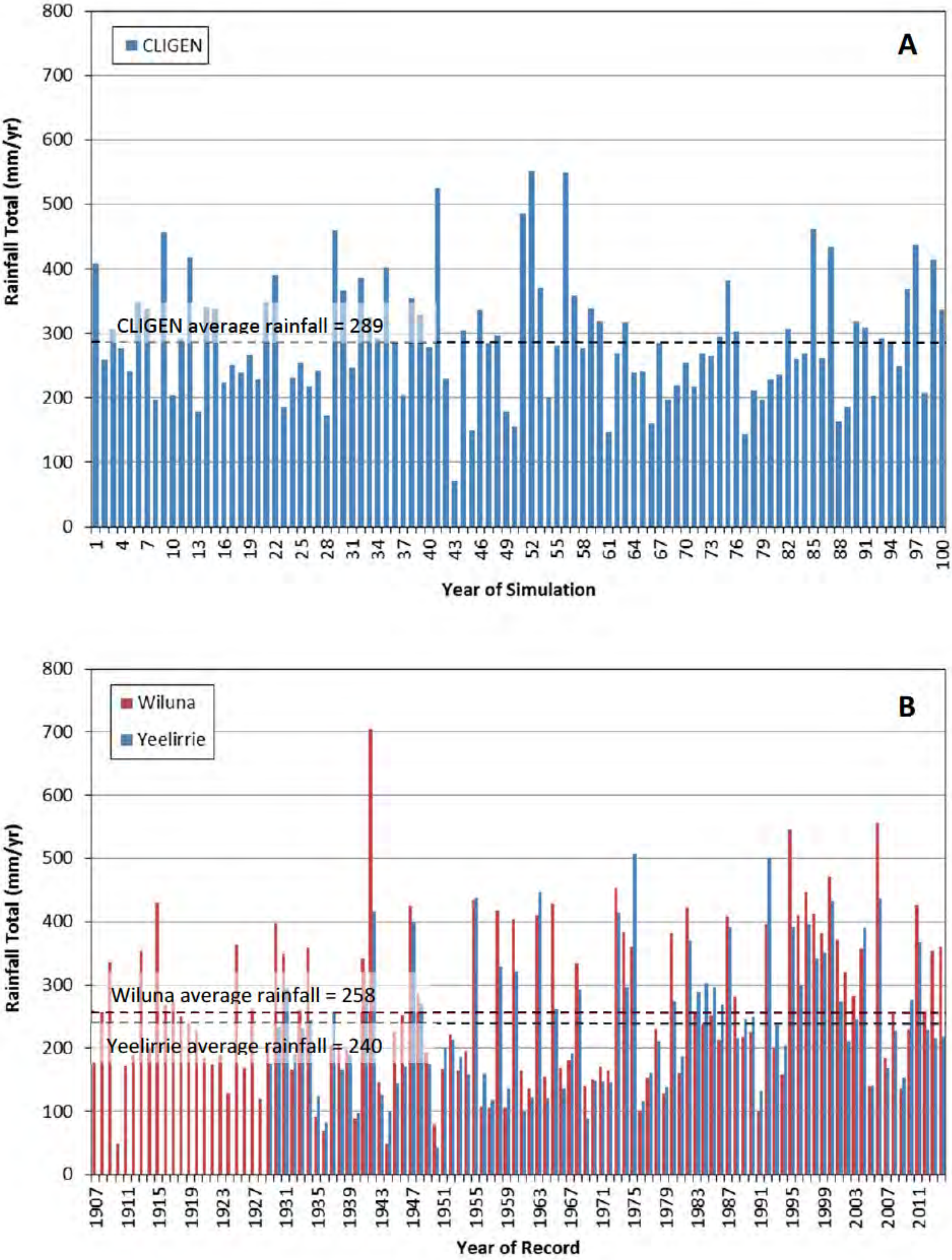

Figure 3: Total annual rainfall, (a) CLIGEN, (b) local climate record

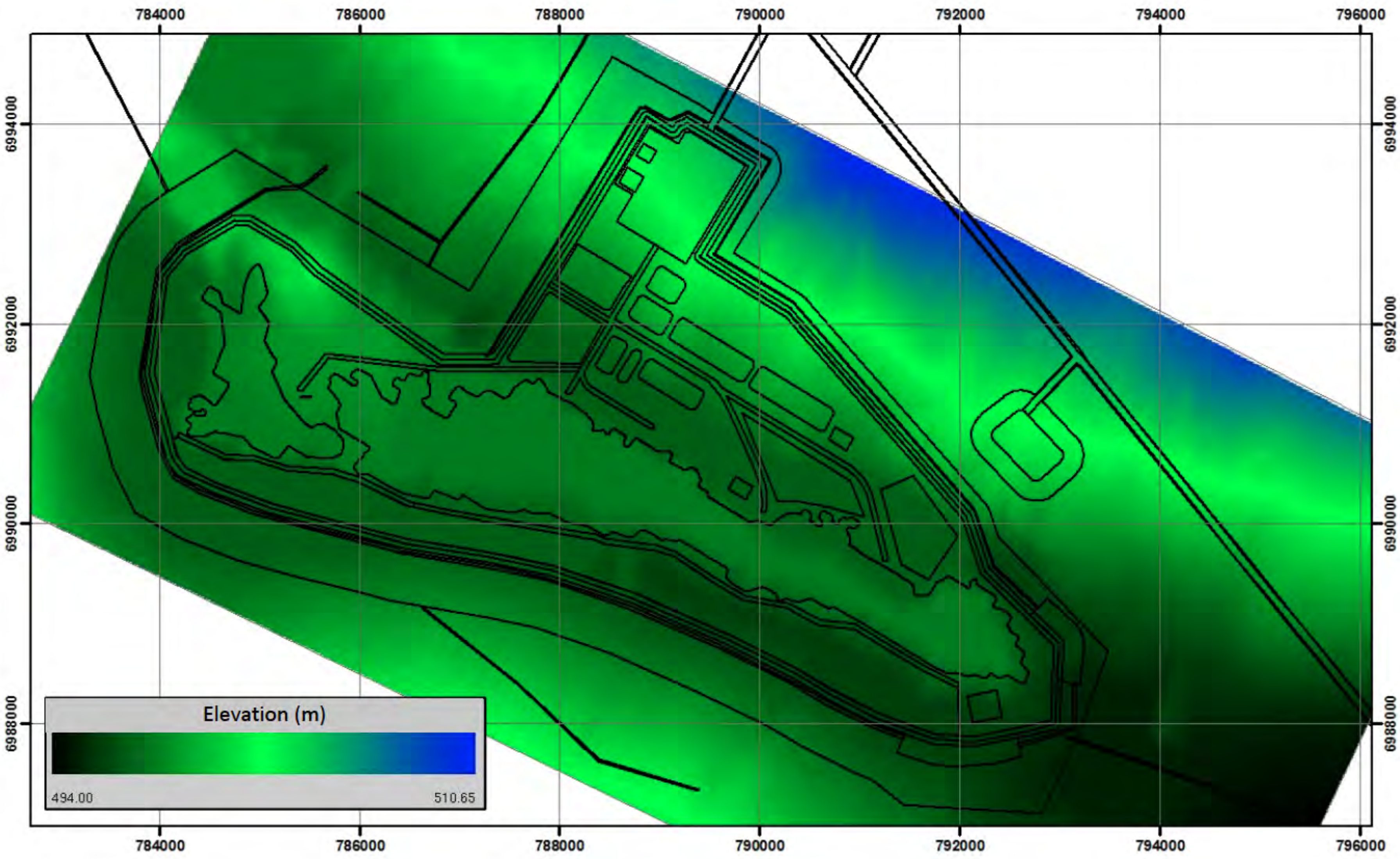

Figure 4: Post-mine landform DEM, used as input to the SIBERIA landform evolution model (URS, 2011)

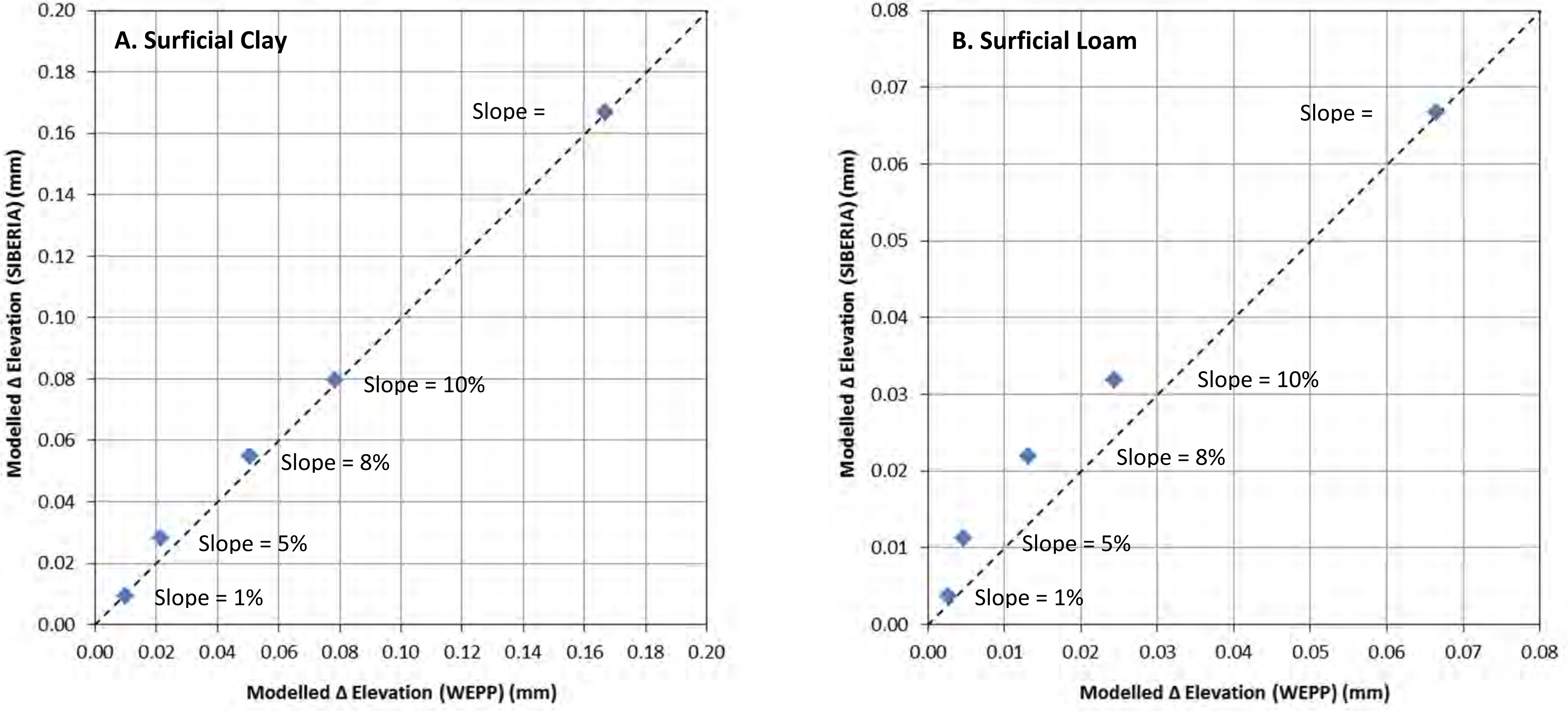

Figure 5: SIBERIA model calibration to WEPP erodibility parameters

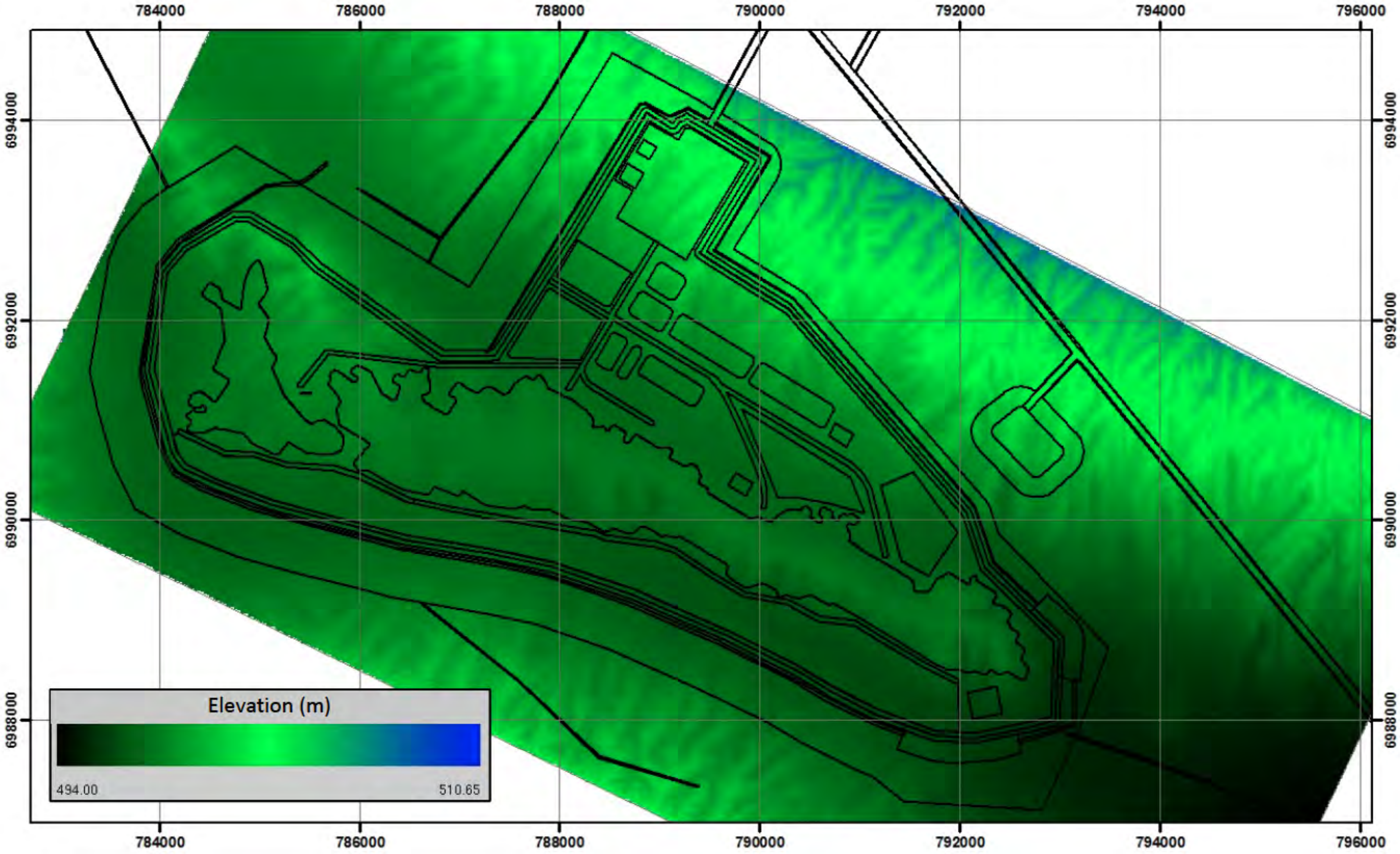

Figure 6: SIBERIA "base case" model output, surficial loam at 10,000 years post-closure

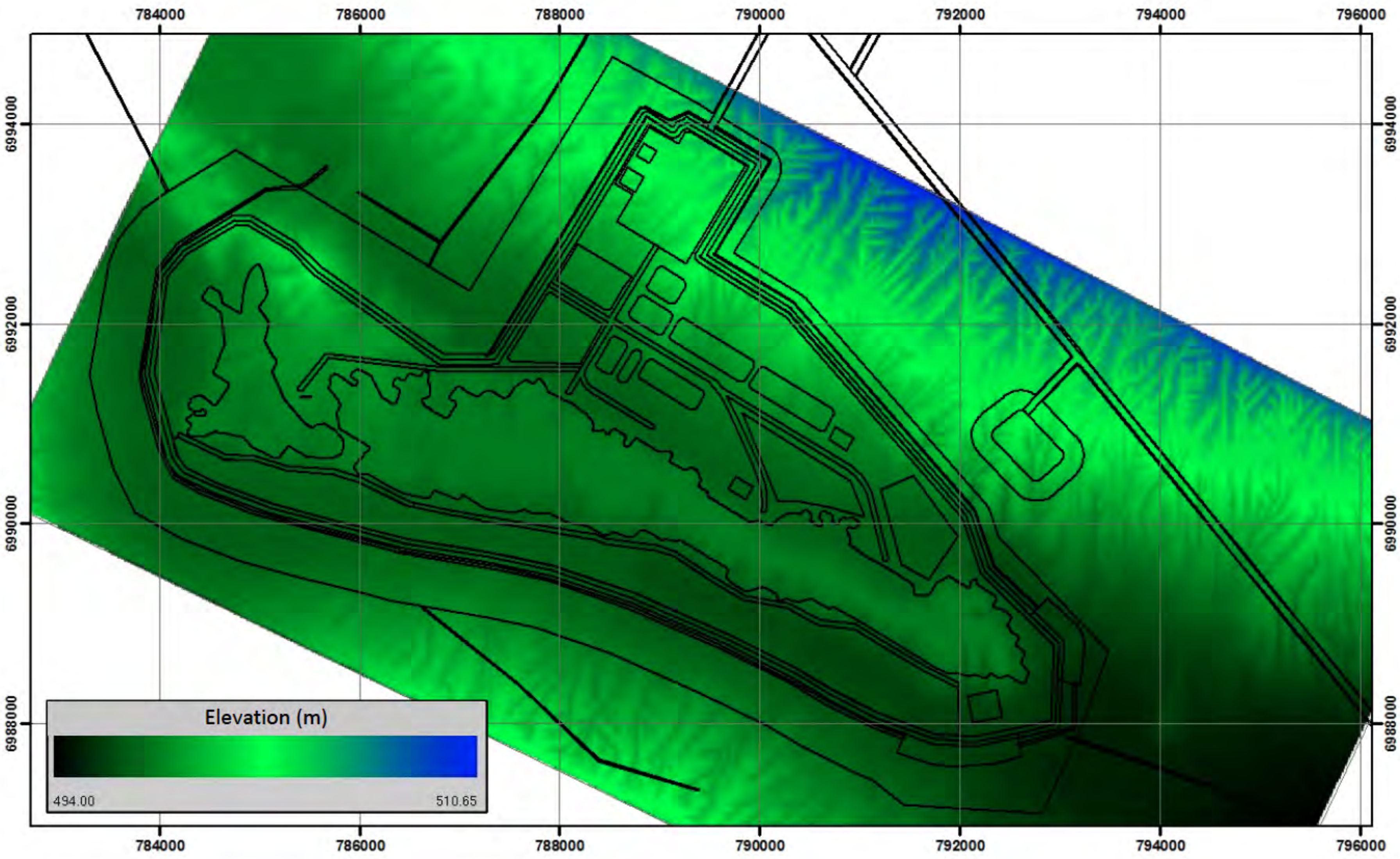

Figure 7: SIBERIA "time-varying erodibility" model output, surficial loam at 10,000 years post-closure

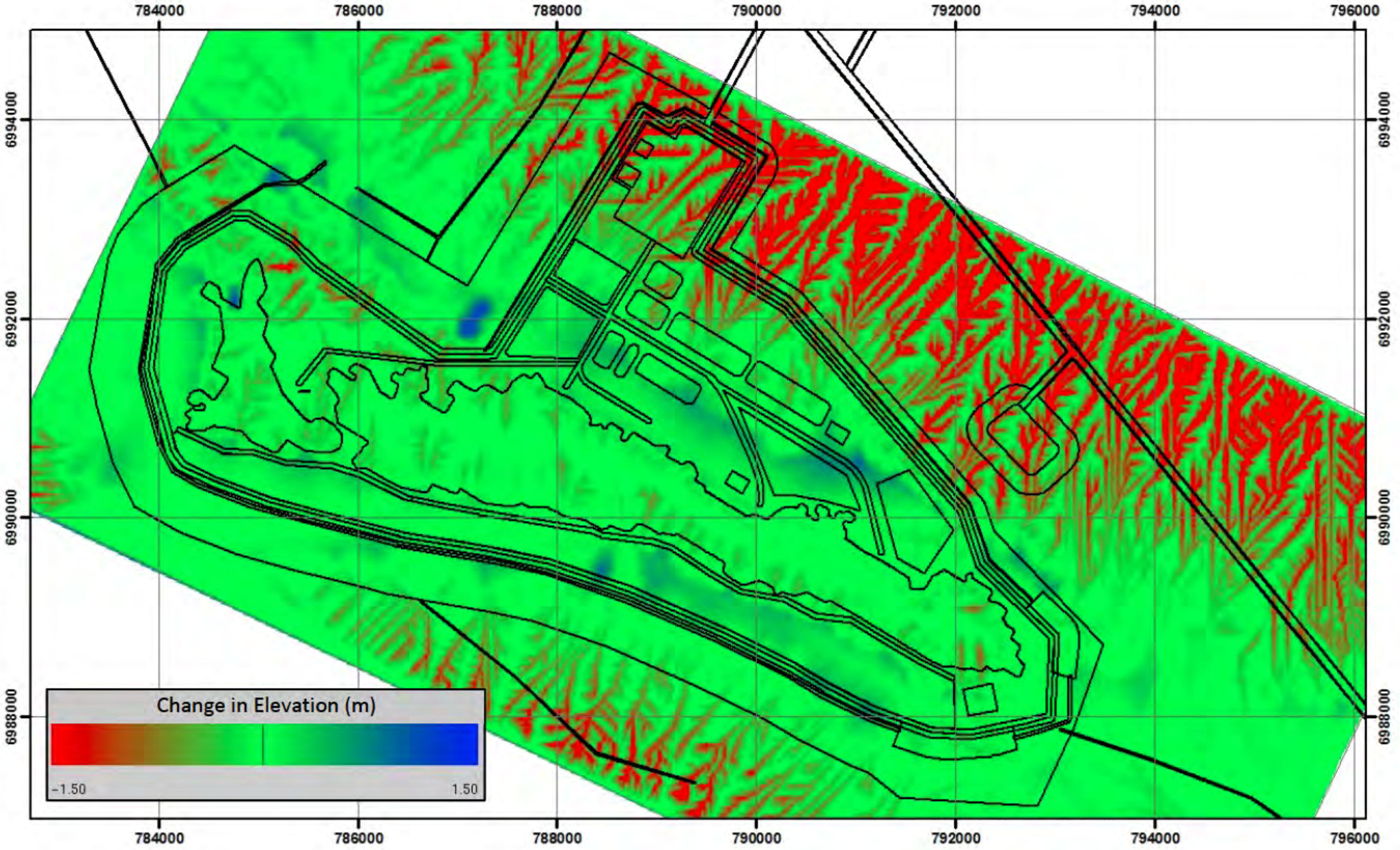

Figure 8: Overall change in elevation predicted by SIBERIA "time-varying erodibility" model, surficial loam at 10,000 years post-closure