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Appendix G – GSL Cover Design Report

NOEF Geosynthetic Liner Cover System – Preliminary Soil Plant Atmosphere Modelling and Analysis

5 December 2017

McArthur River Mining
A GLENCORE COMPANY

O'Kane Consultants




Integrated Mine Waste Management and Closure Services
Specialists in Geochemistry and Unsaturated Zone Hydrology

NOEF Geosynthetic Liner Cover System – Preliminary Soil Plant Atmosphere Modelling and Analysis

750/49-01

December 2017

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Rev. #	Rev. Date	Author	Reviewer	PM Sign-off
00	7 Nov 2017	RES	PG	
01	14 Nov 2017	RES	PG	
02	15 Nov 2017	RES	PG	PG
03	23 Nov 2017	RES	PG	PG
04	30 Nov 2017	RES	PG	PG

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1 INTRODUCTION

Glencore's McArthur River Mining (MRM) submitted a Draft Environmental Impact Study (EIS) to the Northern Territory government in March 2017. The Draft EIS presented a cover system using a compacted clay liner (CCL) as the barrier component of the enhanced store and release cover system for the final rehabilitation of the Northern Overburden Emplacement Facility (NOEF). In a ranking assessment of alternatives, a cover system with a bituminous geomembrane (BGM) as the barrier layer was ranked number one, however there was insufficient knowledge at the time regarding life and constructability to recommend its adoption for the base case. Following submission of the Draft EIS and results from support studies becoming available, further development was conducted into a cover system which utilises a Geosynthetic Liner (GSL), of which a BGM is an example, as the barrier layer. This report supports the design and assessment of a GSL as part of the Supplementary EIS by developing Soil-Plant-Atmosphere (SPA) numerical modelling for optimisation of a GSL cover system.

1.1 Project Objectives and Scope

Numerical modelling and assessment of a GSL cover system was focused on the following three performance metrics:

1) Maintaining sufficient soil moisture for the establishment and survival of vegetation of the plateau cover system;
2) Anticipated cover system performance in terms of stability and drainage performance during and following the 1-in-1,000 year critical storm event, specifically for interflow (i.e. lateral water movement within the cover system);
3) Estimated net percolation (NP) through several cover system design options.

The main cover system designs evaluated for the plateau and batter areas (referred to hereinafter as the "Base-Case Plateau Cover System" and "Base-Case Batter Cover System") are as follows:

Base-Case Plateau Cover System (from surface to underlying NOEF waste rock):

- 100 mm of Topsoil for vegetation support;
- 600 mm of (Upper) Alluvium as growth medium;
- 500 mm of Breccia as a drainage layer;
- 300 mm of (Lower) Alluvium as the GSL protective overliner;
- GSL as the barrier layer (to air and water); and
- 200 mm of HMR as the GSL underliner.

Base-Case Batter Cover System (from surface to underlying NOEF waste rock):

- 100 mm of Topsoil for vegetation support;
- 1,100 mm of Breccia as drainage layer and erosion protection layer;

- 300 mm of (Lower) Alluvium as the GSL protective overliner;
- GSL as the barrier layer (to air and water); and
- 200 mm of HMR as the GSL underliner.

Optimisation of the cover system profile layers with regards to thickness of individual layers was reviewed during the modelling process, with a focus on the drainage and growth medium layers.

1.2 Report Organization

For convenient reference, this report has been subdivided into the following sections.

- Section 1 – Introduction.
- Section 2 – Provides pertinent background information to support the study.
- Section 3 – Summarises the modelling program and input.
- Section 4 – Presents the modelling results.
- Section 5 – Provides reference material quoted throughout this document.

2 BACKGROUND

2.1 Definition of Net Percolation

The term 'net percolation' (NP) is used throughout this report and is defined as presented in Figure 2.1. Rainfall (R) will either be intercepted by vegetation, runoff (RO), or infiltrate into the surface. A portion of the water that infiltrates will be stored in the 'active zone' (ΔS) and subsequently exfiltrate back to the surface and evaporate, or be removed by transpiration (ET). Infiltration can also move laterally downslope within and below the active zone (referred to as interflow). A percentage of the infiltrating water will migrate beyond the active zone as a result of gravity overcoming the influence of atmospheric forcing (i.e. evaporation) and result in NP to the underlying material.

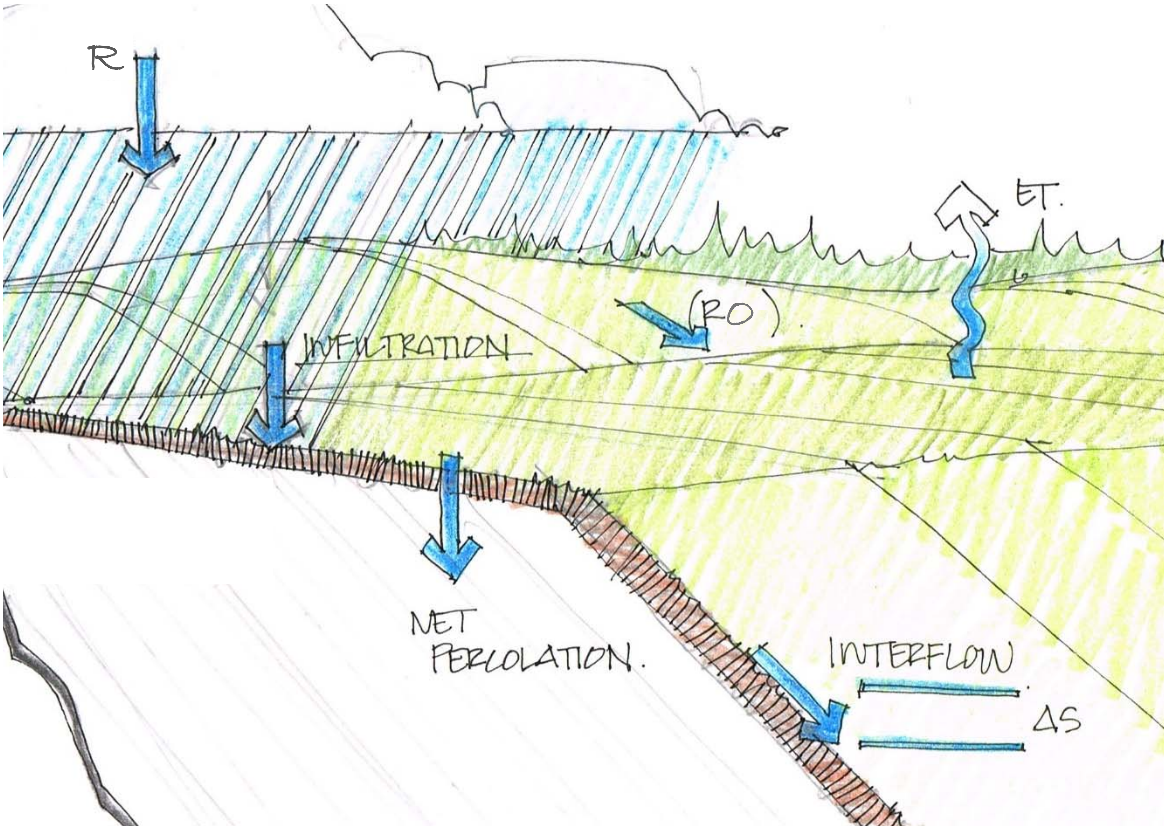

Figure 2-1: Schematic of hydrologic processes that influence performance of sloping cover systems for waste rock.

NP through a cover system using a geomembrane as a barrier element can still occur through diffusion, although the transmission rates are typically very low. In general, the hydraulic conductivity corresponding to water diffusion is in the order of 10^{-14} to 10^{-13} m/s for a BGM, depending on the thickness of the product (Breul et al., 2004). As a result, NP is primarily attributed to leakage through holes in the BGM. In the cover system profile, this leakage can only be triggered when positive pore water pressures (i.e. ponding of water) develop on top of the GSL in proximity to a hole.

A range of performance in terms of NP rates exists for a cover system, which is highly dependent on the climate regime. The range of cover system performance for the NOEF is presented conceptually in terms of "Very Low" (VL), "Low" (L), "Moderate" (Mod), "High" (H), and "Very High" (VH) NP rates.

Within a single climatic regime, the range of NP performance results from the influence of differing abilities of a cover system to evapotranspire water and to promote runoff (and/or interflow) from the landform. Comparing Bureau of Meteorology (BoM) rainfall and actual evapotranspiration (AET) estimates (as presented in Section 3) indicates that for the MRM area an undisturbed site would have approximately 15 mm (2% of average annual rainfall) available for NP (assuming runoff is nil on an areal scale). Hence, for the MRM NOEF cover system:

- "Very High" NP is classified as greater than 50% of average annual rainfall (% R),
- "High" NP is between 15% R and 50% R,
- "Moderate" NP is between 10% R and 15% R,
- "Low" NP is between 5% R and 10% R, and
- "Very Low" NP is less than 5% R.

It must be noted that NP rates and resultant % R can be higher or lower for any given year. For example, a high rainfall year (or, more specifically, a number of successive wetter than average climate years) may result in a high NP rate for the year, even for a site classified, on average, as having a very low NP rate. Therefore, occasional exceedances of the target NP are not necessarily an indication of cover failure.

2.2 Soil Moisture Definition and Classification

Cover system performance with regards to vegetation establishment and survival was evaluated during the growing season (approximated as November to April for MRM) based on the soil water deficit (SWD) for the top 1.0 m of the cover system. SWD is defined as the amount of water required to increase water stored within the soil to field capacity (FC). FC is the water content held in the soil after excess water has drained away and the rate of percolation has decreased. Permanent wilting point (PWP) is defined as the minimum soil water required for a plant to resist wilting. In general, FC is defined as the water content of soil at a suction of 33 kPa, and PWP at a suction of 1,500 kPa. However, this range is very general and does not account for differences in soil and plant characteristics. Based on the estimated properties for the cover system materials and the anticipated tropical grassland savanna vegetation, the FC and PWP for this project were defined at suctions of 10 kPa, and 3,000 kPa, respectively. Model results are presented based on the percentage of time the SWD is less than that required to have the top 1.0 m of the cover system at or above PWP.

2.3 Conceptual Model for NOEF GSL Cover System Design

The purpose of a cover system in reclamation of a mine waste storage facility is to provide a stable, reliable and sustainable engineered interface between the receiving environment and the mine waste (INAP, 2017). It supports agreed-upon land uses while minimising degradation of the surrounding environment. The purpose of the GSL cover system for the NOEF is to limit NP and erosion while still supporting preferred vegetation communities. Modelling was undertaken to determine the most effective way of achieving these objectives.

Cover systems limit NP by one of two methods, representing the bookends of a performance range:

1) Diversion: a layer of the cover system may be constructed from materials with a sufficiently low permeability to limit downward percolation of rainfall, and “release” water as surface runoff or interflow.

2) Store-and-release: infiltrating water is stored within the rooting zone of the cover so it can be subsequently released via AET. In these types of cover systems, the objective is to minimise deep percolation by returning most of the infiltrating waters from storage to the atmosphere via transpiration.

A cover system that utilises both the ‘moisture store-and-release’ and ‘diversion’ concepts (an ‘enhanced’ store-and-release cover system) was identified during the Draft EIS as the most suitable cover system for the NOEF. This is based on MRM receiving a distinct wet and dry season and being situated in a tropical environment. The particular characteristics of these two cover system concepts are then manipulated to meet design criteria and objectives specific to the NOEF.

The presence of an underlying lower permeability GSL beneath the store-and-release component of the cover system aids in reducing NP to the underlying NOEF material. The overlying layers provide for storage and release of infiltration for the majority of the time but the GSL is designed to limit NP when the overlying storage capacity is exceeded.

The overlying cover system layers not only support vegetation, but also protects the integrity of the barrier layer from potential damage due to various site-specific physical, chemical, and biological processes. Rainfall is stored within the cover system and gradually released back to the atmosphere through AET. During periods of high (and more intense) rainfall the moisture store-and-release capacity is typically overwhelmed and the cover system (and landform) are designed to be ‘water shedding’ and therefore sheds excess water from the facility.

The conceptual performance of the Base-Case Plateau and Base-Case Batter Cover Systems are presented in Table 2.1, based on the estimated and assumed climate and material properties detailed in Section 3. As shown in Section 4, other than the minor differences in the water balance, the estimates for NP and soil moisture classifications, are similar to those predicted by the SPA base-case simulations.

Table 2.1: Summary of conceptual performance of base-case cover system designs

Cover System	Rain	AET	Runoff	Interflow	NP Class (% NP)	SWD below PWP
Plateau	715 mm/yr	80 – 95% R	0 – 5% R	5 – 10% R	VL (<5% R)	>90%
Batter	715 mm/yr	65 – 80% R	5 – 10% R	15 – 25% R	VL (<5% R)	~75%

3 MODEL DESCRIPTION AND INPUTS

SEEP/W (GEO-SLOPE, 2017) is a 2D finite element model (which can also perform 1D simulations) that predicts suction in the material profile in response to climatic forcing (such as evaporation) and lower boundary conditions (such as a water table). Based on these calculations, NP is predicted. A key feature of SEEP/W is the ability of the model to predict AET based on potential evaporation and predicted suction, as opposed to the user being required to input these surface flux boundary conditions. The AET rate is generally below the potential rate during prolonged dry periods because the suction, or negative water pressure, in the material profile increases as the surface desiccates.

SEEP/W version 9.0.0.14833 was used to solve the simulations presented in this report.

SPA numerical modelling inputs can be divided into five categories: geometry, material properties, upper boundary conditions, lower and edge boundary conditions, and initial conditions. A brief description of these model inputs are presented in the following sections

3.1 Geometry

GSL cover system modelling focused on the Base-Case Plateau and Base-Case Batter Cover System designs:

Base-Case Plateau Cover System (from surface to underlying NOEF waste rock):

- 100 mm of Topsoil for vegetation support;
- 600 mm of (Upper) Alluvium as growth medium;
- 500 mm of Breccia as a drainage layer;
- 300 mm of (Lower) Alluvium as the GSL protective overliner;
- GSL as the barrier layer (to air and water); and
- 200 mm of HMR as the GSL underliner.

Base-Case Batter Cover System (from surface to underlying NOEF waste rock):

- 100 mm of Topsoil for vegetation support;
- 1,100 mm of Breccia as drainage layer and erosion protection layer;
- 300 mm of (Lower) Alluvium the GSL protective overliner;
- GSL as the barrier layer (to air and water); and
- 200 mm of HMR as the GSL underliner.

SPA models were tailored for each performance metric, namely soil moisture, interflow, and net percolation. The following subsections describe the models developed to evaluate each performance metric.

3.1.1 Soil Moisture

1D SPA models were evaluated for the layers overlying the GSL, allowing for interflow to develop. The thickness of the upper alluvium layer was evaluated from a thickness of 0 mm (i.e. batter cover system with no upper alluvium layer) to a maximum thickness of 1,400 mm. For upper alluvium layers thinner than 600 mm, the breccia layer thickness was increased so that the total thickness of the cover system was maintained at 1,500 mm (including the GSL overliner layer); the minimum thickness acceptable based on root depth estimates (see Section 3.3.2).

3.1.2 Interflow

2D SPA models were based on the longest unbroken batter and plateau slopes (i.e. the longest continuous slope lengths until reaching the toe of the NOEF or a drainage channel). Only the layers above the GSL were simulated as, from an interflow standpoint, no NP through the GSL layer is a worst-case scenario, and a reasonable assumption given the very low hydraulic conductivity of the GSL material. The batter slope configuration was simulated as follows (from toe to crest):

- 4.5H:1V for 225 m plan length (rising 50 m)
- 3.5H:1V for 175 m plan length (rising 50 m)
- 3H:1V for 120 m plan length (rising 40 m)

2D simulations were also completed of a range of lengths for each batter slope component to determine the maximum distance between drainage locations to ensure the cover system does not saturate above the breccia layer.

The plateau slope configuration used for modelling purposes is 100 m in plan length at a 2% slope (i.e. rising 2 m). The plan length is based on the distance from the dump center to drainage channels on the plateau. Figure 3.1 and 3.2 show the meshes used to simulate the 2D models.

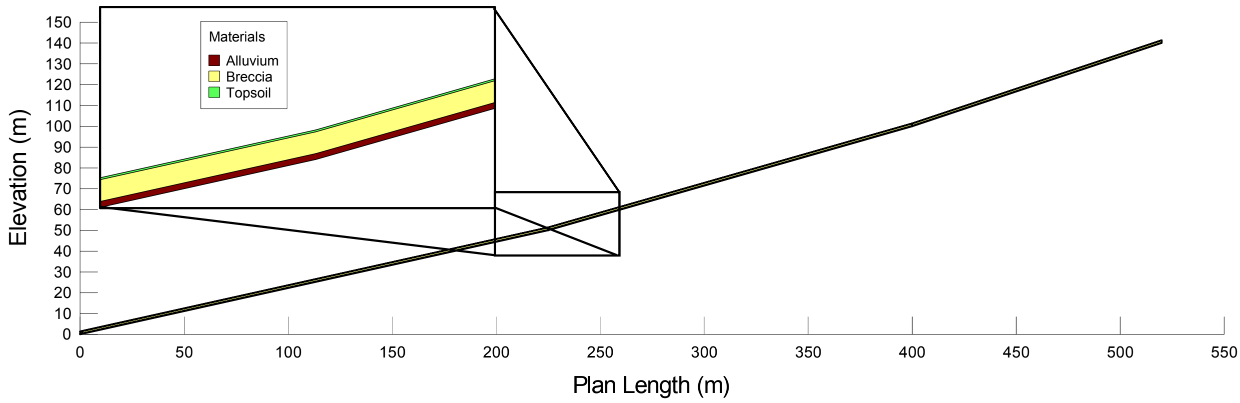

Figure 3-1: Geometry used to simulated 2D SPA model of Base-Case Batter Cover System.

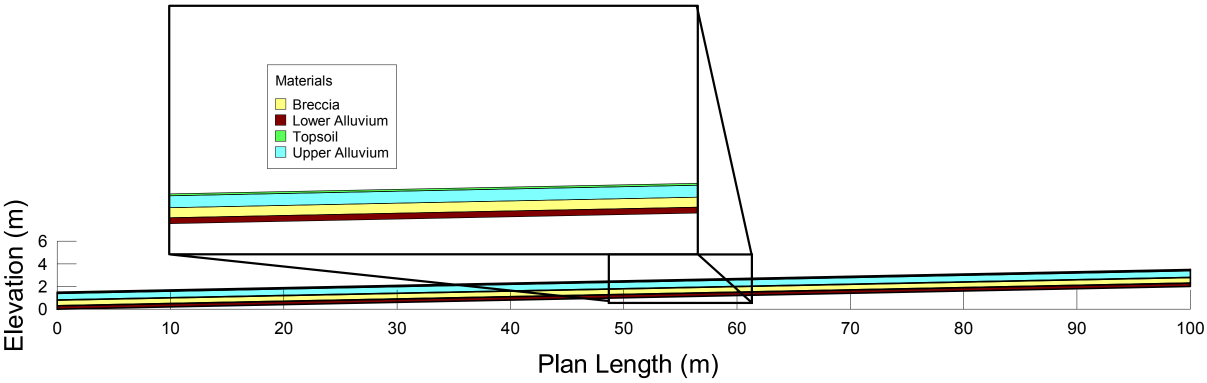

Figure 3-2: Geometry used to simulated 2D SPA model of Base-Case Plateau Cover System

3.1.3 Net Percolation

1D and quasi-three-dimensional (3D) SPA models were evaluated to develop estimates of NP through the Base-Case Plateau and Base-Case Batter Cover System designs. Estimation of NP through a GSL material is challenging due to NP being primarily due to flow through small perforations in the GSL material. Leakage through a geomembrane is influenced by the hydraulic head, size and number of the holes, hydraulic conductivity of the materials and quality of the contact with the geomembrane (Meiers *et al.* (2016)). Analytical solutions after Giroud *et al.* (1989) were used to simulate leakage through defects for good and poor contact of the GSL with the underlying material and determined as follows:

$Q = CP(A^{0.1}h^{0.9}k_{sat}{}^{0.74})$

where: Q is the leakage rate (m^3/s); CP is the contact parameter (0.21 for good and 1.15 for poor); A is the area of the defect (m^2); h is the hydraulic head (m); and k_{sat} is the saturated hydraulic conductivity of the lower alluvium material (m/s). This formula was derived assuming the material underlying the GSL is "plastic" and has a lower k_{sat} than the material directly on top of the GSL layer; however, this is not the case for the base-case GSL cover system designs evaluated for this report. Hence, 1D and quasi-3D SPA simulations were completed of the Base-Case Batter and Base-Case Plateau cover system designs to inform, calibrate, and validate the analytical assessment of NP. Specifically, the 1D simulations were completed to estimate the daily hydraulic head forming on the GSL, whereas the quasi-3D SPA models were completed to provide an estimate of NP through the GSL cover system to which the above formula could be calibrated via the CP parameter. The calibrated CP value for each simulation was assumed to be the performance if the underlying material had "good" contact with the GSL.

Simulations were completed assuming "good" and "poor" contact with the GSL. Good contact was assumed to coincide with excellent construction quality assurance and quality control (QA/QC), resulting in 2 holes per hectare within the GSL layer; each hole with a diameter of 10 mm.

As an upper-bound scenario for the MRM site, estimates of NP were completed assuming poor contact, 13 holes per hectare and each hole with a diameter of 10 mm, which is approximately the average size and number of holes in a geomembrane cited in the literature (Forget *et. al.* (2005), Barroso *et al.* (2006), Nosko and Touze-Foltz (2000) and Needham *et al.* (2004)). Note also that other studies, (eg McQuade and Needham (1999)) reported that the frequency of holes is large, ranging from zero to 120 per hectare; however, where construction QA was conducted, the frequency was zero to 5.7. 13 holes per hectare has been selected as a conservative upper limit, and with the QA/QC proposed for the NOEF installation, a defect rate closer to 0 will be expected.

With the exception of two scenarios using the Base-Case Plateau Cover System, the NP estimates are made based on the assumption that no vegetation has established on the cover system. This was done as it is conservative (i.e. vegetation removes more water from depth within the cover system profile thereby reducing the estimated depth and duration of positive hydraulic head forming on the GSL), and simplifies direct comparisons of the modelled scenarios.

1D SPA modelling simulated only the layers overlying the GSL without interflow permitted to determine a pessimistic estimate of pressure heads on top of the GSL. This enables an analytical estimate of the amount of NP through the given cover system. The analytical estimates were calibrated based on the results of the quasi-3D SPA models. The quasi-3D SPA models were simulated by defining the geometry properties as 360° axisymmetric simulations. These settings make the 2D cross-section shown in Figure 3.3 represent a circular area. The quasi-3D models accounted for the GSL and underlying layers (including 1 m of breccia waste rock), with a 10 mm diameter hole in the GSL at the centre of the circle (i.e. the leftmost 5 mm of the cross-section shown in Figure 3.3 represents the location of the hole in the GSL). Simulating a circular area with a 40 m radius means that the hole is in the middle of a 0.5 ha area, or a hole rate of 2 per hectare.

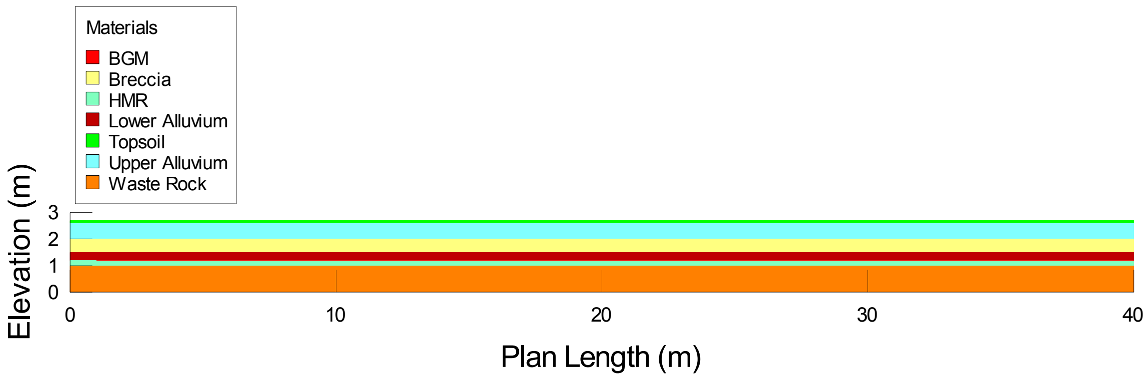

Figure 3-3: Geometry used to simulate a quasi-3D SPA model of the Base-Case Plateau Cover System.

3.2 Material Properties

There were four general material types that needed to be defined for this project: topsoil; alluvium (upper and lower); breccia (cover system and waste rock); HMR; and GSL. The material properties for the alluvium, breccia and topsoil layers were based on estimates first developed by OKC for the "NOEF Cover System and Landform Design in Support of the EIS Submission" report (OKC, 2016). However, the saturated hydraulic conductivity (k_{sat}) estimates were slightly adjusted to align with estimates of other consultants contributing to the project. The "upper" and "lower" alluvium are the same material, but the lower alluvium is estimated to be more compacted due to placement of the overlying layers, and less wet-dry cycling. The HMR was estimated to have properties similar to pea gravel in the SVSoils material database (SoilVision, 2017). The k_{sat} of the GSL was estimated based on BGM data from Breul *et al.* (2004). The material properties are summarized in Table 3.1.

Table 3.1: Summary of material properties.

	van Genuchten (1980) Parameters				
	Θ_S (m^3/m^3)	**Θ_R (m^3/m^3)**	**α (kPa)**	**n**	**k_{sat} (m/s)**
Upper Alluvium	0.444	0	2	1.30	3×10^{-5}
Lower Alluvium	0.370	0	10	1.30	1.85×10^{-6}
Breccia (Cover System and Waste Rock)	0.418	0	0.4	1.40	1×10^{-3}
HMR	0.235	0	9.8	4.00	1.3×10^{-2}
Topsoil	0.444	0	2	1.30	3×10^{-5}
GSL	-	-	-	-	5×10^{-14}

3.3 Upper Boundary Conditions

The upper boundary conditions required for the SPA models can be divided into two parts: climate and vegetation. Details regarding the model inputs developed for each are described below.

3.3.1 Climate

A 125-year climate database for the location of the MRM site (16.45° S, 136.10° E) was developed based on historic data representative of site conditions from 1 July, 1889 to 30 June, 2014 (using a SILO data drill (State of Queensland, 2015)) by OKC for the “NOEF Cover System and Landform Design in Support of the EIS Submission” report (OKC, 2016). Potential evaporation (PE) data was provided in the SILO data drill, and estimated using the Food and Agriculture Organization (FAO) of the United Nations’ method; referred to as FAO56 (FAO, 1998). Areal AET for each month were estimated based on gridded datasets also provided on the Bureau of Meteorology (BoM) website. Table 3.2 provides the monthly average climate conditions for the site based on the database.

Table 3.2: Monthly and annual climate averages

Month	Temperature (°C)		Relative Humidity (%)		Rainfall	PE	AET*
	Max	Min	9 AM	3 PM	(mm)	(mm)	(mm)
January	35.8	24.8	90.0	49.0	188	173	118
February	35.0	24.5	92.7	52.0	172	147	104
March	34.7	23.2	92.6	49.6	141	159	104
April	34.2	20.3	87.2	40.1	32	155	44
May	31.9	16.5	82.6	33.7	7	144	22
June	29.4	12.7	82.5	30.8	5	126	17
July	29.3	12.0	81.0	28.9	1	136	16
August	31.6	13.5	80.6	27.8	0	160	16
September	34.6	16.9	82.0	29.7	3	181	30
October	37.2	20.9	80.7	32.2	14	209	60
November	38.1	23.9	80.5	36.3	42	204	74
December	37.5	24.9	85.9	42.8	109	195	95
Annual	34.1	19.5	84.8	37.7	715	1989	700

*AET from BOM website which estimates regional evapotranspitation rates; will vary based on cover system performance.

Climate files were developed for simulations of each performance metric; namely, soil moisture; interflow; and net percolation, which are described in the following sections.

3.3.1.1 Soil Moisture

The entire 125-year climate database was evaluated for each cover system design scenario, with the primary focus on performance during the growing season (November to April).

3.3.1.2 Interflow

According to the 125-year historical climate database, a three-day (72-hour) storm event occurred during January of 1940 that was representative of a 1-in-100 year storm event. Therefore, to simulate a 1-in-1,000 year storm event, this three-day event was replaced with the following rainfall amounts on each day: 199 mm, 446 mm, and 88 mm. As a result, the simulation accounts for the 1-in-1,000 year 24-hour (446 mm), 48-hour (645 mm), and 72-hour (733 mm) storm events (based on BoM AAR87 Intensity-Frequency-Duration). Although updated 2016 data has become available showing less rainfall, MRM opted to use a dataset consistent with the Draft EIS, which makes the results more conservative. Up to a 72-hour event was included as initial simulations indicated that a 72-hour storm event was the critical event for interflow performance.

To simulate a 1-in-50 year storm event the three-day event described in the previous paragraph was replaced with the following rainfall amounts on each day: 82 mm, 250 mm, and 54 mm. As a result, the simulation accounts for the 1-in-50 year 24-hour (250 mm), 48-hour (332 mm), and 72-hour (386 mm) storm events.

To limit the influence of initial conditions, the models were started using the conditions from 1 July, 1939, to 6 January, 1940; at which point the 72-hour storm events listed above were added to the next three days (i.e. 7, 8 and 9 January, 1940). The simulation was continued until 30 June, 1940, so that a complete year could be reviewed.

3.3.1.3 Net Percolation

The entire 125-year climate database was evaluated for each cover system design scenario's 1D simulation as well as the quasi-3D base plateau cover system simulation. The remainder of the quasi-3D simulations were only simulated for the first 20 years of the 125-year historical climate database (1 July, 1889, to June 30, 1909).

3.3.2 Vegetation

The vegetation biome for the NOEF is a tropical grassland savanna. The model inputs used to simulate a tropical grassland savanna are summarized in Table 3.3, with additional description following the table.

Table 3.34: Vegetation model parameters

Model Parameter	Tropical Grassland Savanna
Root Depth (mm)	1,500
Root Distribution (%; top 300 mm)	80
Soil Cover Fraction	1
Field Capacity (kPa)	10
Permanent Wilting Point (kPa)	3,000

Jackson *et al.* (1996) estimated a typical root distribution for a tropical grassland savanna using the following formula first put forth by Gale and Grigal (1987):

$Y = 1-\beta^d$

Where Y is the cumulative root fraction from the soil surface to depth d (cm), and β is the fitted "extinction coefficient". β is the only parameter estimated in the model and provides a simple numerical index of rooting distribution. Jackson *et al.* (1996) estimated a β of 0.972 for tropical grassland savanna; however, OKC reduced β to 0.95 as it is anticipated that the breccia layer will promote higher root density near the surface than in an undisturbed environment. Figure 3.4 shows the cumulative root distribution estimated for the simulations with vegetation on the NOEF.

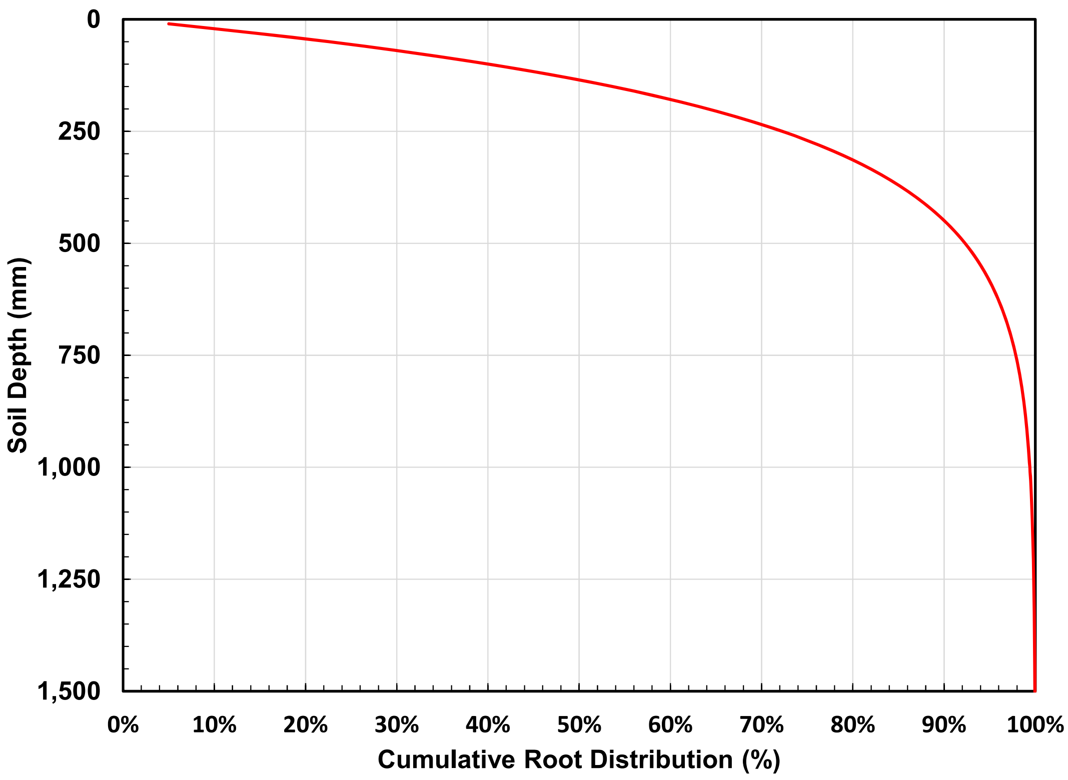

Figure 3-4: Cumulative root distribution estimated for a tropical grassland savanna growing on the NOEF cover system.

In general, FC is defined as the water content of soil at a suction of 33 kPa, and PWP is defined as the minimum soil water required for a plant to resist wilting at a suction of 1,500 kPa. However, this range is very general and does not account for differences in soil and plant characteristics. Based on the estimated properties for the non-compacted overburden and the anticipated grassland vegetation, the FC and PWP for this project were defined at suctions of 10 kPa and 3,000 kPa, respectively. These values were also used to define the plant water limiting function (PWLF) shown in Figure 3.5; which determines the percentage decrease in a plants ability to draw water as suction increases in unsaturated ground.

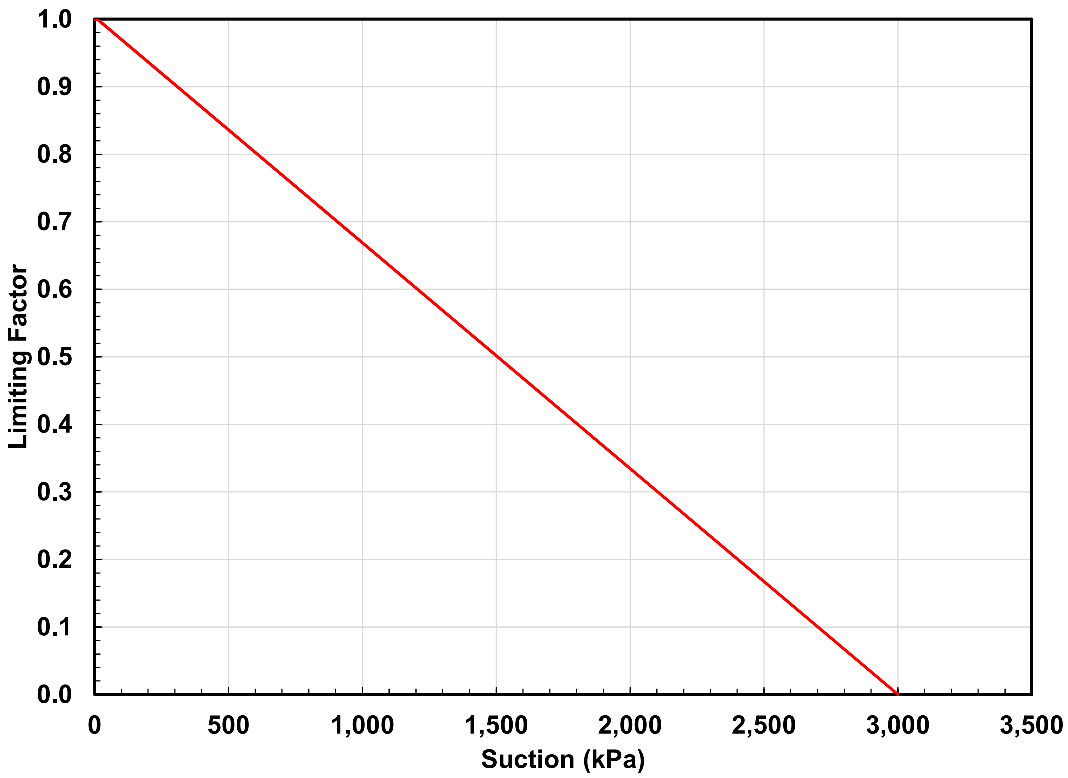

Figure 3-5: Plant water limiting function estimated for tropical grassland savanna.

3.4 Lower and Edge Boundary Conditions

The lower boundary condition was varied based on the performance metric being evaluated as described in the following sections.

3.4.1 Soil Moisture

The lower boundary of the 1D models was simulated as a potential seepage face, so that water was removed when positive pore water pressures formed at the base. This boundary was included to simulate the removal of water via interflow.

3.4.2 Interflow

The 2D models completed to evaluate interflow had a no-flow lower boundary representing an impermeable GSL layer; which is a worst-case but reasonable representation for this layer. A potential seepage face was placed along the lower edge (i.e. toe) of the cover system so that interflow could drain from the mesh.

3.4.3 Net Percolation

The 1D models assumed a no-flow lower boundary to estimate the pressure heads applied to the GSL layer during application of the 125-year historical climate database. The quasi-3D models used a unit hydraulic gradient as the lower boundary. A unit hydraulic gradient boundary condition assumes that at the lower boundary the suction (and as a result, water content and hydraulic conductivity) are constant with depth. For this situation, the total head equals the gravitational head, which results in a unit hydraulic gradient. In other words, a unit hydraulic gradient represents a location in the material profile where water movement is controlled mainly by gravity.

3.5 Initial Conditions

Initial conditions were assigned by setting the activation pore water pressure for each material at -100 kPa. All models were started during the mid-dry season (i.e. July 1), which substantially reduced the influence of the initial conditions on the model performance.

4 MODELLING RESULTS

SPA models were tailored for each performance metric; namely, soil moisture; interflow; and net percolation. The following subsections describe the models results obtained to evaluate each performance metric.

4.1 Soil Moisture

Four, 1D 125-year simulations were completed to estimate the optimum thickness for the upper alluvium layer from a vegetation establishment and survival perspective. The simulations were completed with a potential seepage face lower boundary condition to allow positive pore-water pressures to dissipate immediately; therefore, representing ideal interflow performance and a pessimistic estimate of soil moisture.

As shown in Figure 4.1, thickening the upper alluvium layer to 900 mm (from 600 mm) results in the top 1.0 m of the cover system having sufficient water available for plants (i.e. matric suction remains below the permanent wilting point) for 97% of the time during the growing season (November to April). In comparison, the Base-Case Plateau Cover System (with 600 mm of alluvium growth medium) is estimated to have sufficient water for plants 90% of the time. The Base-Case Batter Cover System has sufficient water available 72% of the time. Hence, the Base-Case Batter Cover System is anticipated to develop a sparse vegetation community with vegetation that prefers an aridic / xeric soil moisture regime. The plateau cover system with a 900 mm alluvium growth medium layer is expected to sustain a grassland vegetation community. As also shown in Figure 4.1, an upper alluvium layer of 1,400 mm results in sufficient water available for plants 99% of the time; only a slight improvement from the 900 mm upper alluvium scenario. Therefore it is concluded that little benefit is gained (from a soil moisture perspective) from making the upper alluvium layer thicker than 900 mm.

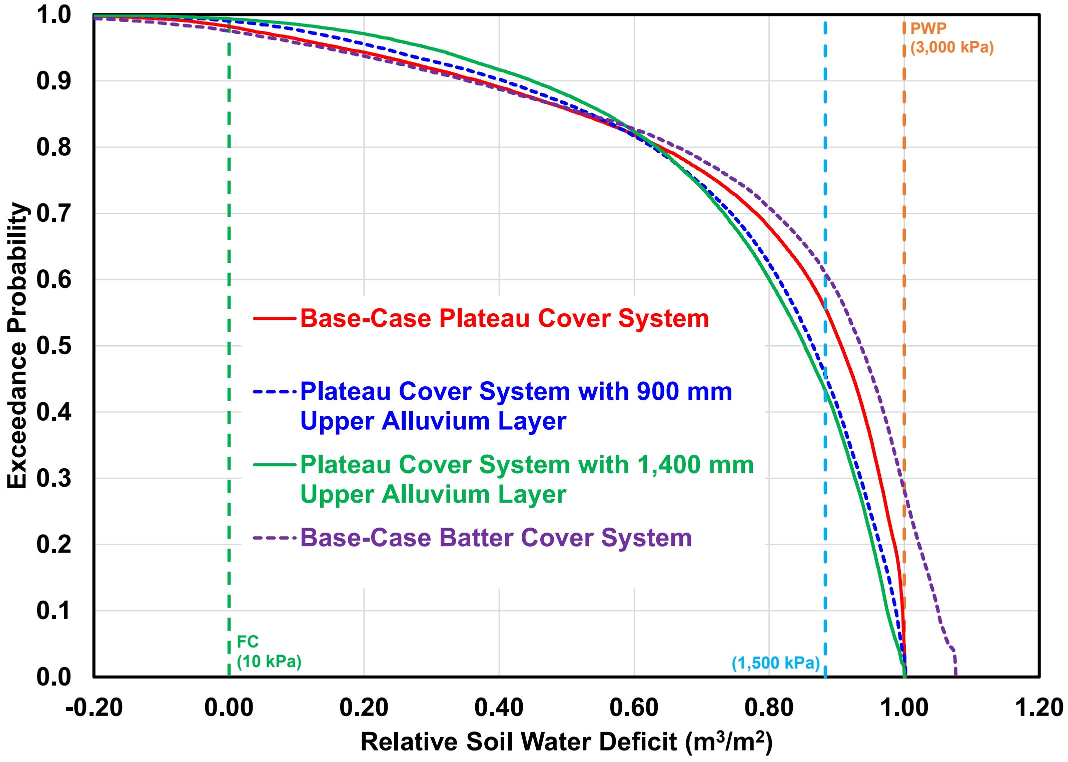

Figure 4-1 : Exceedance probability graph for soil water deficit predicted within cover systems.

4.2 Interflow

2D simulations were completed of the batter and plateau to determine the performance of the cover systems in both areas during the 1-in-1,000 year storm event, and maximum storm event that the cover system would withstand without saturated conditions breaching above the breccia layer.

Figure 4.2 shows that the model predicts the Base-Case Batter Cover System will be fully saturated to the surface for all but the 60 m (plan length) nearest the batter's crest by the last day of the three-day 1-in-1,000 year storm event. However, the positive pore-water pressures are predicted to dissipate below the topsoil layer for the entire slope within three days of the 1-in-1,000 year storm event. Positive pore water pressure to the surface of the cover system may indicated resurgence zones on the slope which may lead to increased erosion and slope instability. Similar results were obtained when the 300 mm Lower Alluvium layer was replaced with additional breccia material; increasing the thickness of the breccia layer to 1,400 mm; however, the additional breccia results in the upper 75 m (plan length) nearest the batter's crest not being fully saturated compared to the Base Cases 60 m.

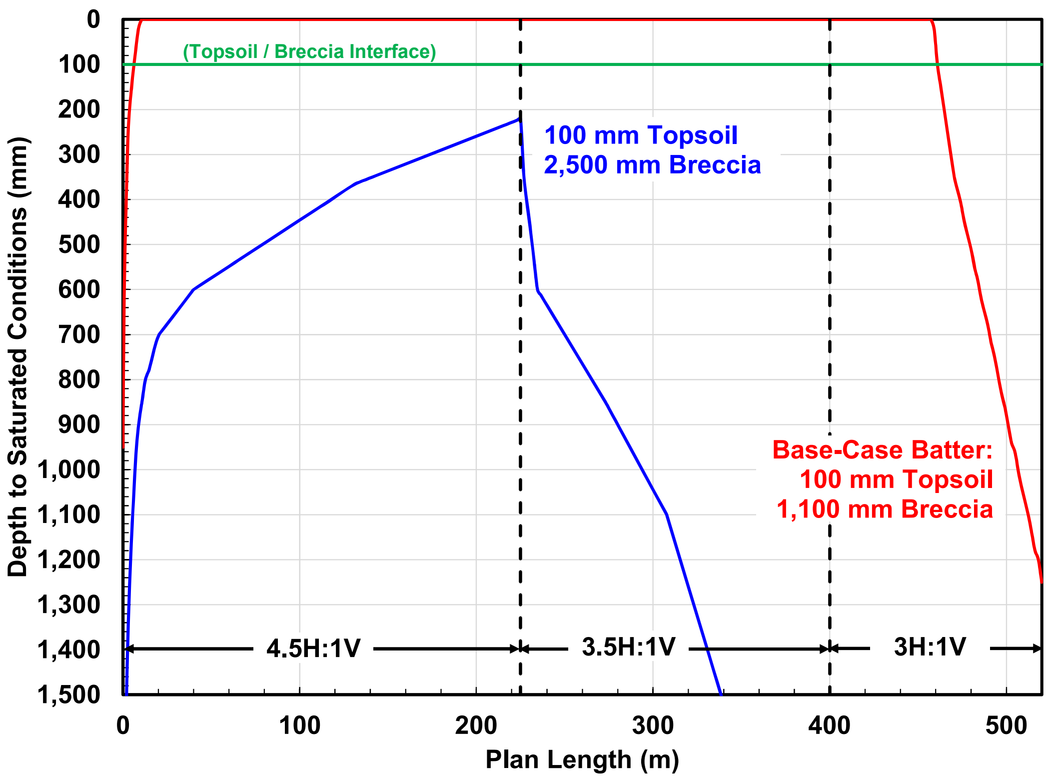

Figure 4-2: Depth to saturation within the batter cover system versus slope position.

Additional simulations showed that the Base-Case Batter Cover System can maintain positive pore-water pressures within the breccia layer for a 1-in-50 year storm event. To maintain positive pore-water pressures within the breccia layer alone for a 1-in-1,000 year storm event would require any, or a combination of:

- Increasing the thickness of the breccia layer from 1,100 mm to 2,500 mm; and / or
- Inclusion of a geosynthetic drainage layer; and / or
- Screening of the breccia to increase its hydraulic conductivity; and / or
- Creating swales with the NOEF waste rock parallel to the slope direction that will direct interflow diagonally to the swale where it can be brought to surface within drainage channels; and / or
- Inclusion of interflow drainage interception channels that would drain the batter cover system at regular intervals and direct runoff and interflow to drainage channels.

Hence, additional simulations were completed to determine the maximum distance between drainage strips on each batter slope for the Base-Case Batter Cover System and a cover system consisting of 100 mm of topsoil overlying 1,400 mm of breccia so that saturated conditions did not enter the topsoil above the breccia layer. The results of these simulations are summarized in Table 4.1.

Table 4.1: Estimated maximum horizontal distance between spline drains

Cover System	Batter Slope		
	4.5H:1V	3.5H:1V	3H:1V
Base-Case Batter	55 m	65 m	72 m
100 mm Topsoil 1,400 mm Breccia	72 m	85 m	93 m

It is assumed that none of these changes to the breccia layer will be necessary as the potential increase in surface erosion will be infrequent and localised. Should saturation of the breccia layer result in increased surficial erosion, such damage would be managed through maintenance during both the operations and closure periods.

As shown in Figure 4.3, interflow is estimated to stay within the breccia layer for the Base-Case Plateau Cover System if vegetation has established on the cover system. This is due mainly to the cover system having more water storage capacity prior to the 1-in-1,000 year storm event because vegetation has removed water from depth via root uptake. Without vegetation, the cover system is estimated to be overwhelmed during the 1-in-1,000 year storm event with positive pore water pressures reaching the surface. However, the positive pore-water pressures are predicted to dissipate quickly, with the topsoil layer being de-saturated (i.e. negative pore-water pressures) the following day, and positive pore-water pressures only within the breccia layer within five days of the 1-in-1,000 year storm event. Saturated conditions are predicted to remain within the cover system for the 1-in-50 year storm event and within the breccia layer for the 1-in-10 year storm event. Positive pore water pressure within the upper layers of the cover system for prolonged periods of time can lead to the formation of erosional channels and surface instability, even at shallow gradients.

Increasing the thickness of the alluvium layer to 900 mm while simultaneously decreasing the thickness of the breccia to 200 mm would improve vegetation establishment (as described in Section 4.1) while still having sufficient rooting depth (1,500 mm), and saturated conditions only form in the breccia layer (as long as vegetation has established on the cover system). This cover configuration is deemed acceptable by MRM as the NOEF would have a very low risk of being completely devoid of vegetation (and remnant root structures that would continue to stabilise the soil) following rehabilitation which will commence during the Mine Operations period and be completed during the TSF Operations period.

The option of using strip drains across the plateau to retain the saturated conditions within the Base-Case Cover System's breccia layer for the 1-in-1,000 year storm event was evaluated. The modelling indicated a maximum spacing of 25 m between strip drains was required on the plateau. The strip drains will be designed to collect lateral drainage from the breccia drainage layer, and prevent the build-up of positive pore water pressures within the growth medium, even during the 1-in-1,000 year storm event. Without the breccia drainage layer (i.e. 100 mm of topsoil overlying 1,400 mm of alluvium), drainage strips would need to be 2 m apart to keep saturated conditions within the lower 500 mm of the cover system for the 1-in-1,000 year storm event. Therefore, it is recommended that the breccia drainage layer remain.

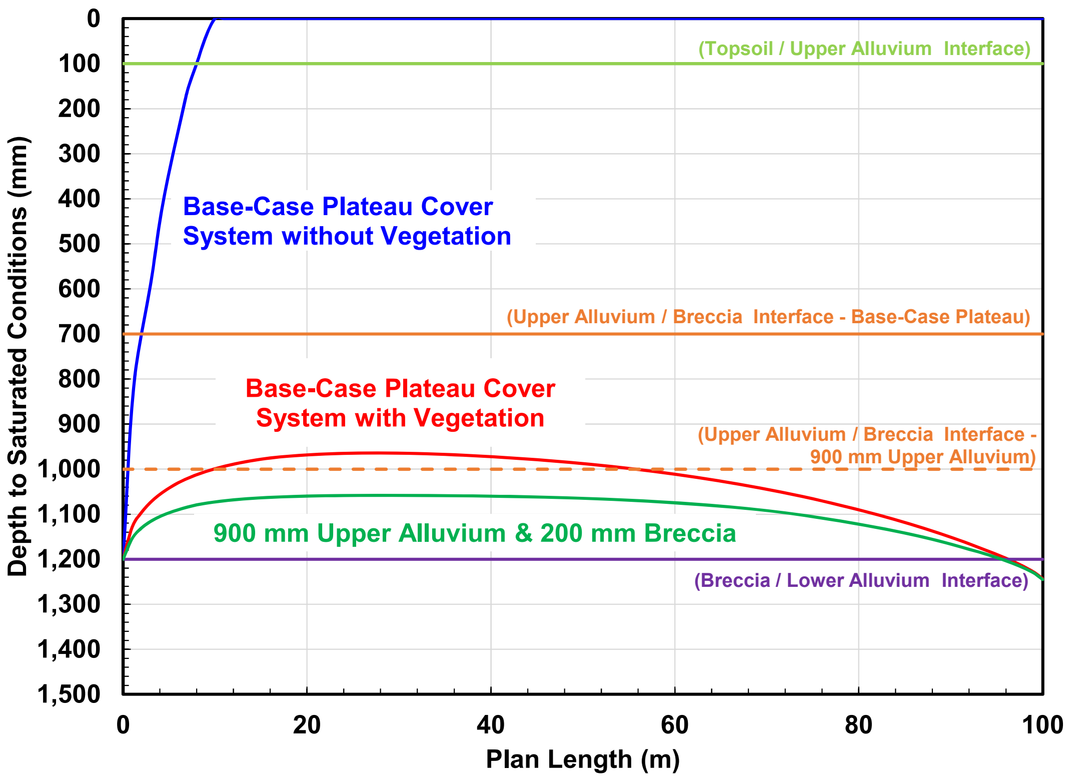

Figure 4-3 : Depth to saturation within the plateau cover system versus slope position.

4.3 Net Percolation

Table 4.2 provides a summary of the Base-case Plateau and Batter scenarios evaluated and their water balance results.

Table 4.2: List of Base-case Plateau and Batter scenarios evaluated and resultant water balance results.

Scenario #	**1**	**2**	**3**	**4**	**5**	**6**
Cover System	Base-case Plateau	Base-case Plateau	Base-case Plateau	Base-case Plateau	Base-case Batter	Base-case Batter
Vegetation?	No	No	Yes	Yes	No	No
GSL Contact	Good	Poor	Good	Poor	Good	Poor
Holes/ha	2	13	2	13	2	13
Rain	715 mm/yr	715 mm/yr	715 mm/yr	715 mm/yr	715 mm/yr	715 mm/yr
AET	73% R	73% R	96% R	96% R	71% R	71% R
Runoff	8% R	8% R	2% R	2% R	7% R	7% R
Interflow	19% R	16% R	3% R	2% R	21% R	19% R
NP (% R) - Class	0.4% - VL	2.5% - VL	0.05% - VL	0.3% - VL	0.6% -VL	2.6% - VL

The net percolation results in Table 4.2 and presented in Figure 4.4 show that:

- NP is anticipated to be classified as Very Low, as even with poor contact and 13 holes per hectare, average NP is less than 3% R with less than 13% of the model years predicting NP in the Low range and no model years with NP above the Low range.

- The establishment of vegetation substantially drops NP (Scenarios 3 and 4), resulting in no model years with NP outside of the Very Low range, even with poor contact and poor QA/QC.

- NP is estimated to mainly influence interflow

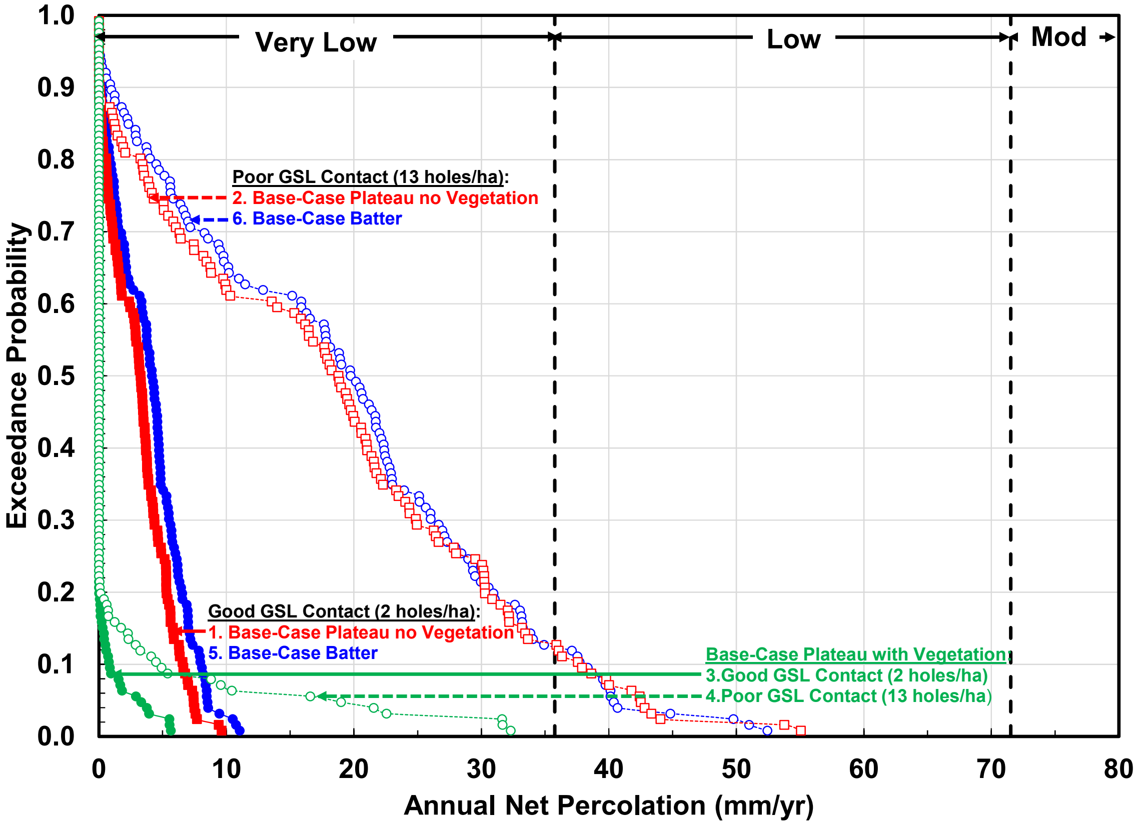

Figure 4-4 : Exceedance probability graph of annual net percolation predicted for Base-case Plateau and Batter scenarios.

4.4 Model Limitations

The SPA models presented in this section are mathematical representations of water transport within the evaluated cover system designs examined for the NOEF. The complex hydrogeology of the site was simplified into conceptual models that could be represented by mathematical models.

The following limitations should be noted when interpreting the results of the model predictions for the SPA numerical modelling program.

- The conceptual model assumes that movement of water in the unsaturated zone can be represented as Darcian flow in a porous media. The model does not account for any potential non-Darcian flow in macropores and/or cracks within the simulated tailings and cover system profiles.
- The conceptual model assumes that the waste rock and cover system profiles can be represented by various material types with homogeneous material properties. The potential influence of local heterogeneity (within a given material type) was not investigated.
- The water movement within the cover systems is defined by the unsaturated hydraulic conductivity versus matric suction relationship. This relationship is extremely difficult to measure *in situ* in a field condition and consequently is derived by a theoretical algorithm based on the value input for saturated hydraulic conductivity and water retention curve. The theoretical relationship defines the k-function over several orders of magnitude, while a single or half order of magnitude change can greatly affect the predicted NP results from a simulation.
- Vegetation development is subjectively defined by the model user and (other than the plant water limiting function) is not controlled by the material and water conditions estimated by the modelling program.

The key advantage to the numerical modelling results summarised herein is the ability to enhance judgment. Hence, rather than a focus on the absolute results predicted, it is recommended that the modelling results be viewed as a tool to understand key processes and characteristics that will influence performance of the cover system, and develop engineering decisions based on this understanding.

5 CONSTRUCTABILITY TEST PLOT NP MODELLING

MRM have planned a series of test plots to investigate the constructability and performance of various GSL-based cover profiles. These trials, planned for the dry season of 2018, will enable work methods, QA/QC methods, productivity and costs to be better understood prior to commencement of final NOEF cover system construction. Modelling of the expected NP of an initial batch of proposed Constructability Test Plot (CTP) was completed using the methods described in section 3.1.3.

5.1 Test Plot Scenarios

The initial CTP trials that were modelled are summarised in Table 5.1~~Table 5.1~~.

Table 5.1: CTP configurations and design specifications

CTP No.	Layers (from top to bottom)	Comment
1	• Alluvial, minimum 0.3 m thick • GSL geomembrane • HMR bedding 0.2 m thick +/- 0.05 m	No restriction on alluvial texture;
2	• Alluvial, minimum 0.2 m thick • GSL geomembrane • HMR bedding 0.2 m thick +/- 0.05 m	Decrease thickness of alluvium to optimise material use. Inform on equipment workability for placement of thinner layers.
3	• Breccia, nominally 0.5 m thick • Geotextile protection layer 1,000 g/m^2 • GSL geomembrane • HMR bedding 0.2 m thick +/- 0.05 m	Exclude alluvial confining layer and include geotextile protector over GSL to resist holes during direct placement of breccia material.
4	• Alluvial, minimum 0.3 m thick • GSL geomembrane • Alluvial bedding 0.2 m thick +/- 0.05 m	Address limited HMR availability and use of 'plastic' material as a bedding material that may deform under haulage traffic.
5	• Breccia nominally 0.5 m thick • Geotextile protection layer 1,000 g/m • GSL geomembrane • Alluvial bedding 0.2 m thick +/- 0.05 m	Alternative to alluvium overliner.
6	• Breccia nominally 0.5 m thick • HMR bedding 0.3 m thick +/- 0.05 m Allowable grade change 0.05 m per 3 m lateral distance • GSL geomembrane • Alluvial bedding 0.2 m thick +/- 0.05 m	Alternative to alluvium overliner.

5.2 Test Plot Modelling Results

The results of the simulations for the initial CTP concepts are shown in the Table 5.2 and Figure 5.1.

Table 5.2: List of CTP scenarios evaluated and resultant net percolation.

Scenario #	7	8	9	10	11	12	13	14	15	16
Cover System	CTP 2	CTP 2	CTP 3	CTP 3	CTP 4	CTP 4	CTP 5	CTP 5	CTP 6	CTP 6
Vegetation?	No	No	No	No	No	No	No	No	No	No
GSL Contact	Good	Poor	Good	Poor	Good	Poor	Good	Poor	Good	Poor
Holes/ha	2	13	2	13	2	13	2	13	2	13
Rain mm/yr	715	715	715	715	715	715	715	715	715	715
AET %R	73%	73%	73%	73%	73%	73%	73%	73%	73%	73%
Runoff	8%	8%	10%	6%	8%	8%	8%	8%	8%	8%
Interflow %R	19%	16%	16%	10%	19%	16%	19%	17%	19%	17%
NP (% R) Class	0.4% VL	2.5% VL	1.8% VL	11.7% Mod	0.4% VL	2.5% VL	0.5% VL	2.6% VL	0.4% VL	2.5% VL

The results indicate the following:

- Other than Scenario 10, NP is anticipated to be classified as very low as even with poor contact and 13 holes per hectare, average NP is less than 3% R with less than 13% of the model years predicting NP in the low range and no model years with NP above the low range.
- As shown by the CTP 3 scenarios, the absence of a plastic, lower permeability material directly above or below the GSL layer results in over a fourfold increase in NP, which results in Scenario 10 being classified as moderate NP. These results indicate the importance of an alluvium layer either directly above or below the GSL. However, it must be noted that the NP estimate for Scenario 10 is conservative as it does not account for reduction in hydraulic head due to drainage through the holes. This result will be considered in the final trial program.
- Reducing the thickness of the lower alluvium layer to 200 mm (CTP 2 – Scenarios 7 and 8) or replacing the HMR layer with alluvium (CTP 4 – Scenarios 11 and 12) had little influence on the predicted NP. However, these changes may have an influence in the real world if they result in more defects in a GSL, which should be evaluated as part of the trial program planned in 2018.
- Using the alluvium as a bedding layer instead of directly overlying the GSL was not detrimental to cover system performance (CTP 5 and 6 – Scenarios 13 to 16).
- Inclusion of a layer of material similar in hydraulic properties to HMR above the GSL resulted in minimal improvement in the cover system performance.

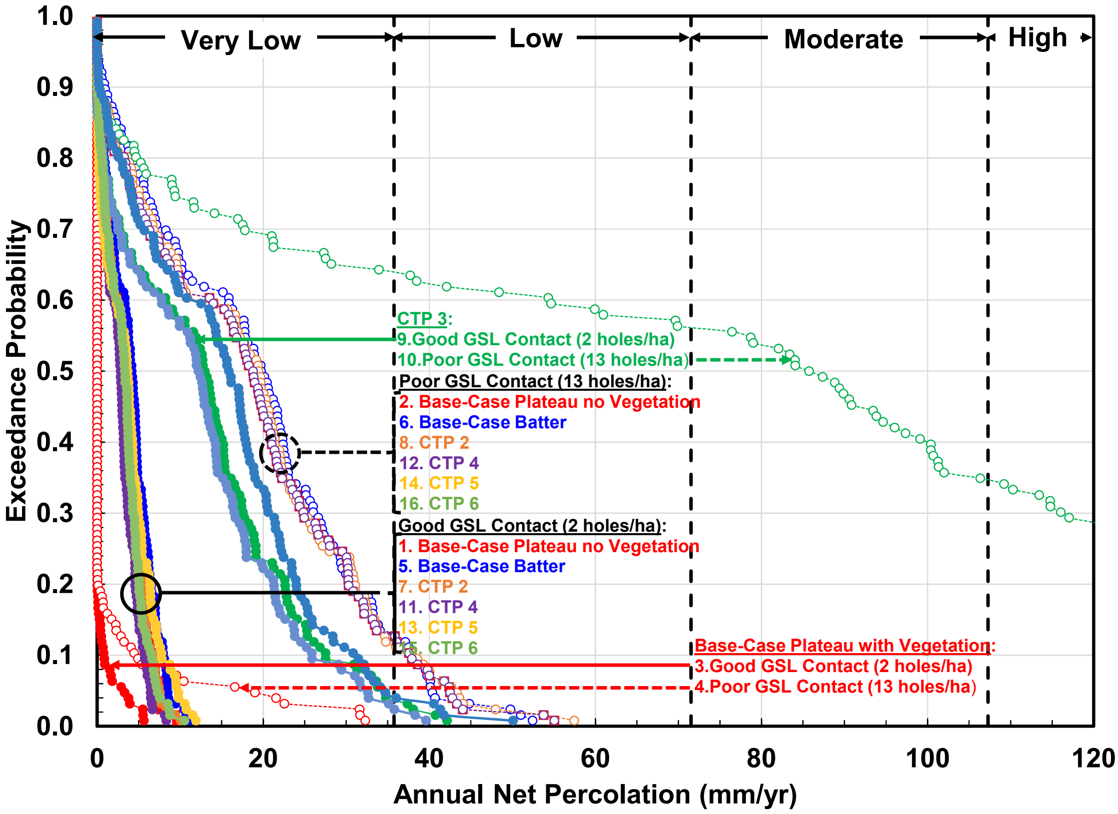

Figure 5-1 : Exceedance probability graph of annual net percolation predicted for all scenarios.

6 CONCLUSION AND RECOMMENDATIONS

The results of the modelling exercise presented in this report indicated the following:

- A minimum of 1,500 mm of cover system material is recommended above the GSL on the plateau to provide sufficient rooting depth for anticipated vegetation growing on the NOEF.

- The Base-Case Plateau Cover System (i.e. 600 mm upper alluvium layer) is sufficient for plant establishment and survival, while a 900 mm upper alluvium layer was found to be well balanced between vegetation sustainability and material requirements. The model results indicated little benefit from a vegetation standpoint of going thicker than 900 mm.

- A 200 mm breccia layer is sufficient for the plateau cover system (once vegetation establishes) to retain saturated conditions within the breccia layer while interflow is occurring.

- Saturated conditions are anticipated to reach the surface along the batters during the 1-in-1,000 year storm event with a 1,100 mm breccia layer; however, positive pore-water pressures are predicted to dissipate below the topsoil layer for the entire slope within three days of the 1-in-1,000 year storm event. Localised erosion may be expected from such events.

- NP through the initial GSL cover system alternatives is anticipated to be classified as Very Low for all the scenarios evaluated with the exception CTP 3 (i.e. No lower alluvium layer above or below GSL).

Based on the modelling results, the preferred Batter Cover System for the batters is:

- 100 mm or Topsoil for vegetation support;
- 1,100 - 1,400 mm of Breccia as the drainage layer and growth medium, to maintain a minimum overall thickness of 1,500mm above the GSL;
- A GSL overliner protection layer comprising of 200mm to 300 mm of (Lower) Alluvium, or a cushioning geotextile (to be confirmed as part of the 2018 CTP plan);
- GSL as the barrier layer (air and water); and
- 200 mm (or greater) of HMR or alluvials as the GSL underliner.

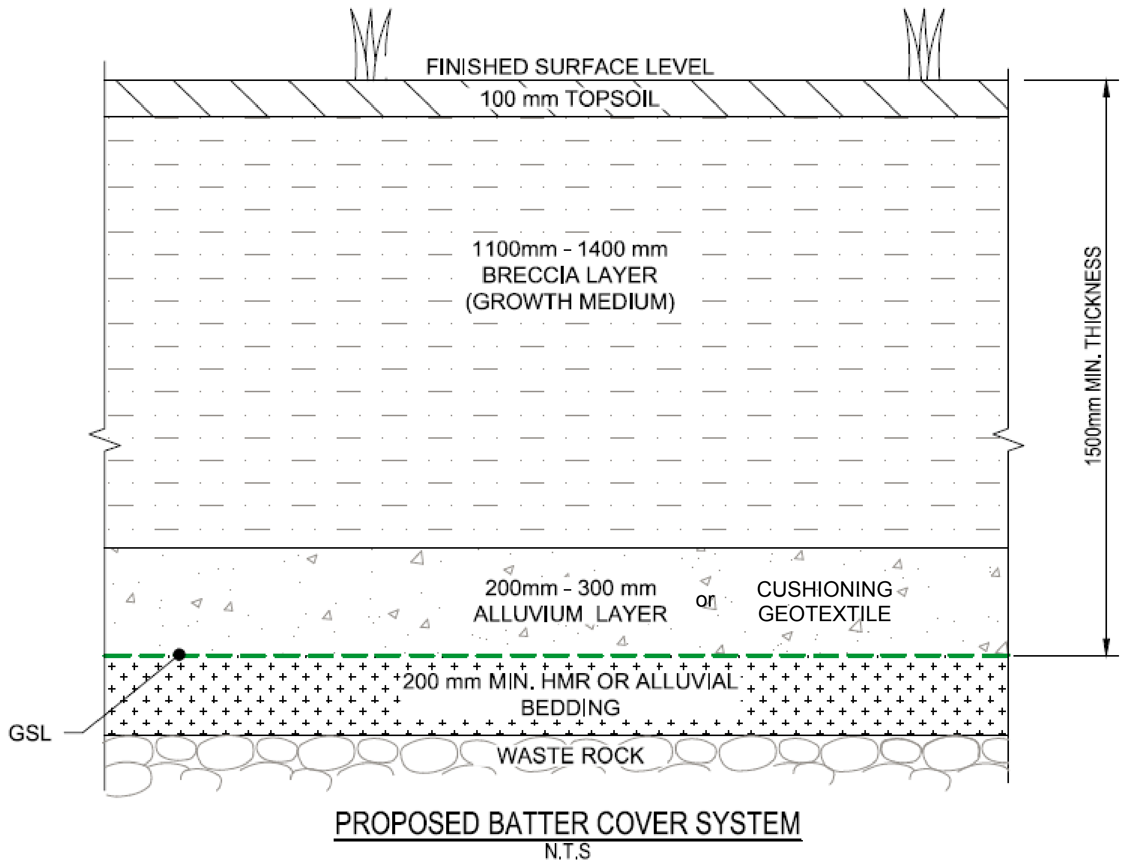

Figure 6-1: Proposed batter cover system profile

The preferred cover system for the plateau consists of the following layering (from surface to underlying NOEF waste rock). Acceptable range in brackets:

- 100 mm of Topsoil for vegetation support;
- 600 mm to 900 mm of (Upper) Alluvium as growth medium, to maintain a minimum overall thickness of 1,500mm above the GSL;
- 200 mm to 500mm of Breccia as a drainage layer;
- 200 mm to 300 mm of (Lower) Alluvium as the GSL overliner;
- GSL as the barrier layer; and
- 200 mm (or greater) of HMR or alluvials as the GSL underliner.

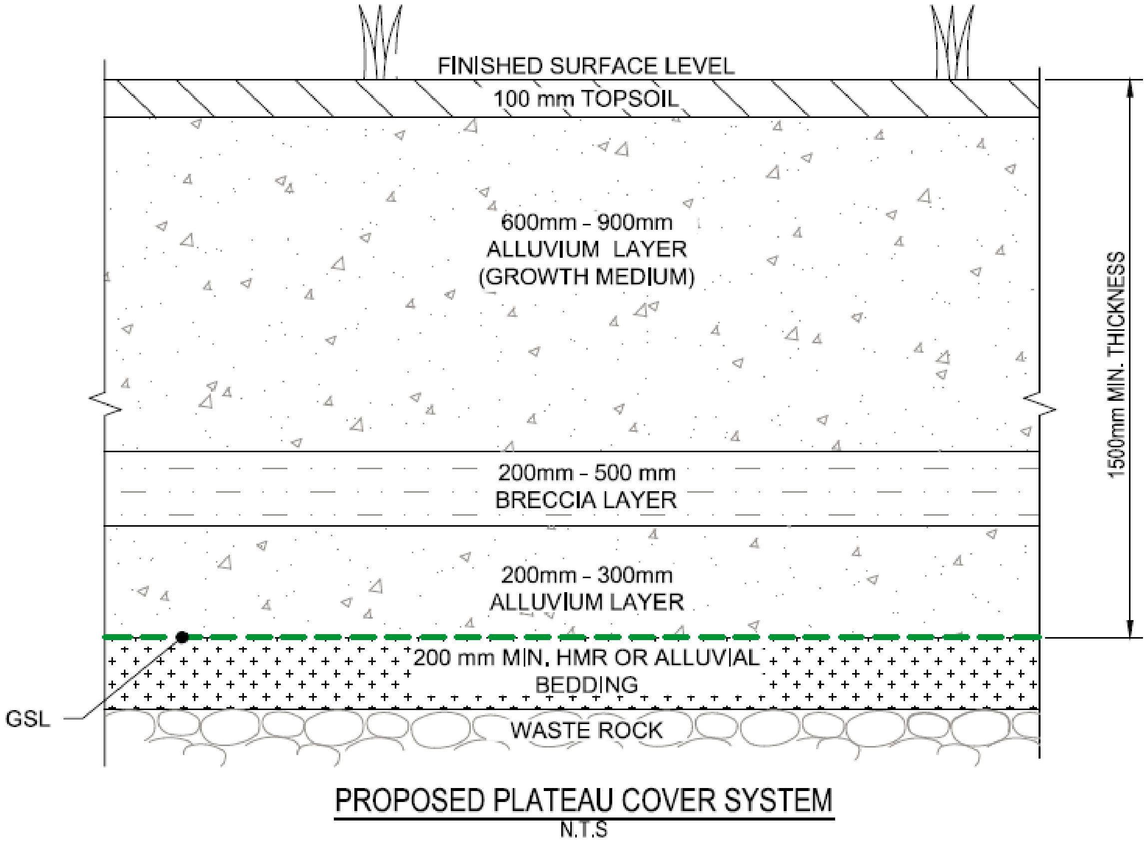

Figure 6-2: Proposed plateau cover system profile

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