Appendix 6.

O'kane (2015a) *Rum Jungle – Numerical Modelling for Waste Storage Facility Construction.* Memorandum from Shurniak. R. Numerical Modelling Group Leader to O'Kane Consultants Pty. Ltd. December 2015.

NORTHERN TERRITORY GOVERNMENT

Department of **Primary Industry and Resources**

O'Kane Consultants
Integrated Mine Waste Management and Closure Services
Specialists in Geochemistry and Unsaturated Zone Hydrology

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Memorandum

To:	Andre Kemp, General Manager, Western Australia, O'Kane Consultants Pty. Ltd.
From:	Robert Shurniak, Numerical Modelling Group Leader
Cc:	Peter Scott; Ian Taylor; Steve Pearce
Our ref:	871-5
Date:	17 December 2015
Re:	**Rum Jungle - Numerical Modelling for Waste Storage Facility Construction**

O'Kane Consultants Pty Ltd (OKC) was tasked with the assessment of basal/toe seepage, and of the oxygen flux within, and from, the planned New Waste Storage Facility (WSF) at the former Rum Jungle Mine site (Rum Jungle). The WSF is, at this time, planned to be constructed using engineered features to:

1. Reduce the volume of net percolation (NP) in real terms that will be transmitted through the WSF during and post construction

2. Reduce the quantity of basal seepage that may report to shallow groundwater during and post construction

3. Reduce the flux of oxygen through the waste mass in the short to long term

4. Provide a means to collect and treat seepage from the WSF during the periods of construction, immediately post construction, and into the short- to medium-term steady state condition.

5. Reduce the potential for acid and metalliferous drainage (AMD) to be generated in seepages reporting from the WSF in the short to long term

A large number of variables will likely influence the timing and volume of seepage, and the flux of oxygen, that can be expected within and from the WSF. This includes spatial variables such as material properties, temporal variables such as current and future conditions, and also pragmatic factors such as construction practices. Currently the detailed design of the WSF has not been finalised mainly because these factors are yet to be assessed quantitatively to determine what the optimum design would comprise.

The purpose of this study is therefore to provide technical information with respect to these factors and the engineered features listed, to inform the detailed design of the WSF.

In brief the technical assessment completed has considered the following engineering scenarios:

- Placement of an engineered cover on the WSF;

- Placement of an engineered liner at the base of the WSF;

- Engineered placement of material within the WSF; and
- Use of temporary covers during construction of the WSF (during the wet season).

The assessment has been completed to “output” the following:

- Oxygen flux via diffusion;
- NP rate;
- Basal seepage rate; and
- Toe seepage rate.

Variables considered as part of the assessment include:

- Climate/variability;
- Material properties/variability;
- Cover system performance/variability;
- Use of temporary covers; and
- Engineered placement technique.

It should be noted that this memo does not include the results of the assessment of advective gas flux. Advective gas flux is considered as part of a separate memo which will include work undertaken to link material properties and waste placement to oxygen ingress.

The analysis of the WSF was broken into three packages of modelling as follows:

1) VADOSE/W Simulations: The soil-plant-atmosphere (SPA) software is required to provide an accurate estimation of daily water balances and oxygen ingress (via diffusion) for all cover system and bare waste rock scenarios currently being proposed for the WSF. The VADOSE/W simulations provide surface flux boundary inputs for the SEEP/W and GoldSim simulations.

2) SEEP/W Simulations: OKC’s expertise with SEEP/W allows for development of a numerical mesh that simulates the staged construction of the WSF over the construction period. SEEP/W is appropriate to examine the base case and a few sensitivity simulations in finer detail. The program evaluated two interior dump construction methods (2 m and 5 m NWSF lifts) over an assumed 3-year construction period. The SEEP/W program examined a base case cover system as well as sensitivity relating to the initial water content of the waste rock at time of placement, placement of temporary cover systems during the wet season, and variation in the magnitude of wet season rainfall (when uncovered). The predicted basal seepage from the WSF footprint is provided with time for each of the completed simulations.

3) GoldSim Simulations. The construction of the WSF is likely to be influenced by a multitude of variables that impact the predicted timing and magnitude of basal seepage. While the simulations

completed with SEEP/W will characterise the base case and key sensitivity parameters, SEEP/W is limited in providing variability and unpredictability in the evaluations. As an example, the SEEP/W simulations will assume a homogenous material property in each discrete zone within the model when OKC experience shows that waste rock properties can vary greatly in materials placed only metres or centimetres apart. The GoldSim model will introduce the randomness and variability of the placed waste rock in its texture and initial placed condition.

This memorandum describes these three modelling tasks.

Development of Simulation Inputs

Inputs for all the simulations can be separated into five categories: geometry, material properties, upper boundary conditions, lower boundary conditions, and initial conditions. The following sections describe these inputs.

Geometry

VADOSE/W simulated one-dimensional (1D) profiles of the cover system atop waste rock, and bare waste rock alone. Five, two-dimensional (2D) cross-sections were simulated with SEEP/W to represent five zones of the WSF, whereas the entire WSF was divided into 20 representative regions for the three-dimensional (3D) GoldSim simulations. This section provides a summary of each geometry.

VADOSE/W 1D Profiles

Two types of 1D profiles have been simulated with VADOSE/W for this project: a cover system, and; bare waste rock configurations.

Cover System Design:

Based on a previous cover system design study (OKC, 2013) for the Rum Jungle, one cover system design was initially considered for numerical analysis: 2.0 m non-compacted growth medium overlying 0.5 m compacted clay layer over waste rock. The geometry of the model consisted of simulating a 1 m^2 column of material as seen in Figure 1.

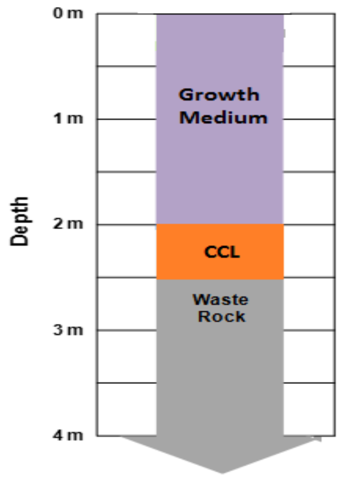

Figure 1: Evaluated cover system design.

Note that if finer-textured PAF material is placed directly under the clay then salt uptake may need to be considered as part of the design. However, assessment and modelling work completed by OKC for similar sites suggests that 2.5m is sufficient depth to impede the salt uptake process.

Bare Waste Rock Configurations:

Models of different waste rock configurations have been generated and simulated to examine performance in terms of limiting net percolation and oxygen ingress with a bare surface. Geometry of the three different waste rock configurations examined are shown in Figure 2. Results of the simulations provide infiltration rates for seepage analyses. In addition, performance in limiting oxygen ingress of the different waste configuration and cover system can be evaluated.

- Option 1 – Non-compacted waste rock to full depth
- Option 2 – 5 m lifts with track-compacted upper 0.2 m
- Option 3 – 2 m lifts and track-compacted upper 0.2 m

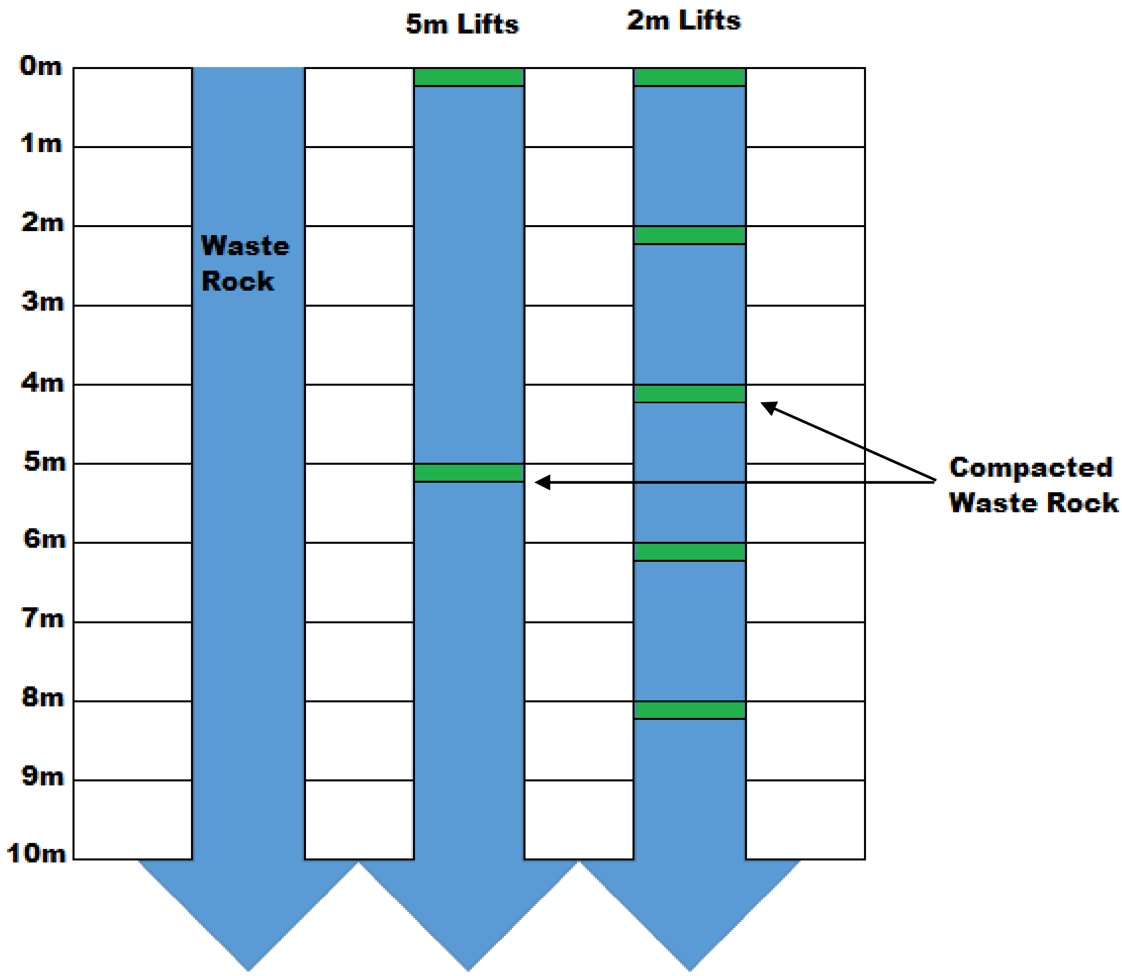

Figure 2: Evaluated waste rock configurations.

SEEP/W 2D Cross-Sections

The SEEP/W program used five, 2D cross-sections (Figure 3) to represent the WSF configuration.

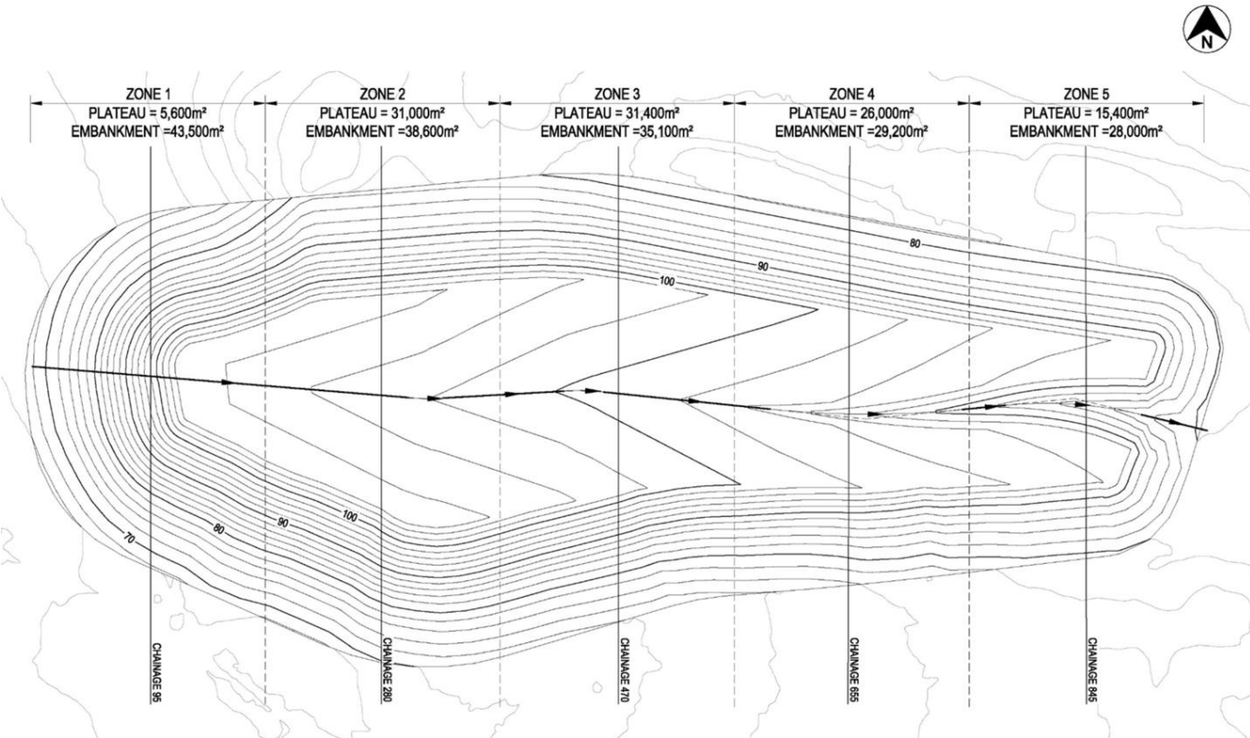

Figure 3: Plan view of the five cross-sections considered in the SEEP/W analysis.

Two base case analyses were developed using the cross-sections identified in Figure 3. The 5 m lift base case simulation completed the construction of the cross-sections in 5 m lifts over a three-year construction period. Figure 4 shows the construction methodology assumed for Zone 2 of the WSF. The waste rock was placed during three consecutive dry seasons as shown in Figure 4. The 2 m lift base case was constructed in a similar manner with 2 m thick lifts.

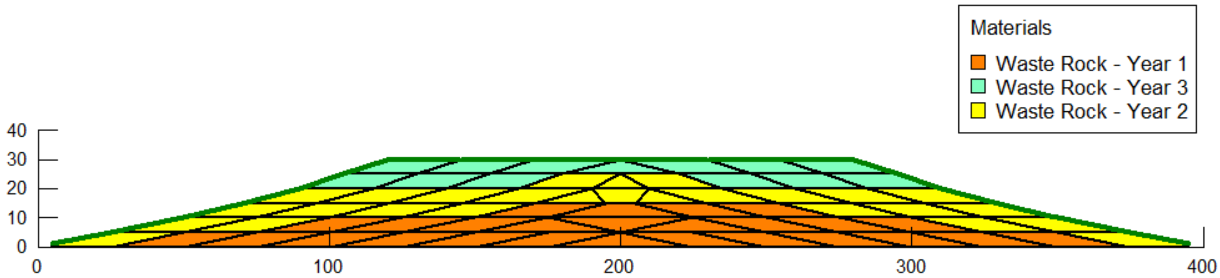

Figure 4: Construction of Zone 2 WSF cross-section with time. Axes in units of m.

GoldSim 3D Regions

Figure 5 shows the 20, 120 m x 120 m regions used to represent the WSF in the GoldSim simulations. The measurement within each region is the average maximum depth of waste rock within each region. Simulations were completed assuming 2 m and 5 m lifts with placement starting in the west and working east. The waste rock placement pattern was estimated so as to minimize the footprint of the facility for as long as possible. Waste rock and cover system placement was estimated to occur over four dry seasons.

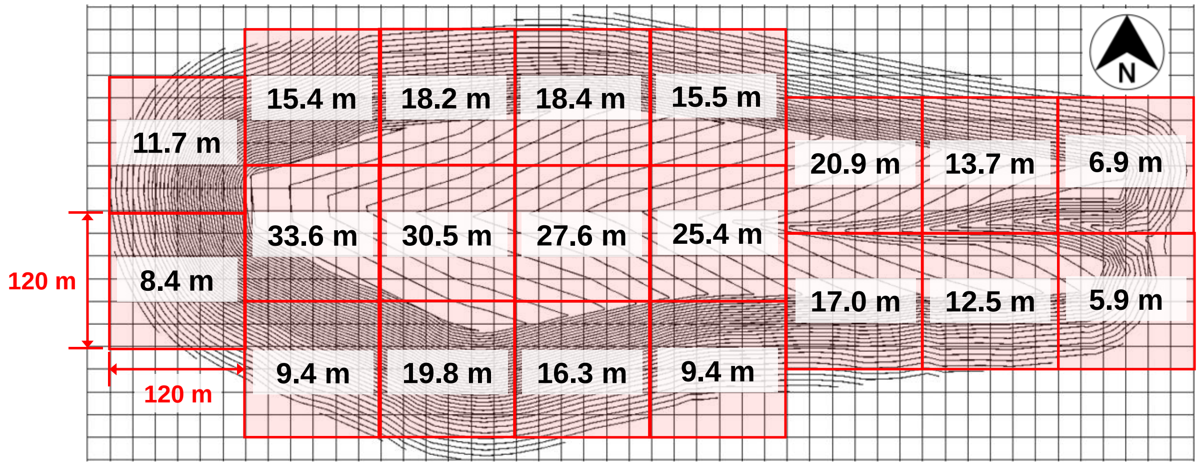

Figure 5: 20 regions used to represent the WSF in the GoldSim simulations. The measurement within each region is the average maximum depth of waste rock within each region.

Material Properties

Material properties and functions required for each material in the VADOSE/W model are as follows:

- water retention curve (WRC - suction versus volumetric water content);
- hydraulic conductivity function (k-function - suction versus hydraulic conductivity);
- thermal conductivity function (volumetric water content versus thermal conductivity); and
- volumetric specific heat function (volumetric water content versus volumetric specific heat).

OKC developed a set of material properties for compacted and non-compacted waste rock, non-compacted growth medium, and a compacted clay layer based on available site information and experience with similar materials at Northern Territory locations.

The modelling input saturated hydraulic conductivity (k_{sat}) values and air-entry values (AEV) are reported in Table 1 for each material tested.

Table 1: Summary of material properties used in the modelling program.

Material	Porosity	k_{sat} (cm/s)	AEV (kPa)
Base Compacted Clay	0.31	2.5×10^{-7}	80
Clay – 5E-7 cm/s	0.31	5.0×10^{-7}	80
Clay – 1E-6 cm/s	0.33	1.0×10^{-6}	30
Clay – 5E-6 cm/s	0.35	5.0×10^{-6}	10
Growth Medium	0.32	1.0×10^{-4}	20
Waste Rock	0.30	5.0×10^{-3}	0.5
Compacted Waste Rock	0.26	5.0×10^{-4}	2
Compacted WR – 1E-4 cm/s	0.26	1.0×10^{-4}	2

The SEEP/W simulations use the same waste rock WRC and k-function inputs as the VADOSE/W simulations. The VADOSE modelling indicated that the compacted waste rock layers were inconsequential with regards to seepage rates once the layers were not exposed at the surface. Hence, compacted waste rock layers were not included in the SEEP/W simulations. It should be noted that a key assumption in the modelling is that compacted waste rock surfaces comprise homogenous surfaces with respect to hydraulic properties. This is why the surface layers act as the primary control on seepage rates, or to put this in design terms compaction is completed to an engineering specification.

The GoldSim simulations accounted for variations in material properties for each layer of placed material in each region. Variations were simulated by setting a minimum, maximum, and most likely value for each van Genuchten parameter (van Genuchten, 1980) used to represent the waste rock material properties. The ranges were fitted to a triangular distribution and the GoldSim software randomly selected parameters for each waste rock placement scenario. The material inputs used for 2 m and 5 m lift scenarios are provided in Table 2. In this table, α is related to the inverse of the AEV, and n is a measure of pore-size distribution.

Table 2: Variations in waste rock simulated with GoldSim simulations.

van Genuchten Input	2 m Lifts			5 m Lifts		
	minimum	most likely	maximum	minimum	most likely	maximum
α	1	10	100	0.1	10	1000
n	1.25	1.3	1.35	1.2	1.3	1.4
Porosity	0.25	0.30	0.35	0.20	0.30	0.40

The residual volumetric water content for all simulations was set at zero to define the WRC. However, the actual base volumetric water content was defined as the volumetric water content corresponding to a suction of 3000 kPa.

The k_{sat} of the waste rock was tied directly to the α input so that the k-function defined using the "most likely" van Genuchten inputs generated a k-function similar to that used for the SEEP/W and VADOSE/W modelling. Hence, a higher α resulted in a higher k_{sat} and vice versa.

Upper Boundary Conditions

The upper boundary conditions required for the VADOSE/W model can be divided into two parts: vegetation and climate. SEEP/W and GoldSim simulations both rely on the results of the VADOSE/W simulations for their upper boundary inputs. Details regarding the model inputs developed for each are described below.

VADOSE/W Simulations

Vegetation:

VADOSE/W incorporates vegetation effects using a nodal vegetative uptake source term that is combined with a surface energy term based on canopy cover (Tratch, 1996). The amount of actual nodal root uptake depends also on root depth and density, and water stress (negative pore water pressure).

In VADOSE/W the user must implement a plant water limiting function, which determines the percentage decrease in the plant's ability to draw water as the negative pore-water pressure increases in unsaturated ground. A generally accepted plant water limiting function was used for this project. In this function the plant reaches a water intake limiting point at a negative pore water pressure of -100 kPa and is completely unable to draw water if the pressure reaches -1,500 kPa (also known as the wilting point).

The leaf area index (LAI) is used by VADOSE/W to reduce the amount of incoming radiation reaching the soil surface, which in turn reduces the computed actual evaporation. In other words, the LAI controls how the energy at the surface is partitioned between that available for direct evaporation from the soil and that which is available to the plants in their attempt to transpire water. A constant vegetation cover with 75% surface coverage (LAI of 2.5) was assumed for the long-term simulations.

Potential evaporation (PE) was reduced by 25% to simulate a bare surface. This reduction was estimated to account for the increased albedo of a bare surface.

Climate:

VADOSE/W requires daily values of: maximum and minimum air temperature; maximum and minimum relative humidity (RH); average wind speed; rainfall (amount and duration); and PE.

A climate database was developed for use by all Rum Jungle project contributors from the SILO Data Drill application of the Australian Bureau of Meteorology (BOM). A 100-year climate database was developed from the data drill representing site conditions between November 1, 1914, and October 31, 2014. The average annual rainfall for this period was 1,460 mm, with the maximum and minimum annual rainfall amounts being 912 mm and 2,423 mm respectively; the monthly average rainfall for the 100-year database is summarised in Figure 6.

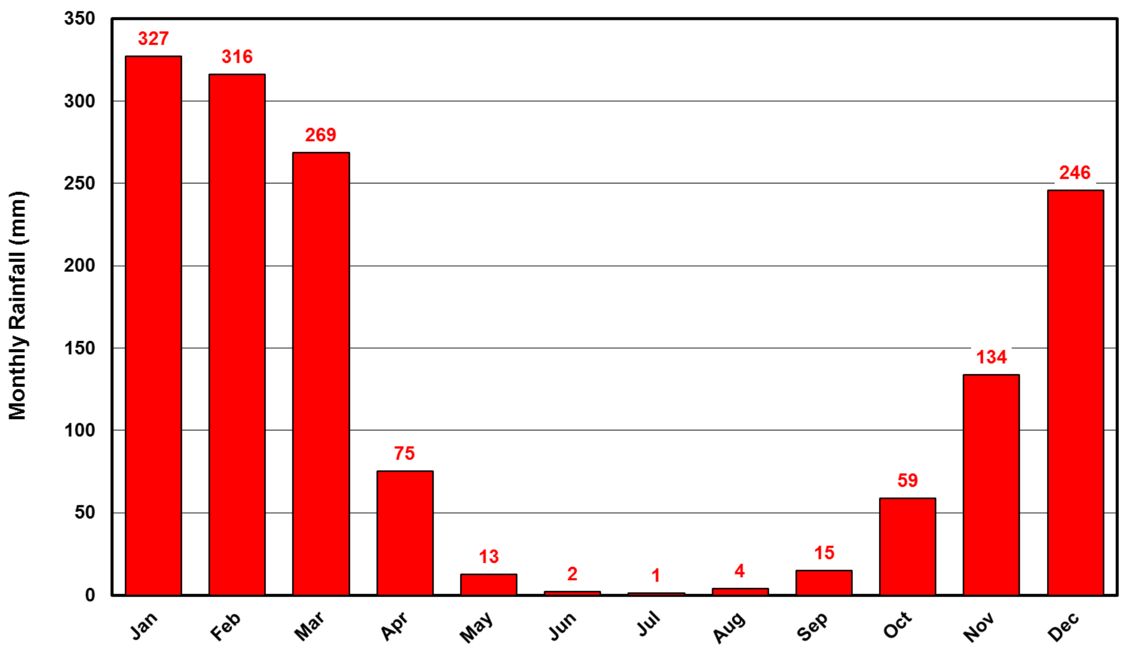

Figure 6: Average monthly rainfall for the 100-year climate database.

A 'synthetic average' climate year was defined by averaging daily climate conditions from the 100-year climate database (e.g. averaging the maximum temperature on January 1st for all 100 years). However, rainfall was not applied just considering the daily average amount, but also the average number of rainfall events per month. Hence, rainfall was applied for the average number of rainfall days per month and on days with the highest chance of rainfall. The daily rainfall amounts for days with lower chances of rainfall were added to the next high-chance rainfall event in the month so that the synthetic average climate year had both the average amount of rainfall and rainfall days.

OKC developed a cumulative deviation from the long-term average (Figure 7) to evaluate the changes in climate cycles during the 100-year database period. As fits with the general trend for Australian sites, the early 20th Century rainfall values are below average and rainfall increases in the latter half of the 1900's. Figure 7 suggests that there are two distinct climate cycles within the 100-year period. Annual rainfall in the past 20 years has averaged 1,760 mm, approximately 300 mm/yr greater than the long-term average. It is unknown whether Rum Jungle remains within the same climate cycle as the past 20 years; however, it is a risk to assume that the long-term average conditions (from the 100-year climate database) will occur during the WSF construction period. Hence, the results of the VADOSE/W simulations during the 1995-2014 climate period were used to develop base inputs for the SEEP/W and GoldSim simulations. The period 1915-1934 was included in VADOSE/W sensitivity simulations to account for dry conditions and the effect on oxygen ingress.

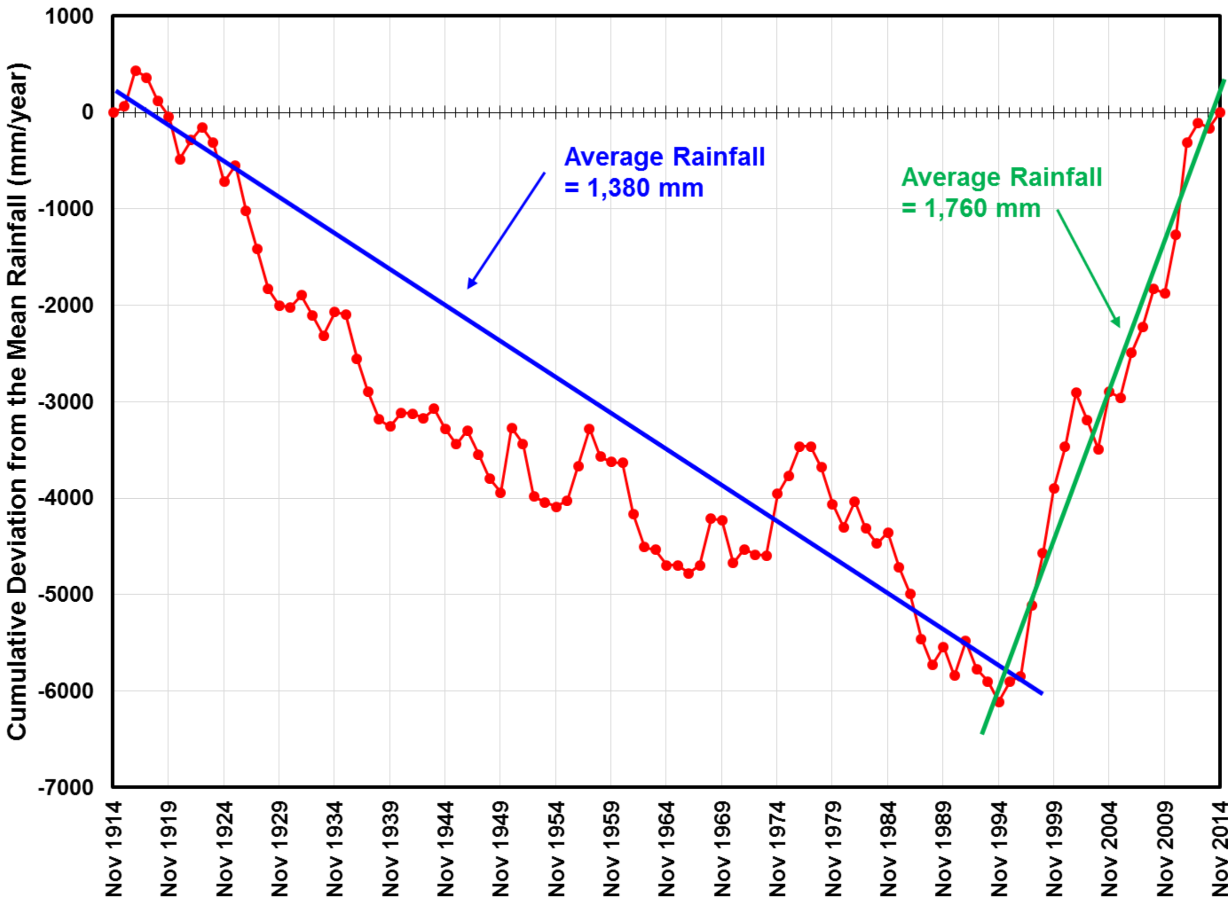

Figure 7: Cumulative deviation from the average annual rainfall during the 100-year climate database.

SEEP/W Simulations

The flux boundary on the surface of the WSF during the construction phase was set using the following steps:

1) The model results for the 1D Bare Waste Rock simulations were reduced and compared. Comparing the results of the models with a 2 m lift to those with a 5 m lift showed minimal difference in net percolation results, so only one set of surface fluxes were estimated for the construction phase.

2) The model results were then analysed to determine three periods for potential inclusion in the 2-D SEEP/W modelling: the wettest period (from a NP perspective) on record, the driest period, and the average period during the last 20 years (1995-2014). The construction period length was set at 931 days (i.e. 133 weeks), so that it included three dry seasons separated by two wet seasons. The first day of placement was estimated as April 15th as analysis of the climate database found that there was a much higher propensity for rainfall in the first two weeks of April than the rest of the month. The dry season was then estimated to last for 26 weeks and ending mid-October. The wet season was then set for 26 weeks to equal one year. The second dry and wet seasons were also set for 26 weeks.

3) Once the three periods were chosen (namely, April 15, 1946 to October 31, 1948 (driest period), April 15, 2007 to October 31, 2009 (average period for the last 20 years), and April 10, 2010 to October 31, 2012 (wettest period)), the 1D VADOSE results were analysed to determine the daily net infiltration into the surface of the waste rock estimated for these periods. The daily data were then averaged on a weekly basis for the dry period and over the entire wet period to improve the model's ability to converge on an accurate solution. Note that each wet season and each week of the dry seasons is different as it is based on real historical data taken directly from the climate database provided for this project.

GoldSim Simulations

Each day of the calendar year was assigned a mean and standard deviation seepage rate as an upper boundary condition. These inputs were calculated from the VADOSE/W simulation results for the 1995-2014 climate period for a bare, non-compacted waste rock at surface. The mean and standard deviation were then used in GoldSim to calculate a normal probability distribution for each day. This was used to randomize the daily “base” surface flux rate for each day of each realization. The simulation of bare, non-compacted waste rock did not allow for runoff; hence, it was assumed to represent the maximum flux anticipated to enter the waste rock. The base surface flux was modified to represent different materials simulated at surface.

It was assumed that the day waste rock was placed that the surface was non-compacted; hence, no modification was made to the base surface flux. The waste rock was then assumed to be compacted, with the model randomly selecting a modifier based on a triangular distribution input in the GoldSim model to represent some degree of compaction. The surface flux is also reduced if/when an interim or final cover system is placed at surface. Again, the model randomly selects a modifier based on a triangular distribution input to represent the uncertainty in the final cover performance. Table 3 provides the modifier ranges and inputs used for the four potential surface conditions.

Table 3: GoldSim surface flux modifiers for potential surface conditions.

Surface	Minimum	Most Likely	Maximum
New Waste Rock	1	1	1
Compacted Waste Rock	0.78	0.89	1
Interim Cover System	0.1	0.3	0.5
Final Cover System	0.05	0.1	0.31

Lower Boundary Conditions

VADOSE/W Simulations

The lower boundary of the VADOSE/W profiles was simulated as a unit hydraulic gradient at the base of the waste material. This boundary condition simulates the water table to be well below the surface. A unit hydraulic gradient represents a location in the modelled profile where water movement is controlled mainly by gravity.

SEEP/W Simulations

The lower boundary of the SEEP/W cross-sections was simulated as a potential seepage face. Hence, positive pore water pressure had to result for water to seep from the base of the cross-section. These results were then placed into an excel spreadsheet to estimate how much of the seepage from the base of the NWSF would reach the toe seepage collection system and how much would pass through the underlying liner. The liner was estimated to have a k_{sat} of 5 x 10^{-9} cm/s with a hydraulic gradient of 10 across the liner.

GoldSim Simulations

The lower boundary of the GoldSim model randomly selects a k_{sat} and hydraulic gradient for the liner at the base of each region of the NWSF. The triangular distribution parameters used to represent the range of performance of the liner are presented in Table 4.

Table 4: Triangular distribution parameters used to simulate range of liner performance.

Liner Parameter	Minimum	Most Likely	Maximum
k_{sat} (cm/s)	5.0 x 10^{-9}	1.0 x 10^{-8}	5.0 x 10^{-8}
Hydraulic Gradient	1	5	10

Note that the liner system was simulated without including the probability of a liner failure, which would allow flow into the ground underlying the WSF at a rate governed by underlying ground's material properties. The aim of the assessment was to indicate upper and lower bounds for toe seepage and basal seepage given that a specific liner specification is not available at this time. The results of the assessment provide guidance as to this range such that informed decisions about the requirement and specification for a liner can be made.

Initial Conditions

VADOSE/W Simulations

Initial pressure and temperature profiles defined for the long-term continuous simulations were developed by simulating the synthetic average climate year for consecutive years until initial and final conditions of the synthetic average model year equilibrated. That is, the conditions at the start of the model year are the same as the conditions at the end, which means no net change in storage throughout the synthetic average model year.

The initial effective reaction rate coefficient for oxygen in the waste rock was set at 0.1532 per day, which was estimated assuming a pyrite concentration of 3.8%. It should be noted that this represents a likely “worse case” as the material placed in the facility is not expected to have average sulfur grade >1%. Control measures are being planned as part of the construction process to ensure higher grade sulfur material is not placed within the facility.

SEEP/W Simulations

Each placement of waste rock is simulated with an initial water content. The base initial water content assumed that all the material was placed with an initial suction of 25 kPa, corresponding to a volumetric water content of approximately 0.11 cm^3/cm^3 (Figure 8).

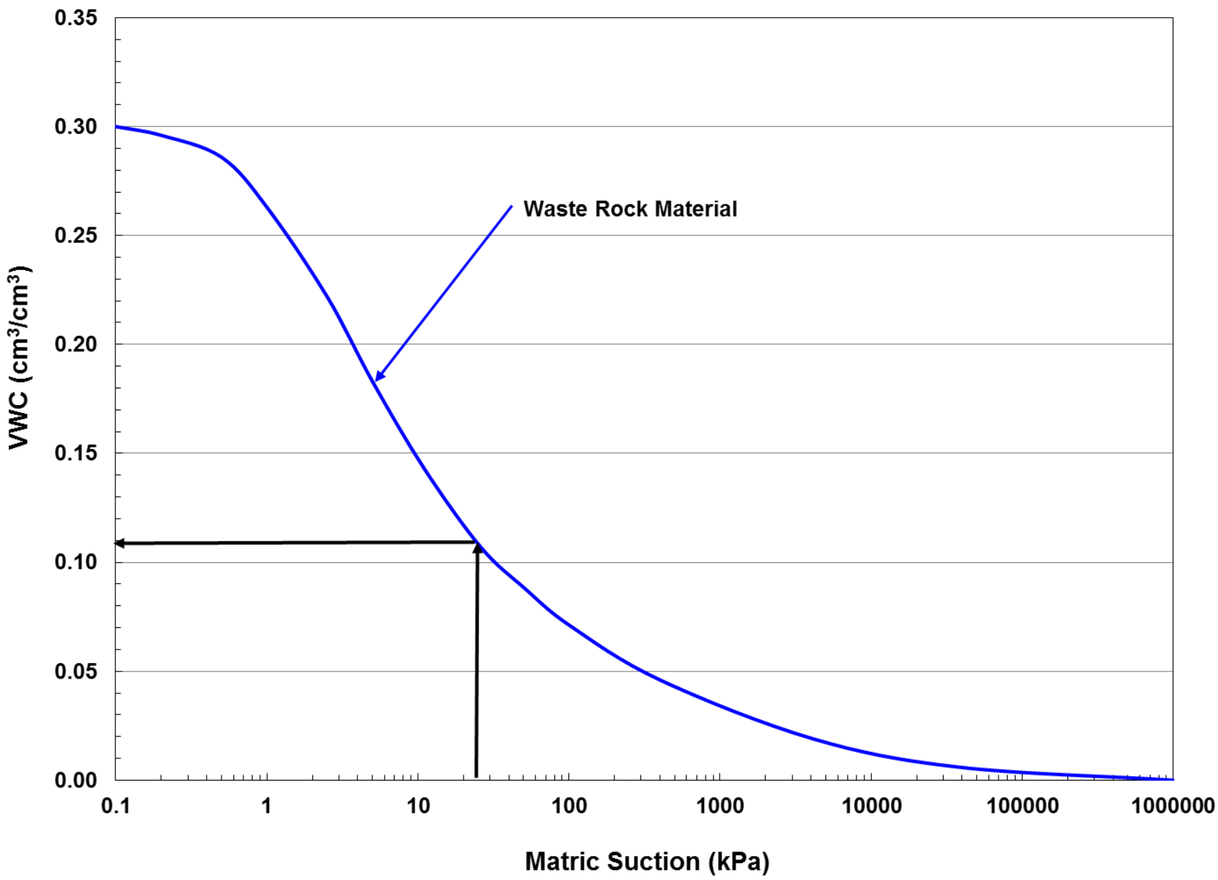

Figure 8: Water retention curve of the waste rock material.

GoldSim Simulations

The GoldSim model randomly selects the initial effective saturation level from the triangular distribution input into the model. This represents both the uncertainty in the material texture (and resulting hydraulic properties) but also the uncertainty from any wetting or drying events that may occur during placement. Table 5 provides the range for these values.

Table 5: Triangular distribution parameters used to simulate effective saturation range.

Parameter	Minimum	Most Likely	Maximum
Effective Saturation	0.15	0.33	0.5

Simulation Results

VADOSE/W Simulations

SPA numerical modelling was undertaken to simulate the long-term performance of the cover system and waste rock configurations and to determine surface flux boundary inputs for the SEEP/W and GoldSim simulations. Two performance indicators were focused upon in the analyses: net percolation (NP) and oxygen ingress. NP and oxygen ingress results from simulations using the cover system geometry were obtained at the interface between the cover system and underlying waste rock, whereas simulations consisting of just waste rock had NP obtained at 2 m depth and oxygen ingress at surface. The following section provides a description of the results of this work.

Table 6 provides a summary of the simulations and results completed during the SPA modelling program. 100-year simulations were completed for the four geometries considered using the anticipated (i.e. base) parameters. These simulations provided results for the entire climate database so that oxygen ingress results over 100 years could be provided and to ensure all rainfall and resultant NP scenarios available had been reviewed before applying the results to subsequent simulations. The 40-year simulations focused on the most extreme 20-year periods (i.e. November 1914 to October 1934 representing the driest 20 years on record followed by November 1994 to October 2014 representing the wettest 20 years on record) so that variations in the properties of the compacted clay and waste rock layers could be more effectively analysed.

Note that no runoff was allowed from the non-compacted waste rock (WR) simulations. All simulations were completed assuming a level surface.

Table 6: Summary of VADOSE/W simulations and results. Results are annual averages.

No.	Geometry	Description	R	AET	RO	NP	O_2 Ingress (Diffusion)
				mm/yr		mm/yr / %R	g/yr/m^2
100-Year Simulations (November 1914 to October 2014)							
1	Cover System	Base Parameters	1460	910	460	90 / 6%	1
2	WR – 2 m Lifts	Base Parameters	1460	640	140	680 / 47%	2,620
3	WR – 5 m Lifts	Base Parameters	1460	640	140	680 / 47%	2,710
4	Non-compacted WR	Base Parameters	1460	650	0	810 / 56%	2,570
40-Year Simulations (November 1914 to October 1934 followed by November 1994 to October 2014)							
5	Cover System	Base Parameters	1560	930	540	90 / 6%	1
6	Cover System	Clay – 5E-7 cm/s	1560	910	480	170 / 11%	1
7	Cover System	Clay – 1E-6 cm/s	1560	880	400	280 / 18%	15
8	Cover System	Clay – 5E-6 cm/s	1560	810	180	570 / 37%	110
9	WR – 2 m Lifts	Base Parameters	1560	620	140	800 / 51%	4,270
10	WR – 5 m Lifts	Base Parameters	1560	620	140	800 / 51%	4,310
11	Non-compacted WR	Base Parameters	1560	660	0	900 / 58%	4,190
12	WR – 2 m Lifts	Compacted WR – 1E-4 cm/s	1560	500	790	270 / 17%	3,800
13	WR – 5 m Lifts	Compacted WR – 1E-4 cm/s	1560	500	790	270 / 17%	4,120

Abbreviations in the table are as follows: R = rainfall, AET = actual evapotranspiration, RO = runoff, NP = net percolation, %R = percent of rainfall, and O_2 Ingress = oxygen ingress.

The results show:

- NP is anticipated to range between 40 and 170 mm/yr with the final cover system in place and between 200 and 1,800 mm/yr when waste rock is exposed at surface (Figure 9).
- Lift thickness variation from 2 m to 5 m has minimal influence on performance (if it is assumed that lift surfaces can be compacted to an engineered specification) with the results showing no change in the water balance and a slight (between 1% and 8%) reduction in oxygen ingress via diffusion when using 2 m lifts instead of 5 m lifts.
- The most important factor for the performance of bare waste rock is the level of compaction of the waste rock at surface.
- Oxygen ingress via diffusion into bare waste rock is rapid during the initial years of exposure (>9,000 g/yr) but then reduces almost logarithmically with time (Figure 10) as pyrite is oxidized (Figure 11). It should be noted that this does not include advective gas flux which may not show the same decline as the driving process of gas flux via advection are different to diffusion. Advective gas flux is considered as part of a separate memo which will include work undertaken to link material properties and waste placement to oxygen ingress.
- The cover system reduces NP below 20% of rainfall and limits oxygen ingress even when the compacted clay layer has a k_{sat} of 1×10^{-6} cm/s, but does not provide a barrier with a k_{sat} of 5×10^{-6} cm/s. Hence, a k_{sat} of 1×10^{-6} cm/s was used as the minimum performance setting for the final cover system in GoldSim (i.e. limited the base surface flux to 0.31). Extrapolating

the NP results for the cover system simulations indicated that the optimum performance of a compacted clay layer would reduce annual NP to approximately 45 mm/yr or 5% of the non-compacted waste rock NP (Figure 12). This supplied the upper limit for the final cover system in GoldSim (i.e. limited the base surface flux rate to 0.05).

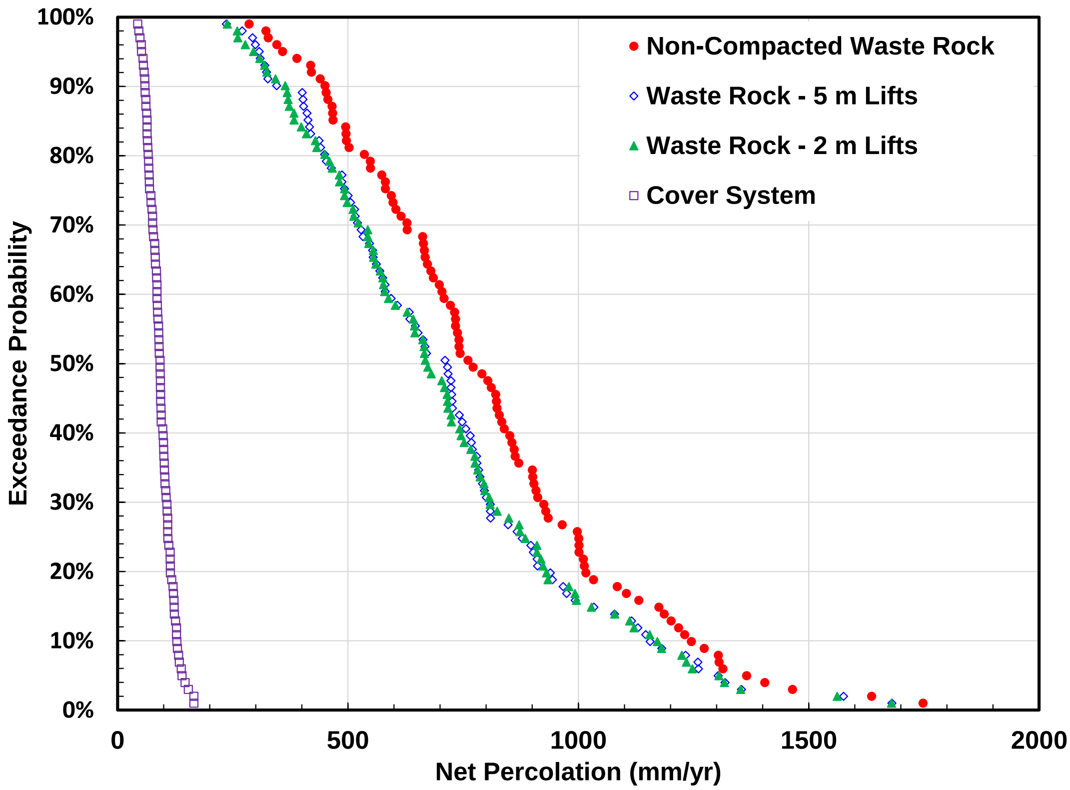

Figure 9: Probability of net percolation exceedance for 100-year simulations.

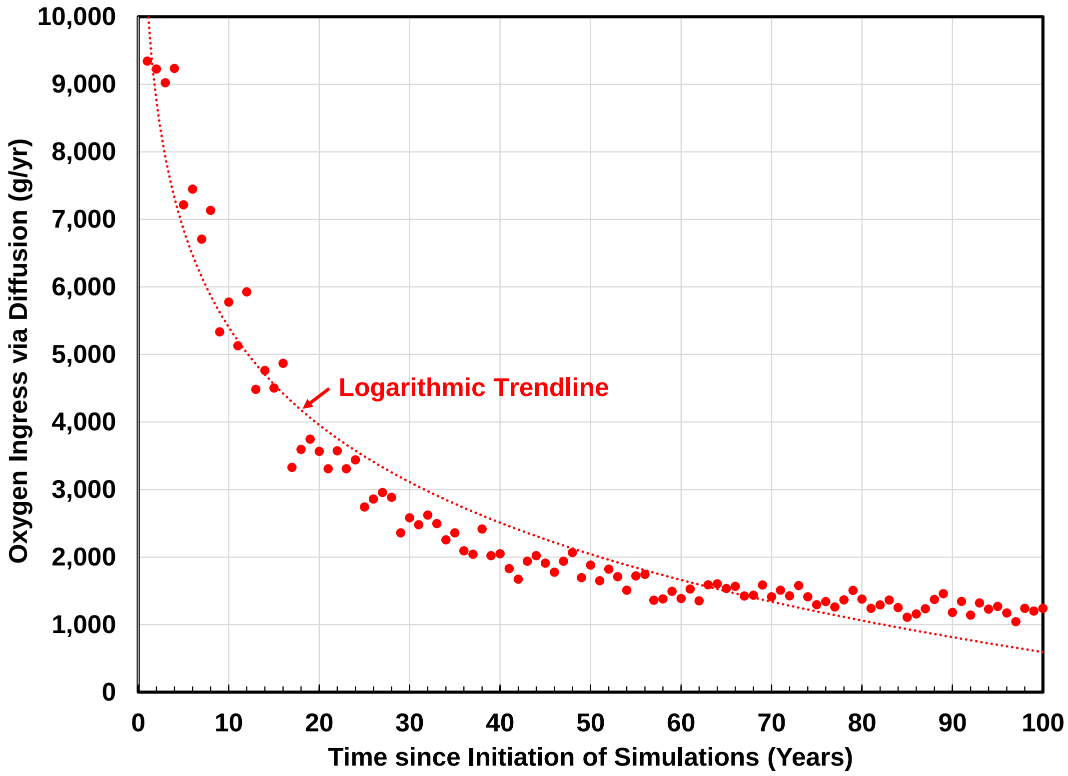

Figure 10: Oxygen ingress rate (diffusion only) over 100 years for “Waste Rock – 2 m Lifts” simulation.

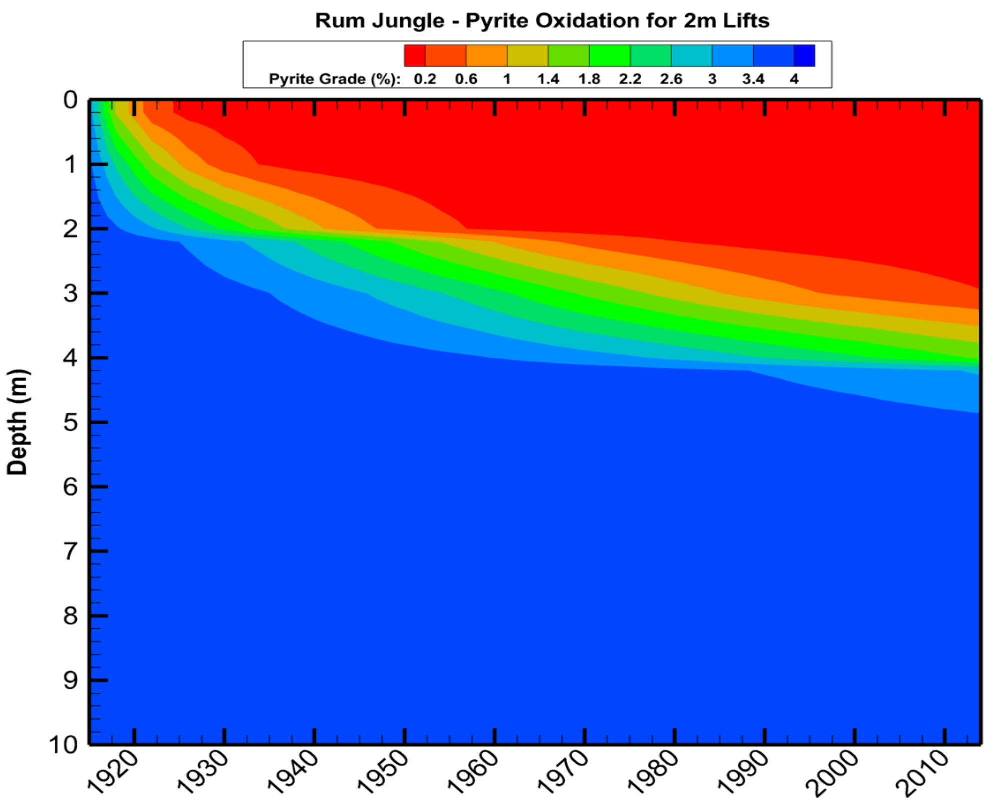

Figure 11: 100-year pyrite oxidation for “Waste Rock – 2 m Lifts” simulation based on diffusive gas flux.

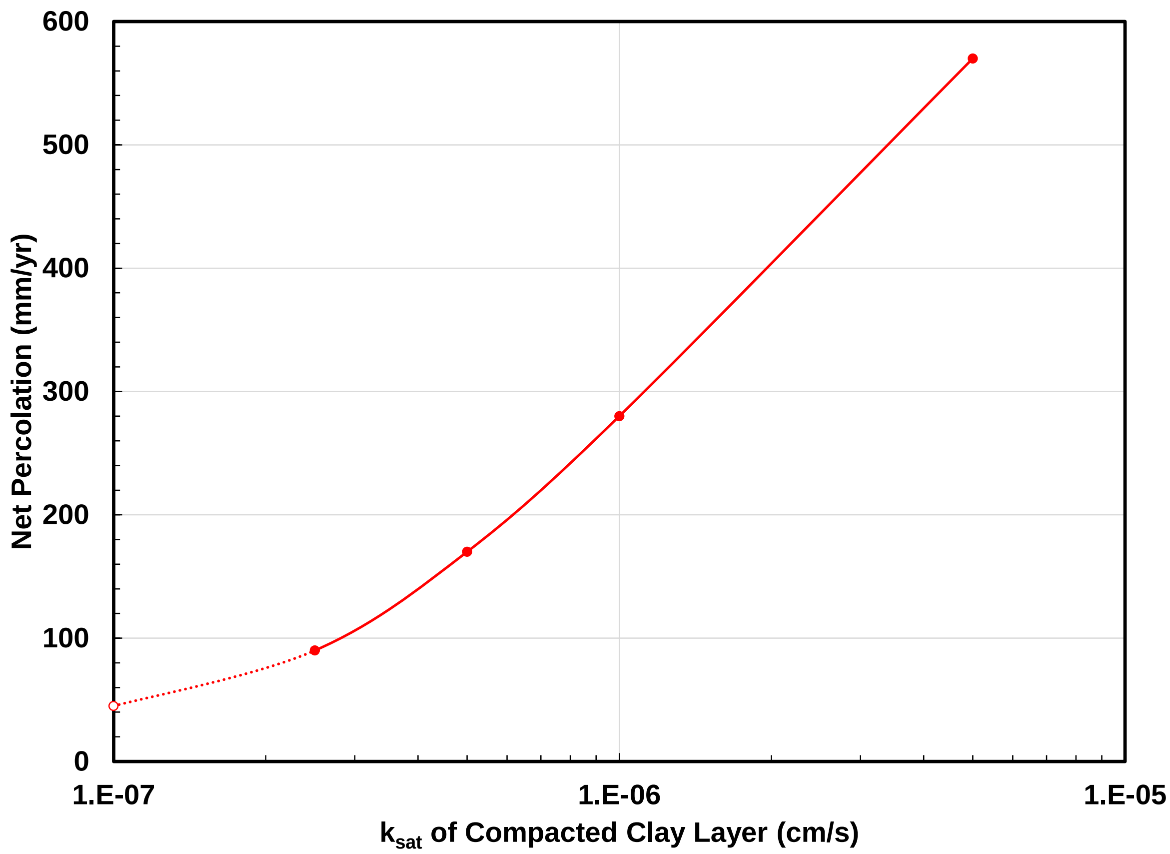

Figure 12: Relationship between net percolation k_{sat} of the compacted clay layer.

SEEP/W Simulations

Simulations with 5 m Waste Rock Layers

Figure 13 shows the results of the base case 5 m waste rock layer simulations with and without a temporary cover system placed over the WSF and the old WSF source material during construction in the wet season. The estimated basal seepage rate for the WSF spikes up to 880 m^3/day during the first wet season in response to high infiltration rates into the bare waste rock surface. The increase during the second wet season is smaller in response to lesser rainfall experienced in the Year 2 wet season compared to the first. While not shown on Figure 13, after placement of the cover system at the end of Year 3 dry season, the system slowly comes to a steady-state seepage rate of 80 m^3/day by Year 20.

Placing a temporary cover system on the WSF during the wet season had a large effect on the prediction of basal seepage. Reduction of the infiltration rate into the system during the wet seasons (assumed to be 150 mm/year) greatly reduced the predicted amount of basal seepage. The majority of the wet season infiltration under the temporary cover system scenario is stored within the waste rock mass.

The sensitivity analyses evaluated the effect of increased / decreased initial waste rock volumetric water content (VWC) at placement and increased / decreased magnitude of wet season rainfall. The results are shown in Figures 14 and 15 compared to the base case simulation without a temporary cover system during the wet season.

The initial VWC of the waste rock at placement had a large influence on the predicted basal seepage rate. If placed in a wetter condition, less storage is available within the waste rock mass producing a large response to the wet season infiltration. If the initial waste rock VWC at placement is 0.18 cm^3/cm^3 instead of the base case 0.11 cm^3/cm^3 the maximum estimated basal seepage rate during the construction period increases up to 1,685 m^3/day. Figure 14 also provides a second estimation of the basal seepage rate with an increased initial placement VWC (0.14 cm^3/cm^3). This additional sensitivity simulation produced a maximum predicted basal seepage rate of 1,460 m^3/day. It is anticipated that the most likely initial placement water content will range between 0.11 cm^3/cm^3 to 0.14 cm^3/cm^3.

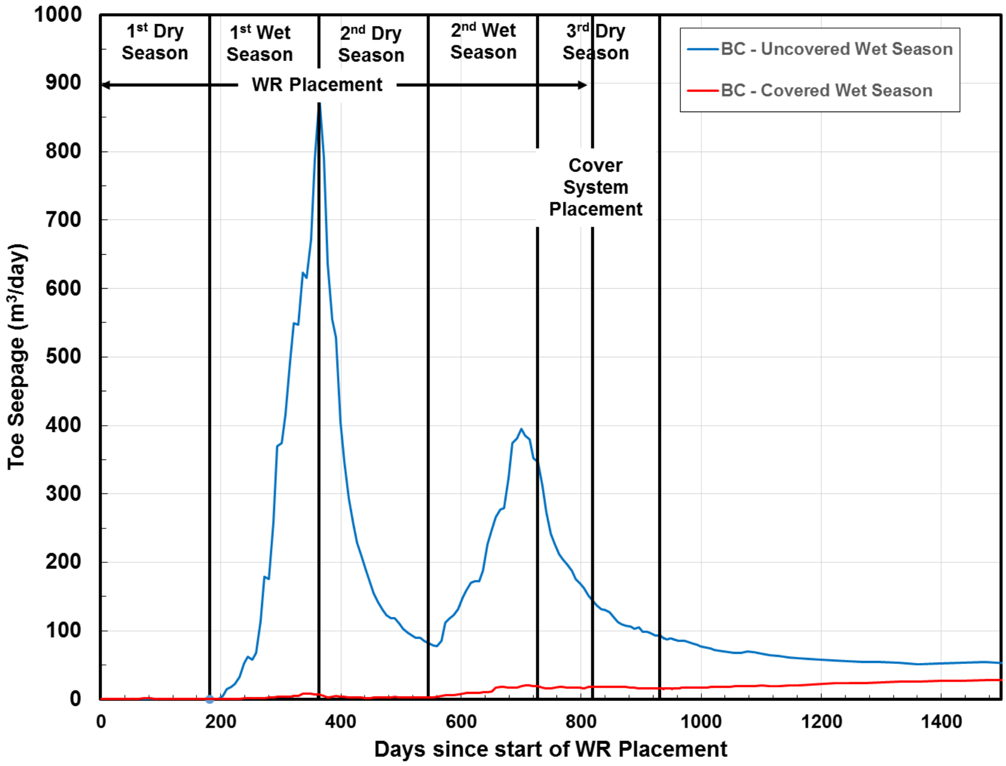

Figure 13: Base case SEEP/W simulations for the 5 m WSF layer configuration.

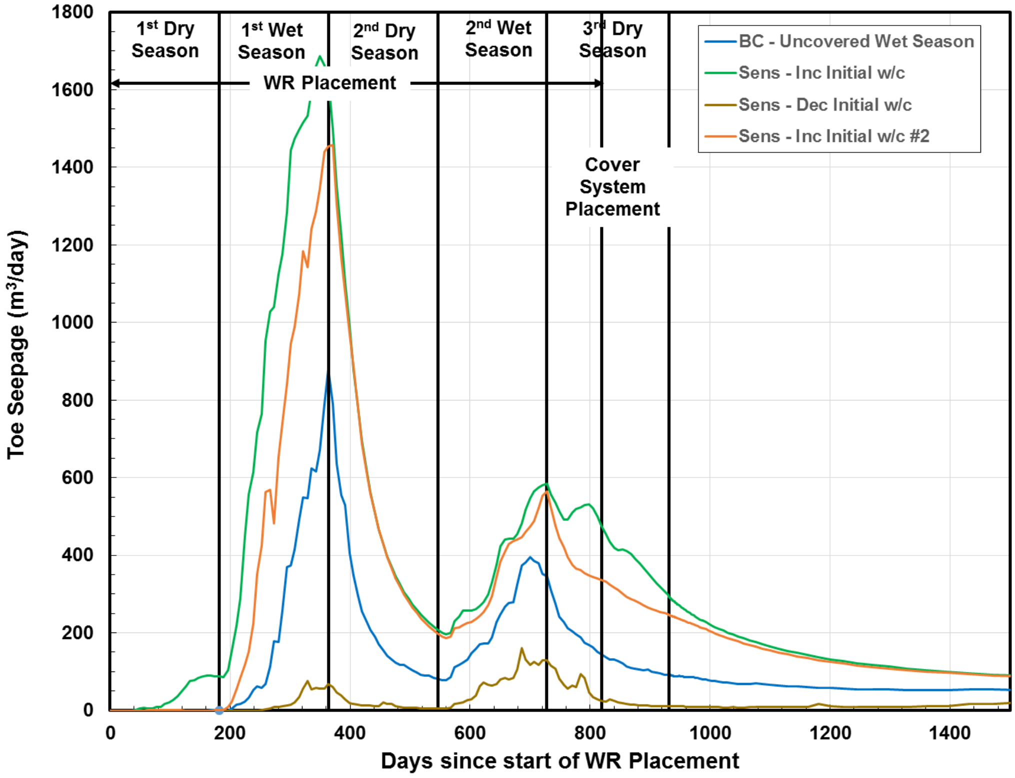

Figure 14: Sensitivity simulation with increase and decrease of the initial VWC of the waste rock material.

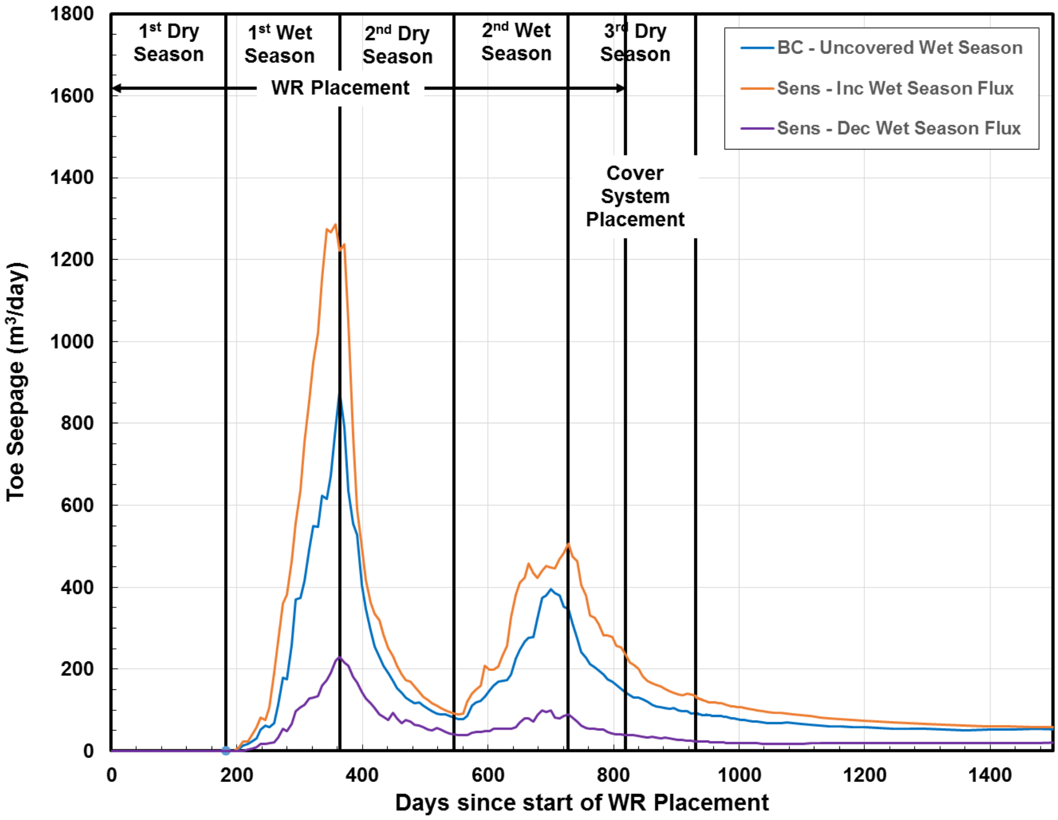

Figure 15: Sensitivity simulation with increase and decrease of the wet season rainfall.

The final sensitivity simulation considered wet season rainfalls above and below the average conditions used in the base case. As expected, the increased rainfall rate during the wet season resulted in higher predicted basal seepage as compared to below average wet season rainfall.

Simulations with 2 m Waste Rock Layers

The SEEP/W simulations completed with 2 m waste rock lifts examined the same set of base case and sensitivity parameters. In general, the results were similar to the simulations with 5 m waste rock lifts because both sets of simulations used the same surface infiltration function. Differences in estimated basal seepage were largely due to the change in construction sequencing, and the 3D representation of the waste mass within the model as blocks, with the thinner waste rock lift and the changes in WSF footprint area with time. The differences noted can be largely attributed to these factors so the results should be interpreted with this in mind (i.e. a higher or lower result between 2m and 5m scenarios should not be considered significant).

Figure 16 presents the results of the base case simulation for the 2 m waste rock lifts with and without the application of a temporary cover system during the wet season. The peak predicted basal seepage is slightly greater during the first wet season for the 2 m placement method in comparison to the 5 m results. Conversely, the peak predicted basal seepage in the second wet season is slightly lower for the 2 m configuration compared to the 5 m configuration.

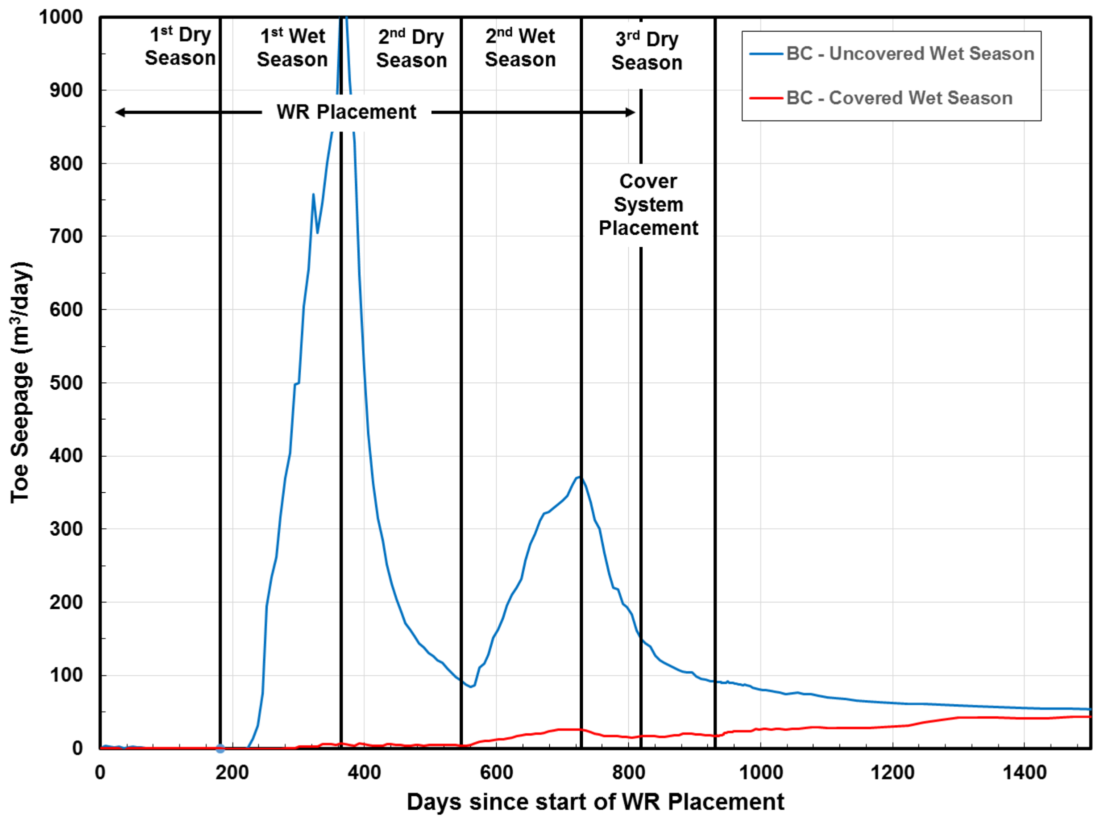

Figure 16: Base case SEEP/W simulations for the 2 m WSF layer configuration.

GoldSim Simulations

Four scenarios were simulated with the GoldSim model:

- 2 m lifts with no interim cover placement during wet seasons;
- 2 m lifts with interim cover placement during wet seasons;
- 5 m lifts with no interim cover placement during wet seasons; and
- 5 m lifts with interim cover placement during wet seasons.

Each scenario was simulated for 50 realisations of 100 years; i.e. GoldSim selected new inputs for all stochastic variables (e.g. van Genuchten parameters of each waste rock placement) to create 50 different scenarios each with a modelled duration of 100 years. The results are probability distributions of liner and toe seepage rates, and are summarised in Table 7. The results indicate:

- Based on expected construction sequencing in both 5 m and 2 m lifts, scenarios for both lift heights produce similar outcomes with respect to seepage outcomes;
- 100 years after initial placement (and 96 years after final cover system placement) toe seepage for all four scenarios is anticipated to be in the 40 to 60 m^3/day range. These results indicate that cover system performance is the key variable for long term seepage rates;
- 100 years after initial placement (and 96 years after final cover system placement) liner seepage for all four scenarios is anticipated to be in the 15 m^3/day range. However, it must be noted that the liner system was simulated without the probability of large tears or other substantial holes in the liner system above those anticipated during proper installation, which would allow flow into the ground underlying the WSF at a rate governed by underlying ground's material properties.
- The use of temporary covers has a significant influence on seepage rates during the construction period. The mean predicted seepage rates are 300% higher with no covers assumed.
- Seepage is expected to occur within the construction period with liner seepage predicted to occur within 1 year and toe seepage within 4 years for the mean predicted seepage rates in all scenarios.
- Significant variability in the results calculated indicates that predictions of exact seepage volumes expected to occur both during the construction period and post construction should be viewed with caution. Although the 50% outputs are considered to be most likely there is a very large deviation noted with the 25% and 75% results. Given the ranges of input values expressed in the model inputs are within the bounds of expected variability (for example with variability in climate and material properties), the 25% and 75% outputs should be considered as potential outcomes rather than very unlikely.

Table 7: Summary of GoldSim Results

Scenario	Variable	Probability				
		5%	25%	50%	75%	95%
2 m Lifts – No Interim Cover	Days until Toe Seepage	19,179	1,089	455	234	69
	Days until Liner Seepage	357	116	101	31	7
	Construction Toe Seepage Rate (m^3/day)	0.0	1.8	29.4	266	1018
	Construction Liner Seepage Rate (m^3/day)	0.0	1.4	8.2	11.6	15.9
	Final Toe Seepage Rate (m^3/day)	0.3	26.9	49.3	119	336
	Final Liner Seepage Rate (m^3/day)	5.7	13.0	14.9	17.7	20.7
2 m Lifts – Interim Cover	Days until Toe Seepage	15,192	3,760	1,348	376	104
	Days until Liner Seepage	7,018	237	113	94	25
	Construction Toe Seepage Rate (m^3/day)	0.0	0.0	0.1	18.0	383
	Construction Liner Seepage Rate (m^3/day)	0.0	0.0	0.4	5.4	14.0
	Final Toe Seepage Rate (m^3/day)	1.5	16.7	38.0	77.0	232
	Final Liner Seepage Rate (m^3/day)	6.2	12.4	14.8	16.8	20.6
5 m Lifts – No Interim Cover	Days until Toe Seepage	23,151	2,944	589	207	56
	Days until Liner Seepage	832	242	111	28	14
	Construction Toe Seepage Rate (m^3/day)	0.0	0.0	11.0	197	791
	Construction Liner Seepage Rate (m^3/day)	0.0	0.0	3.2	8.8	11.9
	Final Toe Seepage Rate (m^3/day)	0.4	13.5	42.6	115	274
	Final Liner Seepage Rate (m^3/day)	5.9	13.3	15.0	16.5	22.1
5 m Lifts – Interim Cover	Days until Toe Seepage	28,646	5,343	839	268	83
	Days until Liner Seepage	5,016	267	110	31	15
	Construction Toe Seepage Rate (m^3/day)	0.0	0.0	2.7	57.8	178
	Construction Liner Seepage Rate (m^3/day)	0.0	0.0	1.0	6.4	10.2
	Final Toe Seepage Rate (m^3/day)	1.1	14.7	52.0	125	178
	Final Liner Seepage Rate (m^3/day)	7.8	13.0	15.2	16.6	18.6

Closure

We trust information provided in this memorandum is satisfactory for your requirements. Please do not hesitate to contact me at rshurniak@okc-sk.com should you have any questions or comments.

Reference

OKC, 2013, Batchelor Region (Former Rum Jungle Mine) – Conceptual Cover System and Landform Design, report number 871/1-01, Northern Territory Government, Department of Mines and Energy, pp.66.

Tratch, D., 1996. "Moisture uptake within the root zone". M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

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