# Winu Tailings Storage Facility High Sulfur Tailings Cover System Numerical Modelling

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Rio Tinto

okane

Integrated Mine Closure and Relinquishment Solutions

# Winu Tailings Storage Facility High Sulfur Tailings Cover System Numerical Modelling

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# EXECUTIVE SUMMARY

Okane Consultants (Okane) was retained by Rio Tinto to complete conceptual cover system design modelling for the high sulfur tailings storage facility (TSF) at the Winu Site (Winu) in the Pilbara region of Western Australia. Okane previously completed modelling for the high sulfur TSF at Winu in 2020 (Okane, 2020). The current scope of work is an update to the existing modelling and conceptual cover system design for the high sulfur TSF, based on new information and additional performance requirements for the TSF at closure. This report details the updated conceptual TSF cover system design and present the results of the updated cover system modelling.

The model results for the high sulfur tailings cover system options indicate that maintaining a high degree of saturation within the high sulfur tailings is achievable but is improved with a cover system consisting of:

- 6 m or greater of low sulfur tailings, overlain with;
- 0.5 m of metasediment.

This design met its performance objective of maintaining a high degree of saturation (>85%) within the high sulfur tailings. Only when a 0.3 m vegetated topsoil layer was included, and extreme climate change conditions (SSP5-8.5) were simulated did substantial desiccation of the high sulfur tailings occur to depth. Even when degradation of the liner at the base of the high sulfur tailings was included (which allowed up to 7% of the total water balance to pass through the liner over the simulation period), the recommended cover system maintained a high degree of saturation as long as the vegetation and extreme climate change (SSP5-8.5) were not also included in the simulation.

The modelling indicates that not encouraging vegetation to establish on a high sulfur tailings cover system is the best way to reduce the risk of the high sulfur tailings desiccating. However, the model may be over-emphasizing this drawback and not correctly accounting for the benefits such as shading and erosion reduction that vegetation can provide. Conversely, the establishment of vegetation on the low sulfur tailings cover system is recommended to reduce net percolation (NP) into the low sulfur tailings.

Additional landform designs could be made to reduce the risk of the high sulfur tailings desiccating below 85% degree of saturation and also lower NP into the low sulfur tailings such as:

- Directing runoff water around the high sulfur tailings cells to collect on and infiltrate into the high sulfur tailings to help maintain its degree of saturation.
- Inclusion of a hummocked terrain on the high sulfur tailings cells to increase infiltration.

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# 1 INTRODUCTION

Okane Consultants (Okane) was retained by Rio Tinto to complete conceptual cover system design and modelling for the high sulfur tailings storage facility (TSF) at the Winu Site (Winu) in the Pilbara region of Western Australia. Okane previously completed modelling for the high sulfur TSF at Winu, in 2020 (Okane, 2020). The current scope of work is an update to the existing modelling and conceptual cover system design for the high sulfur TSF, based on new information and additional performance requirements of the TSF at closure. This report details the updated conceptual TSF cover system design and presents the results of the updated cover system modelling.

## 1.1 Project Objectives and Scope

The primary objective of the Winu Modelling project (0662-272) is to update the TSF conceptual cover system design and modelling, based on additional performance requirements of the TSF at closure.

Updated TSF cover system modelling will provide an understanding of the highest allowable leakage rate from liner required to maintain a tension-saturated degree of saturation (>85%) in the high sulfur tailings and will provide a better understanding of the balance of water from rainfall.

The scope of works for the updated conceptual cover system design and modelling works involved the following:

- Review of the hydraulic properties for all materials relevant to the modelling project, based on new available information provided by Rio Tinto;
- Updates to the climate database to account for climate change conditions beyond 2100; and
- Completion of additional one-dimensional (1D) soil-plant-atmosphere (SPA) numerical modelling to determine the highest allowable leakage rates required to maintain tension-saturated conditions beyond the year 2100.

## 1.2 Report Organization

For convenient reference, this report has been divided into the following sections:

- Section 1: Introduction
- Section 2: Background
- Section 3: Cover Design Attributes
- Section 4: Updated Cover System Modelling
- Section 5: Summary and Recommendations
- Section 6: Provides a list of references.

# 2 BACKGROUND

## 2.1 Location

Winu is a proposed copper-gold project, located approximately 300 km south of Broome, in the Pilbara region of Western Australia and situated in the lands of the Nyangumarta and Martu peoples (Figure 2.1). It is understood that the project will target a copper deposit with associated silver and gold mineralisation.

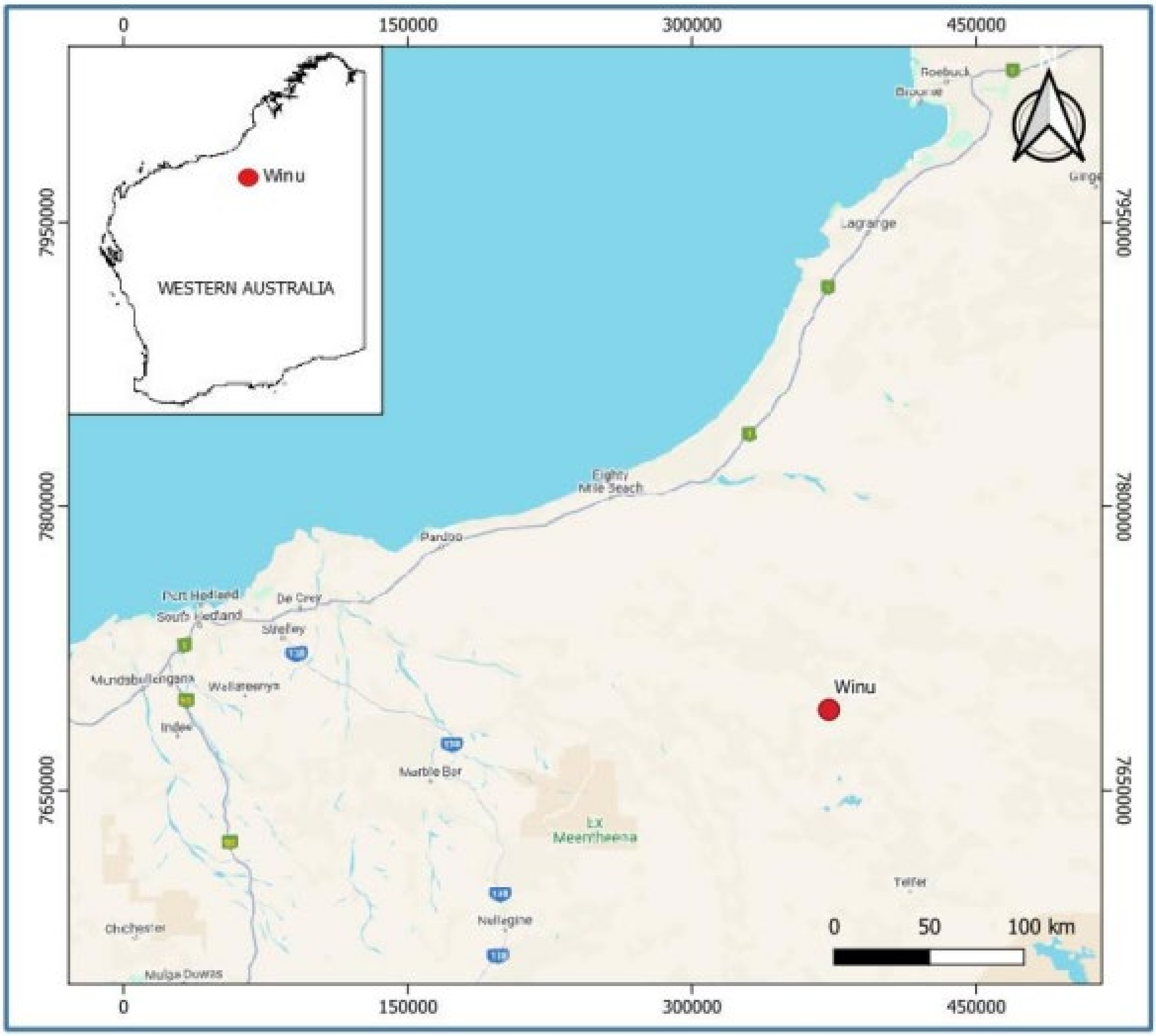



**Figure 2.1: Winu Site Location**

Coordinate Reference System GDA2020/MGA Zone 51

## 2.2 Closure Design and Objectives

The topography at Winu is characterised by sand dunes. Based on the initial mining plan, approximately 435 million tonnes of waste materials, primarily consisting of unmineralised sand and clay overburden, are anticipated to be generated during the mining activities at Winu (Rio Tinto, 2020). Although the overburden materials are generally considered non-acid forming (NAF), the geochemical analysis of the targeted waste materials reveals the presence of some materials with potential for acid formation (PAF).

Tailings material has been further assessed by Rio Tinto (2020b), differentiating between high sulfur flotation tailings, derived from the cleaner flotation circuit, and low sulfur tailings, originating from the rougher flotation circuit. Test work performed on tailings to date, Rio Tinto (2020b) recommended to take a conservative approach to tailings management and design. The current plan for the high sulfur tailings is that they will be managed separately from the low sulfur tailings and disposed of sub-aqueously. The proposal involves maintaining saturation in the high sulfur tailings to minimise oxygen exposure during the tailings facility’s development, thereby preventing the generation of AMD. For closure, it is recommended to install a cover system over the high sulfur tailings to uphold a consistently high degree of saturation within the high sulfur tailings.

## 2.3 Tailings Storage Facility

The Tailings Storage Facility (TSF) will feature a durable final cover system designed to maintain saturation for the high sulfur tailings during closure. Employing a suitable dry cover system will securely encapsulate the deposited tailings (Rio Tinto,2023).

To achieve the objective of this cover system, water's upward movement from the high sulfur tailings is prevented by decoupling the saturated high sulfur tailings from the evapotranspiration zone.

### *2.3.1 High Sulfur Tailings Storage Facility Design*

Based on the preliminary design drawing in Figure 2.2, Okane understands that the high sulfur tailings, generated from the cleaner processing circuit, will be separated from the low sulfur tailings produced by the rougher processing circuit. The high sulfur tailings will be placed in two cells lined with a low permeability liner (1.5 mm LLDPE or equivalent). Throughout the operational phase, the high sulfur tailings will be submerged for storage. During the closure process, a cover system is implemented to uphold a high saturation level within the high sulfur tailings, with the objective of limiting oxygen infiltration into the tailings. (Okane, 2020). The design and effective performance of the cover system for the high sulfur tailings is the focus of this modelling project.

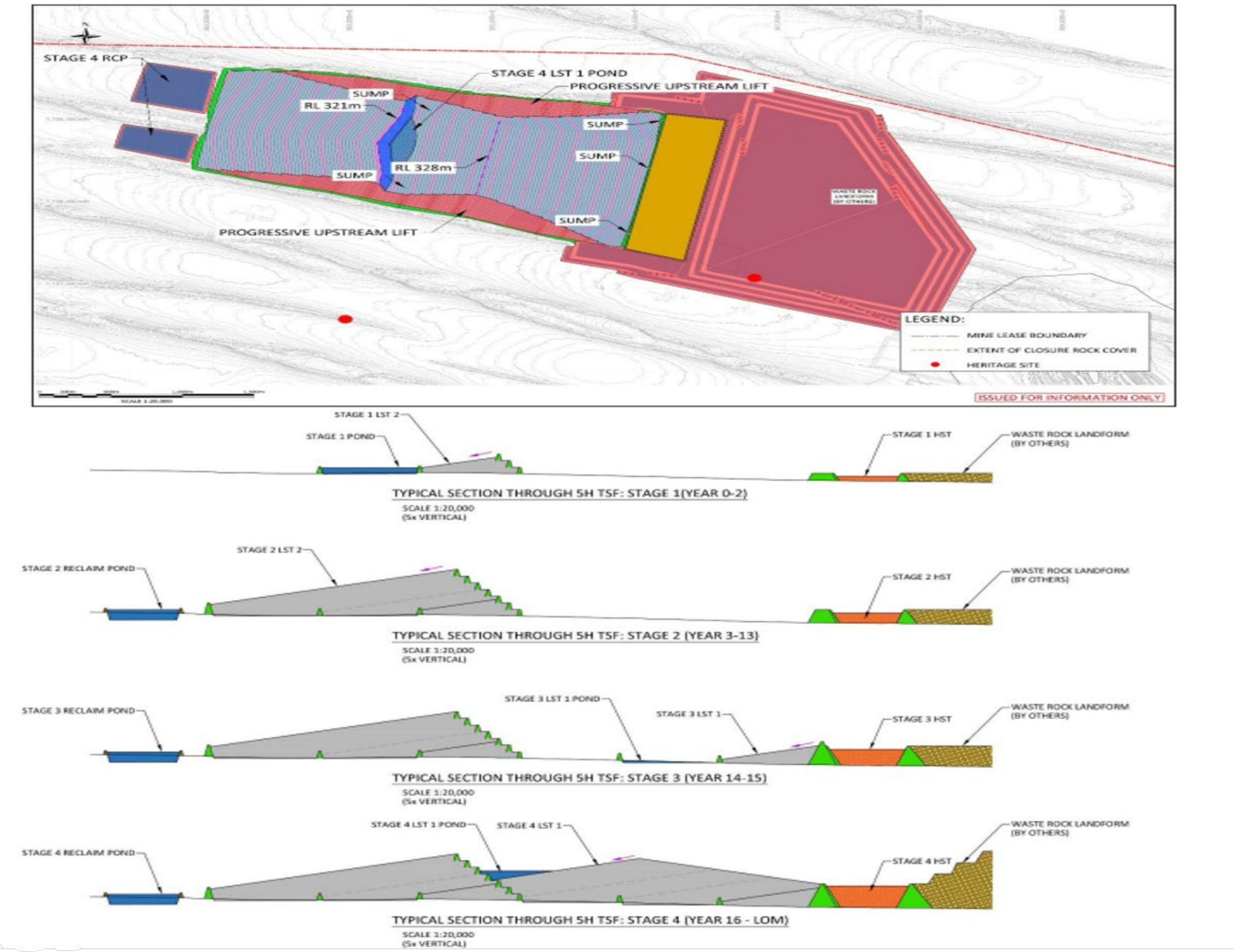



**Figure 2.2: Detailed Design of TSF**

Rio Tinto (2024)

### Cover System Design Purpose

The objective of employing a cover system is to rehabilitate surface mine waste storage facilities, establishing a secure, reliable, and environmentally sustainable engineered barrier between the adjacent environment and the mine waste. This approach enables authorized land uses while curbing the deterioration of the surrounding ecosystem. Customised cover system designs are crucial to fulfill precise design objectives and accommodate site-specific factors such as climate conditions.

For this cover system numerical modelling program, the primary objectives used to assess the conceptual closure cover system designs maintain a high degree of saturation in the high sulfur tailings and consequently, minimise oxygen ingress into the high sulfur tailings.

## 2.4 Proposed Cover System Design for High Sulfur TSF

A cover system that employs the capillary break concept has been proposed for the high sulfur TSF. This approach seeks to impede oxygen infiltration into the high sulfur tailings, thus averting the formation of AMD. To efficiently restrict oxygen penetration, "tension-saturated" conditions require maintaining a degree of saturation equal to or surpassing 85% (McMullen et al 1997, Bussière and Aubertin 1999, MEND 2004). In arid climates such as those at Winu, there's typically not enough excess water to maintain a consistently high degree of saturation in a water cover system at closure (INAP, 2017). However, the aim of this cover system is theoretically met with a dry cover by blocking the upward movement of water from the high sulfur tailings, achieved by separating the saturated high sulfur tailings from the evapotranspiration zone. As a result, the optimal cover system design exceeds the combined depth of evapotranspiration and capillary rise from the high sulfur tailings. Initial modelling completed by Okane (2020) focused on a preliminary design which used low sulfur tailings to achieve most of the necessary thickness of the cover system, along with a minimal thickness of imported soils for dust control and vegetation.

The proposed conceptual cover system options for the low sulfur and high sulfur TSFs, developed by Okane (2020) in collaboration with Rio Tinto, are shown in Figure 2.3, and are used as the starting points for this modelling project.

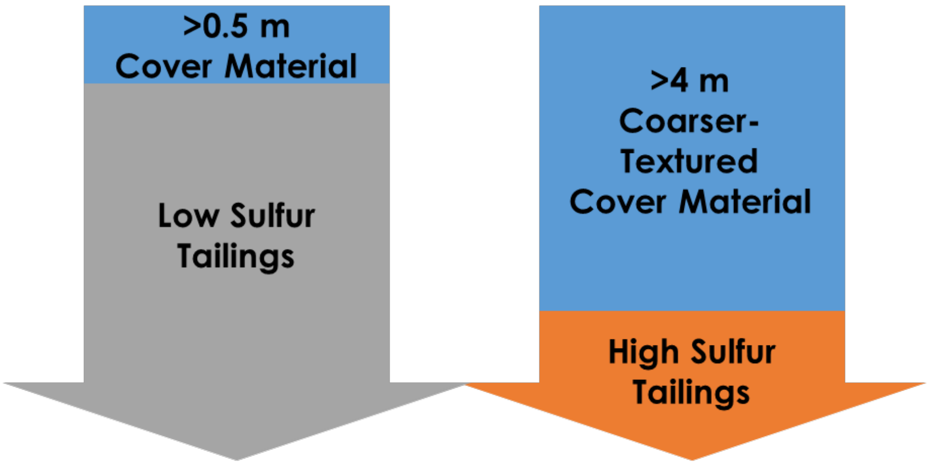



**Figure 2.3: Proposed Conceptual Cover System Design for Low and High Sulfur TSFs**

## 2.5 Geology

The regional geology at Winu is characterised by low-grade metasedimentary rocks with granitic intrusives. The Winu deposit is a structurally controlled vein-hosted gold and copper deposit, hosted by low-grade metasedimentary rocks (siltstone and sandstones) (Rio Tinto, 2020a). Supergene (weathering) alteration has resulted in a leached cap of the metasediments altered to clays, a copper oxide zone, and enrichment of copper mineralisation below the leached cap. The weathering, however, is not uniform and may have localised expressions, for example along a fault plane. Unaltered hypogene primary mineralisation occurs below the enriched supergene. The Winu deposit is unconformably overlain by Permian and Quaternary sedimentary overburden.

The Winu deposit can be sub-divided into three main zones (Figure 2.4):

1) Upper Zone - Oxidised overburden comprised of Quaternary sands, Permian sandstone and mudstone, and leached (oxidised) materials (complete leach, iron leach and copper oxides). Copper mineralisation has been oxidised;

2) Middle Zone - Enriched secondary sulfide zone. Copper is present as secondary sulfide minerals (enriched); and

3) Lower Zone - Hypogene, no enrichment, primary sulfide mineralisation and unweathered.

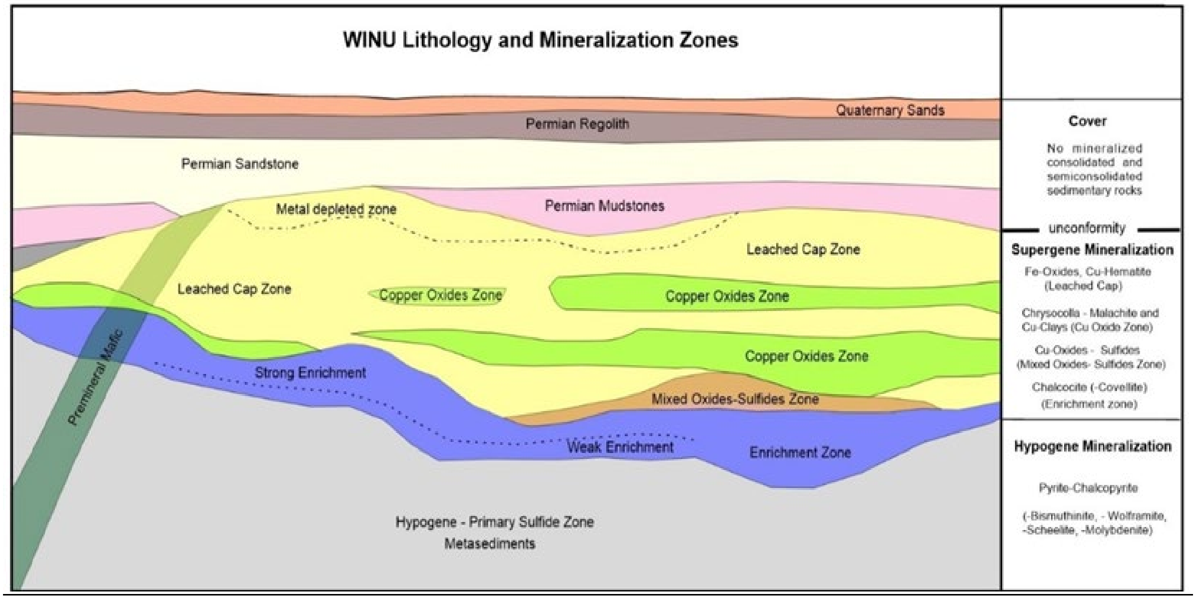



**Figure 2.4: Cross Section of the Winu Deposit**

Provided by Rio Tinto.

# 3 COVER DESIGN ATTRIBUTES

Understanding the characteristics of the site is essential for the design and assessment of suitable cover system designs for WRL and TSFs. The following cover system design 'filters' are assessed at a site-specific level as key inputs into the conceptual cover system design: climate; hydrogeologic setting; materials; and vegetation.

## 3.1 Climate

According to the Köppen-Geiger climate classification system (Peel et al., 2007), the climate of the Winu site is classified as arid, hot desert (BWh). Okane updated the previous historical daily database (gridded data from the SILO (Queensland Government, 2024), which was developed for the site for the 2020 modelling work, to include data from 2020 to 2023.

Table 3.1 presents historical annual average climate data from 1991 to 2020. The climate data from 1991 to 2020 is referred to as the "baseline" reference period for historical data in the climate and climate change data provided by Rio Tinto for Winu. The baseline period was used as a basis to build the future climate change datasets. Adjustments were made to baseline dataset based on the "Change from Baseline" estimates provided in Rio Tinto's Winu climate change datasets to estimate climate change data out to 2300. Okane used the projections for SSP2-4.5 and SSP5-8.5, as these scenarios are similar to those used in the 2020 modelling work (i.e., RCP4.5 and RCP8.5). This is described in more detail in the following sections.

**Table 3.1: Historical annual average climate data (January 1, 1991, to December 31, 2020)**

| Month | Temperature ($^0$C) | | Relative Humidity (%) | | Wind Speed | Precipitation | PE |
|---|---|---|---|---|---|---|---|
| | Max | Min | Max | Min | (m/s) | (mm) | (mm) |
| January | 38 | 26 | 65 | 33 | 2.21 | 111 | 210 |
| February | 37 | 25 | 68 | 36 | 2.07 | 124 | 174 |
| March | 37 | 24 | 62 | 31 | 1.89 | 98 | 179 |
| April | 35 | 21 | 54 | 25 | 1.66 | 20 | 148 |
| May | 30 | 16 | 53 | 23 | 1.54 | 17 | 117 |
| June | 27 | 12 | 57 | 26 | 1.56 | 18 | 93 |
| July | 27 | 11 | 52 | 21 | 1.55 | 11 | 104 |
| August | 30 | 12 | 47 | 18 | 1.61 | 3 | 131 |
| September | 33 | 16 | 44 | 17 | 1.81 | 1 | 165 |
| October | 37 | 20 | 45 | 18 | 2.05 | 4 | 206 |
| November | 38 | 23 | 48 | 21 | 2.23 | 11 | 214 |
| December | 39 | 25 | 55 | 27 | 2.21 | 64 | 218 |
| ***Annual*** | ***34*** | ***19*** | ***54*** | ***25*** | ***1.87*** | ***483*** | ***1,960*** |

SILO (2024)

Employing the methodologies delineated in the Global Cover System Design – Technical Guidance Document (INAP, 2017), a conceptual overview of the cover system performance in NP terms is delivered. The INAP NP classifications corresponding to the climate conditions observed at Winu are outlined below (Okane,2020):

- Very low: <1% of rainfall;
- Low: between 1% and 5% of rainfall;
- Moderate: between 5% and 10% of rainfall; and
- High: >10% of rainfall.

#### *3.1.1 Future Climate*

Climate change is a potential factor influencing the performance of cover systems. As part of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), the IPCC adopted four representative concentration pathways (RCPs); RCP2.6, RCP4.5, RCP6.0 and RCP8.5 which are named after the radiative target forcing level for 2100. Radiative target forcing levels are based on the forcing of greenhouse gases and other agents and are relative to pre-industrial levels. The surface atmospheric mole fraction of $CO_2$ for each RCP scenario is shown in Figure 3.1.

RCP4.5 represents a medium RCP with stabilisation of radiative forcing before 2100 using technology and climate policy. RCP8.5 represents a high RCP with increasing emissions that do not stabilise until after 2100. This RCP is typically used as a worst-case scenario where no climate policy is undertaken. The RCP8.5 results can be used as an extreme to estimate performance if the change in forcing is lower.

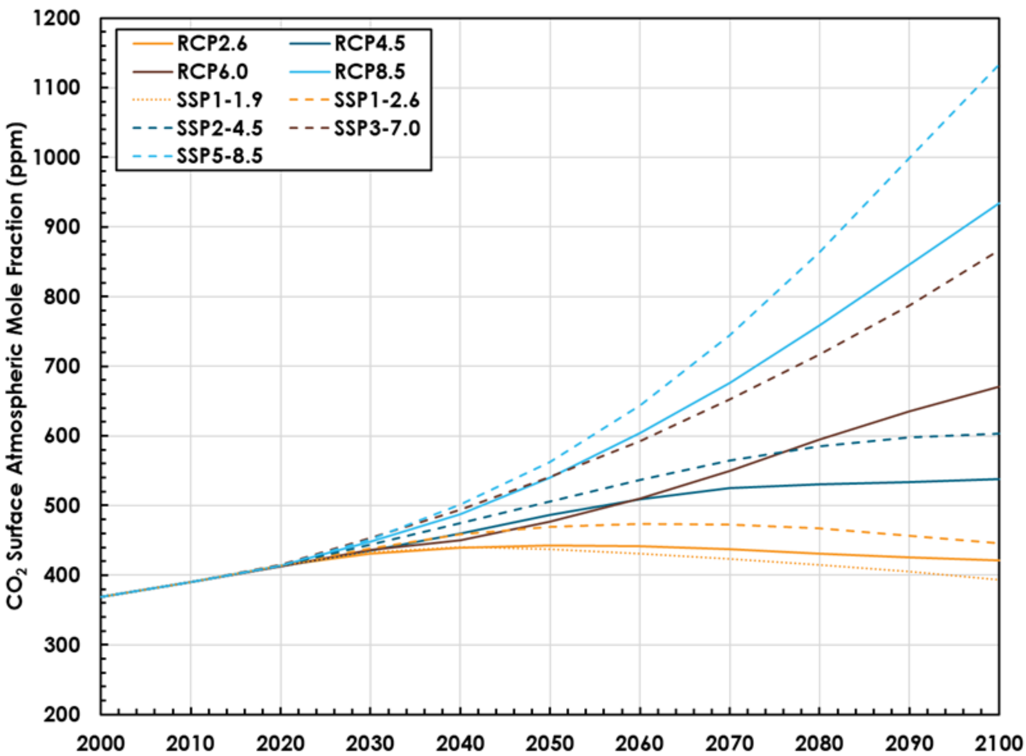



**Figure 3.1: Comparison of Surface Atmospheric Mole Fraction of $CO_2$ for the RCPs and Core SSPs**

IPCC (2021).

With the release of the IPCC's Sixth Assessment Report (AR6) in 2021 and 2022, the IPCC replaced the RCPs with five Shared Socioeconomic Pathways (SSPs), which provide a range of plausible trends in the evolution of society over the twenty-first century (IPCC, 2021). Each SSP family consists of two elements: a set of qualitative, narrative storylines describing societal futures; and a set of quantitative measures of development at aggregated and/or spatially resolved scales. The SSP families represent 'sustainability' (SSP1), 'middle of the road' (SSP2), 'regional rivalry' (SSP3), 'inequality' (SSP4), and 'fossil fuel intensive' development (SSP5). More details of each SSP are provided in Okane (2024).

#### 3.1.1.1 Climate Change Predictions to 2100

Rio Tinto provided monthly climate change projections up to 2100 for Winu for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. These projections are given relative to the baseline conditions for 1991 to 2020. Hence, Okane repeated and adjusted the baseline climate period so that it represented the climate change projections of SSP2-4.5 and SSP5-8.5 from 2024 to 2100 as provided by Rio Tinto for Winu. The projections for Winu under SSP2-4.5 and SSP5-8.5 indicate that rainfall is predicted to drop by 2.8% and 6.4%, respectively, and mean temperatures are predicted to rise by 2.1 °C and 4.8 °C, respectively.

#### 3.1.1.2 Climate Change Projections Beyond 2100

Lee *et al.* (2021) assessed simulations of future global climate change, spanning time horizons from the near term (2021–2040), mid-term (2041–2060), and long term (2081–2100) out to the year 2300.

Changes are assessed relative to both the recent past (1995–2014) and the 1850–1900 approximation to the pre-industrial period. Figure 3.2 shows that (a) temperatures and (b) global precipitation, are projected to continue to rise until approximately 2150 under SSP5-8.5, whereas both are projected to level off under SSP2-4.5 (Lee *et al.,* 2021). Hence, Okane used available projections and trends for SSP2-4.5 and SSP5-8.5 to adjust site climate predicted from 2081 to 2100 to account for site climate until 2300.

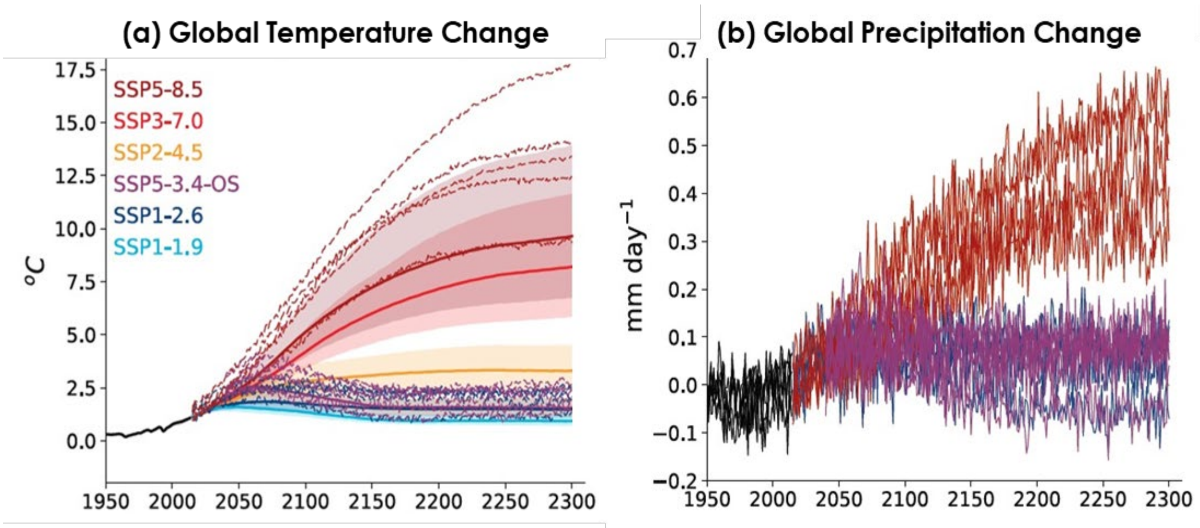



**Figure 3.2: Simulated climate changes up to 2300 under the extended SSP scenarios.**

Lee et *al*. (2021).

Okane investigated the SSP2-4.5 and SSP5-8.5 climate change scenarios for impact on future climate at the site. The percentage change in climate factors from the 1991 to 2020 averages was analysed using the SILO climate database. Climate change comparisons in this document are expressed as the difference between 2024 to 2300 climate data compared to 1991 to 2020 historical averages.

Average annual rainfall is predicted to decrease by approximately 4% relative to the baseline period by the 2070 to 2100 period under SSP2-4.5. The average annual rainfall between 2270 to 2300 is expected to be the same as the baseline period. Annual rainfall and potential evaporation (PE) are shown in Figure 3.3 for the baseline period and SSP2-4.5 until 2300. The PE values are expected to increase approximately 4.9% by 2070 to 2100 relative to baseline and 5.3% for the period of 2270 to 2300, relative to the baseline period.

The average annual maximum and minimum temperatures for the baseline period and SSP2-4.5 until 2300 are shown in Figure 3.4. The mean annual temperature is expected to increase 2.0 °C by 2070 to 2100 from baseline and 2.3 °C by 2270 to 2300 from the baseline period.

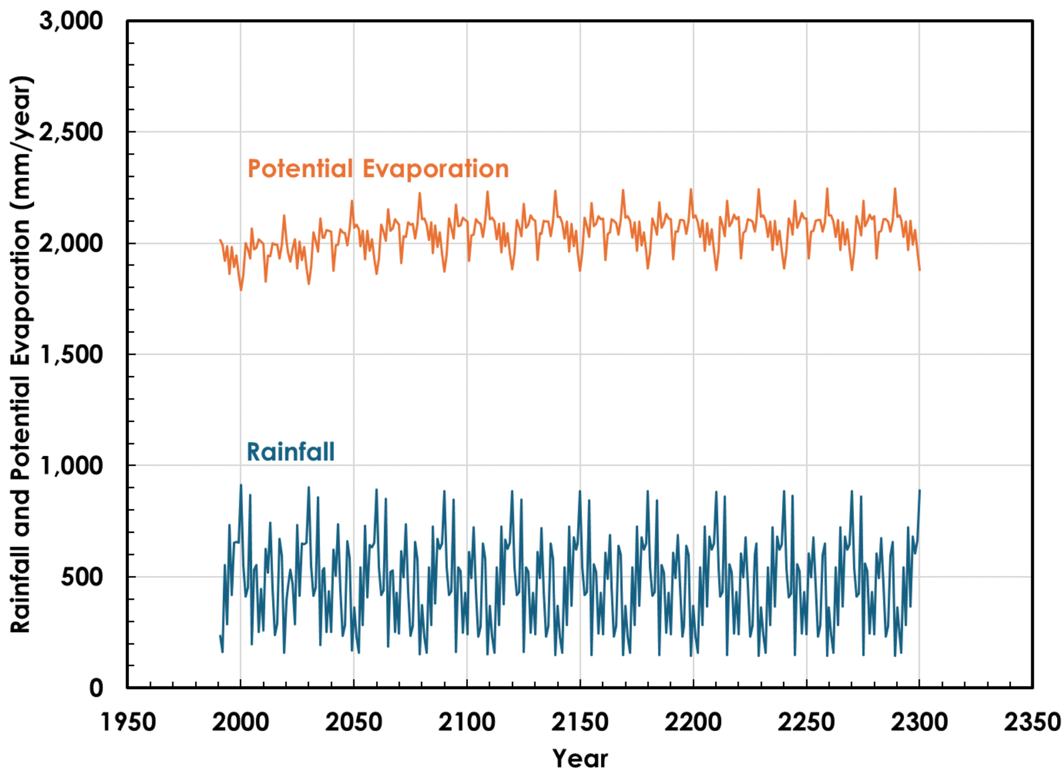



**Figure 3.3: Rainfall and potential evaporation under SSP2-4.5 from 1991 to 2300.**

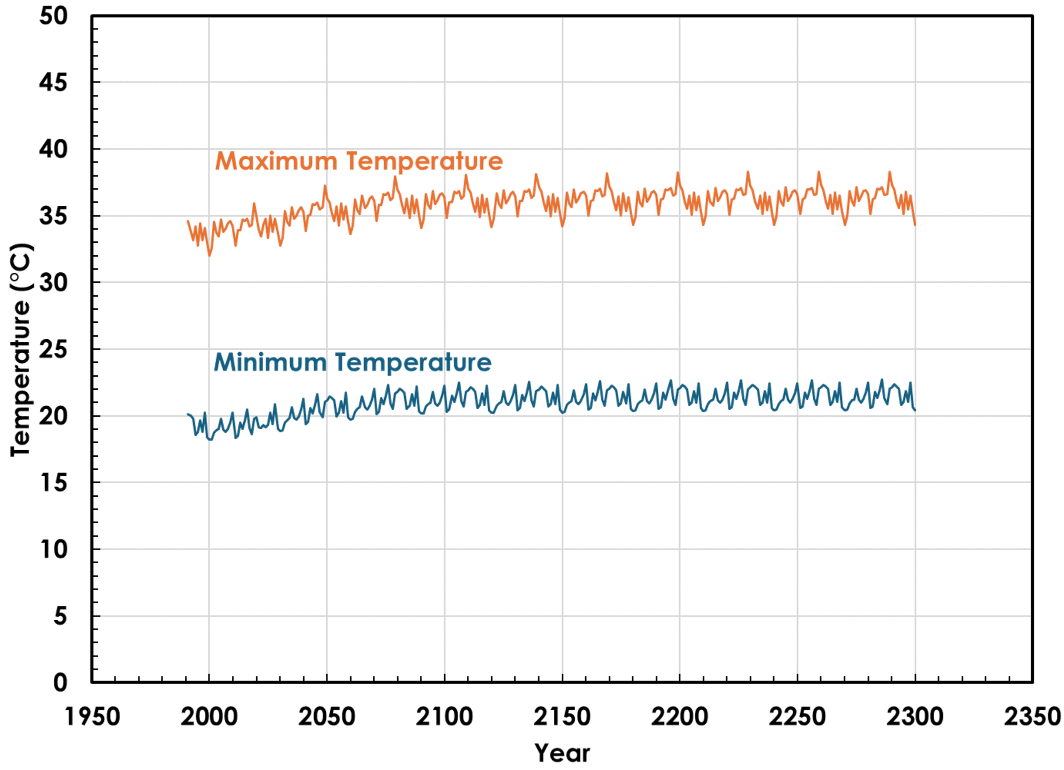



**Figure 3.4: Maximum and minimum temperature according to SSP2-4.5 from 1991 to 2300.**

Figure 3.5 presents the annual rainfall and PE under SSP5-8.5 conditions. Average annual rainfall is predicted to decrease by approximately 7% by the 2070 to 2100 period and 12% by 2270 to 2300, both relative to baseline conditions. Annual average PE is expected to increase 9% by 2070 to 2100 and 27% by 2270 to 2300, relative to baseline conditions.

The average annual maximum and minimum temperatures for the baseline period and SSP2-4.5 until 2300 are shown in Figure 3.6. The mean annual temperature is expected to increase 3.8 °C by 2070 to 2100 from baseline and 11.0 °C by 2270 to 2300 from the baseline period.

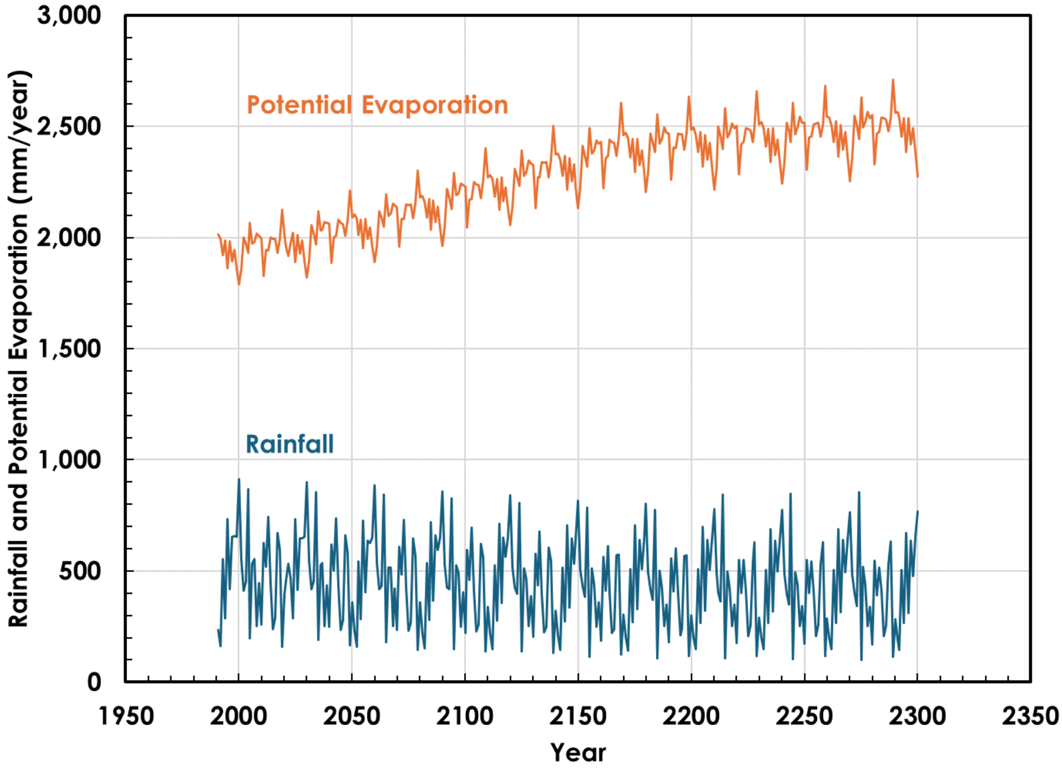



**Figure 3.5: Rainfall and Potential Evaporation according to SSP5-8.5 from 1991 to 2300.**

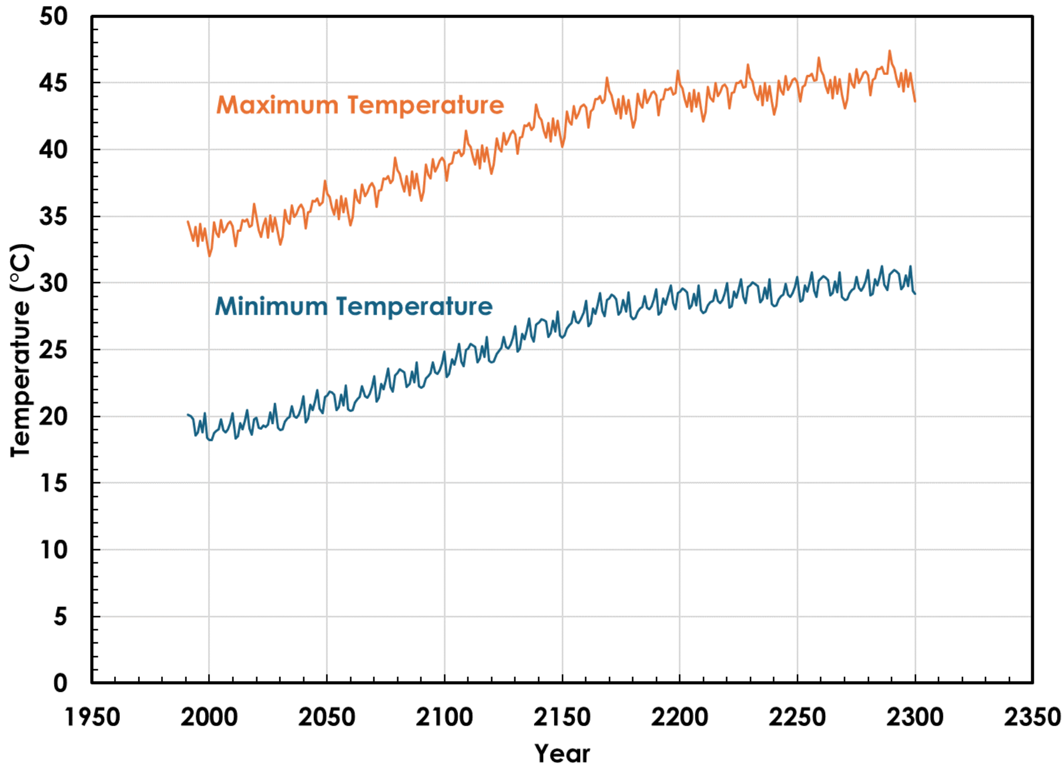



**Figure 3.6: Maximum and minimum temperature according to SSP5-8.5 from 1991 to 2300.**

## 3.2 Hydrogeological Setting

The current high sulfur TSF design includes lining its base with a 1.5 mm thick liner. The embankments of the high sulfur TSF cells will also be lined to keep the high sulfur tailings saturated during operations and post-closure. Modelling completed in 2020 represented this lower boundary as a flux rate. To quantify potential leakage from geomembranes under TSFs, GeoEngineering Centre (Klohn Crippen Berg, 2018) studied geomembranes under simulated field conditions and found that leakage through holes up to 2 cm in diameter is less than 5 mL/s/km$^2$ (0.15 mm/year) (Rowe et al. 2016), which was used as the base case lower boundary condition in the high sulfur tailings models. A lower boundary condition one order of magnitude above the findings of Rowe et al. (2016) (i.e., 1.5 mm/year) was also simulated as a sensitivity for the 2020 project.

For the current modelling project, Okane included the liner and a layer of compacted aeolian sand with fines added beneath the liner in the simulations. The liner properties were simulated as described in the subsequent "Materials" section.

## 3.3 Material

The hydraulic properties estimated for this project are presented in Table 3.2. These estimates are primarily based on the work completed for the 2020 project, but the saturated hydraulic conductivity ($k_{sat}$) and porosity estimates have been augmented to align with data provided in the Water, Waste & Land (WWL) Winu HDTSF Seepage Modelling Report (WWL, 2023). Updated $k_{sat}$ values have been italicised in Table 3.2, however, all changes are within half an order of magnitude of the original $k_{sat}$

estimates. WWL (2023) estimated a $k_{sat}$ of 5E-7 m/s in their model for the low sulfur tailings, however, their hydraulic conductivity testing indicated a $k_{sat}$ of 1E-6 m/s. Hence, Okane's original estimate of 1E-6 m/s has been kept, as the low sulfur tailings being modelled for this project are near the surface and estimated to be more permeable than those under compression at depth. The properties provided in Table 3.2 define the water retention curve and hydraulic conductivity function for each material using the Van Genuchten (1980) method.

Figure 3.7 shows the textures measured (points)/estimated (ovals) for the metasediment, sand, and low and high sulfur tailings. The measurements for the metasediment and sand were provided previously by Okane (2020).

**Table 3.2: Summary of Material Inputs for Van Genuchten (1980) method**

| Material | Porosity | Air Entry Value (kPa) | n | Residual VWC | $k_{sat}$ (m/s) |
|---|---|---|---|---|---|
| Aeolian Sand | 0.33 | 1 | 1.2 | 0 | $2.5 \times 10^{-5}$ |
| Metasediment | 0.25 | 10 | 1.5 | 0 | $2.4 \times 10^{-5}$ |
| Low Sulfur Tailings | 0.45 | 10 | 1.2 | 0 | $1 \times 10^{-6}$ |
| High Sulfur Tailings | 0.56 | 20 | 1.2 | 0 | $2 \times 10^{-7}$ |
| Topsoil | 0.30 | 5 | 2 | 0 | $5 \times 10^{-6}$ |
| Compacted Aeolian Sand with Fines added | 0.25 | 10 | 1.2 | 0 | $1 \times 10^{-8}$ |

n: soil water retention curve fitting parameter, VWC: volumetric water content, $k_{sat}$: saturated hydraulic conductivity.
Data from Okane (2020). Saturated hydraulic Conductivity ($k_{sat}$) and porosity estimates derived from WWL (2023).

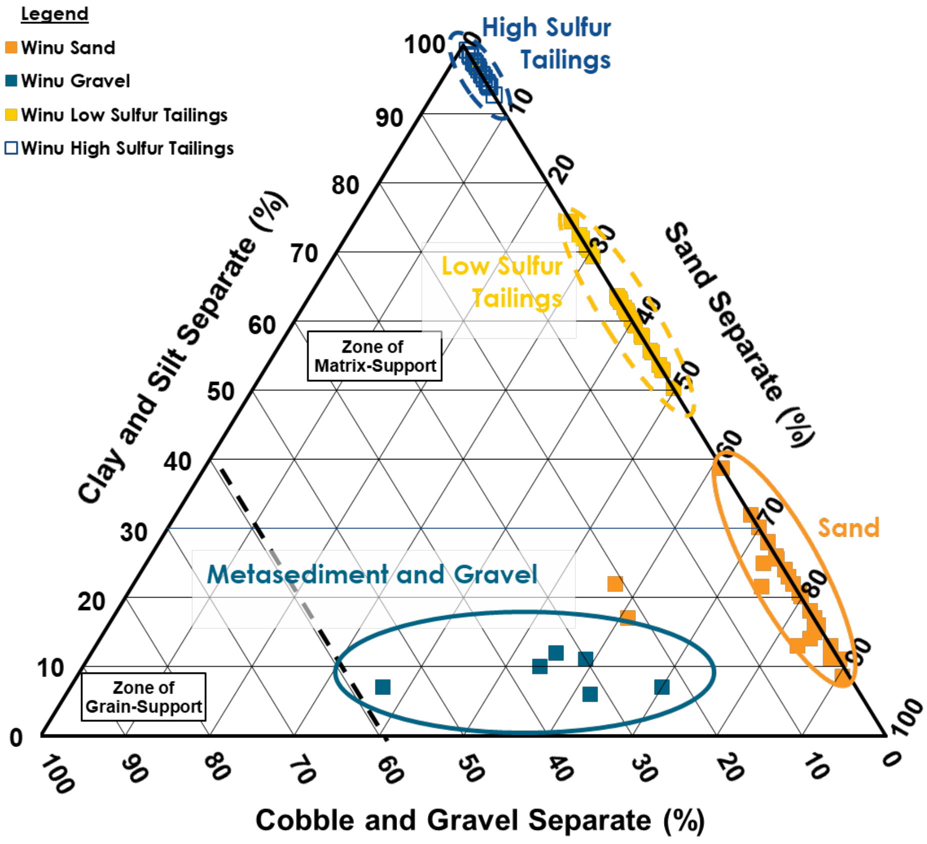



**Figure 3.7: Texture triangle for the metasediment, sand, and low and high sulfur tailings.**

WWL also proposed the degradation function for the geomembrane liner presented in Table 3.3, which was evaluated as a model scenario. However, it was noted in communications with Rio Tinto that work completed at other sites has shown that the liner was only required for 30 to 50 years and then the residue would have a permeability low enough to slow fluxes leaving the system due to consolidation. This eventuality was considered by including the liner and a layer of compacted aeolian sands in which additional fines had collected beneath the liner (referred to as "Compacted Aeolian Sand with Fines added" in Table 3.2).

**Table 3.3: Degradation Function for the Geomembrane Liner**

| Time Period (years) | Description | Lower Bound $k_{sat}$ (m/s) | Upper Bound $k_{sat}$ (m/s) |
|---|---|---|---|
| 0 – 20 | Liner 100% intact | $10^{-12}$ | $10^{-12}$ |
| 20 – 35 | Liner between 100% and 90% intact | $10^{-12}$ | $10^{-11}$ |
| 35 – 50 | Liner between 90% and 80% intact | $10^{-11}$ | $10^{-10}$ |
| 50 – 100 | Liner between 80% and 70% intact | $10^{-10}$ | $10^{-9}$ |
| 100 – 200 | Liner between 70% and 50% intact | $10^{-9}$ | $10^{-8}$ |
| 200 – 250 | Liner between 50% and 20% intact | $10^{-8}$ | $10^{-7}$ |

## 3.4 Vegetation

The Winu site is located in a biome that can be classified as desert and dry shrublands. For modelling inputs, it was assumed that the vegetation would predominantly consist of sparse bushes and grasses, with root depth estimated using the method outlined by Jackson *et al.* (1996). This method indicates that the majority (72%) of roots will be shallower than 0.5 m, 90% shallower than 0.9 m, and all roots shallower than 3 m, as shown in Figure 3.8.

Within the modelling program, a plant water limitation function was utilized to determine the decrease in the plant's ability to absorb water as negative pore-water pressure increases in unsaturated soil. This project adopted a widely recognized plant water limitation function, whereby the plant reaches a water limiting point at a pore-water pressure of -10 kPa and loses its ability to draw water completely (also referred to as the "permanent wilting point") if the pressure reaches -1,500 kPa.

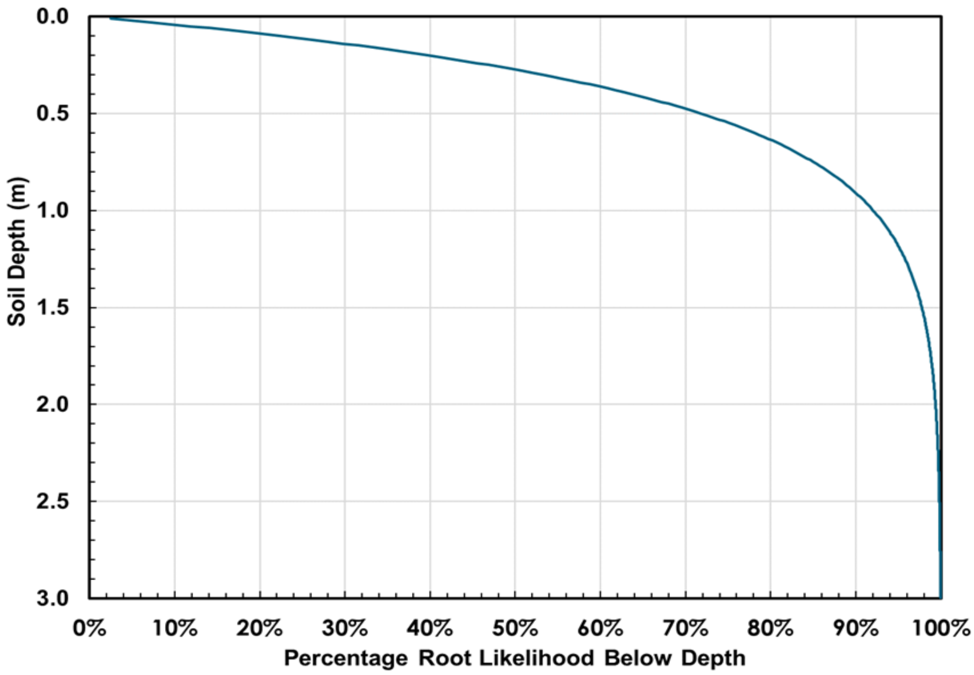



**Figure 3.8: The root depth distribution curve used in the numerical modelling.**

Jackson *et al.* (1996).

# 4 UPDATED COVER SYSTEM MODELLING

One-dimensional (1D) Soil-Plant-Atmosphere (SPA) modelling was completed using the GeoStudio Flow software suite (Seequent Ltd, 2022) to assess the performance of the proposed conceptual cover system designs for high and low sulfur tailings. These simulations can be divided into two groups: cover systems consisting mainly of single layer of coarser-textured material similar to that of the metasediment on site; and cover systems consisting mainly of low sulfur tailings overlain with thinner layer(s) of metasediment, sand, and/or topsoil. Simulations were conducted using two future climate scenarios (SSP2-4.5 and SSP5-8.5) representing the period from 1 January 2024 to 31 December 2300 for each cover design option.

The simulated cover system options are listed in Table 4.1 and shown in Figure 4.1 and Figure 4.2. Cover system design options were evaluated with and without simulating the degradation of the geomembrane liner at the base of the high sulfur tailings (as per the function defined in Table 3.3) and including vegetation (but only when a topsoil layer was included in the cover system design). In total, 80 simulations were completed accounting for each of the 40 options being simulated with two future climate scenarios (SSP2-4.5 and SSP5-8.5).

**Table 4.1: List of cover system options simulated. Note that all options were simulated with two future climate scenarios (SSP2-4.5 and SSP5-8.5).**

| Option #* | Predominant Layer** (Material – m) | Intermediate Layer(s) (Material – m) | 0.3 m Topsoil Surface Layer | Vegetation | Degraded Liner |
|---|---|---|---|---|---|
| 1 | MS – 4.0 m | None | No | No | No |
| 2 | MS – 4.0 m | None | No | No | Yes |
| 3 | MS – 3.7 m | None | Yes | No | No |
| 4 | MS – 3.7 m | None | Yes | No | Yes |
| 5 | MS – 3.7 m | None | Yes | Yes | No |
| 6 | MS – 3.7 m | None | Yes | Yes | Yes |
| 7 | MS – 6.0 m | None | No | No | No |
| 8 | MS – 6.0 m | None | No | No | Yes |
| 9 | MS – 5.7 m | None | Yes | No | No |
| 10 | MS – 5.7 m | None | Yes | No | Yes |
| 11 | MS – 5.7 m | None | Yes | Yes | No |
| 12 | MS – 5.7 m | None | Yes | Yes | Yes |
| 13 | MS – 8.0 m | None | No | No | No |
| 14 | MS – 8.0 m | None | No | No | Yes |
| 15 | MS – 7.7 m | None | Yes | No | No |
| 16 | MS – 7.7 m | None | Yes | No | Yes |
| 17 | MS – 7.7 m | None | Yes | Yes | No |
| 18 | MS – 7.7 m | None | Yes | Yes | Yes |

| Option #* | Predominant Layer** (Material – m) | Intermediate Layer(s) (Material – m) | 0.3 m Topsoil Surface Layer | Vegetation | Degraded Liner |
|---|---|---|---|---|---|
| 19 | MS – 0.5 m (LS TSF) | None | No | No | N/A |
| 20 | MS – 0.5 m (LS TSF) | None | Yes | Yes | N/A |
| 21 | LST – 4.0 m | MS – 0.5 m | No | No | No |
| 22 | LST – 4.0 m | MS – 0.5 m | No | No | Yes |
| 23 | LST – 4.0 m | MS – 0.5 m | Yes | No | No |
| 24 | LST – 4.0 m | MS – 0.5 m | Yes | No | Yes |
| 25 | LST – 4.0 m | MS – 0.5 m | Yes | Yes | No |
| 26 | LST – 4.0 m | MS – 0.5 m | Yes | Yes | Yes |
| 27 | LST – 6.0 m | MS – 0.5 m | No | No | No |
| 28 | LST – 6.0 m | MS – 0.5 m | No | No | Yes |
| 29 | LST – 6.0 m | MS – 0.5 m | Yes | No | No |
| 30 | LST – 6.0 m | MS – 0.5 m | Yes | No | Yes |
| 31 | LST – 6.0 m | MS – 0.5 m | Yes | Yes | No |
| 32 | LST – 6.0 m | MS – 0.5 m | Yes | Yes | Yes |
| 33 | LST – 8.0 m | MS – 0.5 m | No | No | No |
| 34 | LST – 8.0 m | MS – 0.5 m | No | No | Yes |
| 35 | MS – 2.0 m | Sand – 0.5 m | Yes | No | No |
| 36 | MS – 2.0 m | Sand – 0.5 m | Yes | No | Yes |
| 37 | LST – 2.0 m | MS – 0.5 m underlying Sand – 0.5 m | Yes | Yes | No |
| 38 | LST – 2.0 m | MS – 0.5 m underlying Sand – 0.5 m | Yes | Yes | Yes |
| 39 | MS – 4.0 m | None | No | No | No |
| 40 | MS – 4.0 m | None | Yes | Yes | Yes |

*Cover System Options 19 and 20 simulated overlying low sulfur tailings
**MS = Metasediment; LST = Low Sulfur Tailings

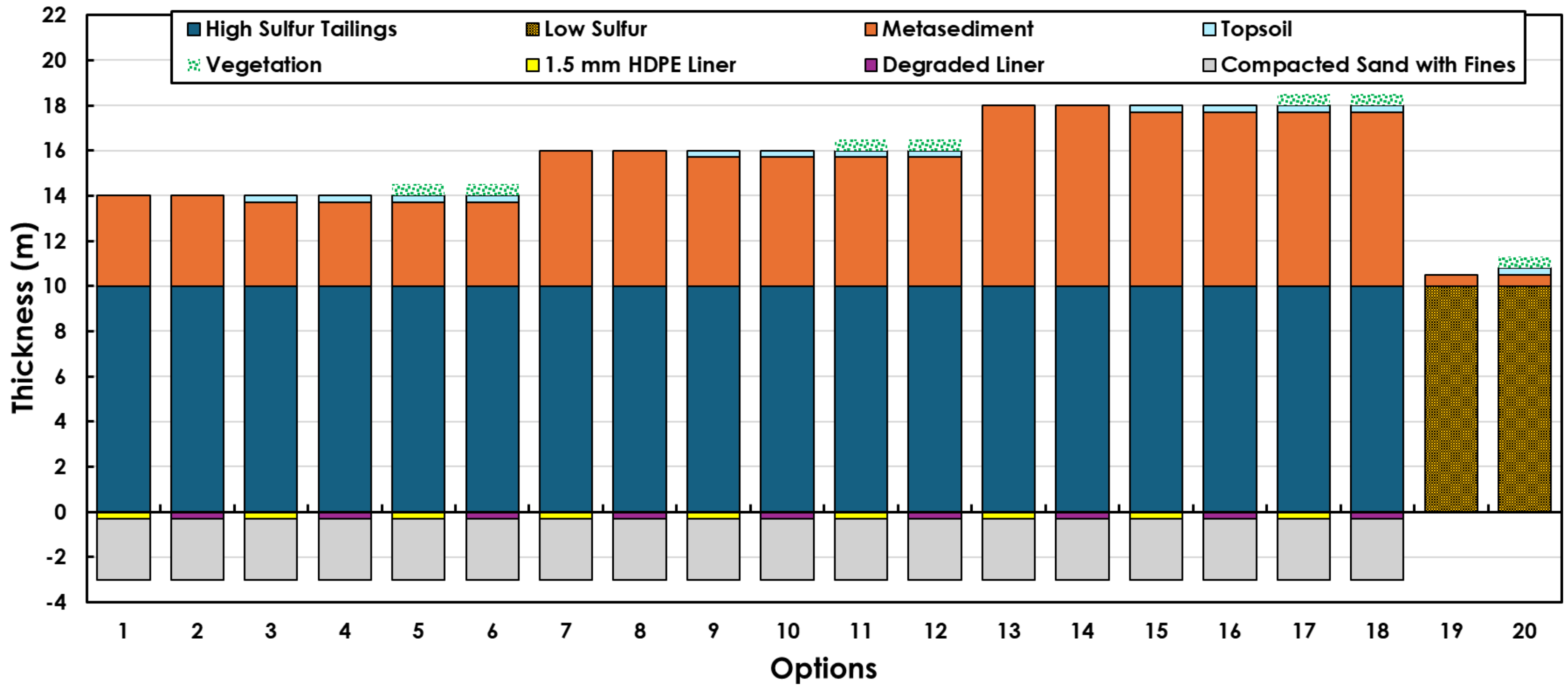



**Figure 4.1: Simulated coarser-textured (metasediment) cover system designs for high sulfur tailings (Options 1 to 18) and low sulfur tailings (Options 19 and 20).**

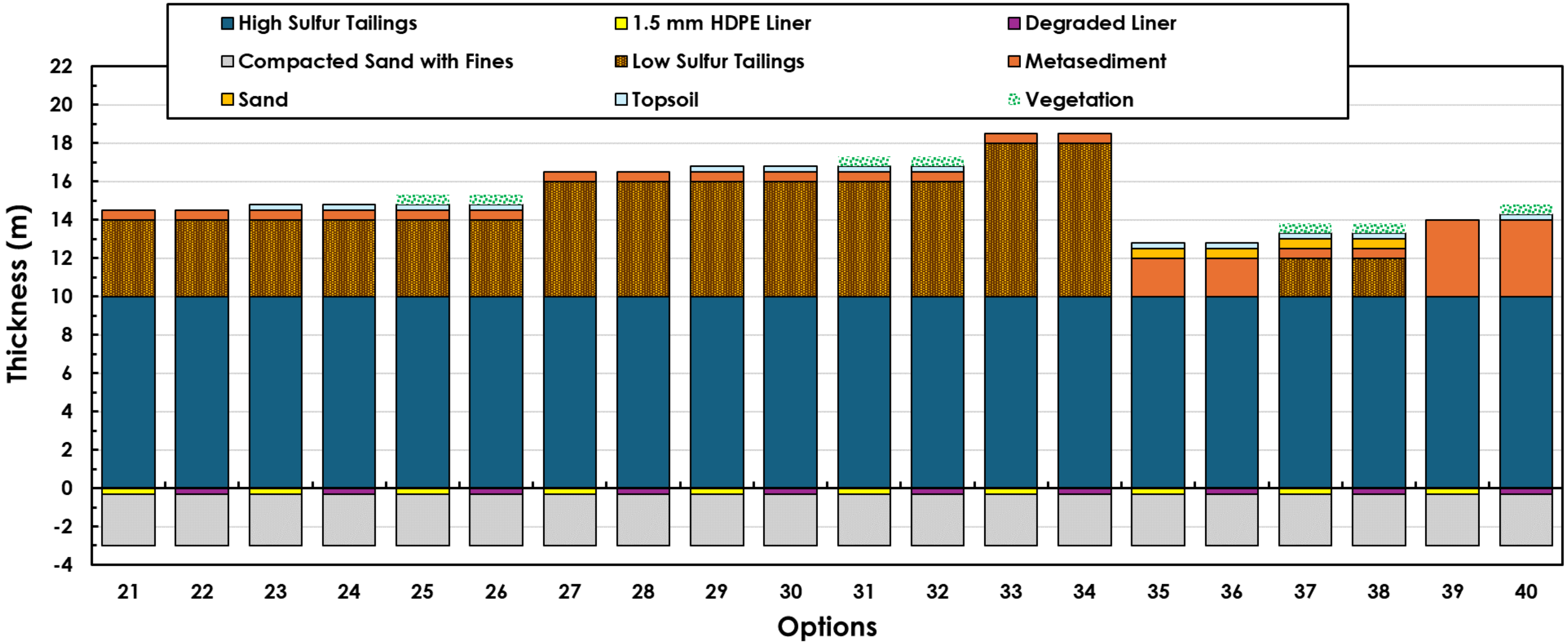



**Figure 4.2: Simulated 0.5 m metasediment over low sulfur tailings cover system designs (Options 21 to 34) and thinner cover system design options (Options 35 and 40).**

Table 4.2 summarizes the annual average water balances for the simulated cover systems options. Figure 4.3 shows how the water balance parameters relate to each option. Runoff is assumed to be removed from the landform; hence, is not available to increase net percolation or degree of saturation of the tailings. For the simulations of a cover system for low sulfur tailings (Options 19 and 20) the base liner layer was not included in the simulations, so water crossing the cover system / low sulfur tailings interface (i.e., net percolation) is reported. For all other simulations, a liner was included in the simulation at the base of the high sulfur tailings. The amount of water passing through this liner was reported for these simulations, referred to as "liner leakage" in Table 4.2.

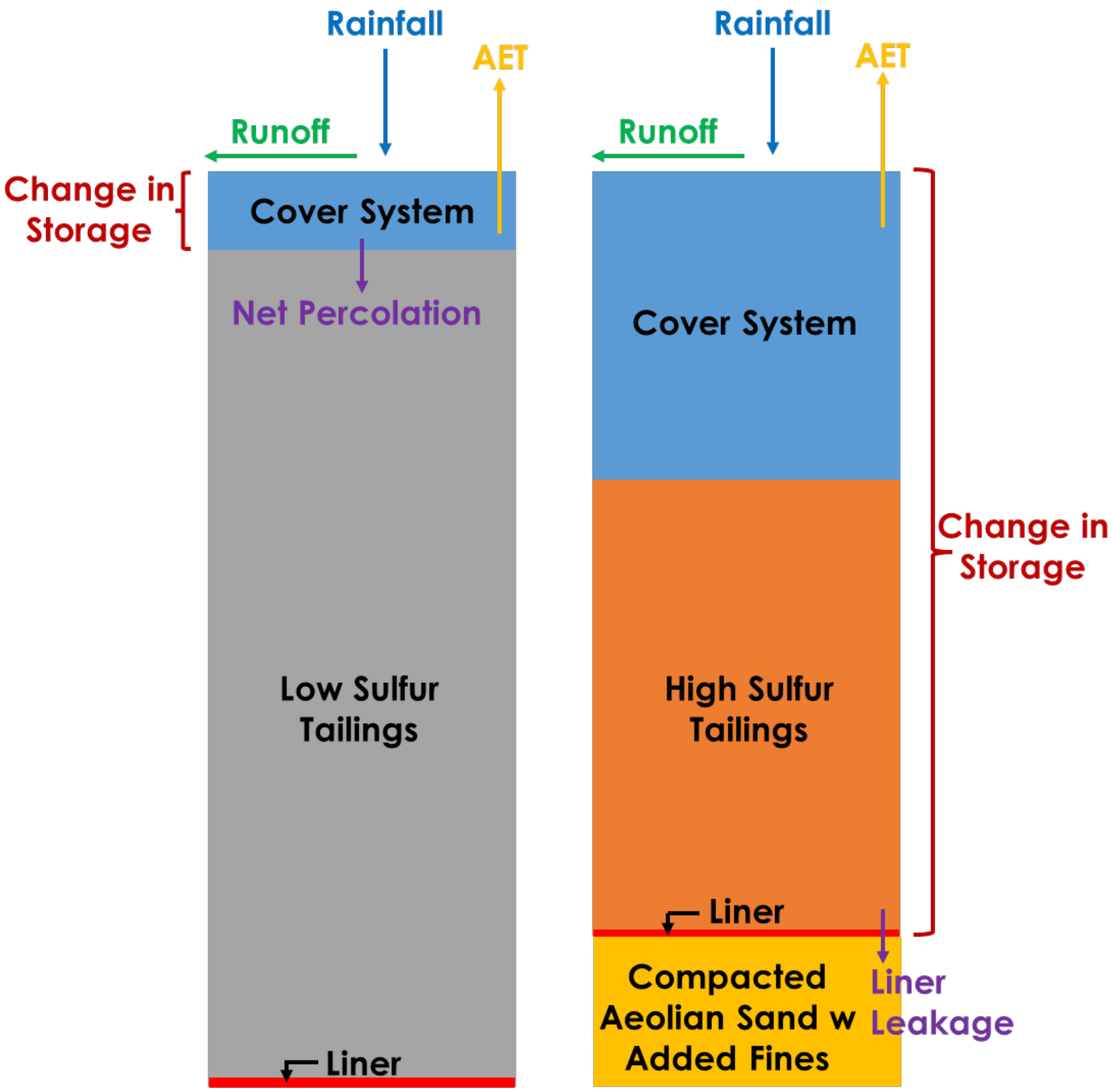



**Figure 4.3: Diagram of water balances for low sulfur (options 19 and 20) and high sulfur tailings cover systems.**

**Table 4.2: Summary of average annual water balances for simulated cover system options (2024 to 2300).**

| Option* | Climate Change Scenario | Rainfall (mm) | Runoff (% Rainfall) | AET (% Rainfall) | Net Percolation / Liner Leakage (% Rainfall) | Change in Storage** (% Rainfall) |
|---|---|---|---|---|---|---|
| 1 (4.0 m MS) | SSP2-4.5 | 473 | 0% | 100% | 1% | -1% |
| | SSP5-8.5 | 439 | 0% | 100% | 1% | -1% |
| 2 (4.0 m MS-DL) | SSP2-4.5 | 473 | 0% | 95% | 6% | -1% |
| | SSP5-8.5 | 439 | 0% | 95% | 6% | -1% |
| 3 (3.7 m MS-TS) | SSP2-4.5 | 473 | 26% | 72% | 2% | 0% |
| | SSP5-8.5 | 439 | 26% | 72% | 2% | 0% |
| 4 (3.7 m MS-TS-DL) | SSP2-4.5 | 473 | 24% | 70% | 6% | 0% |
| | SSP5-8.5 | 439 | 24% | 69% | 7% | 0% |
| 5 (3.7 m MS-TS-V) | SSP2-4.5 | 473 | 4% | 100% | 1% | -5% |
| | SSP5-8.5 | 439 | 4% | 102% | 0% | -6% |
| 6 (3.7 m MS-TS-V-DL) | SSP2-4.5 | 473 | 5% | 97% | 5% | -7% |
| | SSP5-8.5 | 439 | 5% | 99% | 2% | -6% |
| 7 (6.0 m MS) | SSP2-4.5 | 473 | 0% | 100% | 1% | -1% |
| | SSP5-8.5 | 439 | 0% | 100% | 1% | -1% |
| 8 (6.0 m MS-DL) | SSP2-4.5 | 473 | 0% | 95% | 6% | -1% |
| | SSP5-8.5 | 439 | 0% | 95% | 6% | -1% |
| 9 (5.7 m MS-TS) | SSP2-4.5 | 473 | 26% | 72% | 2% | 0% |
| | SSP5-8.5 | 439 | 26% | 72% | 2% | 0% |
| 10 (5.7 m MS-TS-DL) | SSP2-4.5 | 473 | 24% | 70% | 6% | 0% |
| | SSP5-8.5 | 439 | 24% | 69% | 7% | 0% |
| 11 (5.7 m MS-TS-V) | SSP2-4.5 | 473 | 5% | 103% | 1% | -9% |
| | SSP5-8.5 | 439 | 4% | 101% | 1% | -6% |
| 12 (5.7 m MS-TS-V-DL) | SSP2-4.5 | 473 | 5% | 95% | 6% | -6% |
| | SSP5-8.5 | 439 | 5% | 98% | 3% | -6% |
| 13 (8.0 m MS) | SSP2-4.5 | 473 | 0% | 99% | 2% | -1% |
| | SSP5-8.5 | 439 | 0% | 99% | 2% | -1% |
| 14 (8.0 m MS-DL) | SSP2-4.5 | 473 | 0% | 95% | 6% | -1% |
| | SSP5-8.5 | 439 | 0% | 94% | 7% | -1% |
| 15 (7.7 m MS-TS) | SSP2-4.5 | 473 | 26% | 72% | 2% | 0% |
| | SSP5-8.5 | 439 | 26% | 71% | 2% | 0% |
| 16 (7.7 m MS-TS-DL) | SSP2-4.5 | 473 | 24% | 69% | 6% | 0% |
| | SSP5-8.5 | 439 | 24% | 69% | 7% | 0% |
| 17 (7.7 m MS-TS-V) | SSP2-4.5 | 473 | 5% | 101% | 1% | -7% |
| | SSP5-8.5 | 439 | 5% | 99% | 1% | -5% |
| | SSP2-4.5 | 473 | 5% | 95% | 6% | -6% |

| Option* | Climate Change Scenario | Rainfall (mm) | Runoff (% Rainfall) | AET (% Rainfall) | Net Percolation / Liner Leakage (% Rainfall) | Change in Storage** (% Rainfall) |
|---|---|---|---|---|---|---|
| 18 (7.7 m MS-TS-V-DL) | SSP5-8.5 | 439 | 4% | 97% | 5% | -7% |
| 19 (0.5 m MS) | SSP2-4.5 | 473 | 0% | 78% | 23% | -1% |
| | SSP5-8.5 | 439 | 0% | 79% | 22% | -1% |
| 20 (0.5 m MS-TS-V) | SSP2-4.5 | 473 | 4% | 95% | 7% | -6% |
| | SSP5-8.5 | 439 | 5% | 96% | 6% | -7% |
| 21 (4.0 m LST-0.5 m MS) | SSP2-4.5 | 473 | 1% | 99% | 1% | -1% |
| | SSP5-8.5 | 439 | 1% | 99% | 1% | -1% |
| 22 (4.0 m LST-0.5 m MS-DL) | SSP2-4.5 | 473 | 0% | 95% | 6% | -1% |
| | SSP5-8.5 | 439 | 0% | 94% | 7% | -1% |
| 23 (4.0 m LST-0.5 m MS-TS) | SSP2-4.5 | 473 | 26% | 72% | 2% | 0% |
| | SSP5-8.5 | 439 | 26% | 72% | 2% | 0% |
| 24 (4.0 m LST-0.5 m MS-TS-DL) | SSP2-4.5 | 473 | 25% | 70% | 6% | -1% |
| | SSP5-8.5 | 439 | 25% | 69% | 7% | -1% |
| 25 (4.0 m LST-0.5 m MS-TS-V) | SSP2-4.5 | 473 | 5% | 102% | 1% | -8% |
| | SSP5-8.5 | 439 | 4% | 102% | 1% | -7% |
| 26 (4.0 m LST-0.5 m MS-TS-V-DL) | SSP2-4.5 | 473 | 5% | 97% | 6% | -8% |
| | SSP5-8.5 | 439 | 4% | 99% | 4% | -7% |
| 27 (6.0 m LST-0.5 m MS) | SSP2-4.5 | 473 | 1% | 99% | 1% | -1% |
| | SSP5-8.5 | 439 | 0% | 99% | 2% | -1% |
| 28 (6.0 m LST-0.5 m MS-DL) | SSP2-4.5 | 473 | 0% | 95% | 6% | -1% |
| | SSP5-8.5 | 439 | 0% | 99% | 2% | -1% |
| 29 (6.0 m LST-0.5 m MS-TS) | SSP2-4.5 | 473 | 26% | 72% | 2% | 0% |
| | SSP5-8.5 | 439 | 26% | 72% | 2% | 0% |
| 30 (6.0 m LST-0.5 m MS-TS-DL) | SSP2-4.5 | 473 | 25% | 70% | 6% | -1% |
| | SSP5-8.5 | 439 | 25% | 69% | 7% | -1% |
| 31 (6.0 m LST-0.5 m MS-TS-V) | SSP2-4.5 | 473 | 5% | 101% | 1% | -7% |
| | SSP5-8.5 | 439 | 5% | 101% | 1% | -7% |
| 32 (6.0 m LST-0.5 m MS-TS-V-DL) | SSP2-4.5 | 473 | 5% | 96% | 6% | -7% |
| | SSP5-8.5 | 439 | 5% | 98% | 5% | -8% |
| 33 (8.0 m LST-0.5 m MS) | SSP2-4.5 | 473 | 1% | 98% | 2% | -1% |
| | SSP5-8.5 | 439 | 0% | 99% | 2% | -1% |
| 34 (8.0 m LST-0.5 m MS-DL) | SSP2-4.5 | 473 | 0% | 95% | 6% | -1% |
| | SSP5-8.5 | 439 | 0% | 94% | 7% | -1% |

| Option* | Climate Change Scenario | Rainfall (mm) | Runoff (% Rainfall) | AET (% Rainfall) | Net Percolation / Liner Leakage (% Rainfall) | Change in Storage** (% Rainfall) |
|---|---|---|---|---|---|---|
| 35 (2.0 m MS-0.5 m S-TS) | SSP2-4.5 | 473 | 28% | 70% | 2% | 0% |
| | SSP5-8.5 | 439 | 27% | 72% | 2% | -1% |
| 36 (2.0 m MS-0.5 m S-TS-DL) | SSP2-4.5 | 473 | 26% | 68% | 6% | 0% |
| | SSP5-8.5 | 439 | 25% | 69% | 7% | -1% |
| 37 (2.0 m LST-0.5 m MS-0.5 m S-TS-V) | SSP2-4.5 | 473 | 24% | 76% | 2% | -2% |
| | SSP5-8.5 | 439 | 4% | 102% | 1% | -7% |
| 38 (2.0 m LST-0.5 m MS-0.5 m S-TS-V-DL) | SSP2-4.5 | 473 | 23% | 73% | 6% | -2% |
| | SSP5-8.5 | 439 | 4% | 99% | 4% | -7% |
| 39 (4.0 m MS) | SSP2-4.5 | 473 | 0% | 100% | 1% | -1% |
| | SSP5-8.5 | 439 | 0% | 100% | 1% | -1% |
| 40 (4.0 m MS-TS-V-DL) | SSP2-4.5 | 473 | 5% | 97% | 5% | -7% |
| | SSP5-8.5 | 439 | 5% | 99% | 2% | -6% |

*MS=Metasediment; LST=Low Sulfur Tailings; S= Sand; TS = 0.3 m Topsoil Layer; V = Vegetation; DL = Degraded Liner
**Change in storage includes storage changes in the simulated tailings layer as well as the cover system.
***

The modelling results for the metasediment sediment high sulfur tailings cover system options (1 to 18) indicate:

- Average liner leakage over the 276 years is simulated by the models to be between 0% and 2% when the liner stays intact and increase up to 7% of rainfall when the liner is simulated to degrade (Table 3.3).

- With the exception of the models run with a topsoil layer but no vegetation, there is a reduction in the amount of water stored within the cover system and tailings layer to make up for water balances losses (i.e., runoff actual evapotranspiration (AET), and liner leakage amounts). Hence, this indicates desiccation of the high sulfur tailings layer from its starting point of 100% degree of saturation.

- As shown in Figure 4.4 to Figure 4.9, all the cover system thicknesses are effective at maintaining the entire high sulphur tailings layer fully saturated when a topsoil layer is added, but with no vegetation included. This is due to the topsoil layer creating a capillary break with the underlying metasediment and stopping water from being drawn up from depth via AE. However, this benefit is lost when vegetation is simulated as the plant roots are able to extract water from depth and create a gradient upward out of the high sulfur tailings.

- Increasing the thickness of the cover system reduces the depth to reach tension saturated conditions. Excluding the results for the options simulated with SSP5-8.5 climate and a vegetated topsoil layer, the depth to tension saturated conditions is maintained within the top 2 m of the high sulfur tailings for an 8 m cover system. In comparison, a 6 m cover system limits the depth of tension saturation to 3.5 m and a 4 m cover system has the depth to tension saturation between 3 m and 7 m for the same simulated conditions.

- Over half of the high sulfur tailings desiccate below 85% degree of saturation for options simulated with a vegetated topsoil layer and SSP5-8.5 climate.

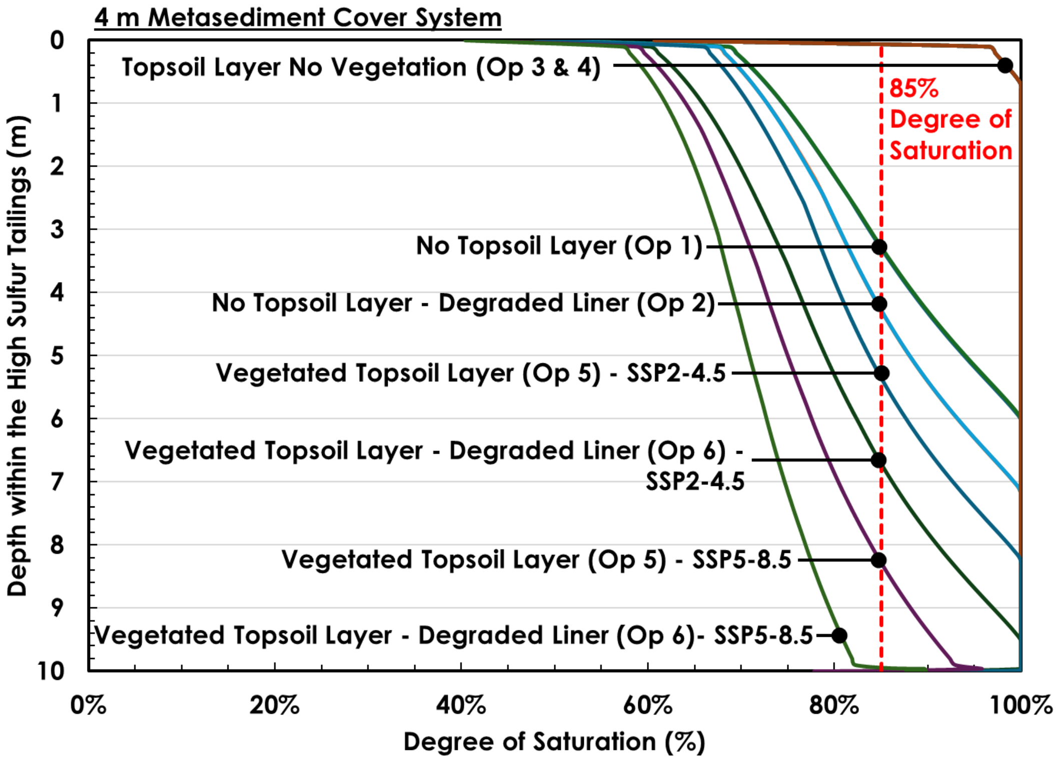



**Figure 4.4: Minimum degree of saturation profile for the 4 m MS cover system options 1 to 6.**

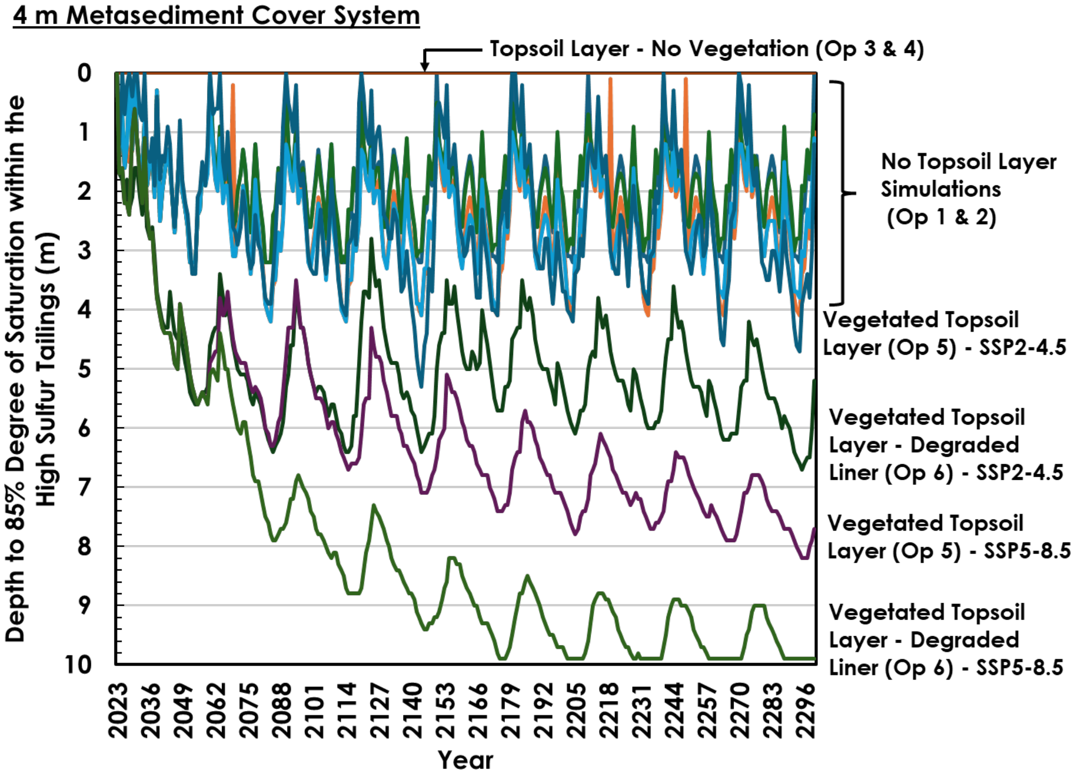



**Figure 4.5: Depth to 85% degree of saturation within the high sulfur tailings with time for the 4 m metasediment cover system options 1 to 6.**

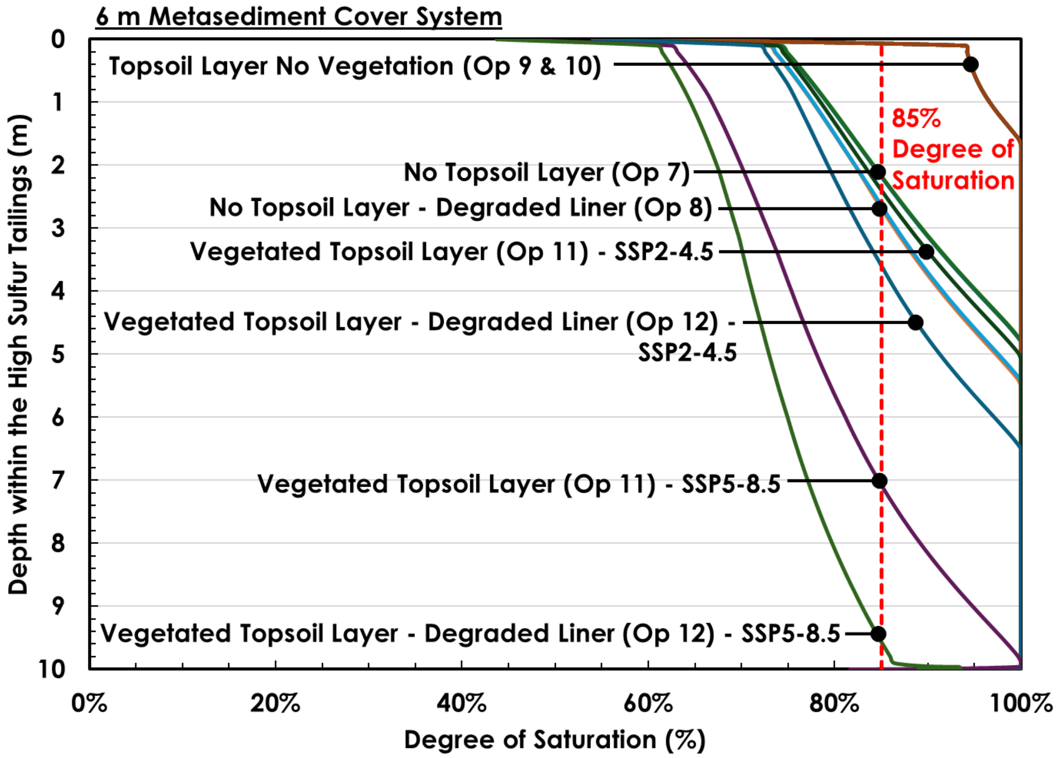



**Figure 4.6: Minimum degree of saturation profile for the 6 m MS cover system options 7 to 12.**

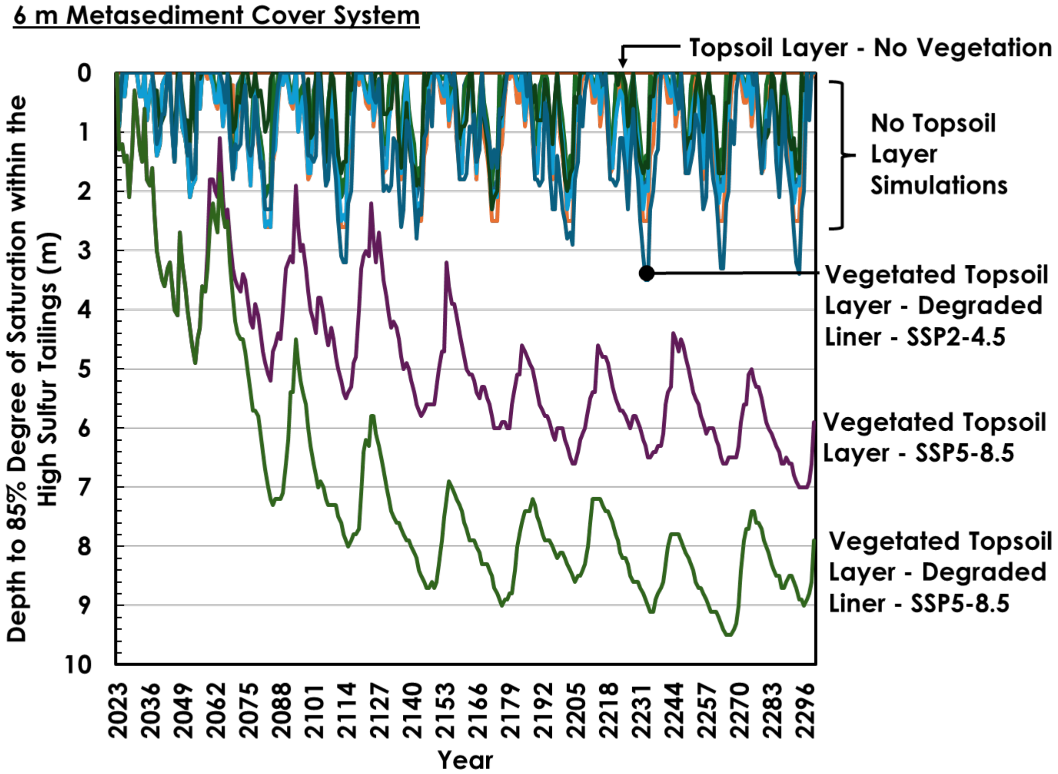



**Figure 4.7: Depth to 85% degree of saturation within the high sulfur tailings with time for the 6 m metasediment cover system options 7 to 12.**

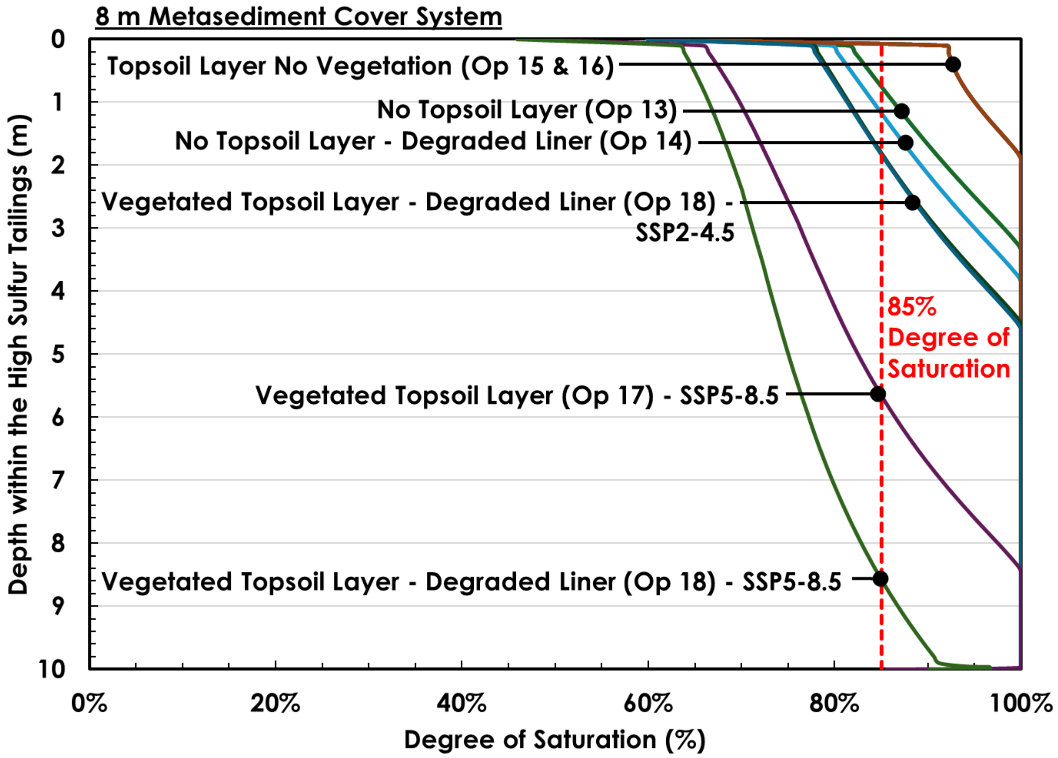



**Figure 4.8: Minimum degree of saturation profile for the 8 m MS cover system options 13 to 18.**

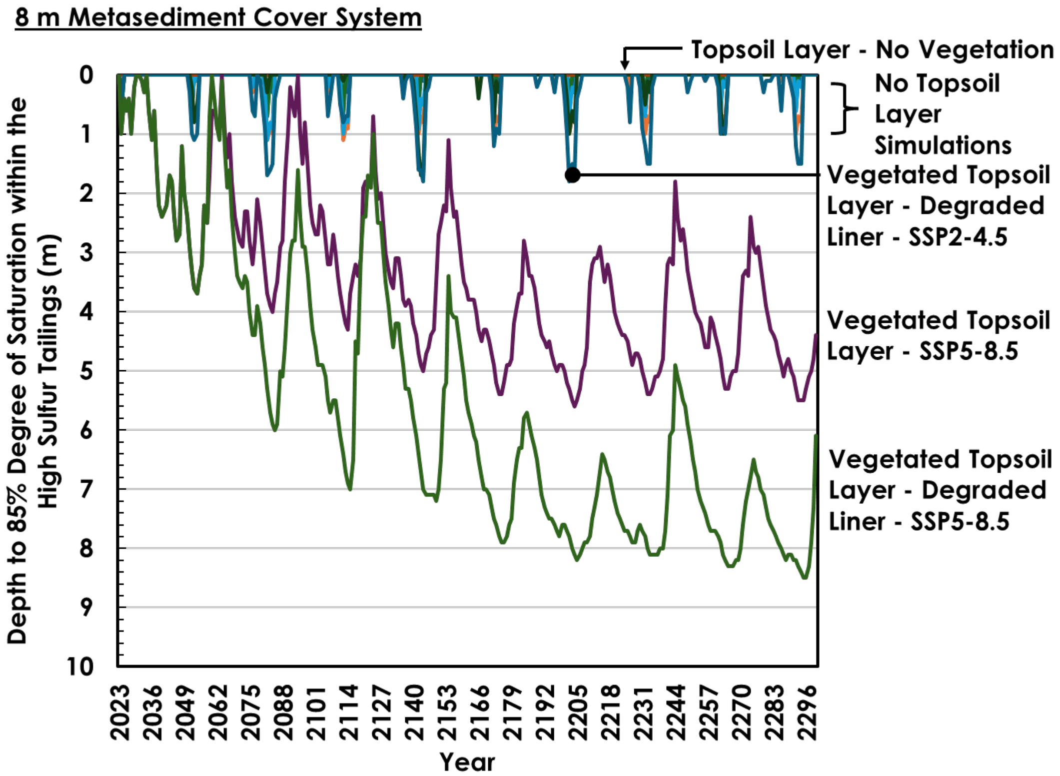



**Figure 4.9: Depth to 85% degree of saturation within the high sulfur tailings with time for the 8 m metasediment cover system options 13 to 18.**

The results for the cover system options for low sulfur tailings (19 and 20) indicate:

- With only a 0.5 m metasediment layer, the cover system has a high (>20% of rainfall) rate of net percolation. Note that the cover system simulations for low sulfur tailings do not include a liner layer at the base of the low sulfur tailings, and the lower boundary condition is simulated as a unit hydraulic gradient. Hence, the material is able to freely drain, but in reality there will be a liner under the low sulfur tailings cell.

- Adding a 0.3 m layer of topsoil on top of the 0.5 m metasediment layer and including vegetation reduces the average annual NP rate to moderate (between 5% and 10% of rainfall).

- As shown in Figure 4.10 Net percolation exceedance probability results for the low sulfur cover system options (19 and 20)., without the vegetated 0.3 m topsoil layer, over 50% of the annual NP amounts are in the "High" range. The amount of "High" NP years drops below 20% when the vegetated 0.3 m topsoil layer is included.

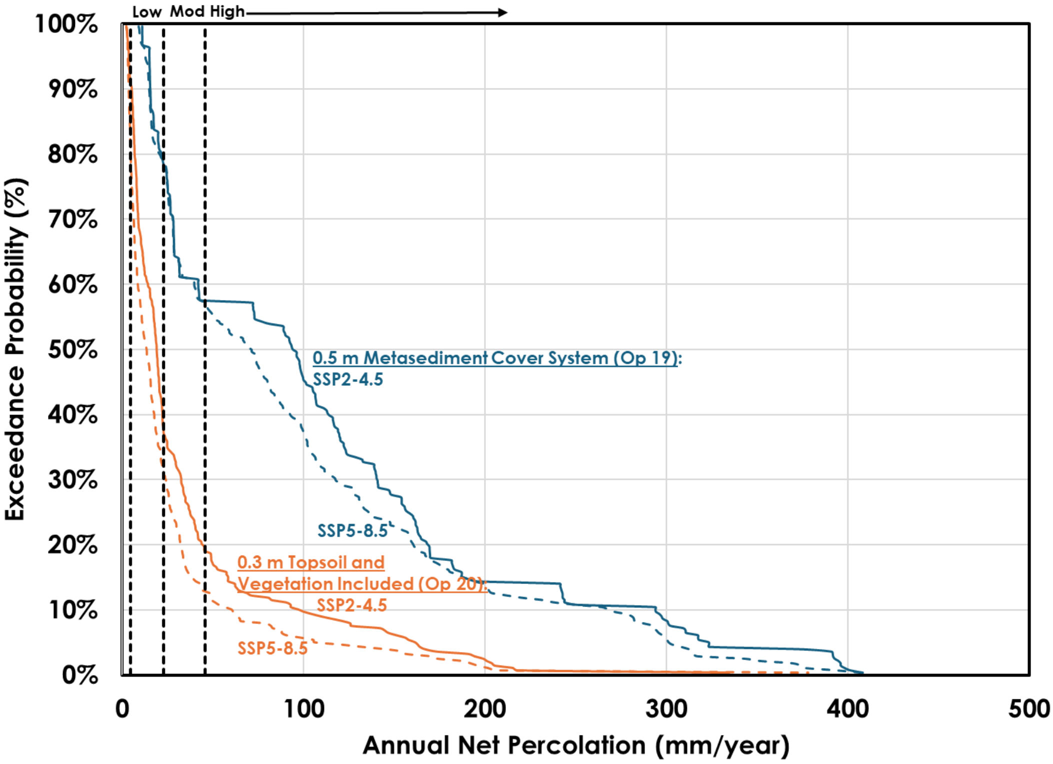
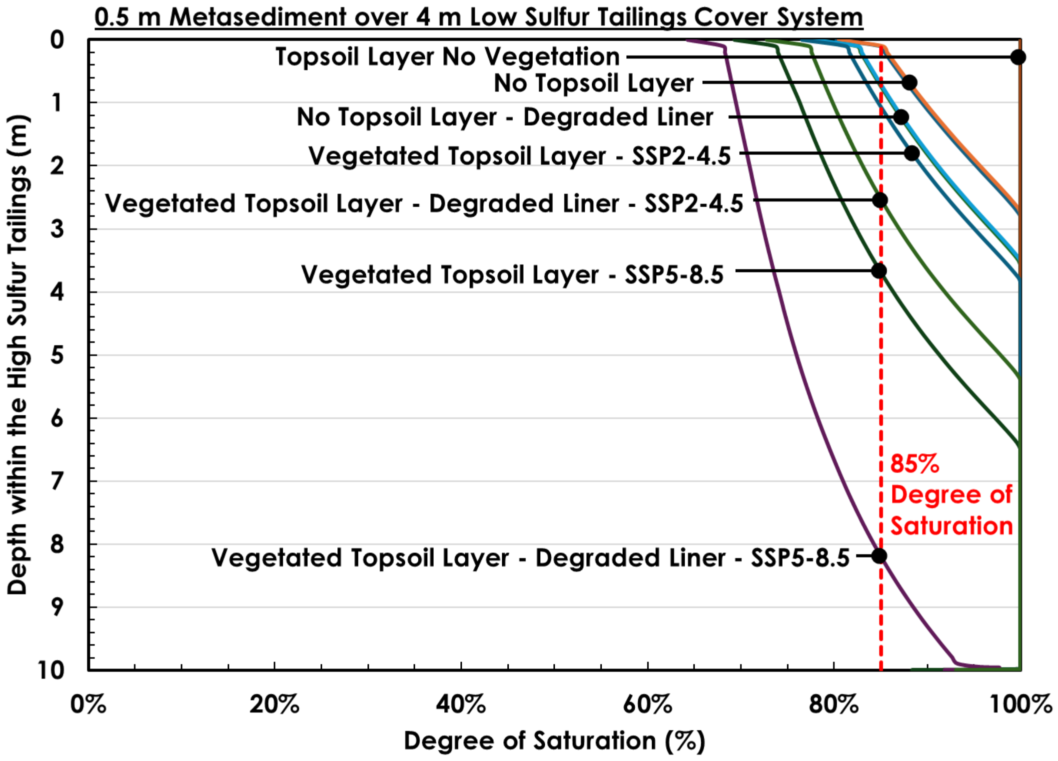



**Figure 4.10: Net percolation exceedance probability results for the low sulfur cover system options (19 and 20).**

The modelling results for the high sulfur tailings cover systems consisting of 0.5 m of metasediment overlying low sulfur tailings (Options 21 to 34) indicate:

- Improved performance with regards to maintaining a high degree of saturation within the high sulfur tailings relative to the metasediment cover system (Figure 4.11 to Figure 4.14).
- With the inclusion of 6 m of low sulfur tailings the model results predict that almost none of the high sulphur tailings profile will desiccate below a degree of saturation of 85% unless climate change follows the SSP5-8.5 path and there is vegetation established on the cover system. Even with both these conditions, the depth to 85% degree of saturation stays within the top 2 m of the high sulfur tailings unless degradation of the base liner is also included in the simulation (Figure 4.14).


0.5 m Metasediment over 4 m Low Sulfur Tailings Cover System
Topsoil Layer No Vegetation
No Topsoil Layer
No Topsoil Layer - Degraded Liner
Vegetated Topsoil Layer - SSP2-4.5
Vegetated Topsoil Layer - Degraded Liner - SSP2-4.5
Vegetated Topsoil Layer - SSP5-8.5
85% Degree of Saturation
Vegetated Topsoil Layer - Degraded Liner - SSP5-8.5
Depth within the High Sulfur Tailings (m)
0
1
2
3
4
5
6
7
8
9
10
0%
20%
40%
60%
80%
100%
Degree of Saturation (%)

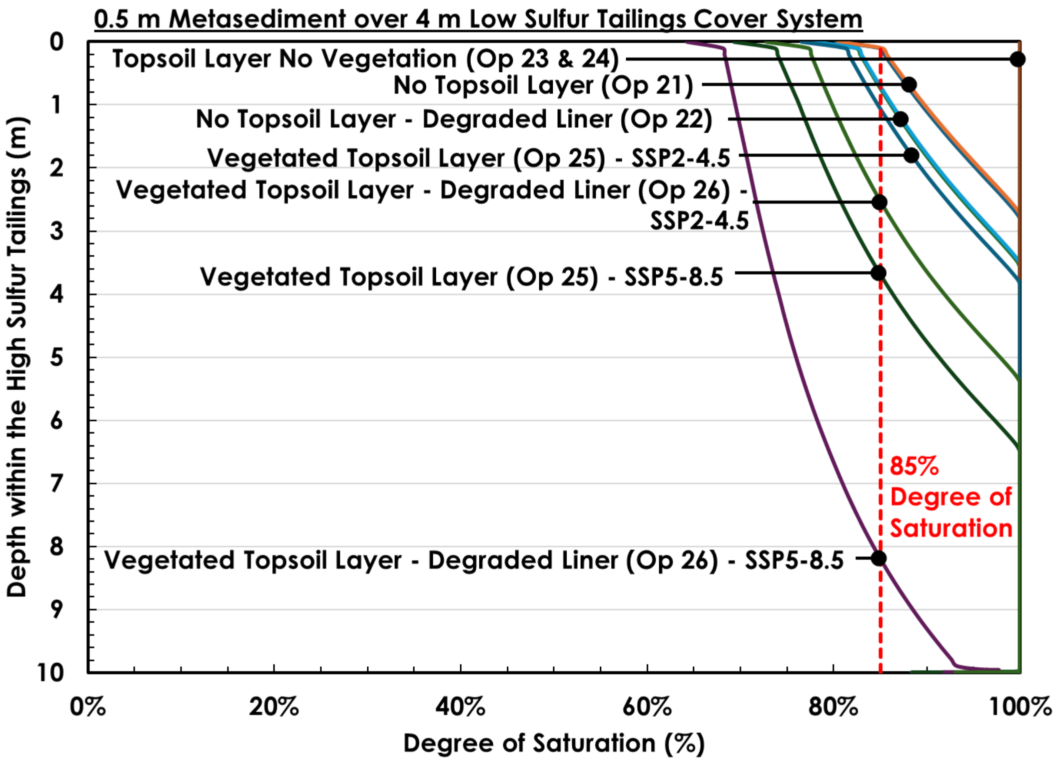

0.5 m Metasediment over 4 m Low Sulfur Tailings Cover System
Topsoil Layer No Vegetation (Op 23 & 24)
No Topsoil Layer (Op 21)
No Topsoil Layer - Degraded Liner (Op 22)
Vegetated Topsoil Layer (Op 25) - SSP2-4.5
Vegetated Topsoil Layer - Degraded Liner (Op 26) - SSP2-4.5
Vegetated Topsoil Layer (Op 25) - SSP5-8.5
85% Degree of Saturation
Vegetated Topsoil Layer - Degraded Liner (Op 26) - SSP5-8.5
Depth within the High Sulfur Tailings (m)
0
1
2
3
4
5
6
7
8
9
10
0%
20%
40%
60%
80%
100%
Degree of Saturation (%)

**Figure 4.11: Minimum degree of saturation profile for the 0.5 m Metasediment over 4 m Low Sulfur Tailings cover system options 21 to 26.**

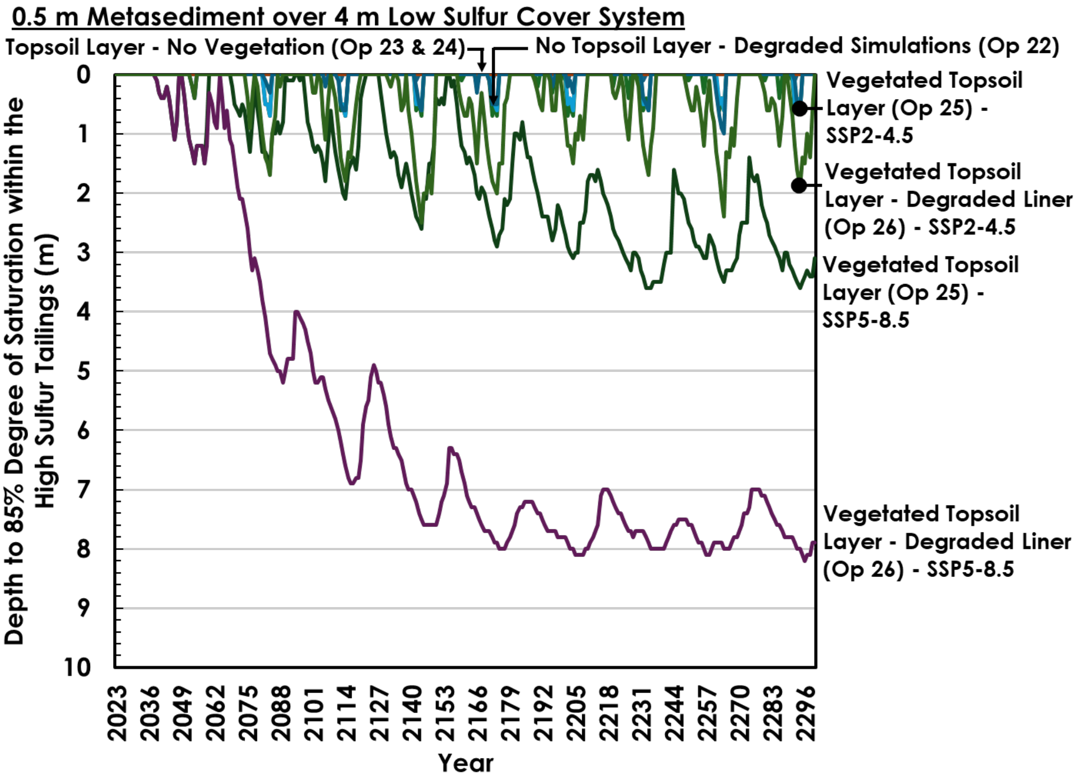



**Figure 4.12: Depth to 85% degree of saturation within the high sulfur tailings with time for the 0.5 m Metasediment over 4 m low sulfur tailings cover system options 21 to 26.**

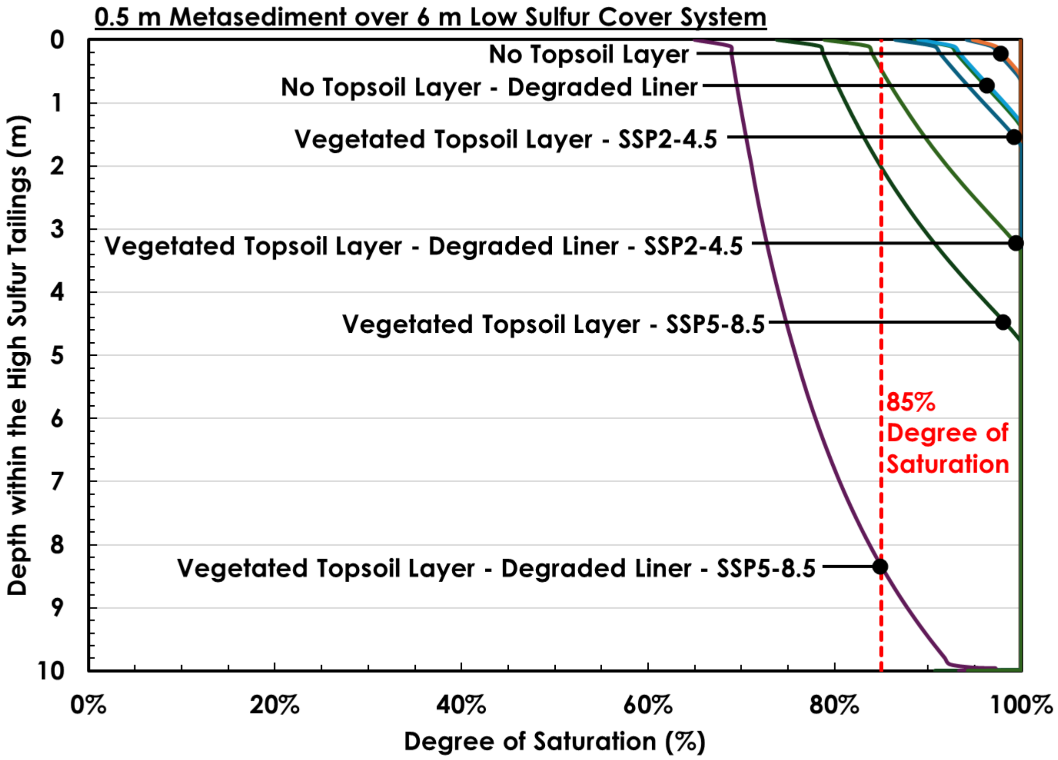



**Figure 4.13: Minimum degree of saturation profile for the 0.5 m Metasediment over 6 m Low Sulfur Tailings cover system options 27 to 32.**

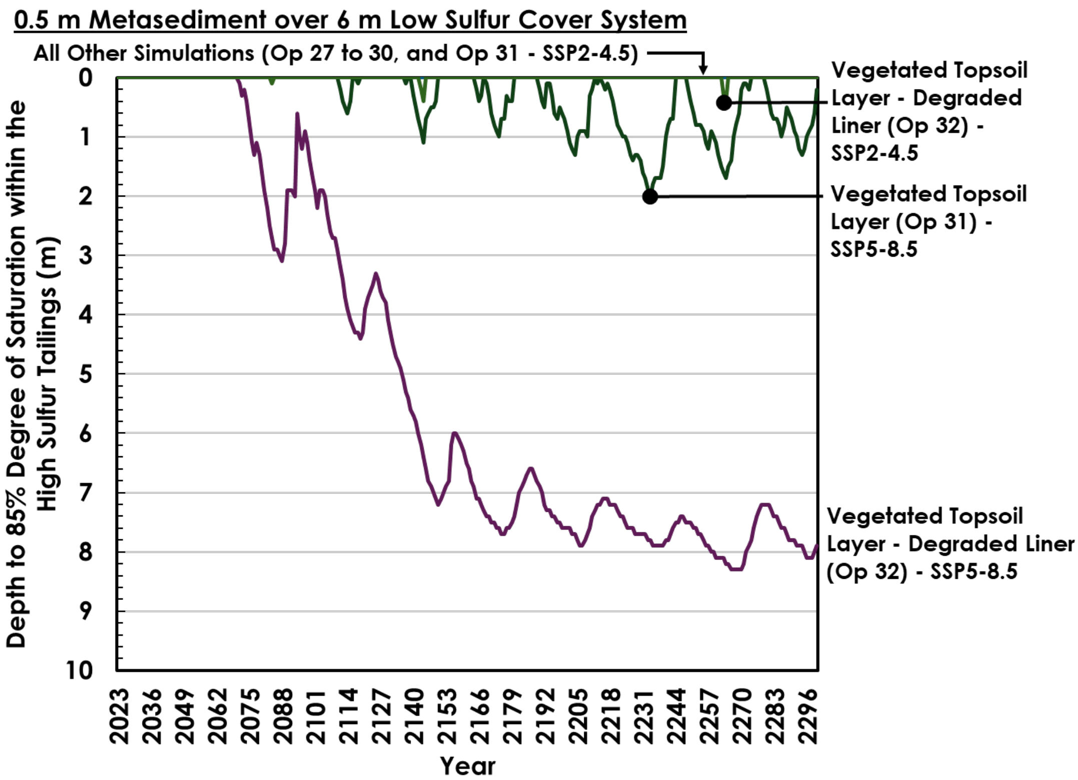



**Figure 4.14: Depth to 85% degree of saturation within the high sulfur tailings with time for the 0.5 m Metasediment over 6 m low sulfur tailings cover system options 27 to 32.**

The remaining options (33 to 40) indicate:

- 0.5 m of metasediment over 8 m of low sulfur tailings performs marginally better than the same cover system with 6 m of low sulfur tailings.
- Inclusion of a sand layer has the potential to improve maintaining a high degree of saturation within the high sulfur tailings due to the addition of an additional capillary break.
- Thin cover systems (i.e. less than 4 m) do not provide sufficient separation between the high sulfur tailings and atmospheric forces to adequately maintain a high degree of saturation within the high sulfur tailings.

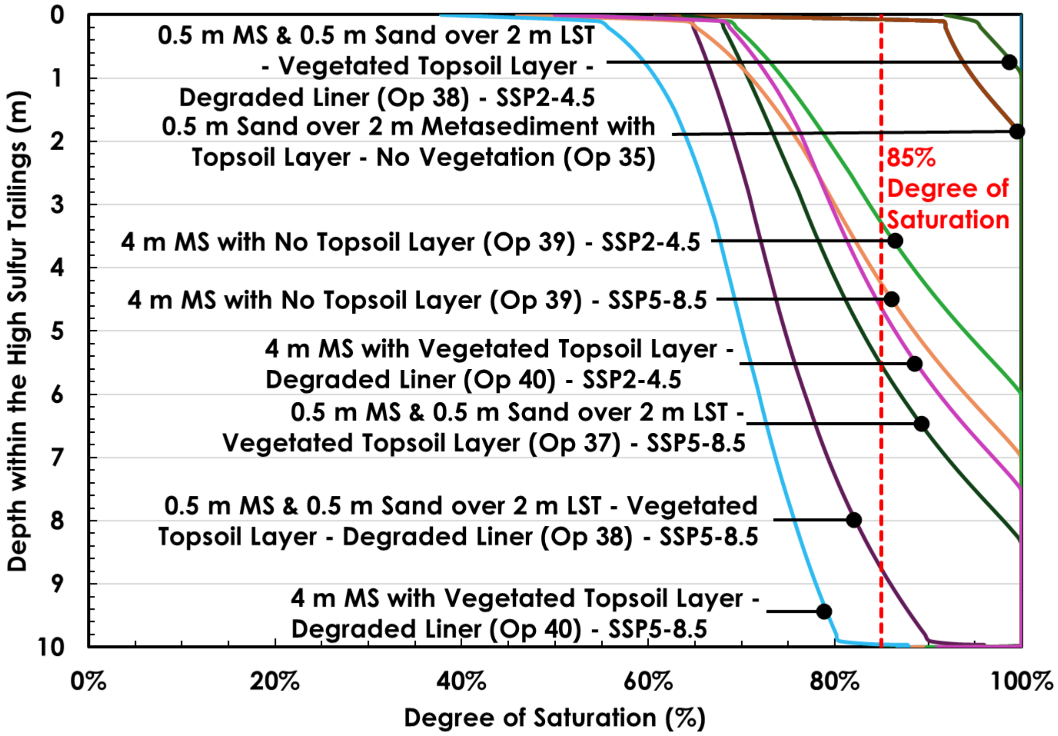



**Figure 4.15: Minimum degree of saturation profile for cover system options 33 to 40.**

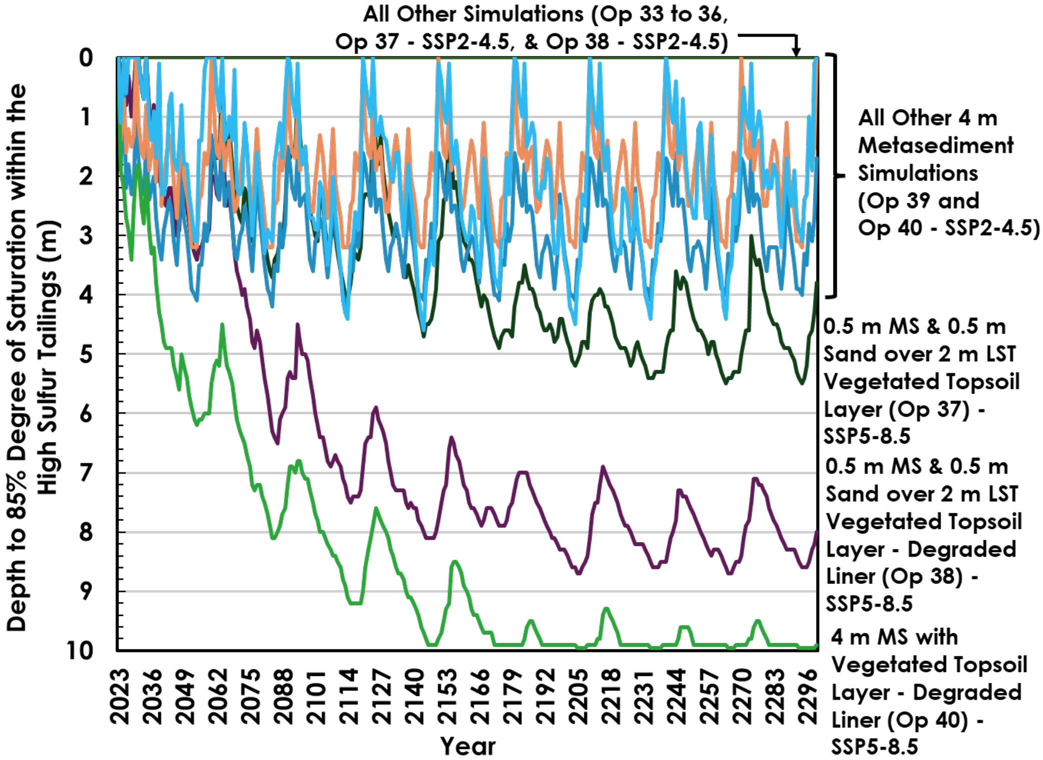



**Figure 4.16: Depth to 85% degree of saturation within the high sulfur tailings with time for cover system options 33 to 40.**

# 5 SUMMARY AND RECOMMENDATIONS

In summary, the model results for the high sulfur tailings indicate that maintaining a high degree of saturation within the high sulfur tailings is achievable with a cover system consisting of:

- 6 m or greater of low sulfur tailings, overlain with;
- 0.5 m of metasediment.

This design met its performance objective of maintaining a high degree of saturation (>85%). Only when a 0.3 m vegetated topsoil layer was included, and extreme climate change conditions (SSP5-8.5) were simulated did substantial desiccation of the high sulfur tailings occur to depth. Even when degradation of the liner at the base of the high sulfur tailings was included (which allowed up to 7% of the total water balance to pass through the liner), the recommended cover system maintained a high degree of saturation as long as the vegetation and extreme climate change (SSP5-8.5) were not also included in the simulation.

The modelling indicates that not encouraging vegetation to establish on a high sulfur tailings cover system is the best way to reduce the risk of the high sulfur tailings dessicating. However, the model may be over-emphasizing this drawback and not correctly accounting for the benefits such as shading and erosion reduction that vegetation can provide. Conversely, the establishment of vegetation on the low sulfur tailings cover system is recommended to reduce net percolation (NP) into the low sulfur tailings.

Additional landform designs could be made to reduce the risk of the high sulfur tailings desiccating below 85% degree of saturation and also lower NP into the low sulfur tailings such as:

- Directing runoff water on and around the high sulfur tailings cells to collect on and infiltrate into the high sulfur tailings to help maintain its degree of saturation.
- Inclusion of a hummocked terrain on the high sulfur tailings cells to increase infiltration.

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