Landform Evolution Modelling

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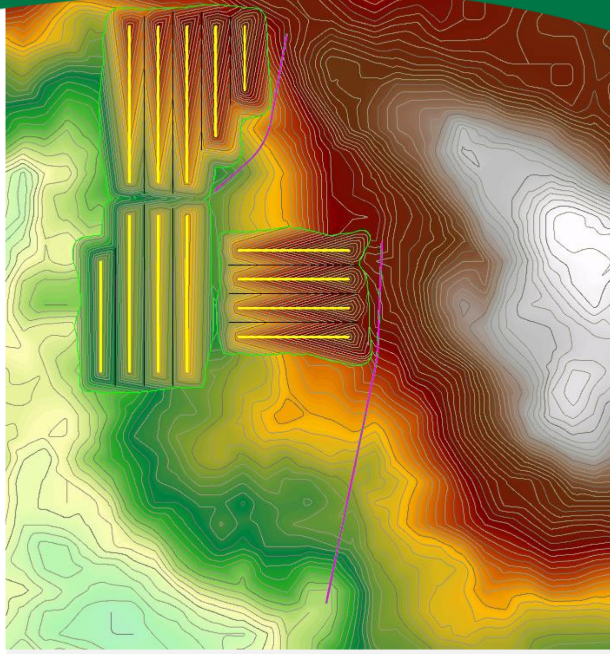

SANDY RIDGE LANDFORM EVOLUTION MODELLING

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1 INTRODUCTION

The Sandy Ridge Project (the Project) is proposed to be developed by Tellus Holdings Ltd (Tellus) and is located approximately 140km north west of Kalgoorlie. The proposed mine will extract kaolin clay from the Sandy Ridge kaolin bed for use in industrial applications. The Project is situated on exploration tenement 16/440 (59km^2 in extent), of which there is a development envelope of 1,004ha (Figure 1) comprising various mining infrastructure such as a mine pit, offices and workshops, and an accommodation camp (Figure 2).

Part of the development will include the storage and isolation of hazardous and intractable waste in mine voids (herein referred to as 'cells').These cells will be located in the pit/cell area identified in Figure 2. The waste facility will receive waste that will be placed in the excavated mine voids, backfilled, and capped with 3 metres of impermeable clay (Figure 3). Further backfill, approximately 4m, will be used to bring the level of the cell up to ground surface, where a 2m thick layer of compacted kaolinised granite cap (KGC) material will be domed to provide a permanent cover before placement of a topsoil cover and final rehabilitation.

Tellus are seeking long-term (10,000 years) landform evolutionary modelling to assess the erosion of the landform. This assessment will identify the safe and stable erosional limits of using the KGC material in the proposed designs. Based on the results of the material characterisation and long term erosion modelling, the design may be revised following new recommendations.

1.1 Purpose

The purpose of the clay cap is to prevent water ingress into the cells. An assessment of the capping material's erosion potential is required to ensure the design integrity over the very long term. This report details the studies undertaken by Landloch to assess the current design and provide recommendations on erosion-related aspects of the design. The overarching aim is to ensure that the Sandy Ridge cells are safe, stable, and non-polluting feature for the long term.

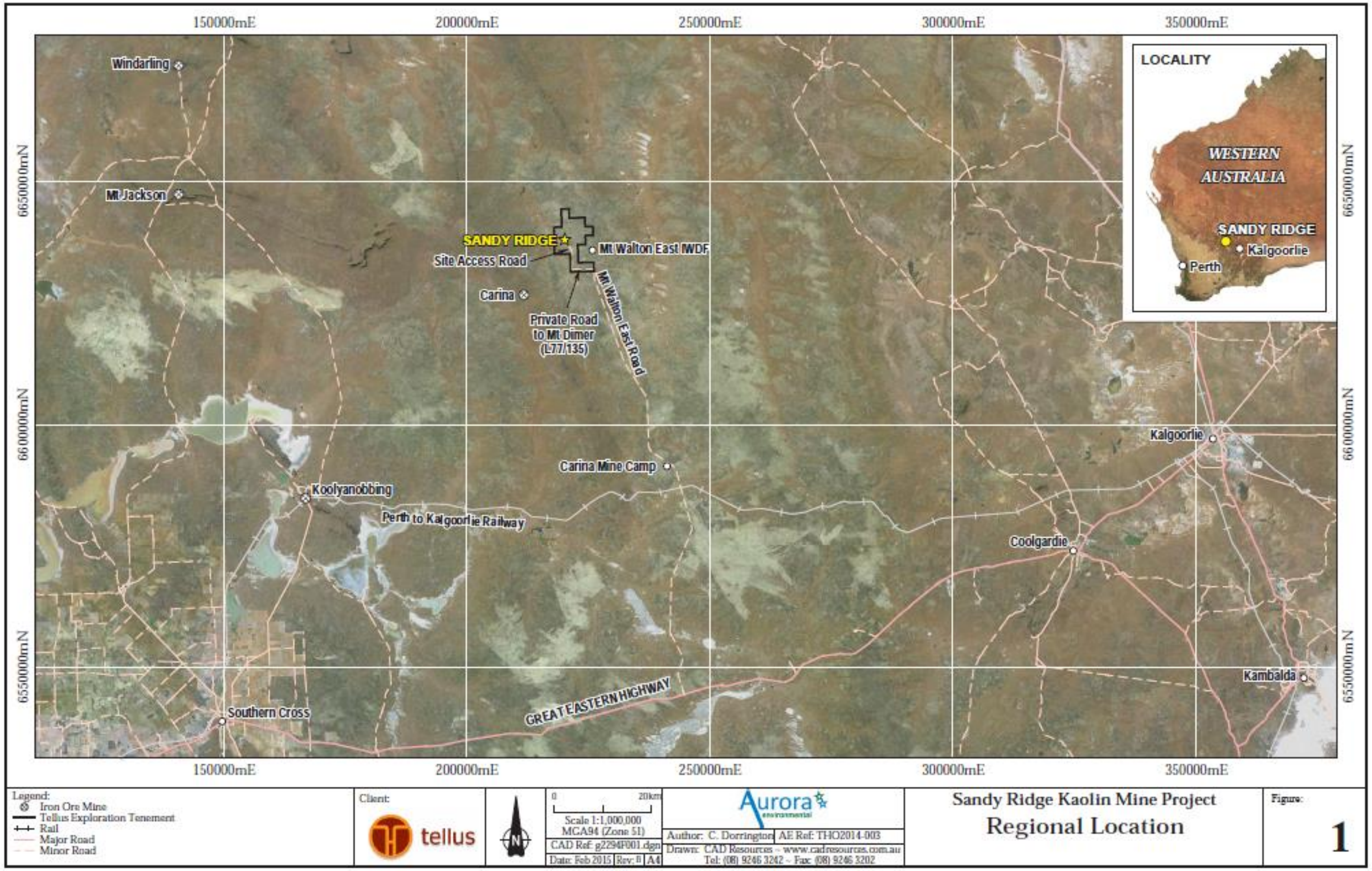

Figure 1: Location of the Sandy Ridge Project. (Source: Aurora Environmental)

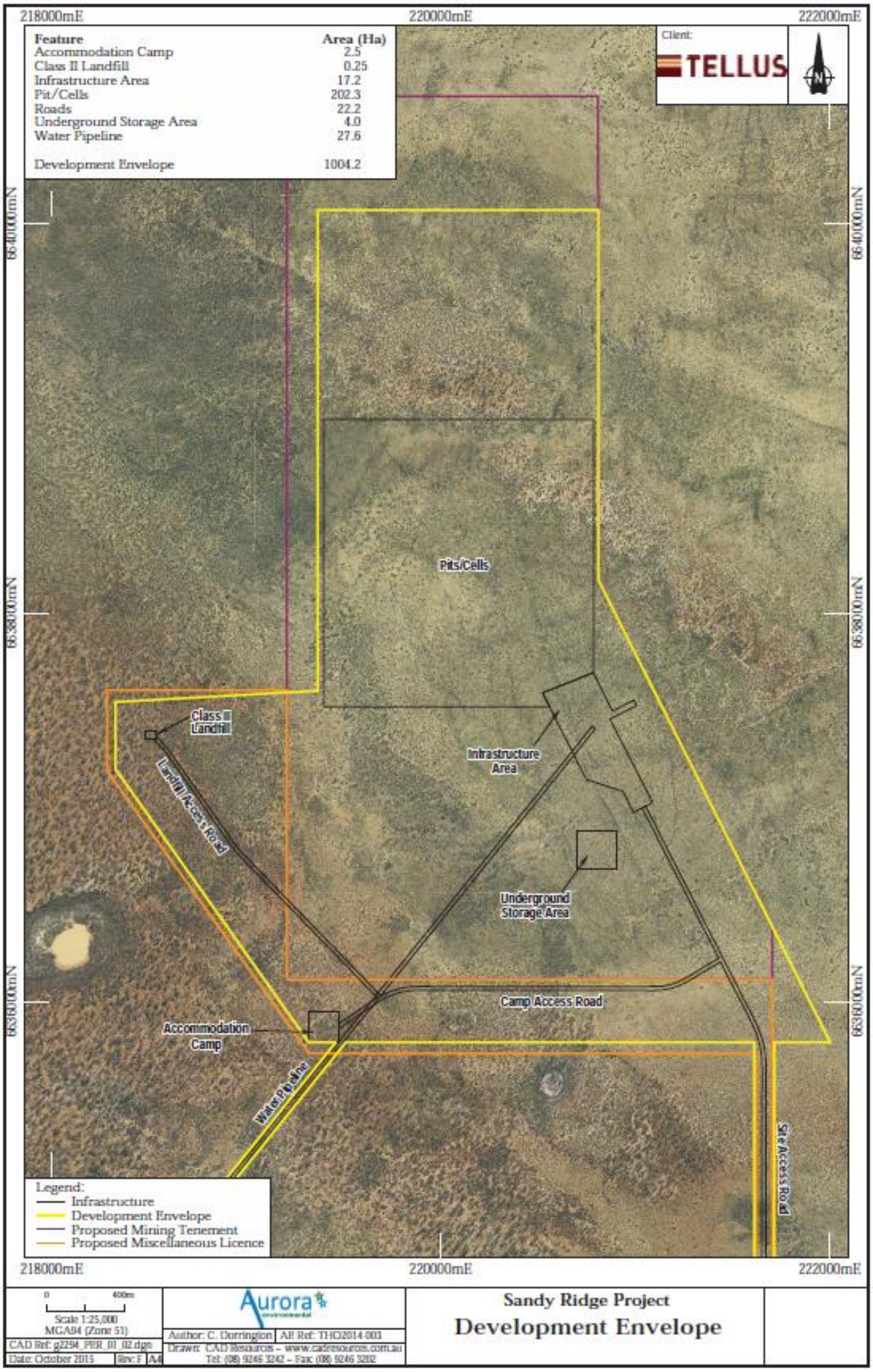

Figure 2: Development envelope of the Sandy Ridge Project. (Source: Aurora Environmental)

Figure 3: Example of placing intractable waste into the excavated clay slot at the Mt Walton IWDF (Dept. of Finance, 2014).

1.2 Proposed waste facility design

The cell will be excavated to ensure that there is at least a 5m separation distance between the base of the cells and the granite basement. The waste will be stored between 8-23m below ground level. Once waste is placed within the zone, the remaining void space will be backfilled with sand and a 3m compacted KGC layer will be placed above it. A mixed laterite/silcrete/clay/sand layer will be compacted to bring the waste facility up to surface level (~4m layer depth). The final surface layer will be a compacted domed kaolinised granite cap (KGC) up to 100m wide with a very low gradient (5%). A conceptual design showing the vertical layering of waste and materials is shown in Figure 4. The kaolin clay cap will remain in place for geological time. Following subsidence monitoring of the cap, a deep layer of topsoil will be replaced and vegetated. The purpose of the design is to prevent water entering the backfilled pit or waste leachate escaping from the base and entering aquifers.

Details of the Sandy Ridge conceptual design is shown in Figure 5. Multiple cells are proposed to be constructed, in rows. The final landform will comprise of three groups of cells which will be approximately 100m wide, 650m long, approximately 5m high, with low batter gradients of 5% (3°). Temporary operational bunds will be constructed on the eastern side to divert water during mining operations and have an expected life of ~25 years.

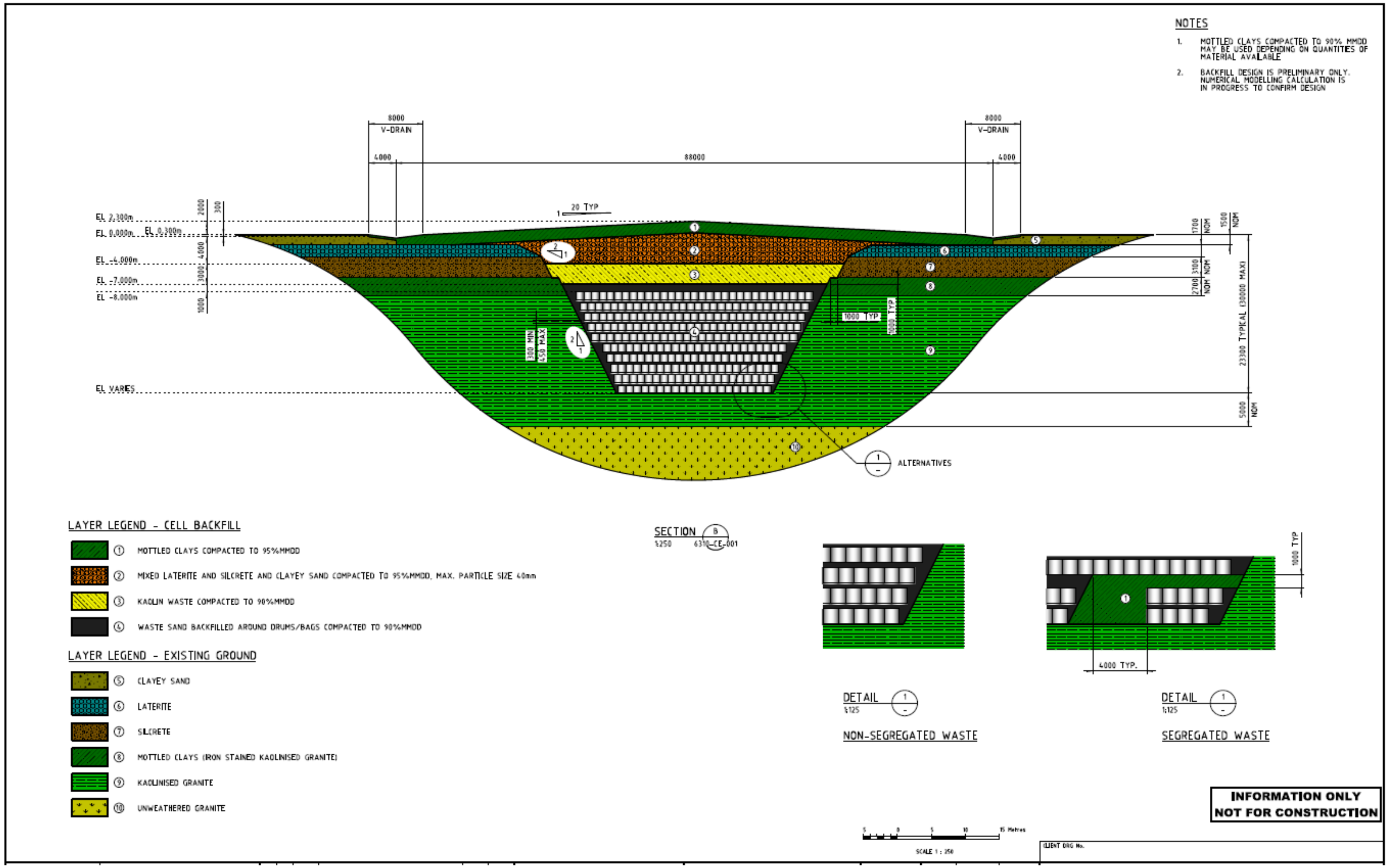

Figure 4: Conceptual design of the waste facility (Source: Tellus Holdings Ltd).

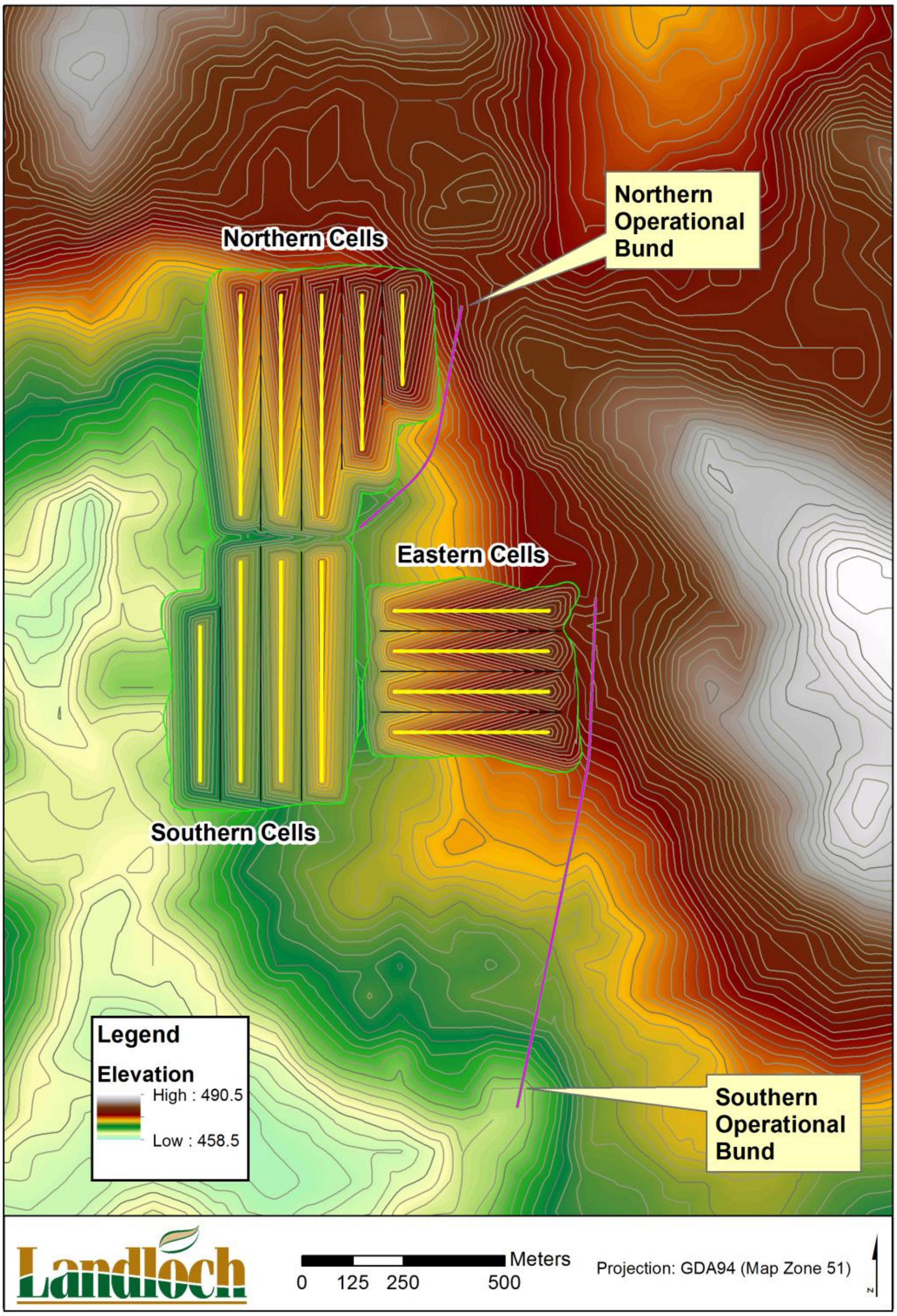

Figure 5: Proposed layout of the Sandy Ridge waste facility cells.

2 SCOPE

Tellus are seeking an assessment of the proposed design. Specifically, Tellus wants to assess the long term (10,000 years) behaviour and performance of landforms and associated containment systems, including waste cell capping systems, modelled under the prevailing climate, including landform evolution modelling. This study will:

- Assess the design in terms of its erosional stability,
- Assess the operational bunds,
- Identify high risk features of the design, and
- Make recommendations for design improvements.

The works completed include:

1. Chemical and physical testing of bulk samples of the topsoil and KGC material.
2. Erodibility studies of the topsoil and KGC material using simulated rain and overland flow studies.
3. Derivation of Water Erosion Prediction Project (WEPP) erosion model (Flanagan and Livingston 1995) and SIBERIA landform development model (Willgoose *et al.* 1989, Willgoose *et al.* 1991) parameters from data collected during the erodibility studies.
4. Assessment of erosion potential of batters constructed from topsoil and KGC material using WEPP erosion model. This included determination of constraints to achievable batter height and gradient.

3 MATERIALS

The main materials of Sandy Ridge have been previously assessed by Landloch. This included an assessment of the natural topsoils extent and properties (Landloch 2015a), and a chemical characterisation of the clay capping material (Landloch 2015b). These reports informed selection of the main materials considered in this study. They are:

1. **Topsoil (TE1)** – in the pits/cells area the main topsoil is a deep yellow sandy material. This topsoil is assumed to constitute the surrounding catchment of the pits/cells and the material that will be used to cover the KGC caps for final closure. Landloch travelled to site and collected the bulk samples of the topsoil for characterisation in the previous Landloch (2015) report.
2. **KGC (TE4)** - comprising of a composite of two samples, SRBS116 and SRBS117 from exploration drilling. Each sample is a blend of drill core material from 6 - 8m, 9 - 10m, and 12 - 31m and these two samples were in turn mixed to form the TE4 sample characterised in this report. The KGC material was supplied to Landloch by Tellus.

4 LANDFORM DESIGN METHODOLOGY

4.1 Overview

For this project, two models were used; WEPP and SIBERIA. The WEPP model was used to estimate long term erosion rates of the materials at typical batter configurations from the design shown in Figure 5. The SIBERIA landform evolution model was used to assess the long term erosional durability of the waste facility design, and also assess the operational bunds. Material characterisation, model description and calibration are described below.

4.2 Determination of baseline properties

The fine components (<2mm diameter) of both the Sandy Ridge KGC and topsoil were assessed for the following chemical and physical characteristics:

- Soil $pH_{1:5}$;
- Electrical Conductivity ($EC_{1:5}$);
- Total N;
- Total P;
- Available (Colwell) P and K;
- Available Sulphur (KCl);
- Available trace elements (Cu, Zn, Mn, and Fe);
- Exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and Al^{3+});
- Exchangeable Sodium Percentage;
- Effective Cation Exchange Capacity;
- Particle size distribution of the fine material (sand, silt, clay);
- Saturated hydraulic conductivity;
- Organic Carbon; and
- Emerson class number.

These properties were used to:

- define the plant growth potential of the soil;
- identify any hazards posed using these materials in rehabilitation designs; and
- enable parameterisation of the WEPP model.

5 MATERIAL CHARACTERISATION

5.1 Baseline soil and KGC properties

Baseline soil and KGC data are provided in Table 1. Overall, the results support Landloch's previous studies (Landloch 2015a, 2015b) of the soil and KGC. In these studies the soil is a sandy, acidic, non-saline, low nutrient, slightly sodic material. The KGC is a sandy silt, neutral, low salinity, very low nutrient, sodic material.

Table 1: Baseline soil and KGC data.

Analyses	Unit	TE1 (Soil)	TE4 (KGC)
$pH_{1:5}$ in water	pH units	5.6	6.52
Electrical Conductivity ($EC_{1:5}$)	dS/m	0.03	0.17
Total Nitrogen	mg/kg	310	72.5

Total Phosphorus		mg/kg	31.8	65.9
Organic Carbon		%	0.64	<0.05
Plant Available Nutrients	Phosphorus - Colwell	mg/kg	9.2	7.9
	Potassium - Colwell	mg/kg	407	101
	Sulphur - KCl	mg/kg	3.9	17.9
	Copper – DTPA	mg/kg	0.4	0.35
	Iron – DTPA	mg/kg	26.2	3.6
	Manganese – DTPA	mg/kg	1.08	0.25
	Zinc – DTPA	mg/kg	0.16	0.19
Exchangeable Cations	Calcium	meq/100g	1	0.58
	Magnesium	meq/100g	0.23	1.39
	Potassium	meq/100g	0.16	0.20
	Sodium	meq/100g	0	0.81
	Aluminium	meq/100g	0.07	0.00
	Effective Cation Exchange Capacity	meq/100g	1.53	2.99
	Exchangeable Sodium Percentage	%	11.0	27.2
Particle Size Distribution of Fine Fraction (<2mm)	Coarse Sand 0.2-2.0mm	%	70.4	39.5
	Fine Sand 0.02-0.2mm	%	23.9	36.2
	Silt 0.002-0.02mm	%	3.3	18.8
	Clay <0.002mm	%	2.4	5.5
Emerson Class		Class	6	8
Saturated hydraulic conductivity		mm/hr	13.4	0.15

5.1.1 pH and salinity

The pH of the surface soil is acidic as expected. Previous results show that the deep yellow sand soils increase in acidity with depth. The KGC is slightly acidic and this result is replicated from many different depth levels analysed at Sandy Ridge.

Both the soil and the KGC have very low salinity values, with both having $EC_{1:5}$ values <0.17dS/m. Only one KGC sample previously analysed had a high salinity value, but this was the exception. Surface soils and the KGC material pH and salinity levels would not be expected to greatly inhibit plant growth.

5.1.2 Fertility

Both materials have very low nutrient levels, in particular the KGC material but this is expected. Rehabilitation plans should include a provision for soil amendment to increase the establishment of vegetation.

5.1.3 Exchangeable cations and dispersion

The Exchangeable Sodium Percentage (ESP) for the soil and KGC are above the 6% threshold (11% and 27% respectively). Although these materials would be defined as sodic, the likelihood of dispersion occurring from the topsoil would be low. It has a very low ECEC and very low clay content. Hence the high ESP value (calculated using the

ECEC value) hides the fact that very low concentrations of sodium actually exist on the soil exchange surfaces. Further, there is very low clay contents (2.4%) and therefore if clay dispersion was to occur, it would have very little impact on the structure of the material as a whole.

The KGC contains similar ECEC values and clay contents. The most significant risk posed by the presence of a potentially dispersive soil with elevated silt contents is the formation of hardset surfaces. Hardset soils are prone to increased runoff and erosion, and vegetation germination and establishment are adversely affected. A very hardset (and cracked) surface was observed by Landloch after the KGC material was packed into the test plots and underwent several wet/dry cycles (Figure 6). Agricultural gypsum could be added to the KGC to mitigate this risk during rehabilitation.

While surface cracking was observed, these pores quickly sealed during rainfall simulation leading to a very low saturated hydraulic conductivity result. This in combination with the low height of the waste facility caps would not constitute a high risk of these features tunnelling.

Figure 6: Kaolinised granite capping material in a Landloch test plot before rainfall simulation.

5.1.4 Saturated hydraulic conductivity

Both materials were packed into test funnels to determine their saturated hydraulic conductivity (KSat). As expected the sandy topsoil had the highest average value of 13.4mm/hr. Rockwater (2015) reported that the sandy soils can have an infiltration rate as high as 720mm/day.

The KSat results for the KGC material were very low. Landloch repeated the experiment by packing the funnels in layers with moist clay and compacting each layer to replicate the anticipated earth works practices of constructing the KGC cap by watering and rolling in layers. Landloch could not achieve any infiltration of water into this material.

6 COMPUTER SIMULATIONS AND RESULTS

6.1 Computer simulation of runoff and erosion from waste facility batters

6.1.1 The WEPP model

The WEPP model was developed by the United States Department of Agriculture to predict runoff, erosion, and deposition for hillslopes.

WEPP is a simulation model with a daily input time step, although internal calculations on days when rainfall occurs uses shorter time steps. 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 the WEPP model uses a steady-state sediment continuity equation as the basis for the erosion computations. Soil detachment in interrill areas is calculated as a function of the effective rainfall intensity and runoff rate. Soil detachment in rills is predicted to occur if the flow hydraulic shear stress is greater than the soil's critical 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.

All WEPP model simulations completed by Landloch uses a 100-year stochastic climate sequence for Kalgoorlie-Boulder developed from observed daily and sub-daily data from nearby weather stations.

6.1.2 Climate file

Climate sequences are needed to simulate runoff and soil loss with the WEPP model. For each day of simulation, the WEPP model requires ten daily weather variables:

- Precipitation (mm),
- Precipitation duration (hr),
- Peak storm intensity,
- Time to storm peak,
- Average minimum temperature,
- Average maximum temperature,
- Dew point temperature,
- Solar radiation,
- Wind speed, and
- Wind direction.

Of these, the four rainfall-related variables (underlined in list above) are of particular importance because previous studies have shown that predicted runoff and erosion are most sensitive to these rainfall variables (Nearing et al. 1990; Chaves and Nearing 1991).

For most sites around the world, complete historical weather data on these variables are not available. To use the WEPP model for runoff and erosion prediction, synthetic weather sequences that statistically preserve the mean and variations in the historical observations are required.

CLIGEN is a stochastic weather generator that can be used to provide WEPP model climate input files. CLIGEN has been extensively assessed for a wide range of climates in Australia, and it was found that CLIGEN was most suitable to provide the required climate input for the WEPP model to predict runoff and erosion in Australia (Yu 2003).

Daily climate data for Kalgoorlie-Boulder were sourced from the Australian Bureau of Meteorology (BoM). Rainfall intensity (6-minute pluviograph) data were also sourced from the Bureau of Meteorology for Kalgoorlie-Boulder.

Using the two data sets, the following parameter values were computed and used to develop the synthetic climate sequence for Sandy Ridge:

- Mean daily rainfall on wet days for each month,
- Standard deviation and skewness coefficient of daily rainfall for each month,
- Probability of a wet day following a dry day for each month,
- Probability of a wet day following a wet day for each month,
- Mean daily max. temperature for each month,
- Standard deviation of daily max. temperature for each month,
- Mean daily min. temperature for each month,
- Standard deviation of daily min. temperature for each month,
- Mean maximum 30-min rainfall intensity for each month, and
- Probability distribution of the dimensionless time to peak storm intensity.

These parameter values were assembled to create a CLIGEN parameter file for the site. Wind data (used to calculate soil evaporation) were not synthesised by CLIGEN because Priestley-Taylor's method for estimating the potential evaporation will automatically be used by the WEPP model. A 100-year climate sequence was generated using CLIGEN version 5.1 (Yu 2002).

6.1.3 Determination of WEPP model erodibility parameters

Although the concept of "erodibility" is broadly understood, its precise meaning can vary considerably within the framework of some erosion prediction models. The WEPP model (Flanagan and Livingston 1995) was used in assessing the erosion potential of landform designs for the Sandy Ridge Project. Within the WEPP model, erodibility is described via a number of specific parameters:

- Interrill erodibility (K_i);
- Rill erodibility (K_R);
- Critical shear for rill initiation (τ_c); and
- Effective hydraulic conductivity (K_e).

The WEPP model erodibility parameters for the KGC and topsoil surfaces were derived from data collected using laboratory-based experimental methods involving the application of:

- Simulated rain and measurement of runoff rate and sediment in runoff to obtain estimates of K_i and K_e; and
- Concentrated surface water flows to obtain estimates of K_R and τ_c.

Interrill erosion was measured by applying a simulated rain event with known rainfall intensity to simulation plots 0.75m wide and 0.75m long (Figure 7). The rainfall simulator configuration used in this report is described in Loch et al. (2001). Rill erosion was measured by applying overland flow to simulation flumes 0.4m wide and 2.0m long (Figure 8).

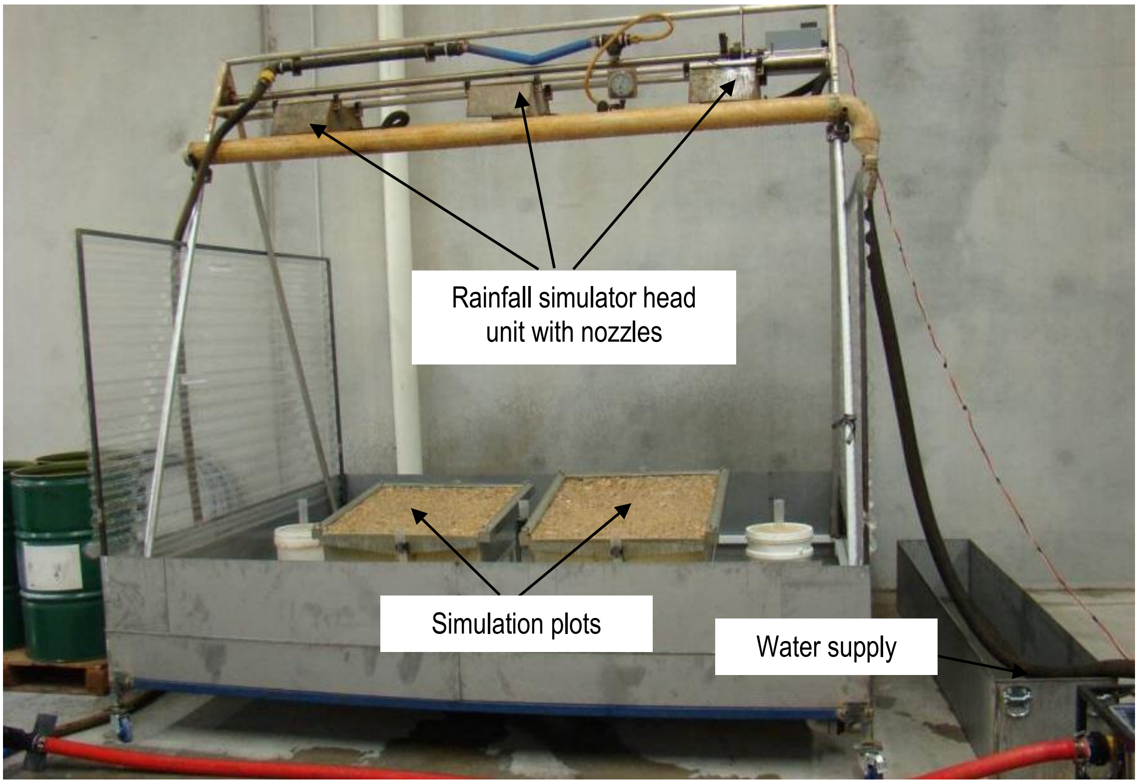

Figure 7: Laboratory-based rainfall simulator installation.

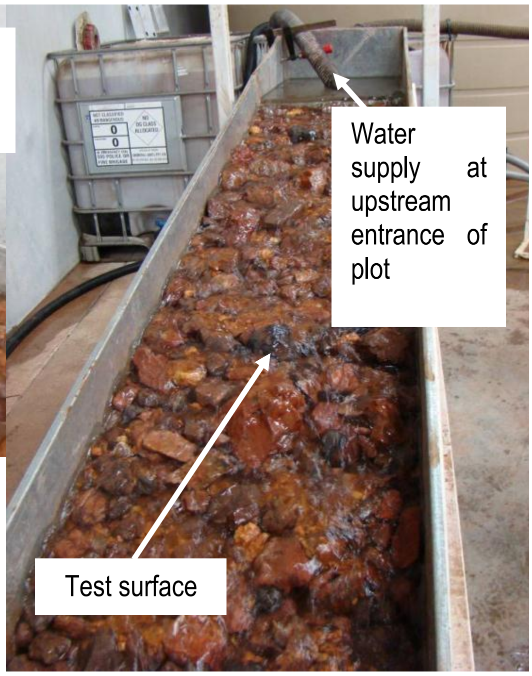

Figure 8: Example of flume setup used to apply overland flows.

6.1.4 Sediment properties

Estimates of erosion rates are sensitive to the particle size and density distributions of the eroded sediment. This is particularly true for situations in which erosion is strongly limited by sediment transport capacity such as can occur for cohesionless soils such as sands.

The version of the WEPP model available for general use has been coded to estimate sediment properties solely on the basis of input soil particle size data. However, Landloch has access to a version of the WEPP model not generally available that specifically allows input of detailed sediment particle size and density data. Consequently, this modified version of the model can more accurately predict erosion and has been applied in this study.

Settling columns (Figure 9) were used to develop equivalent sand size distributions for the sediment (Loch 2001). This approach is particularly useful as it integrates both particle size and density into a single testing parameter, and can be readily entered into the WEPP model.

Consequently, several samples of the rain-impacted surface of all samples were taken using sampling and handling methods described by Loch (1994).

Figure 9: Landloch's automated settling columns deployed on site in support of field based rainfall simulation.

6.1.5 WEPP model erodibility parameters

The WEPP model erodibility parameters derived by laboratory testing are provided in Table 2.

Within the WEPP model, effective hydraulic conductivity (K_e) is derived through analysis of a material's steady infiltration rate and runoff rates. The effective hydraulic conductivity values measured are high for the sandy topsoil in comparison to the KGC material. A higher hydraulic conductivity value will mean that runoff and erosion potential for the topsoil will be lower than that of the KGC material.

Interrill erodibility (K_i) describes the detachment and movement of particles by the combined action of raindrops and shallow overland flows. K_i values for the topsoil were slightly higher than for the KGC material.

Critical shear is an important property of material erodibility and describes the force of flowing water necessary to initiate rills. Both the soils and KGC material have very low values, similar to that of agricultural soils.

The rill erodibility (K_R) results for the two materials are similar. The relatively high K_R results combined with low critical shear means that little force is required within concentrated flows to initiate rilling, and that once initiated, detachment rates within rills will be high.

Table 2: WEPP model parameters derived from laboratory testing.

Parameter	Unit	TE1 (Soil)	TE4 (KGC)
Effective hydraulic conductivity, K_e	mm/h	39	6
Interrill erodibility, K_i	kg.s/m^4	1,177,986	823,302
Rill erodibility, K_R	s/m	0.0015	0.0012
Critical shear, τ_c	Pa	2.5	2.7

6.1.6 Definition of 'acceptable' erosion

The concept of 'acceptable' erosion is widely mentioned, but it appears to have little relevance to minesite rehabilitation. An acceptable erosion rate has been defined as a rate of erosion such that land productivity was not reduced, and is therefore of greatest relevance to agricultural situations. The definition ignores the pronounced temporal variations in erosion rates evident in arid regions and gives no information on the way in which that erosion may develop and impact on a landform over the long-term. In practice, rilling in one year may well develop into gullies in subsequent years if the erosion continues to incise the soil surface at a reasonably high rate at the same place. Alternatively, a rill may become armoured, and erosion rates reduce through time. To date, there is no methodology for assessing what is an acceptable erosion rate for rehabilitated lands.

With those issues in mind, Landloch's approach to landform design aims to create slopes on which rilling will be minimal or absent. Such slopes will have little potential to become heavily gullied, and any interrill erosion that occurs will be relatively insignificant relative to potential rates of erosion by rilling that could develop on long, steep, slopes. If rilling and gullying is avoided, the slope should be sustainable. (Surfaces eroded by interrill erosion typically become armoured in any case.)

Landloch has considerable experience in modelling erosion, and assessing erosion processes and rates in the field. In the WA Goldfields area, landforms designed with a predicted average erosion rate (averaged over the whole slope) less than **5t/ha/y**, together with a predicted maximum erosion rate at any point on the slope less than **10t/ha/y** exhibit a low tendency to rill.

These erosion threshold values were adopted as acceptable for this report. To date, observations made by Landloch on several sites indicate that this erosion threshold definition has produced batters with low rilling potential that have been consistent with rehabilitation success (DRET 2009).

6.1.7 WEPP model assumptions

Each material was used in several simulations of runoff and erosion. The typical waste facility batter configuration is 5m high with a 3° gradient. A slightly higher configuration of 7m high and 4° was simulated, along with a range of hypothetical 5m and 10m high batter sections was also run to compare the materials. All batters considered had a linear profile shape and did not contain berms. No allowance was made for vegetation effects on erosion. This is consistent with cover levels in the arid zone as vegetation tends to be too low to effectively contribute to reducing erosion of steep batter slopes. No allowance was made for water from upslope areas to discharge onto the batter slopes.

6.1.8 WEPP model input conditions considered within simulations

WEPP model simulations were conducted on the two materials using the following model settings:

a) Rill spacing was set at 5 m. This will allow for some conservatism in the WEPP model erosion predictions.
b) Surface roughness was set at 3cm for all materials, consistent with the value used when calibrating the model runoff predictions using the rainfall simulator infiltration data. A roughness of 3cm is equivalent to a surface with elevations changes of ~0.2m (i.e. small rip lines).
c) The climate file used is based on the current climatic conditions and variations due to global warming were not considered.

6.1.9 WEPP modelling results

The WEPP model was run for the waste facility slopes of 5m and slope gradients of 3°, with some other hypothetical batter configurations also modelled. The results are given in Table 3. Cells shaded green indicate batter configurations that are at or below the defined erosion threshold levels. Cells shaded red indicate batter configurations that are above the defined erosion threshold levels.

Table 3: WEPP model results for the Tellus soil and KGC materials for a range of lineal batter configurations.

Batter Configuration			Long-term Annual Erosion Predictions (t/ha/y)			
			TE1 (Soil)		TE4 (KGC)	
Height (m)	Gradient (°)	Footprint (m)	Avg	Peak	Avg	Peak
5	3	95	0.17	0.21	4.22	6.85
5	4	71	0.3	0.37	5.58	9.26
5	5	57	0.41	0.54	6.55	11
7	3	134	0.17	0.2	5.09	7.83
7	4	100	0.29	0.35	6.63	10.5
7	5	80	0.42	0.52	7.97	12.9
10	10	57	1.18	1.53	17.15	28.4
10	15	37	1.65	2.31	18.45	31
10	18	31	1.79	2.58	18.66	31.5

6.1.10 Tellus topsoil

The results show that the sandy topsoil is within acceptable erosion limits for all batter configurations considered. The result is due to the relatively high effective hydraulic conductivity (K_e) value measured for the soil (Table 2). In this arid environment, there are not enough rainfall events of sufficient magnitude to generate runoff and transport the material off the batter.

6.1.11 Tellus KGC

Tellus KGC was modelled at the same configurations as the topsoil. The results were a contrast to the soil in that it eroded above the acceptable thresholds at all but the lowest gradient and height. This is attributable to a very low K_e resulting in many events that caused surface flows that readily detached material from the batter.

6.1.12 Summary

The results of the WEPP modelling indicate that:

- Batters constructed of KGC will erode at rates above the acceptable erosion thresholds for all but the lowest gradient (3°) and height (5m) configuration considered.
- Batters constructed of topsoil are more erosionally stable due to the high effective conductivity that prevents surface flows and the consequent erosion, but a suitable substrate would need to be provided.

6.2 Computer simulations of 3D landform evolution

6.2.1 The SIBERIA model

Long-term simulations (hundreds or thousands of years) of the impacts of erosion on a constructed landform can only be done using landform development models, of which the SIBERIA model (Willgoose *et al.* 1989, Willgoose *et al.* 1991) is the most developed and accepted.

The SIBERIA model is a 3-dimensional topographic model that predicts the long-term development of channels and hillslopes in a catchment on the basis of runoff, erosion, and deposition. The location and speed with which rills and gullies develop are controlled by a channelisation function. The SIBERIA model does not input actual rainfall or material erodibility parameters. Rather, the input parameters define this channelisation function that is related to both runoff and soil erodibility (Willgoose *et al.* 1989) and must be derived for each particular material at each particular site.

The SIBERIA model solves for two variables:

1. Elevation, from which slope geometries are determined, and
2. An indicator function that determines where channels exist.

Channel growth is governed by an activation threshold that is dependent on discharge and slope gradient. When the activation threshold is exceeded, a channel is predicted to develop. In this way, it is possible for a modelled surface to initially have no gullies, and for channels to develop when the activation threshold is exceeded.

The SIBERIA model has been successfully applied to explain aspects of geomorphology of natural landforms (Willgoose 1994) and has been extensively used in the context of mining, and subjected to extensive validation. In general, the validation work indicates that, provided the model is adequately calibrated, SIBERIA predictions of landform development appear to be reasonable (Hancock *et al.* 2000, Hancock *et al.* 2002, Hancock *et al.* 2003, Willgoose *et al.* 2003). In addition, Hancock (2004) notes that rates of erosion predicted by the SIBERIA model for a catchment in the Northern Territory compared favourably with estimates of erosion derived using the caesium-137 method. As the two methods used completely independent input information, the agreement is particularly significant.

The SIBERIA model has been widely used for assessment of the development of constructed landforms on a range of 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). The model is equally applicable to any climatic regime as its input parameters are derived by calibration to runoff and erosion data. Input parameters can be derived from output from the WEPP model using methods developed by Landloch in consultation with the developers of SIBERIA.

6.2.2 The SIBERIA model input parameters

The SIBERIA model predicts the long-term average change in elevation of a point by predicting the volume of sediment lost from a 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, q is discharge (m^3/y), m_1 is the discharge exponent, S is the slope (m/m), and n_1 is the slope exponent. The SIBERIA model does not directly model runoff, but uses sub-grid effective parameterisation which relates discharge to area draining through a point as:

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

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

To run the SIBERIA model, the parameters β_1 , m_1, n_1, β_3, and m_3 are usually needed. However, if the batter area to be modelled is identical to the batter for which erosion data is available for calibration, m_3 and β_3 can be taken as 1.0 and a value of 1.5 for n_1 can be adopted for situations where slope gradient does not affect slope erodibility (Willgoose pers. comm.). Where steeper slopes are subject to greater armouring, the exponent n_1 may be as low as 0.7 (Evans *et al.* 1998). Therefore, the two key parameters that require derivation are 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. However, in practice, there is interaction between all of the 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. For this reason, fixed values of n_1 and m_3 are adopted where possible, reducing the difficulty of deriving parameter values.

6.2.3 Derivation of the SIBERIA model input parameters from laboratory data

Input parameters for the SIBERIA model are typically derived by fitting the model equations to time series data of runoff and erosion. However, in most instances, sufficiently long series of these data is not available for landforms of interest. Therefore, in consultation with the model developers, Landloch has developed an alternative approach for developing the required input parameters. The general approach applied is to:

a) Make laboratory or field based measurements on materials to derive calibrated WEPP model parameters.
b) Run the WEPP model to generate data sets of runoff and erosion for batter slopes and materials of interest using long (100 years), site specific climate sequences.
c) Analyse the WEPP model output to derive the required SIBERIA model input parameters.

6.2.4 Derived SIBERIA model input parameters

The derived SIBERIA model parameters are provided in Table 4.

Table 4: SIBERIA model parameters derived from laboratory testing.

Parameter	TE1 (Soil)	TE4 (KGC)
m_1	0.9821	0.9739
β_1	0.00155	0.032147

6.2.5 SIBERIA model assumptions

The SIBERIA model is used in this study to primarily focus on the long term erosional stability (10,000 years) of the waste facility. It has also been used to examine the durability of the operational bunds. The assumptions used for the long term landform evolution of the waste facility are:

- To ensure the best possible resolution, the eastern cells were used to assess the long term erosional response of the waste facility design.
- The SIBERIA model was calibrated with the topsoil (TE1) material parameters.
- The eastern cells are assumed to be rehabilitated and therefore are covered in a deep layer of topsoil. This simulation does not include the 0 – 10 year inspection phase were the KGC caps are left exposed.
- No vegetation was assumed on the waste facility. The observed native vegetation growing on the sandy topsoils were dispersed shrubs with single stems. The assumption of no vegetation adds a level of conservancy to the model results.
- The SIBERIA model simulated the long term runoff and erosion of the eastern cells for a 10,000 year period, and land surface evolution changes were captured at 50, 100, 250, 500, 750, and 1,000 year periods, and then every 1,000 years to 10,000 years.

To examine the durability of the operational bunds (life ~25 years), the SIBERIA model used the following assumptions:

- A sub-catchment was delineated that was contributing to the northern cells that was bordered by the northern operational bund (Figure 5).
- The SIBERIA model was calibrated with the KGC material parameters.
- The operational bunds were assumed to be constructed from the KGC material.
- The contributing catchment was assumed to be the KGC material, so that a 'worst case' scenario could be modelled as the KGC has a low infiltration rate and therefore in the arid Sandy Ridge climate, would more readily conduct flows from rainfall events onto the operational bunds.
- As the operational bunds are a relatively narrow feature and the SIBERIA model has input grid size limitations, the bund's width (but not height) was increased so that the feature was able to be delineated within the available cell size, and to also include the contributing catchment.
- SIBERIA simulated the long term runoff and erosion of the waste facility operational bunds for a 1,000 year period, and land surface evolution changes were captured at 50, 100, 150, 200, 300, 400, 500, 750, and 1,000 year periods.

As the SIBERIA model is calibrated to WEPP parameters, SIBERIA uses the same climate assumptions as described in Section 6.1.2.

6.2.6 SIBERIA model results: waste facility long term landform evolution

The results for the 10,000 year landform evolution model runs of the eastern cells using the SIBERIA model are shown in Figure 10. The results show that there is predicted to be relatively little change to the waste facility surface over the simulation period. There has been surface lowering along the cell batters, but this is typically less than 200mm. The material has been eroded from the individual cell batter slopes and deposited in between the cells with maximum deposition values of 500mm. This deposition can be seen in cross section A-A shown in Figure 10. The cross section is shown in Figure 11. The profile shows the deposition of material in between the cells and toe of slope, but no discernible changes to the waste facility batters or cell height.

The most significant surface change has occurred along the western side in between the individual cells and indicated by the arrows in Figure 10, and these small gullies are termed 'north,' 'middle', and 'south.' After the 10,000 year model run, the maximum erosion results (i.e., the greatest reduction in the Z value between the original surface and final simulation) is 412mm for the northern gully, 536mm for the middle gully, and 697mm for the southern gully. This appears to be caused by water flow from the cell batters into the mid lines, and then from the mid lines draining towards the west.

The Sandy Ridge topsoil is a sandy material that has a high infiltration rate and in combination with the arid climate, there are very few events that lead to any significant runoff. Where runoff does occur, the gentle batter gradients ensure flow velocities are low and does not entrain material and form significant rilling. If the sheeting of topsoil over the KGC material for rehabilitation is >1m, then it would be anticipated that even the small gully development will not intersect the clay capping material below.

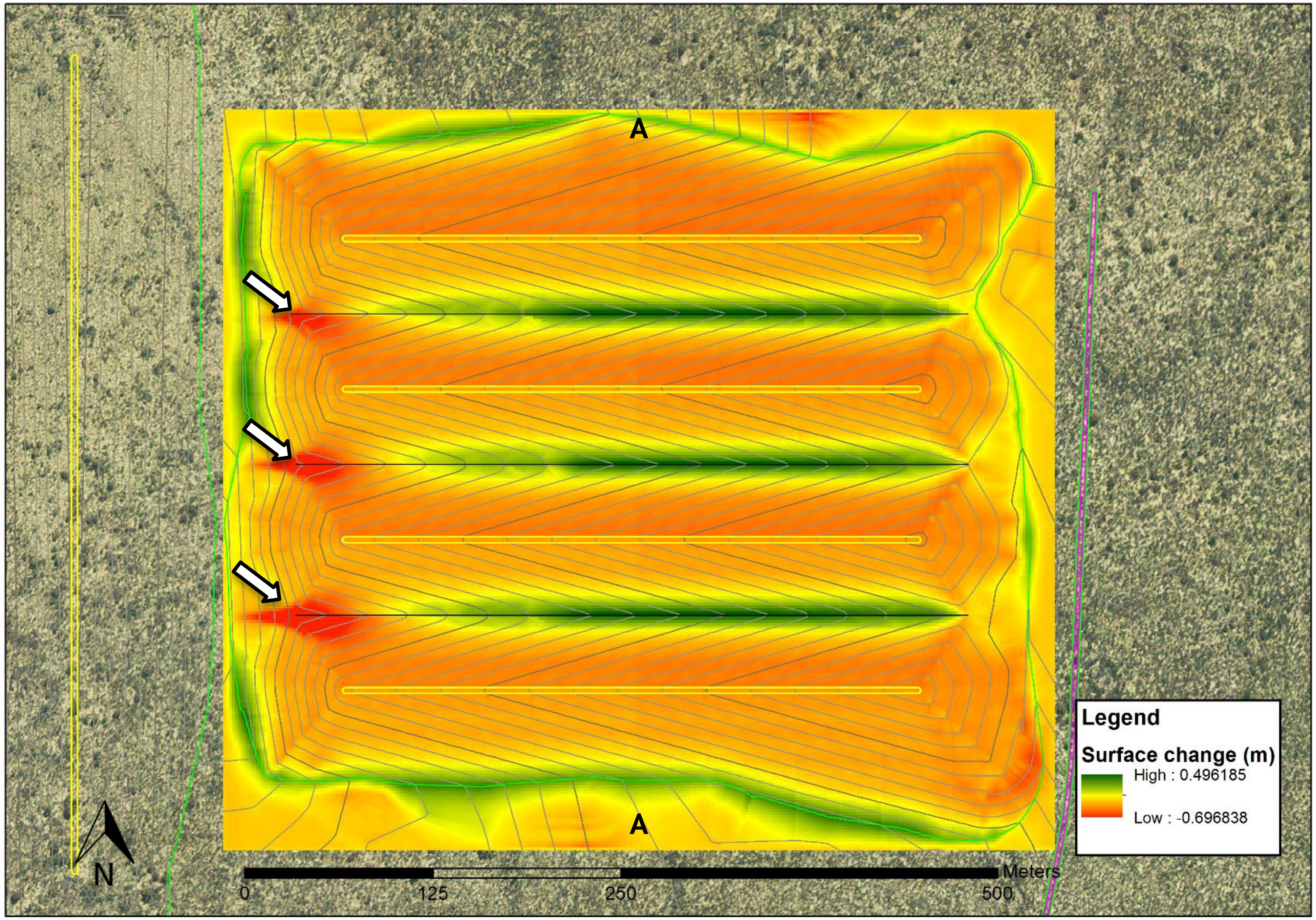

Figure 10: SIBERIA model 10,000 year results for long term landscape evolution of the eastern cells.

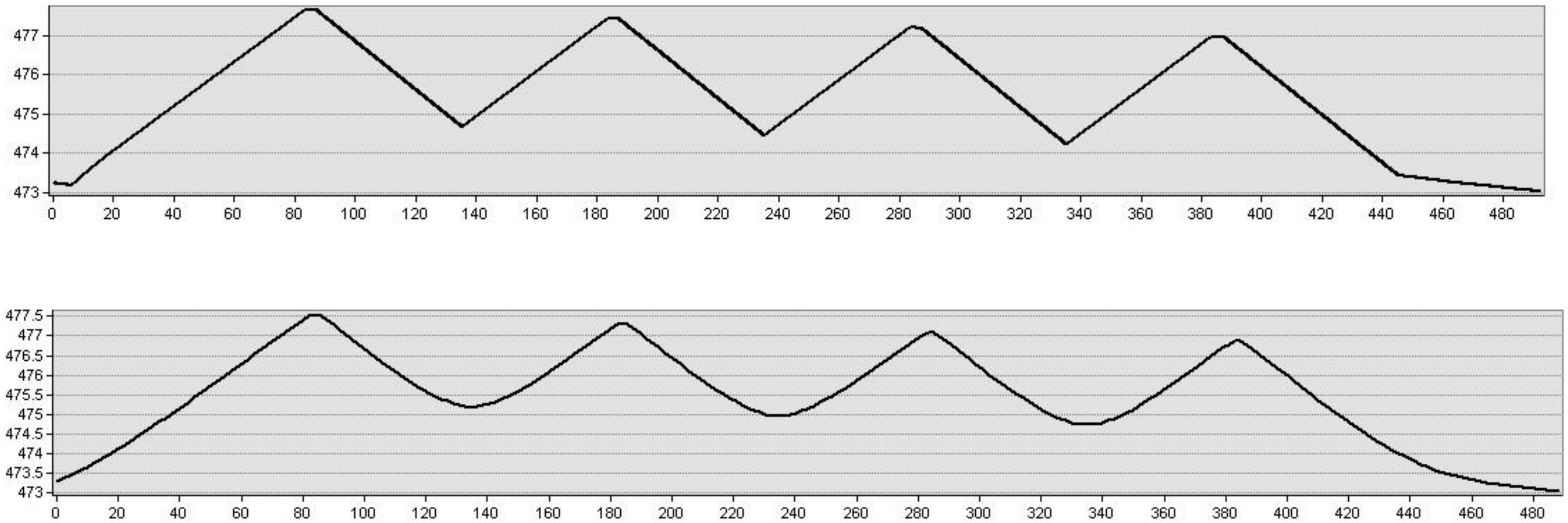

Figure 11: SIBERIA model results cross section for the original surface (top) and 10,000 year simulation (bottom). Axes in meters.

6.2.7 SIBERIA model results: operational bunds

The results are shown in Figure 12 for a 200 year period of simulation. The cross sections show that the KGC flood bunds lose their shape relatively quickly and halve in elevation over 50 years. As was identified in the original hydrology report, the flood bunds are to intercept potential surface flows of around 20cm. The bunds appear to be functional from this point of view for around the 100 year period, but then have eroded to a point where they will not be able to intercept flows of this magnitude. As seen on the cross sections, the width of the flood bunds is much greater than is proposed in the waste facility designs. It is only the mass of material that remains once the batter angles have been decreased over the shorter term that keeps these features distinguishable on the landscape over the longer period. As the bunds are only intended to function for ~20 years, the model results would indicate that they would remain functional for this period but Tellus operational staff may need to inspect and repair them during the mining operations. There may also be an implication for closure as the operational bunds will most likely erode to a point where they are indistinguishable from the natural surface over the much longer term.

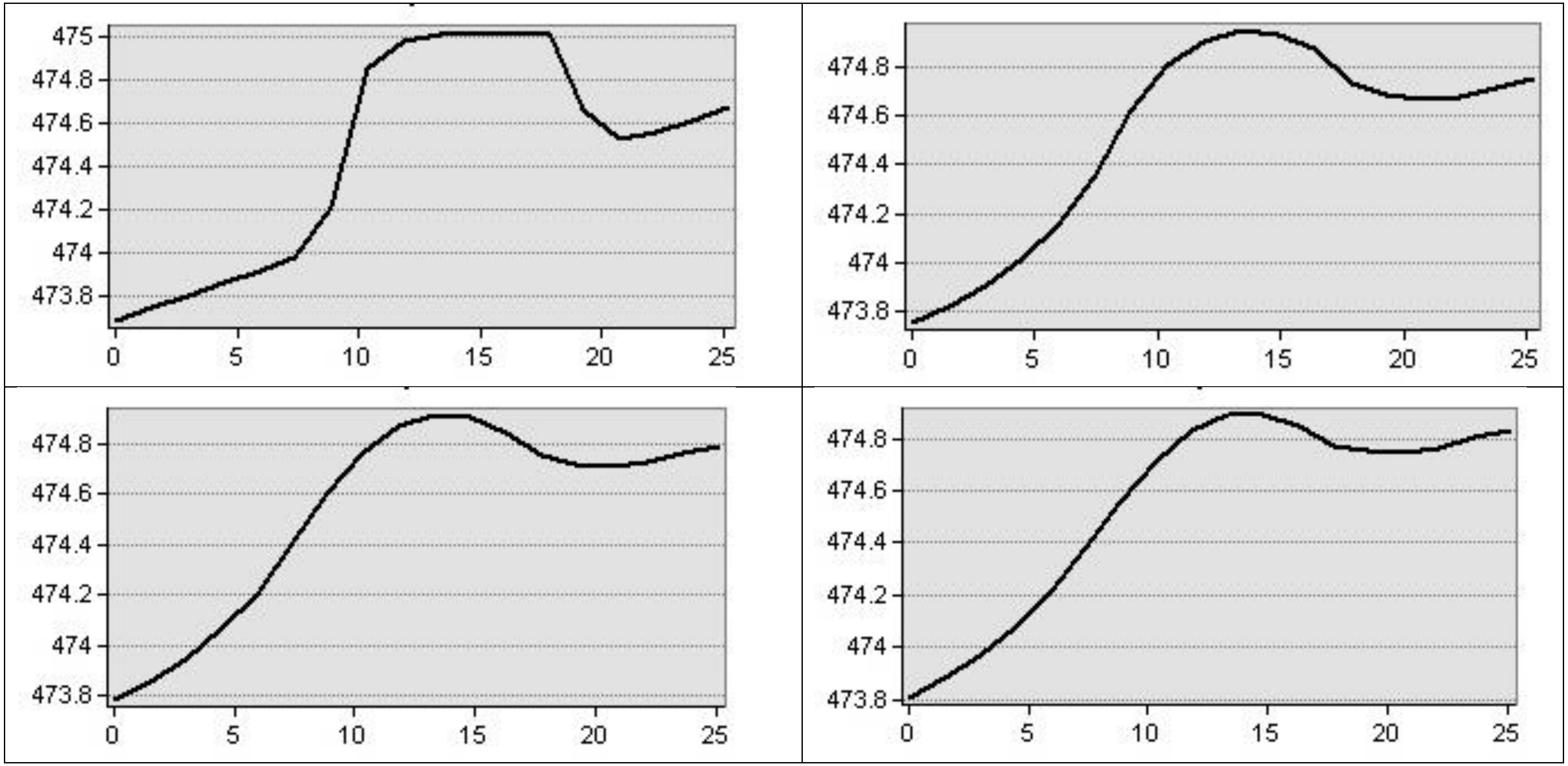

Figure 12: SIBERIA model results for the flood bund cross section for year 0 (top left), 50 years (top right), 100 years (bottom left), and 150 years (bottom right). Horizontal axis in meters, vertical axis in centimetres.

7 DISCUSSION

7.1 Model limitations

The WEPP model has been widely used and is well understood. Landloch has been using this model since 1998 and has been constantly developing methods for improved calibration and model accuracy, the most recent example being the acquisition of a modified version that allows incorporation of material particle size and destiny into erosion prediction. Landloch has also been conducting work on WEPP model validation by comparing simulation results with field erosion plot data, and there has been good agreement between the two data sets (Howard and Roddy 2012). The WEPP model, when run in hillslope mode, is not suited to modelling very complex landscapes (e.g., dissected) or for landscapes with permanent rivers or gullies as these processes are not simulated within the model. However, the WEPP model is well suited to erosion simulation on waste landform batters.

The SIBERIA model's main limitation is that it evolves the landscape constantly through the period of simulation at a rate equal to the long-term erosion rates. It does not consider erosion caused by individual events. Consequently the model is best suited for landscape evolution studies over long periods and not focussed on single events or short periods of time. As with all models, calibration is important and the SIBERIA model is most reliably calibrated from WEPP model output that in turn was derived from measurements made on the specific materials.

It should be noted that no model is currently able to adequately represent physical processes in conjunction with erosion, such as long term physical and chemical weathering of materials, vegetation and actual climatic changes, and bush fires.

7.2 Climate sensitivity

The original scope of works presented to Landloch from Tellus was to investigate the erosional stability of the waste facility for a range of climatic events. Using the most extreme climate change emission scenario of RCP 8.5[1], ~30% of the models predict a wetter climate; ~70% predict little change or a dryer climate for Australia's arid interior as shown in Table 4 (Whetton *et al.* 2012). A detailed climate change assessment of the Pilbara found the largest increase to annual rainfall estimated is an extra 24 to 30mm/yr for RCP 8.5. There was also a corresponding increase in potential evaporation of 77mm/yr for the same scenario (Charles *et al.* 2015). Assuming that an increase to annual rainfall of 24-30mm/yr did occur and the hypothetical result was a doubling of the waste cell long term erosion rate, this would mean that the erosion rate is an order of magnitude lower than Landloch's threshold of acceptable erosion.

[1] Representative Concentration Pathway of 8.5Wm^2 in 2100, with a CO_2 equivalent of 1370ppm, and temperature anomaly of 4.9°C (Riahi *et al.* 2011).

Table 4: Predicted changes to annual rainfall and mean surface temperatures from 48 Australian climate change models for the arid interior.

		Annual Mean Surface Temperature (C)			
		Slightly warmer <0.5°	Warmer 0.5 - 1.5°	Hotter 1.5 - 3°	Much hotter >3°
Annual Rainfall (%)	Much wetter >15			3	4
	Wetter 5 to 15			1	7
	Little Change -5 to 5				11
	Drier -15 to -5				9
	Much Drier < -15			1	12

7.3 Modelling results and the current proposed design

From the material characterisation of the topsoil and the KGC, the long term erosion modelling using WEPP, landscape evolution modelling using SIBERIA, the following points are made in relation to the current proposed waste facility design:

- The topsoil and KGC material's fine particle size distribution, low critical shear, and high interrill and rill erodibility indicate that both materials are prone to erosion.
- The topsoil's high saturated conductivity however means that rainfall will infiltrate and may not be converted to runoff (as is the case for the KGC) and therefore produces less erosion events than the KGC material.
- The predicted erosion of topsoil is below the threshold of acceptable erosion for 10m high landform with linear batters up to 20°, whereas erosion of the KGC material is only below this threshold at low height (<5m) and gradient (<4°) configurations.
- The proposed waste facility design of 5m high cells with 3° batters covered with a deep layer of topsoil is erosionally stable over the very long term due to the permeability of the topsoil, arid climate, and a gently sloping design. The model results indicate that the topsoil layer should be at least 1m thick.
- The KGC material will be suitable for the construction of operational bunds (life ~20 years) provided they are inspected and maintained as necessary.

7.4 Potential design modifications

7.4.1 Cover design

The SIBERIA model results show that there is some direction of flows into the between cell areas, which are then conveyed to the cell outlets where the greatest surface lowering occurs (Figure 10). The following design modification are suggested to potentially improve the waste facility design and may to be considered for further work.

7.4.2 Cover materials

The present design calls for each cell to be capped with KGC and left exposed to allow for subsidence inspections. The modelling results show that the KGC material is hardsetting and erodible, and this can be observed on the caps of previous stockpiles of kaolin where the material rills and delivers fine material out into the receiving environment (Figure 13).

In low rainfall arid zones where the evaporation rate is high, there are rarely (if any) rainfall event that would wet the soil profile deeper than ~500mm (assuming a soil porosity of 30% and a 150mm storm event) (R. Loch *pers. comm*). This is combined with the Mt Walton study stating that there is currently no water tables in the area (Dept. of Finance 2014), and that there may be 8 to 23m of compacted KGC material between the waste and the ground surface. Rather than designing impermeable above ground caps that are likely to erode, change surface hydrology, require follow up rehabilitation for closure, and costly earth works to compact and construct, some potential alternatives may use the available materials' inherent properties to achieve design aims and closure goals.

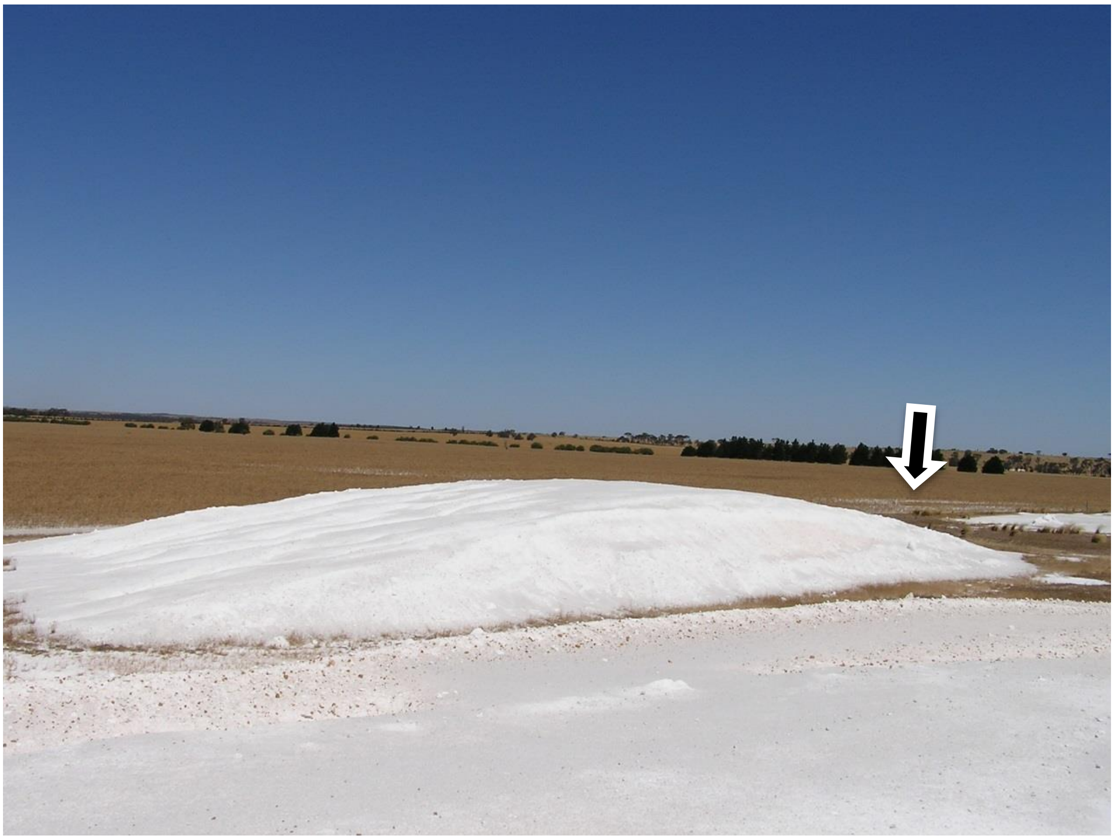

Figure 13: KGC stockpile in Western Australia with eroded fine material indicated by the arrow.

7.4.2.1 Store and release cover

As it is unlikely that surface water will penetrate to significant depth, the use of an impermeable cap may not be required. It may be better to design a cover that will store any rainfall, make it available for plants, and hold the moisture for evaporation. The design would:

- Follow the proposed design for the deeper layers,
- Place KGC into the top part of the pit (machine trafficked, not compacted) so that a low dome is formed above the ground surface,
- The KGC material is amended to prevent hard setting,
- 500mm of topsoil is placed over the KGC material, fertilised, and seeded (Figure 14).

The advantages of a cover would be that it would not place an erodible material on the surface for a long period of time. It would reconstitute the natural topsoil so that it could hold moisture and allow the regeneration of native plants. It would also mean more efficient earth works to construct (i.e., no compaction in thin layers) and eliminate the necessity to return in a decade to complete the rehabilitation. The other advantage is that it would avoid constructing a texture contrasting profile where a highly permeable material is placed over a highly impermeable material. The drainage pattern of a natural texture contrast soil is shown in Figure 15. There is a potential for subsurface drainage to be initiated after final rehabilitation that would lead to the erosion of the surface material. A store and release cover would seek to minimise the hard contact of the KGC with the sandy topsoil.

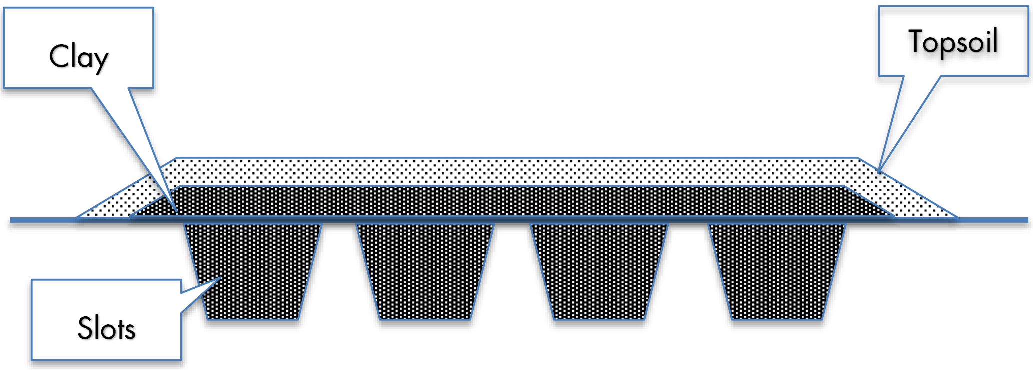

Figure 14: Store and release cover system.

Figure 15: Texture contrast soil (sand over clay) and the subsurface drainage pattern (green dye).

7.4.2.2 Re-established drainage surface

A modification to the store and release design would be to reinstate the previous natural surface as practically as possible. This would require the KGC material to be backfilled to within ~1m of the surface, with sandy topsoil used to bring the level up to the original RL (Figure 16). Settlement of the materials would have to be factored in, but the advantages of the design would be a very low relief/low erosion surface that would store and release water but that matches the aesthetics of the surrounding areas. Vegetation would also be re-established to further aid the stability of the surface, mimicking the present catchment function/erosional stability due to low relief and broad sheet wash drainage patterns.

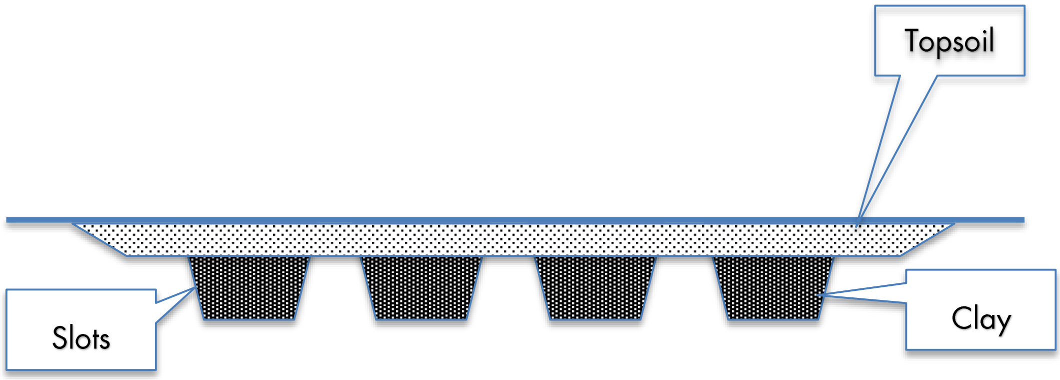

Figure 16: Reinstated natural surface cover system.

7.5 Further works

As the WEPP and SIBERIA models are now calibrated, these could be rapidly run to examine any modifications to the current waste facility design (such as doming the capping layer) and assessing changes to the mining plan. Also of value would be to confirm the water movement into the near-surface subsoil material using soil water balance modelling. This modelling can examine the water movement through a profile of different materials and could compare the effectiveness of the proposed KGC caps against any store and release design.

This report did not explore the impacts of wind erosion. This may potentially be a factor in placing sandy topsoil over 5m thick KGC caps in a low relief arid environment. The correct use of tree debris will likely be important in minimising the wind's surface contact with the reinstated topsoil (Figure 17).

Topsoil and KGC material amendment and fertilisation (to encourage the rapid development of native vegetation) has not been detailed in this report. Amendment and fertilisation rates and application techniques could be recommended based on existing material characterisation data.

Field trial plots would also be beneficial to validate model results, assess the placement of sandy topsoil over clay, and trial wind erosion and vegetation establishment strategies.

Figure 17: Example of using tree debris on a freshly reinstated sandy topsoil on a waste dump to minimise wind erosion in Western Australia.

8 CLOSING

The long term landform evolution modelling indicates that the rehabilitated waste facility at Sandy Ridge is erosionally stable over the very long term. Landloch has identified some potential improvements for the proposed waste facility design. These primarily involve eliminating the flow concentrating features, and examining alternatives to the capping layer design that may best work with the natural materials to ensure a long term erosionally stable surface and support the reestablishment of native vegetation.

Erosion potential for the main materials from the Sandy Ridge Project have been assessed. The assessment is based on:

- Consideration of the prevailing climate and its erosivity.
- Known factors critical for stability of natural and disturbed surfaces.
- Assessment of the variability of materials found on site.
- Characterisation of the erodibility of the typical surface materials present.
- Computer simulations of runoff and erosion on the range of typical slopes.
- Consideration of the role of rock on erosion potential.
- Issues relating to measured sediment characteristics.

Consequently, the results are based on site data and its interpretation using well-validated procedures.

REFERENCES

Boggs, G. S., Evans, K. G., Devonport, C. C., Moliere, D. R., and Saynor, M. J. (2000) Assessing catchment-wide mining-related impacts on sediment movement in the Swift Creek catchment, Northern Territory, Australia, using GIS and landform-evolution modelling techniques. J. Environmental Management 59: 321-334.

Charles, S., Guobin, F., Silberstein, R., Mpelasoka, F., McFarlane, D., Teng, J., Gabrovesk, C., Ali, R., Barron, O., Aryal, S., and Dawes, W. (2015) Hydroclimate of the Pilbara: past, present and future. CSIRO Land and Water Report, 7th October, 2015.

Chaves, H. M. L., and Nearing, M. A. (1991) Uncertainty analysis of the WEPP soil erosion model. Transactions of the ASAE, 34: 2437-2444.

Dept. of Finance. (2014) Intractable waste disposal facility, Mt Walton East. Information Handbook. Department of Finance, Building Management and Works. October, 2014.

DRET. (2009) Case Study: Erosion monitoring for stable landforms, in Evaluating performance: Monitoring and auditing. Leading Practice Sustainable Development Program for the Mining Industry. pp 45-46. Department of Resources, Energy and Tourism, Australian Government.

Evans, K.G., Willgoose, G.R., Saynor, M.J., and House, A. (1998) Effect of vegetation and surface amelioration on simulated landform evolution of the post-mining landscape at ERA Ranger Mine, Northern Territory. Supervising Scientist Report 134, Environment Australia.

Flanagan, D.C., and Livingston, S.J. (1995) Water Erosion Prediction Project (WEPP) Version 95.7 User Summary. In (Flanagan and Livingston, editors) 'WEPP user summary', NSERL Report No 11, July 1995.

Hancock, G.R. (2004) The use of landscape evolution models in mining rehabilitation design. Environmental Geology 46: 1432-1495.

Hancock G.R., and Willgoose G.R. (2004) An experimental and computer simulation study of erosion on a mine tailings dam wall. Earth Surface Processes and Landforms 29: 457-475.

Hancock, G., Evans, K.G., Willgoose, G.R., Moliere, D., Saynor, M. and Loch, R.J. (2000) Long-term erosion simulation on an abandoned mine site using the SIBERIA landscape evolution model. Australian Journal of Soil Research 38: 249-264.

Hancock, G., Willgoose, G.R., and Evans, K.G. (2002) Testing of the SIBERIA landscape evolution model using the Tin Camp Creek, Northern Territory, Australia, field catchment. Earth Surface Processes and Landforms 27: 125-143.

Hancock, G. R., Loch, R. J., and Willgoose, G. R. (2003) The Design of Post-Mining Landscapes Using Geomorphic Principles. Earth Surface Processes & Landforms 28: 1097-1110.

Hancock, G.R. and Turley, E. (2006) Evaluation of proposed waste rock dump designs using the SIBERIA erosion model. Environmental Geology 49: 765-779.

Howard, E.J., and Roddy, B.P. (2012) Evaluation of the water erosion prediction project model – validation data from sites in Western Australia. Mine Closure 2012 – Fourie, A.B and Tibbett, M (eds). Australian Centre for Geomechanics, Perth.

Landloch. (2015a) Sandy Ridge Project Soil Assessment. Report No. 2216.15a. June, 2015.

Landloch. (2015b) Characterisation of the clay capping material from the Sandy Ridge Mine Site. Report No. 2230.15a. August, 2015.

Loch, R.J. (1994) A method for measuring aggregate water stability of dryland soils with relevance to surface seal development, Australian Journal of Soil Research 32: 687-700.

Loch, R.J. (2001) Settling velocity – a new approach to assessing soil and sediment properties, Computers and Electronics in Agric. 31: 305-316.

Loch, R. J., Robotham, B. G., Zeller. L., Masterman, N., Orange, D. N., Bridge, B. J., Sheridan, G., and Bourke, J. J. (2001) A multi-purpose rainfall simulator for field infiltration and erosion studies. Australian Journal of Soil Research 39: 599–610.

Mengler, F.C., Hancock, G.R., Gilkes, R., and Grant, C. (2004) Managing erosion in rehabilitated bauxite mine soils using the SIBERIA landform evolution model. In "SuperSoil 2004". Australian Society of Soil Science Inc.

Nearing, M. A., Dear-Ascough, L, and Laflen, J. M. (1990) Sensitivity analysis of the WEPP Hillslope Erosion Model. Transactions of the ASAE, 33: 839-849.

Riahi, K., Krey, V., Rao, S., Chirkov, V., Fischer, G., Kolp, P., Kindermann, G., Nakicenovic, N., and Rafai, P. (2011) RCP-8.5: exploring the consequence of high emission trajectories. Climatic Change. doi: 10.1007/s10584-011-0149-y

Rockwater. (2015) Surface water assessment and management plan: Sandy Ridge Kaolinite Project. Report No. 454-0/15/01. July 2015.

Willgoose, G.R., Bras, R.L., and Rodrigues-Iturbe, I. (1989) Modelling of the erosional impacts of land use change: A new approach using a physically based catchment evolution model. In Hydrology and Water Resources Symposium 1989, Christchurch, NZ. National Conf. Publ. no 89/19, The Institution of Engineers, Australia, 325-329.

Willgoose, G.R., Bras, R.L., and Rodriguez-Iturbe, I. (1991) A physically-based channel network and catchment evolution model: I Theory. Water Resources Research 27: 1671-1684.

Willgoose, G.R. (1994) A physical explanation for an observed area-slope-elevation relationship for declining catchments. Water Resources Research 30: 151-159.

Willgoose, G.R. (1995) A preliminary assessment of the effect of vegetation on the long-term erosional stability of the proposed above-grade rehabilitation strategy at Ranger Uranium Mine. Open File Record 119, Supervising Scientist for the Alligator Rivers Region, Canberra.

Willgoose, G.R. and Riley, S.J. (1993) Application of a Catchment Evolution Model to the Prediction of Long-Term Erosion on the Spoil Heap at Ranger Uranium Mine. Open File Report 107, The Office of the Supervising Scientist, Jabiru.

Willgoose, G., Hancock, G., and Kuczera, G. (2003) Testing of an erosion-based landform evolution model using objective statistics. Geophysical Research Abstracts, Vol. 5, EAE03-A-11904.

Yu, B., (2002) Using CLIGEN to generate RUSLE climate inputs. Transactions of the ASAE, 48: 993-1001.

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