Infiltration & Seepage Modelling

TELLUS

The Assessment of Long-term Recharge to Encapsulated Waste Isolation Cells – Sandy Ridge Project

Tellus Holdings Ltd

The Assessment of Long-term Recharge to Encapsulated Waste Isolation Cells Sandy Ridge Project

Prepared For

Tellus Holdings

August 2016

By

CyMod Systems Pty Ltd
ABN 77 072 954 824
PO Box 917
Armadale WA, 6992

2015008.001

EXECUTIVE SUMMARY

Tellus Holdings Limited (Tellus) is proposing to develop the Sandy Ridge Project (the Proposal) located approximately 75 kilometers (km) north east of Koolyanobbing, in the Shire of Coolgardie, within the Goldfields Region of Western Australia. The Proposal is to develop a kaolin open cut mine and use the mine voids as are repository for the secure storage and isolation of hazardous, intractable and low level radioactive waste in a near surface geological repository using best practice storage and isolation safety case. As part of obtaining regulatory approval for the Proposal, Tellus needs to quantitatively assess what water movement (if any) will occur in the repository over an extended period of time (i.e. greater than 25 years).

Tellus recognised that the proposed repository configuration needed to be assessed using unsaturated flow modelling to confirm the design of the encapsulation, with respect to long term infiltration and seepage. Tellus contracted CyMod Systems to undertake selected unsaturated flow modelling to quantify the likely magnitude of infiltration and seepage of water through the proposed repository. This report describes the models used in the assessment of infiltration and seepage, and makes conclusions and recommendations based on the results of that modelling.

To meet the above objectives, CyMod Systems used the two-dimensional unsaturated flow program Vadose/W, as developed by GeoSlope (GeoSlope, 2012), to construct column models of part of an encapsulated waste storage cell (the 'cell'). Note that these models, with respect to applicable modelling guidelines, are characterised as Class 1, in that they are uncalibrated and are constrained to two-dimensional vertical and horizontal flow (Barnett et al., 2012).

Rockwater Pty Ltd, (Rockwater) drilled seven investigation holes in the development envelope, all of which intersected a granite weathering profile consisting of:

- 2 to 3 metres (m) of surficial aeolian sand;
- overlying up to 8 m of silcreted clay and/or laterite;
- mottled and pallid zone clays/weathered granite; and
- slightly weathered to fresh granite at depth in the deep holes, at a depth of 26 to 31 m.

Rockwater concluded that little or no groundwater has been intersected within the project area, in either the mineral exploration drilling or the 2015 investigation programme, indicating that there is no effective aquifer in the area.

The low rainfall recharge implied by the lack of groundwater in the area is also supported by the prevailing climatic conditions. The area is characterised as semi-arid, with annual average rainfall in the area of less than 300 mm, and evaporation exceeding 2400 mm/annum. Under these conditions, the sporadic rainfall events (which may be intense) result in local runoff, and infiltration of rainfall into the thin aeolian surface sand. However, during subsequent dry periods, evaporation and evapotranspiration act to remove this rainfall infiltration from the top few metres of soil, which results in little if any net recharge.

Based on a chloride mass balance, existing rainfall recharge is estimated to range from 0.0023 mm/annum to 0.07 mm/annum.

A number of flow models were constructed as part of the assessment of infiltration and seepage to the repository. These models included:

- Existing in situ hydrogeological models with historical rainfall;
- Column models of the proposed capping design with different lower boundary conditions; and
- Column models of the proposed capping design with different surface boundary geometry and material properties.

To represent conservative estimates, rainfall input to modelling assessments was based upon repeated cycles of the 10 wettest years since 1890 as worst-case climatic conditions. Seven of the wettest 20 years have occurred since 1990, suggesting conditions may be getting wetter in the future. Consequently, using the wettest 10 years as an analogue for climate change is consistent with recent historical trends.

None of the models presented in this report have been calibrated against measured data, reflecting the absence of time series hydrogeological information in the area. Models were verified by comparing simulated results to similar capping designs in semi-arid climates that have measured data or have been modelled using unsaturated flow and heat transfer. In the case of the simulations of natural ground, the model was compared to prevailing condition, and measured soil moisture profiles in the area, and was found to be consistent with the conceptual hydrogeological model.

In the case for the cells, the results were compared to data in published literature of similar containment cells and the results found to be consistent and reasonable.

Conclusions

The results of the simulations indicate that the infiltration of rainfall into the repository is limited by:

1. A lack of recharge due to runoff from the relatively low hydraulic top soil/subsoil and kaolinised granite, due to the sloping of the cell's clay cap; and
2. evaporation and evapotranspiration of infiltrated water from the top 4 metres of soil that is retained above the cell cap.

The simulations indicate that it is important to retain the water near the surface, allowing it to be evaporated/evapotranspired, which given the semi-arid nature of the prevailing environment, is sufficient to reduce recharge to less than 0.20 mm/year below the clay cap. If the top soil cover is too thick (i.e. greater than 4 metres depending on the grading of the cover material), infiltration may collect on the surface of the clay cap to form a thin saturated layer, which would significantly increase the infiltration reaching the compacted kaolinised granite seal.

Based on the model results, it is likely that less than 0.008 mm/year of infiltration will occur through the Kaolin seal in the waste storage cell. This seepage will enter the in situ kaolinised granite which has an estimated hydraulic conductivity of $4x10^{-6}$ m/sec, which is significantly higher than the capping system. It is anticipated that this seepage will vertically migrate to the water table which in this area is at depth, or be stored in the unsaturated zone, below the repository.

Given the volume of seepage estimated from the simulation, the hydraulic conductivity of the kaolinised granite, the inferred depth to the water table, and the in situ saturation of the unsaturated zone below the repository, it is unlikely that any groundwater mounding or lateral flow of seepage will occur in the vicinity of a cell, as seepage will be stored in the unsaturated zone or enter the water table at depth and flow laterally to the northwest.

Recommendations

Groundwater and climate monitoring should be undertaken to establish base line conditions in the area of the Project. This will allow the impact of mining and waste storage to be quantitatively assessed.

The unsaturated hydraulic properties of the silcrete and backfill material should be determined quantitatively, and used to reduce the uncertainty in future modelling.

Soil moisture probes and other instrumentation should be installed at various depths above the silcrete to establish soil moisture profiles during rainfall events and subsequent dry periods. This data should be used to calibrate any unsaturated flow models that are developed in the future.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

Abbreviation	Definition
cell	encapsulated waste storage cell
Cl_p	Chloride concentration in rainfall
Cl_g	Chloride concentration in groundwater
CMB	Chloride-mass balance
EWSC	encapsulated waste storage cell
EVT	Evapotranspiration
$J/m^3.C$	Specific Heat Capacity
J/s.m.C	Heat transfer coefficient
k	horizontal hydraulic conductivity
kL	kilolitre
m	meters
m^2	Square meters
m^3	Cubic meters
mbgl	metres below ground level
mbtoc	metres below top of casing
mm	millimetres
m/d	meters per day
m/s	meters per second
mg/L	milligrams per litre
P	Annual Precipitation
Q_r	Recharge due to rainfall, mm/annum
R_c	recharge coefficient
Rockwater	Rockwater Pty Ltd
TDS	Total Dissolved Solids
Vadose/W	2-D unsaturated flow model as developed by GeoSlope

1 INTRODUCTION

Tellus Holdings Limited (Tellus) is proposing to develop the Sandy Ridge Project (the Proposal) located approximately 75 kilometers (km) north east of Koolyanobbing, in the Shire of Coolgardie, within the Goldfields Region of Western Australia. The Proposal is to develop a kaolin open cut mine and use the mine voids for the secure storage and isolation of hazardous, intractable and low level radioactive waste in a near surface geological repository using best practice storage and isolation safety case. As part of obtaining regulatory approval, Tellus needs to quantitatively assess what water movement (if any) will occur in the repository over an extended period of time (i.e. greater than 25 years).

Tellus recognized that the proposed cell configuration as shown in Figure 1, needed to be assessed using unsaturated flow modelling to confirm the design of the encapsulation, with respect to long term infiltration and seepage. The objectives of this modelling are:

- To estimate long term seepage and recharge rates for a typical cell using measured and estimated material properties and historical rainfall sequences;
- Undertake a qualitative sensitivity analysis to better quantify the risks and uncertainties in the cell design due to recharge and seepage;
- Optimize the proposed design to minimize or eliminate recharge into the cell, and
- Provide a report presenting the results of the near surface hydrogeology modelling of the repository.

Tellus contracted CyMod Systems to undertake selected unsaturated flow modelling of a typical encapsulated waste storage cell, to quantify the likely magnitude of infiltration and seepage of water through each cell. This report describes the models used in the assessment of seepage, and makes conclusions and recommendations based on the results of that modelling.

2 MODELLING APPROACH

The objective in developing an unsaturated flow model of the shallow (less than 50 m thick) hydrogeological environment in the vicinity of the repository is to provide a quantitative tool that can be used to assess the likely rainfall recharge into the cells over long time frames (i.e. in excess of 25 years). The modelling of unsaturated flow is typically computer resource intensive, which generally precludes undertaking full three-dimensional unsaturated flow modelling. Consequently, simplified two-dimensional cross sectional models are used to assess vertical flow in and around the repository. This simplification is justified given the absence of significant horizontal flow and focus is on vertical unsaturated flow processes.

The models are required to simulate the rainfall recharge processes that affect the volume of recharge that may enter a cell and must account for the:

- thickness and material properties of soils that may be used in constructing the cell;
- semi-arid climate and irregular nature of rainfall in the area;
- potential revegetation of the surface of the cell; and
- climate uncertainty.

2.1.1 Model Confidence Level Classification

To meet the above objectives, CyMod Systems used the two-dimensional unsaturated flow program Vadose/W, as developed by GeoSlope (GeoSlope, 2012), to construct column models of an encapsulated waste storage cell (EWSC, and referred to as a cell). Note that these models, with respect to applicable modelling guidelines are characterised as Class 1, in that they are uncalibrated and are constrained to two-dimensional vertical and horizontal flow (Barnett et al., 2012).

2.1.2 System of Units

The system of units used for modelling in this report is shown in Table 1, by model component.

Model	Length	Time	Mass	Energy	Temperature
Vadose/W 2012	metres (m)	seconds (s)	gram (g)	joules (J)	Celsius (C)

Table 1: Systems of Units

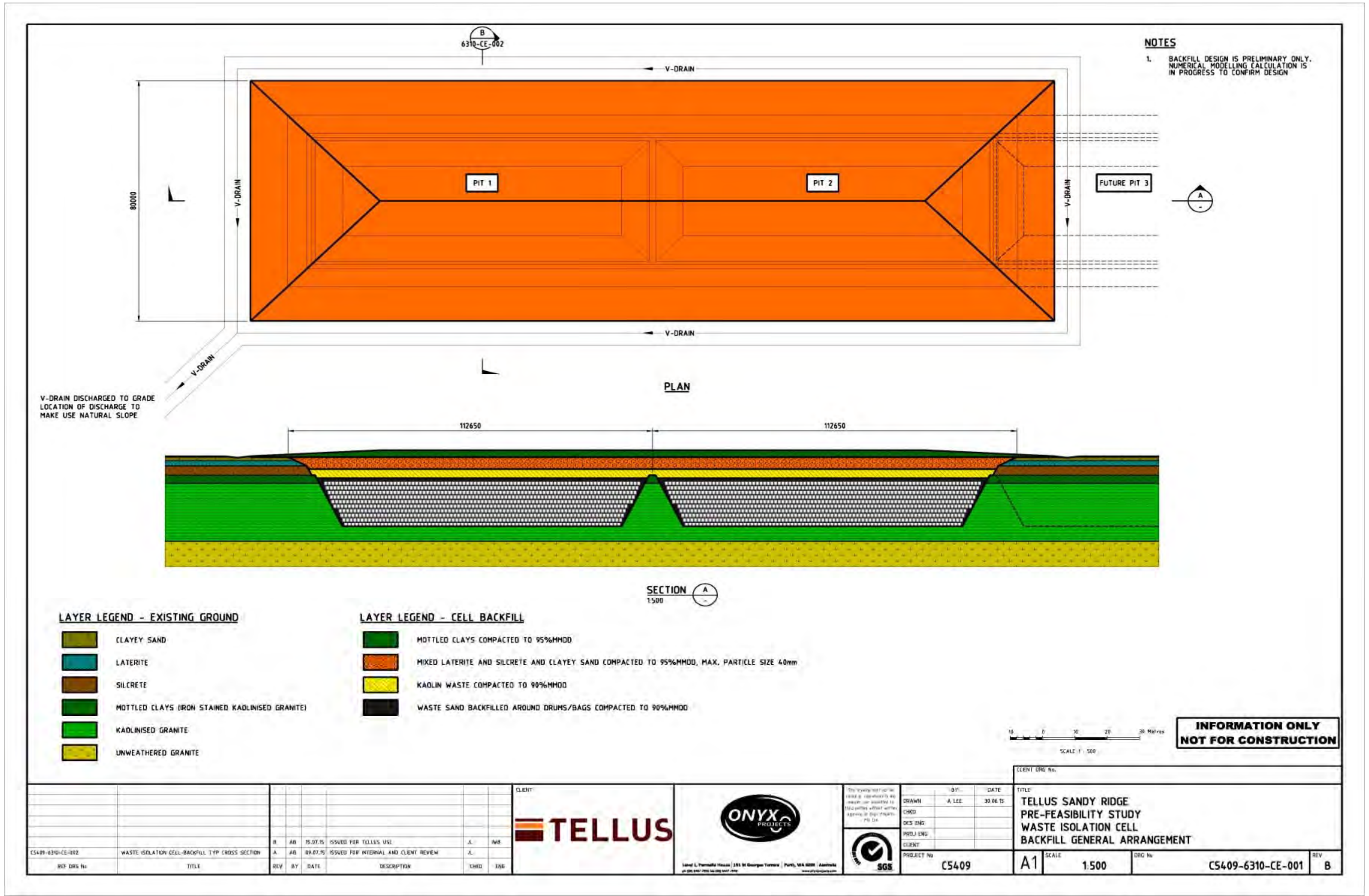


Figure 1: Proposed Cells – Sandy Ridge Project

3 CONCEPTUAL HYDROGEOLOGICAL MODEL

3.1 Geology

Rockwater Pty Ltd, (Rockwater) drilled seven investigation holes in the development envelope, all of which intersected a granite weathering profile consisting of:

- 2 to 3 m of surficial aeolian sand;
- overlying up to 8 m of silcreted clay and/or laterite;
- mottled and pallid zone clays/weathered granite; and
- slightly weathered to fresh granite at depth in the deep holes, from 26 to 31 m in depth.

Minor vugs were noted in the silcrete, clay, kaolinite and weathered granite. A typical geological cross section is shown in Figure 2.

3.2 Hydrogeology

The drilling investigation program undertaken by Rockwater in 2015 showed that of seven groundwater exploration holes drilled in the proposed storage area, four were dry, in that they did not intersect the water table (Rockwater 2015). In addition, all of the kaolinite resource exploration holes drilled by Tellus were dry in the proposed pit/cells area. Of the water exploration holes, five of them intersected some damp kaolinite/weathered granite, but only two were within the proposed pits/cells area.

The water from bores SRMB150 and SRMB152 is saline, with salinities of 6,570 and 6,030 mg/L TDS (total dissolved solids), respectively. All three bores that intersected groundwater had a water level at a depth lower than the planned excavation depth of 30 m. Bore SRMB150 had the shallowest water level (34.23 metres below top of casing, mBTOC) on 6 May 2015, but this bore is located outside of the repository area.

Rockwater concluded that the low airlift yields from investigation bores and low permeability of the weathered profile suggest that the zones containing groundwater do not constitute an aquifer.

3.2.1 Moisture Content

Resource samples were acquired during exploration drilling of the kaolin orebody, that indicate that for weathered granite below 6mbgl (metres below ground level); moisture content is typically between 10-12% by weight.

This suggests:

- the soil is very dry,
- the area has limited recharge,
- the depth to the water table is well below the base of weathered granite, and
- the material is free draining (i.e. water flows vertically under a unit gradient due to gravity).

3.2.2 Material Properties

A program of testing was undertaken on selected bores to estimate the saturated hydraulic conductivity (k) of the weathered granite. Table 2 shows the results of those tests, which characterize the weathered granite as having low hydraulic conductivity.

Bore	Test No.	k	k	Lithology of Screened Interval
		(m/d)	(m/s)	
SRMB146	1	0.14	1.62×10^{-6}	Kaolinite, & deeply weathered granite
SRMB146	2	0.12	1.39×10^{-6}	
SRMB147	1	0.93	1.08×10^{-5}	Kaolinite (saprolite)
SRMB148	1	0.99	1.15×10^{-5}	Kaolinite (weathered granite)
SRMB149	1	0.39	4.51×10^{-6}	Weathered granite
SRMB149	2	0.22	2.55×10^{-6}	
SRMB152	2	0.18	2.08×10^{-6}	

Table 2: In Situ Hydraulic Conductivity Test Results (Rockwater 2015)

Note that most in situ hydraulic conductivity tests are considered to have an accuracy of about one order of magnitude, and hence they should only be used for relative comparison of hydraulic conductivity (Nagy et al, 2013).

In addition to in situ pumping tests, eleven core samples from 4 bores were recovered from the silcrete and unweathered granite for laboratory testing. The selected cores were chosen to provide representative estimates of bulk saturated hydraulic conductivity (k_v) for the silcrete and unweathered granite. The results of the testing showed that:

- Silcrete k_v was 5×10^{-8} m/s;
- Unweathered granite k_v ranged from 4×10^{-8} to 31×10^{-8} m/s,

The saturated hydraulic conductivity represents the maximum hydraulic conductivity of the material. Consequently, the saturated hydraulic conductivity is greater than the unsaturated hydraulic conductivity, as shown for each soil type in Appendix A, as defined by a conductivity and matric suction relationship, with matric suction dependent on water content.

3.2.3 Recharge

The lack of a saturated aquifer in the Project area suggests that the low rainfall, high evaporation rate and lithology of the site mitigates against the formation of an aquifer. Consequently, rainfall recharge may be insufficient to cause groundwater to accumulate and saturate the weathered granite to form an aquifer. This conclusion is consistent with the prevailing hydraulic conductivity of the geological formations making up the stratigraphic sequence in the area, which limits the rate of deep infiltration, while increasing the exposure of soil moisture to high evapotranspiration rates in shallow soils.

The low rainfall recharge implied by the lack of groundwater aquifers in the area is also supported by the prevailing climatic conditions. The area is characterized as semi-arid, with annual average rainfall in the area of less than 300 mm, and evaporation exceeding 2400 mm/annum. Under these conditions, sporadic rainfall events (which may be intense) result in local runoff, and infiltration of rainfall into the thin aeolian surface sand. However, during subsequent dry periods, evaporation and evapotranspiration act to remove this rainfall infiltration from the top few metres of soil, which results in little if any net recharge.

The geology of the area enhances the store and release nature of the natural recharge processes. Figure 2 shows there are 2-4 metres of top soil and laterite, underlain by 3-8 metres of hard, dense silcrete which is inferred to have a hydraulic conductivity of $5x10^{-8}$ m/s. Therefore, in the instance of a large, intense storm event, any significant surface infiltration will be temporally stored in the unsaturated top soil and laterite, within 4 metres of the surface. In this instance, when infiltration is sufficient, an increase in water storage in the unsaturated layer will develop in the top soil/laterite on top of the less permeable silcrete.

Given the thickness of the top soil and laterite, and the shallow depth of the silcrete, it is likely that any rainfall recharge that infiltrates below the shallow topsoil would be subsequently evaporated, or evapotranspired by deep-rooting vegetation, resulting in the drying of the material lying above the silcrete, between rainfall events. This process results in limited infiltration of rainfall recharge to depth, and is consistent with the lack of either perched water or a saturated zone at depth in the weathered granite profile.

Below the silcrete is weathered kaolinised granite, grading to fresh granite. If the silcrete is absent or more permeable (i.e. vuggy - containing macropores for preferential flow), in the above instance of an extreme rainfall event, infiltration may extend through the weathered granite profile to form a damp to saturated zone lying on top of the fresh granite. The absence of a water table in the weathered kaolinised granite on top of the fresh granite, suggests any such deep infiltration would subsequently migrate into low permeability fresh granite (hydraulic conductivity of $4.5x10^{-8}$, and porosity 0.1 – 1%, Cook, 2003), with storage of water in fresh granite forming localised fractured rock aquifers.

3.3 Recharge Estimated using a Chloride Mass Balance

A chloride-mass balance (CMB) is a widely used technique that provides a direct estimate of rainfall recharge based on readily attainable data. However, the following assumptions must be satisfied to accurately apply the CMB method as an estimate of long term, average groundwater recharge:

- All chloride in the groundwater originates only from direct rainfall recharge to the aquifer;
- The chloride-mass flux is in steady state (i.e. invariant with time); and
- There are no processes that result in the loss or concentration of chloride in the aquifer (i.e. no mineral dissolution, adsorption or precipitation).

Based on the conceptual hydrogeology of the area the following observations can be made:

- the limited groundwater is at depth, and has minimal interaction with other groundwater processes:
- There are no other sources of groundwater in the area, suggesting rainfall is the primary source of this water;
- Given the geological stability of the lithology in the area, there are no geochemical processes in the area that would react with chloride, thus it can be considered conservative; and
- Given the prevalence of a semi-arid climate for a long period, it is likely that the chloride mass flux is in steady state.

Therefore, based on the conceptual hydrogeological model, it is likely that the stated assumptions above are applicable to the project area and justify use of a CMB.

Under the above conditions, the spatially averaged recharge flux to the aquifer under natural rainfall recharge can be expressed as:

$Q_r = (P)(Cl_p)/Cl_g$ (Wood, 1999).

Where:

Q_r is the average ground water recharge flux (mm/annum);
P is the average annual precipitation (mm/annum);
Cl_p is the average precipitation-weighted chloride concentration (mg/L); and
Cl_g is the average chloride concentration in the groundwater (mg/L).

For the project area the variables defined above are as indicated below:

1. P is 287 mm/annum;
2. Cl_p is 0.05 to 1.5 mg/L (Turner et al, 1995); and
3. CL_g is estimated as 4050 mg/l (Rockwater 2015, assuming same composition as seawater and a TDS of 6300 mg/L).

Based on these parameter estimates, rainfall recharge to the project area may range from 0.0035 to 0.106 mm/annum, with the lower estimate more applicable to the project area.

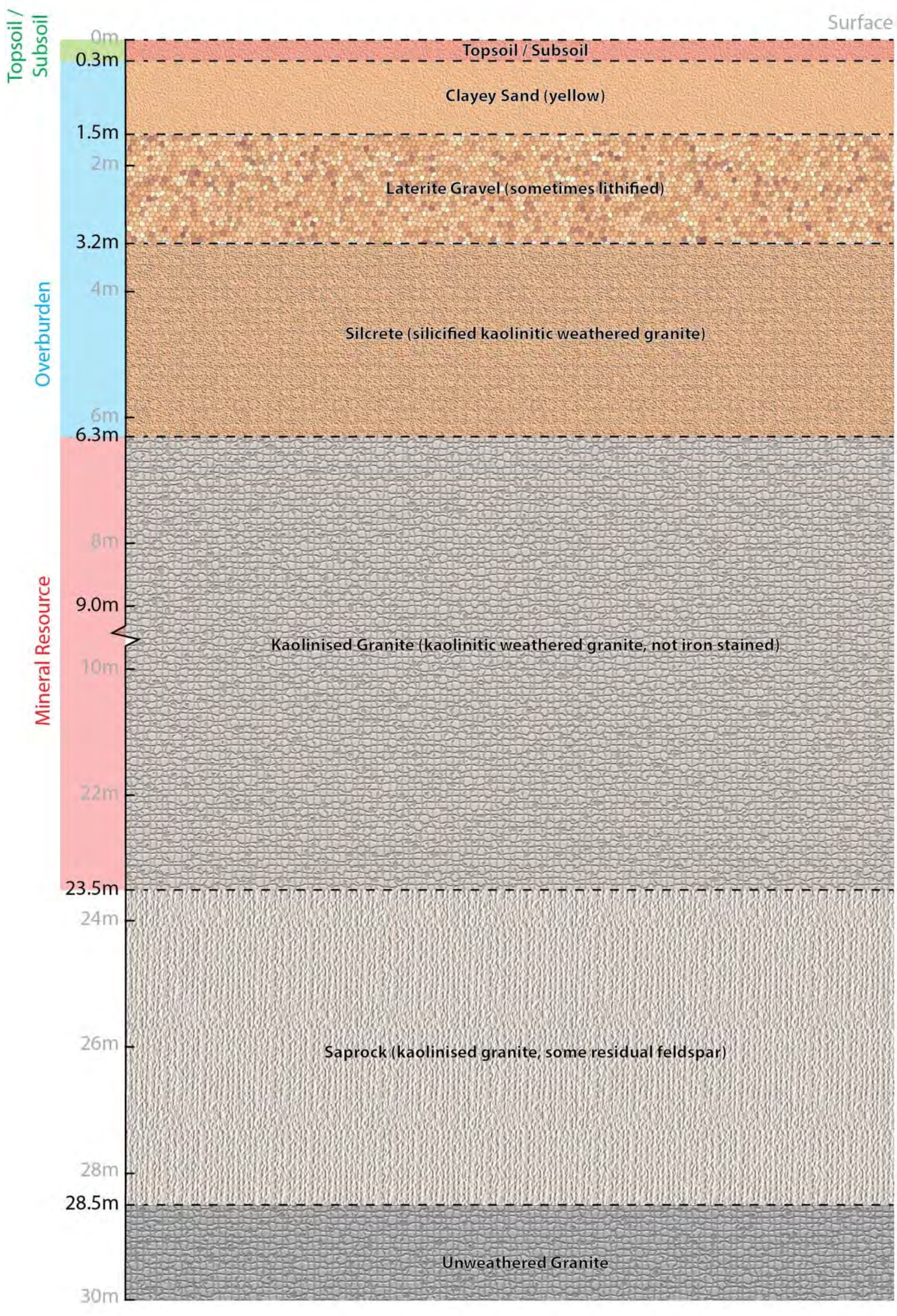


Figure 2: Geological Cross-section

4 MODEL CONSTRUCTION

A number of flow models have been constructed as part of the assessment of infiltration and seepage into/out of a cell. These models include:

- Existing in situ hydrogeological models with historical rainfall;
- Column models of the proposed capping design with different lower boundary conditions; and
- Column models of the proposed capping design with different surface boundary geometry and material properties.

The column models are all based on information provided by Tellus with respect to the proposed cell configuration. Figure 3 shows a cross-section through a single cell that was used to construct the unsaturated column models. Consequently, all the models use the same environmental inputs and are based on the same conceptual hydrogeological model, as described in Section 3. These common components of the unsaturated flow models are described below.

4.1 Material Properties

The material properties, as used in the models, describe the unsaturated flow properties that determine how water flows through both natural and engineered ground. Tables 3 and 4 list the hydraulic properties of the materials used in the models, and their corresponding saturated properties. The saturated hydraulic conductivity of the materials is as provided by Tellus (Ingram, 2015). The hydraulic conductivity of in-situ materials were estimated from:

- in situ testing (i.e. slug test); or
- based on Hazen's formula, and
- assumed in the case of silcrete.

For made ground (i.e. capping and kaolinised granite seals) saturated hydraulic conductivity was based on laboratory measurements of remoulded samples (Douglas Partners, 2015). Appendix A shows the relationships used to model hydraulic conductivity and saturation as a function of matric suction pressure.

In the absence of measured data (i.e. measured saturation at different pore pressures, and measured hydraulic conductivity at different pore pressures or saturation) generic curves, as provided by GeoSlope based on a material's grain size classification, were used to approximate the unsaturated flow material properties.

The Vadose/W models presented here use the full thermal model (required for climate boundary conditions). The thermal properties were modelled using material types as shown in Table 5. The estimates of thermal conductance and thermal storage for the in-situ materials and cap were taken from the literature (Abu-Hamdeh et al., 2000; Farouki, 1981).

Material	Generic Material	Saturated Hydraulic Conductivity (m/s)	Water Content at Saturation (fraction)	Comments
Clayey Sand	Silty Sand	$1x10^{-6}$	0.35	
Laterite	Silty Sand	$2.5x10^{-5}$	0.35	
Silcrete	Sand/gravel	$5x10^{-8}$	0.10	Silicified with poorly connected vugs, as measured from selected cores
Mottled Clays	Clay	4.62×10^{-6}	0.45	
Kaolinised Granite	Clay	4.62×10^{-6}	0.45	
Fresh Granite	Sand/gravel	$4.5x10^{-8}$	0.02	Base of model, assumed to be fractured

Table 3: Hydraulic Properties of Natural Materials

Material	Generic Material	Saturated Hydraulic Conductivity (m/s)	Water Content at Saturation (fraction)	Comments
Kaolinised Granite – uncompacted	Silty Sand	$1x10^{-6}$	0.35	Used as cover over compacted mottled clay
Mottled Clays - compacted	Clay	$6.13 x10^{-8}$	0.40	
Kaolinised Granite - compacted	Clay	$6.13 x10^{-8}$	0.40	
Mixed Laterite, silcrete and clayey sand compacted	Silty Sand	$1x10^{-7}$	0.35	
Kaolin Waste Compacted	Silty Sand	$2.2x10^{-8}$	0.45	May not be available, replaced with compacted Kaolinised granite
Granular material backfilled around waste packages	Sand	5×10^{-5}	0.35	

Table 4: Unsaturated Flow Material Properties - Cell Construction

Material	Generic Material	Thermal Conductivity Dry (J/sec• m•C)	Volumetric Specific Heat Capacity Dry (J/m^3•C)
Clayey Sand/Top Soil/ Granular material backfilled around waste packages	Silty Sand	0.5	2.3 x10^6
Laterite	Silty Sand	0.3	2.5x10^6
Silcrete	Sand	0.3	2x10^6
Mottled Clays natural and compacted Kaolinised Granite	Clay	0.3	2.5x10^6
Kaolinised Granite Kaolin Waste	Clay	0.3	2.5x10^6
Unweathered Granite	Sand	0.3	2x10^6

Table 5: Thermal Model Material Properties

4.2 Vertical Discretisation

The model layers are defined by digital cross-sections of the inferred geology that is likely to be encountered in the area. The cross-sections have all been constructed from data as shown in Figure 3. Each geological layer is defined as polygonal region, in which material properties are uniform. These regions are subdivided (i.e. discretised) into quadrilateral cells, that are used to solve the state equations describing unsaturated water and energy flow in the region using a finite element approach.

Vadose/W uses two types of finite elements, standard and surface elements as defined by a surface region. For standard finite element regions, the actual gridding of cells is automatically done by Vadose/W, using a specified characteristic length (i.e. 1 m), that determines the scale of the finite elements. In the case of the surface elements, the region is automatically applied to the top surface of the model when a transient climatic boundary condition is used. Due to the steep temperature and pressure gradients near the soil surface, the surface region has enhanced vertical discretisation, through the use of automatically generated thin cells. The thickness of the surface layer is manually specified by defining the number of layers; dependent on the nature of the problem, and the thickness of the surface layer. The surface region is then solved for the flow and thermal equations using enhanced numerical and spatial resolution.

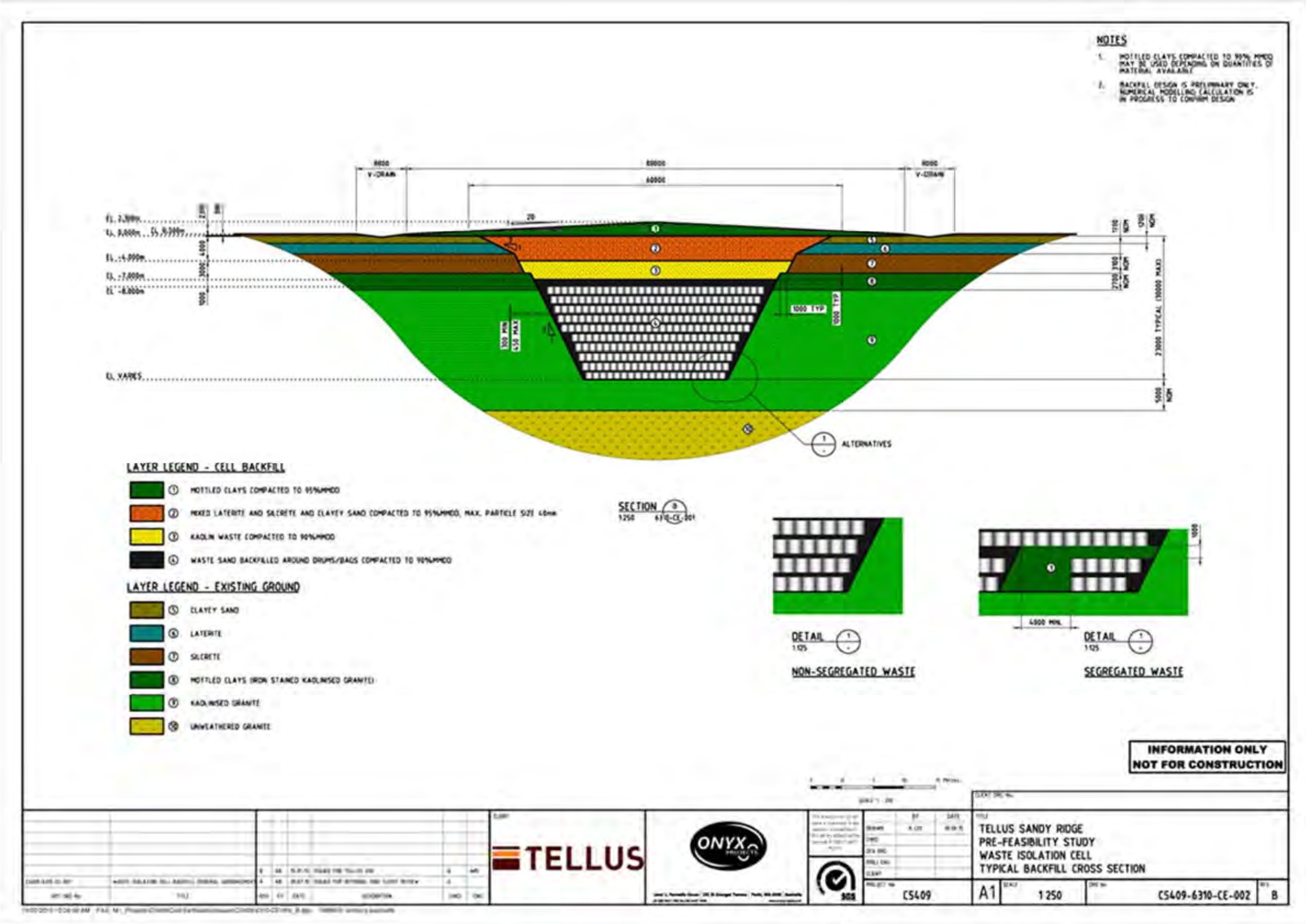


Figure 3: Cross-section of Cell

4.3 Initial Conditions

The initial conditions for the model simulations are generated by assuming average climate conditions and running a steady state model. The steady state model calculates the saturation and pressure distribution assuming no change in water storage, which is consistent with time invariant recharge conditions. However, average climate conditions may not be representative of typical conditions in the area, as these will depend on preceding rainfall conditions.

To limit the impact of the initial conditions on model results, the models were also run for an initial 80 years using time-varying climate inputs so as to minimize model artefacts due to the use of average conditions in a semi-arid climate, in the steady state model. The 80-year conditioning time is limited by the computational resources required for long transient simulations, and may result in estimates of vertical fluxes still being influenced by the initial conditions.

4.4 Boundary Conditions

All of the models employ boundary conditions on the top and bottom horizontal extents of the model domain. The vertical boundaries of the models are considered stream lines, which by definition do not allow flow across them: these boundaries are defined as no flow both for water and energy.

4.4.1 Bottom of the Model

The hydrogeological conditions at the bottom of the model are ambiguous in the area of the proposed pits/cells, as no saturated aquifer exists, and the extent of saturation is spatially variable. Consequently, for the purposes of this study, the nature of the boundary on the bottom of the models is addressed using a sensitivity analysis.

There are three viable boundary conditions that are used for the bottom of the model:

- Unit gradient boundary condition;
- A specified pore pressure boundary condition; and
- No flow boundary condition.

The effects of these boundary conditions have been assessed as part of a sensitivity analysis of the results, and reflect the ambiguous conditions associated with the fresh/weathered granite basement. Rockwater found in some areas that the fresh granite was saturated, indicating likely localised fractured rock aquifers, while in the vicinity of the proposed cells the fresh/weathered granite was dry, with only 3 areas indicated as damp.

Consequently, the three boundary conditions are used to model:

- Gravity drainage through the fresh bedrock from the weathered granite, where the flow is controlled by the unweathered granite;
- Potential for elevated soil moisture, causing dampness; and
- Impermeable bedrock resulting in a saturated zone and horizontal flow in the weathered bedrock.

Subsequently, the unit gradient flow boundary condition was used to report results as this was considered most representative of the prevailing conditions in the proposed pit/cells area.

4.4.2 Ground Surface – Top of Model

The top surface of the model has three important boundary processes that directly affect the amount of recharge that can occur:

- Rainfall;
- Runoff; and
- Evapotranspiration (EVT).

All of the models used a transient climate model to simulate these conditions at ground surface, which may include a thermal model, a runoff model, and an evapotranspiration model. In order to simulate these environment components, the models use daily climate data, applied to Vadose/W surface elements with a full thermal model.

4.5 Recharge and Evapotranspiration

The surface zone in Vadose/W calculates net flux (recharge) to the unsaturated zone, accounting for water and vapour movement, utilizing a full thermal model. This results in a computational intensive simulation, which can effectively simulate evapotranspiration and the heating of the soil due to insolation and high ambient temperatures. Numerically, the surface zone can experience very high negative pore pressures due to high surface temperatures which rapidly decrease with depth, resulting in steep hydraulic and thermal gradient in this region.

The application of a climate-based boundary condition for recharge, runoff and evaporation and evapotranspiration allows the model to more accurately simulate the processes that are relevant to estimating recharge at the site by constraining the solution to respect the physical limits of pore pressure (which drives water flow) and available energy which limits evaporation and hence pore saturation. Note that evapotranspiration was not included in some of the models as excluding EVT is a conservative assumption with respect to estimating the risk of infiltration/recharge.

4.5.1 Rainfall and Evaporation

The drilling results (Section 3) showed that the proposed cells area does not have a saturated aquifer, and dampness was only found in three bores at depth. This indicates rainfall recharge in the area is small, and insufficient to cause the accumulation of groundwater to form a saturated layer. The lack of recharge is due to:

- Low average rainfall;
- Large intermittent rainfall events that are typically followed by long periods of no rainfall;
- High ambient temperature and high potential evaporation; and
- Runoff from relatively low hydraulic conductivity top soil.

These conditions are also consistent with the assessment of the area against the Thornthwaite Moisture Index (TMI). The use of this climatic parameter is a predictor of the depth of seasonal moisture change and is widely accepted as a method to categorise aridity in Australia and the depth of the drying on soils. The estimated TMI for the site is -45, suggesting that seasonal moisture changes can occur to a depth of 4 m below ground level. This depth extends to below the top of silcrete in natural ground, which effectively acts as an aquitard.

In the case of the proposed cell, the compacted mottled clay cap will be about 2 metres below the surface, given the thickness of the top soil and subsoil. Consequently, the compacted mottled clay cap, which has a hydraulic conductivity similar to the silcrete (6.13×10^{-8} m/s versus 5×10^{-8} m/s), will act in the same manner by delaying vertical flow, and increasing soil saturation in and above the cap, thereby providing more time for evaporation to occur.

The average climate parameters as estimated for the project location are given in Table 6.

Max Temp (C)	Min temp (C)	Max Relative Humidity (%)	Min relative Humidity (%)	Wind Velocity (m/s)	Rainfall (mm/annum)	Evaporation (mm/annum)
25.5	11.4	80	35	3	252	2467

Table 6: Interpolate Average Annual Climate Parameters 1890-2015

For the purposes of this study an interpolated dataset of daily climate time series data was generated for the location using SILO data (Jefferies et al, 2001). This data was then used as input into the models, using the climate boundary condition in Vadose/W. Figure 4 shows the interpolated monthly rainfall in the area from 1990 to 2015.

To account for some of the uncertainty in the model and rainfall dataset, daily rainfall input for the forward modelling assessments were constructed using repeated cycles of the 10 wettest years since 1890. This climate sequence was used as it may result in a conservative (i.e. larger than will actually occur) estimate of infiltration and seepage under high rainfall conditions for the predictive scenario assessments (Scenarios 2 through 4) of the proposed cell design. The initial scenario assessment (Scenario 1) to establish existing conditions used 20 years of historic climate data starting in 1995 as shown in Figure 4.

Table 7 summarizes the wettest 20 years since 1890, with the wettest 10 years of these used for the rainfall data set in forward scenarios (Scenarios 2 through 4). The wettest 20 years listed in Table 7 is also shown in Figure 5 as monthly rainfall. It is interesting to note that seven out of the wettest 20 years have occurred since 1990, suggesting conditions may get wetter in the future.

Year	Max Temp (C)	Min temp (C)	Max Relative Humidity (%)	Min relative Humidity (%)	Wind Velocity (m/s)	Rainfall (mm/annum)
1992	23.72	11.19	41.87	82.37	3	553.8
1999	25.16	11.82	36.97	78.55	3	521.2
1995	24.41	11.29	42.22	86.82	3	499.6
1963	24.83	11.86	40.68	81.81	3	476.6
1974	24.34	11.17	40.58	82.76	3	443.2
1975	24.23	10.47	39.31	83.28	3	412.9
2011	25.26	12.23	38.34	80.42	3	411.6
1915	25.37	11.92	39.02	83.64	3	405.6
2000	24.82	10.39	38.31	84.43	3	399.8
2006	26.02	11.42	34.63	80.78	3	386.9
1942	24.46	10.88	36.67	79.60	3	385.8
1917	24.01	10.39	39.15	84.85	3	382.7
1930	26.22	11.76	36.48	82.29	3	366.6
1980	25.78	11.96	35.08	74.81	3	348.9
1955	24.03	10.89	40.20	83.94	3	347.7
1918	25.73	11.65	38.31	84.71	3	347.2
1943	24.60	10.81	37.01	80.75	3	343
2014	26.57	12.28	33.16	74.54	3	341.5
1892	25.42	11.47	35.03	80.76	3	337
2004	26	11	36	81	3	333.8

Table 7: 20 Highest Rainfall Years Since 1890

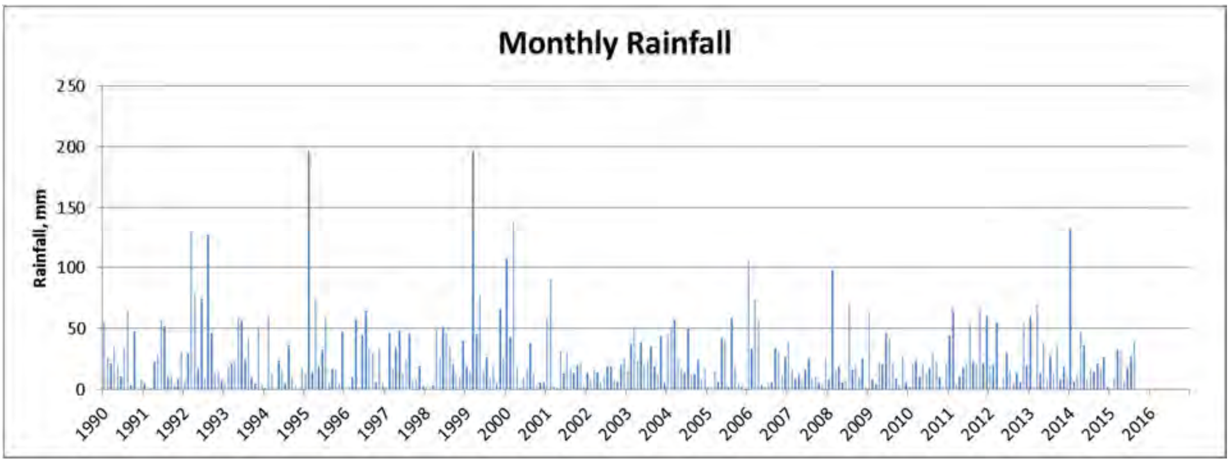


Figure 4: Monthly Rainfall – Sandy Ridge

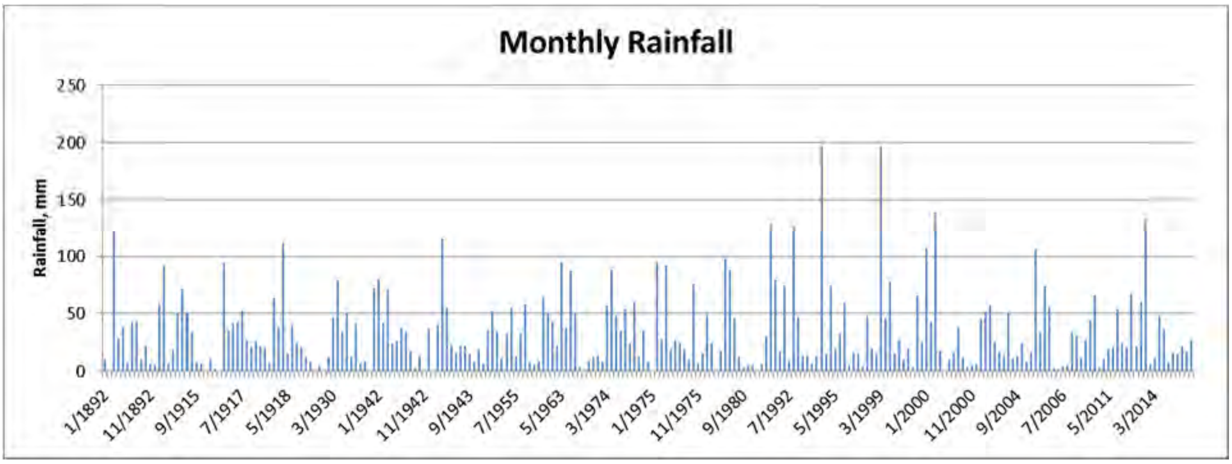


Figure 5: Monthly Rainfall – 20 Highest Rainfall Years

5 MODEL CALIBRATION AND VERIFICATION

None of the models presented in this report have been calibrated against measured data, reflecting the absence of time series hydrogeological information in the area. However, the models were verified by comparing simulated results to similar situations that have measured data or that have been modelled using unsaturated flow and heat transfer. In Scenario 1, for natural ground, the modelling results were compared to the prevailing conditions in the area, and were found to be consistent with the conceptual hydrogeological model. Additionally, seasonal soil temperatures were compared to data in published literature and found to be consistent, for the climatic conditions.

A review of measured moisture content in samples deeper than 6 m below ground level (mbgl) indicates that soil moisture is typically between 10-12%. A review of modelling results for Scenario 1 show similar soil moisture conditions as those measured. These results support the model's implementation of the proposed conceptual hydrogeological model of the area.

In the case for the a cell, the results were compared to data in published literature of capping systems in similar climatic conditions and the results found to be consistent and reasonable and are discussed in Section 6.

6 MODEL SCENARIOS

All of the scenarios were simulated using a vertical column 1 m thick, by either 12 or 20 m wide. Vertically, the column represents approximately 40 m of soil, and was constructed from the information contained in Figure 3. Results of the scenario water balances are reported as totals for the entire model, and as normalized vertical fluxes passing through a one square metre area, specified as mm per year. The normalized flux is used to calculate infiltration and seepage estimates for an entire cell.

6.1 Run Parameters

All of the scenarios modelled were simulated using transient conditions, with the following Vadose/W options:

- Initial conditions for saturation and temperature taken from previous model simulations;
- Minimum pressure head difference for convergence of 0.01 kPa, and minimum temperature difference of 0.01 C.
- Maximum of 100 iterations with 10 reviews; and
- Adaptive time stepping with a minimum time step of 60 seconds and a maximum time step of 720 seconds.

Using the above model options, the execution times for a 20-year run ranged from 12 to 24 hours, using a parallel solver (40 cores).

The results of the unsaturated modelling are presented as soil moisture in decimal percent (i.e. 0.1 = 10%). This soil moisture can then be compared to the graphed curves of soil hydraulic properties, for the relative soil type, as shown in Appendix A. The corresponding matric suction then implies the estimated suction pressure holding soil moisture in the soil unit. Water content held at matric suction above 100kPa (approximate atmospheric pressure) is held against gravity and thus is no longer freely draining. The matric suction pressure can be used to estimate the unsaturated hydraulic conductivity of the soil type at a specific soil moisture, which can result in k being orders of magnitude less than the saturated hydraulic conductivity for the same material.

6.2 Scenario 1: Existing Conditions

A one-dimensional column model, shown in Figure 6, was constructed to simulate the existing conditions at the site. Two cases were simulated:

- Case A - uses estimated material properties based on soil characteristics
- Case B – material properties are adjusted to account for no runoff for rainfall on the order of 50 mm in twelve hours.

The objective of scenario 1 (S1A and S1B) is to establish that the model can replicate known conditions, thereby confirming that the model correctly simulates the conceptual hydrogeology, which will reduce the uncertainty in subsequent model simulations. This approach is used in lieu of model calibration, as there is no quantitative data available for calibration.

The Scenario 1A model uses the soil properties as defined in Tables 3, 4 and 5, and has the following boundary conditions:

- 20 years of historic climate data starting in 1995;
- Evapotranspiration from sparse vegetation;
- lower boundary is specified as a unit gradient which is typically recommended for one-dimensional column models that do not have a water table; and
- ponding of water is allowed, which eliminates runoff, as the top of the model is flat.

Scenario 1B is the same as Scenario 1A, but has modified topsoil material properties to allow rainfall to infiltrate given very dry preceding conditions and includes evapotranspiration. This scenario is based on anecdotal evidence that under some conditions, rainfall does not runoff but infiltrates into the ground.

The twenty-year simulations are run five times, with subsequent runs using the results from the previous model run as the initial condition. This effectively makes the scenario run 100 years long. The concatenating of runs was required due to the relatively long runtimes of a single twenty-year run. Results of the simulations are presented below for the last 20 years of the simulation.

6.2.1 Scenario 1A - Model Results

Figures 7 and 8 show the predicted soil moisture (as the volumetric fraction of water in a unit volume of soil) and the fractional saturation (volumetric soil moisture divided by soil porosity) as a function of depth at the end of 100 years. From the figures, all of the geological materials remain unsaturated (i.e. fractional saturation is less than 1), though there is increased saturation at the top of the silcrete, due to the low hydraulic conductivity of this material. The saturation profile confirms that for the climatic conditions simulated and the characteristics of the soil column, it is unlikely that a saturated aquifer will occur either perched atop the silcrete or at the interface between weathered and fresh granite. The low moisture content of the soils results in very low unsaturated hydraulic conductivity (i.e. due to very large suction pressures > 10,000 kPa), which reduces water flow in these soils.

These results are consistent with measured water content in sampled soil from exploration holes drilled in the area, which showed soil moisture ranging from 10-12%, below 6 mbgl.

The SA1 results are consistent with the conceptual hydrogeology and confirm that the model is a reasonable analogue of the existing conditions at the project site. Note that the model does predict increased soil moisture on top of the unweathered granite, which is due to its low assumed hydraulic conductivity. A review of available bore logs does indicate that water occurs in the vicinity of the interface between the fresh granite and the overlying weathered granite in the area of the proposed cells. There were no soil samples taken above 6 mbgl, so no comparison of simulated soil moisture to measured data can be made above the silcrete.

6.2.1.1 Water Balance

Table 8 and 9 shows the water balance for S1A, for the last 20 years of the simulation. Figure 9 shows the water balance error, which in this case is the difference between the cumulative water balance versus the change in storage. For transient models, the water balance error is generally defined as the change in storage (as indicated by the difference in moisture content between the start and the end of the model) divided by the cumulative water balance (net fluxes) for the same period. Figure 10 shows the cumulative boundary fluxes for the model, as a function of time. Figure 13 shows the evapotranspiration of water by deep rooted vegetation, with a maximum leaf area index (LAI) of 0.5.

Based on a change in storage of -0.25 m^3, versus a water balance error of 0.012 m^3, the percentage water balance error is 5% which is acceptable for this type of groundwater model (Barnett et al., 2012).

Table 10 shows the annual fluxes passing vertically through the topsoil/subsoil, silcrete and weathered granite, in terms of infiltration and seepage over the last 20 year simulation period.

Based on the water balance, most rainfall is evaporated with some evapotranspired after heavy rainfall, with infiltration into the topsoil/subsoil layer of 0.20 mm/annum. The infiltration below the silcrete layer, which is indicative of rainfall recharge, is on average 0.19 mm/annum. This modelling result is consistent with, but larger than the average rainfall recharge based on a chloride mass balance (section 3.3), which indicated a range from 0.0036 to 0.10 mm/annum. The larger recharge estimated by the model is likely due to the use of measured silcrete vertical hydraulic conductivity of $5.x10^{-8}$ m/s from cores which may not characterize the spatial variability of the silcrete accurately.

Run Duration	Model Area	Rainfall	EVT	Evaporation	Change in Storage	Water Balance Error	Water Balance Error
Years	m^2	m^3	m^3	m^3	m^3	m^3	%
20	20	111.5	-2.27	-109.36	-0.25	-0.013	5

Table 8: S1A - Model Water Balance

Rainfall	EVT	Evaporation	Change in Storage	Water Balance Error	Water Balance Error
mm	mm	mm	mm	mm	%
279	-5.7	-273.4	-0.6	0.03	5

Table 9: S1A – Annual Water Balance

Rainfall	Infiltration to Top Soil/Subsoil	Infiltration Below Silcrete
mm	mm	mm
279	0.20	0.19

Table 10: S1A – Annual Rainfall, Infiltration and Seepage

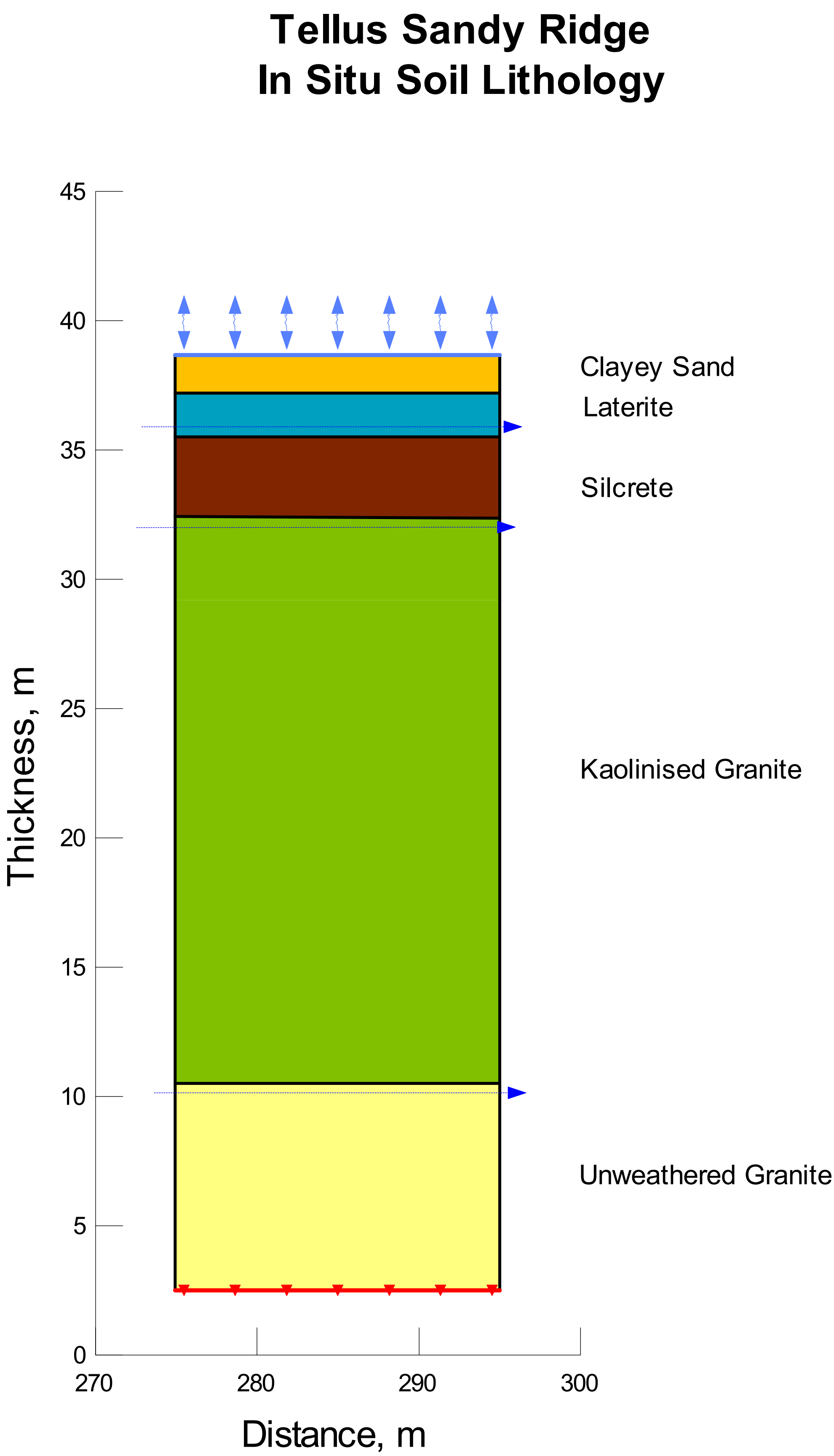


Figure 6: SA1 – Model Structure (Natural Ground)

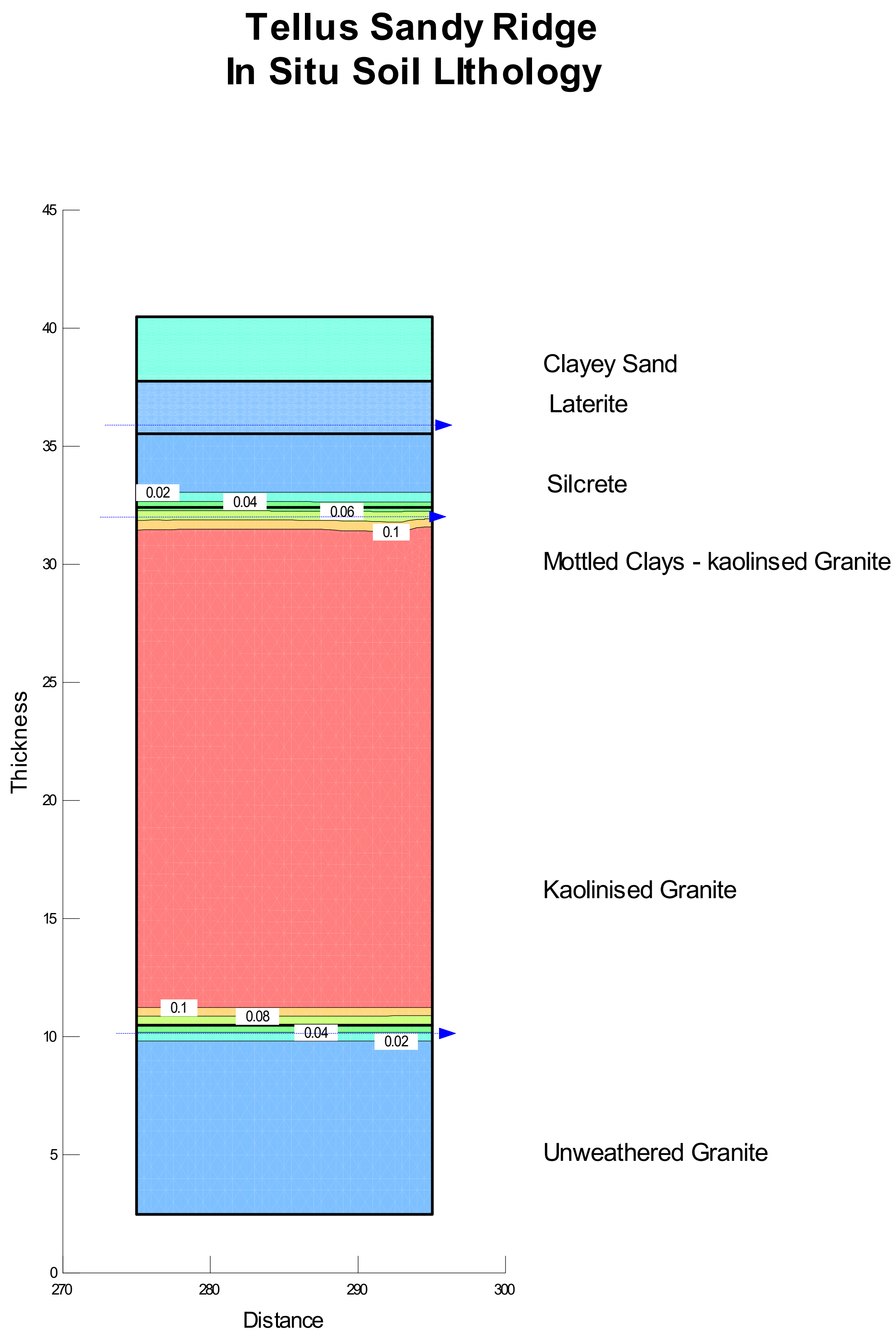


Figure 7: S1A - Predicted Soil Moisture after 100 years

Tellus Sandy Ridge
In Situ Soil LIthology

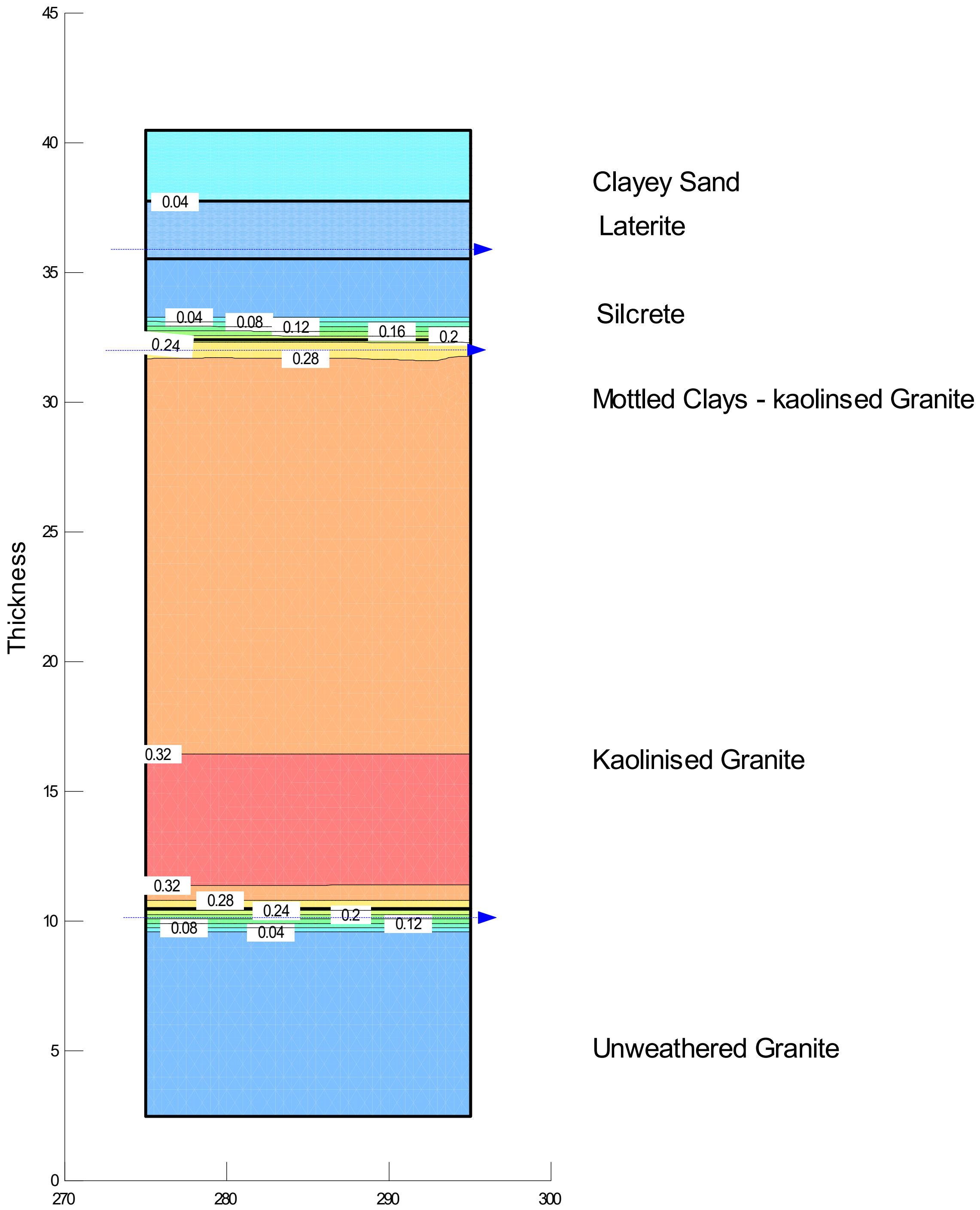


Figure 8: S1A - Predicted Soil Saturation after 100 years

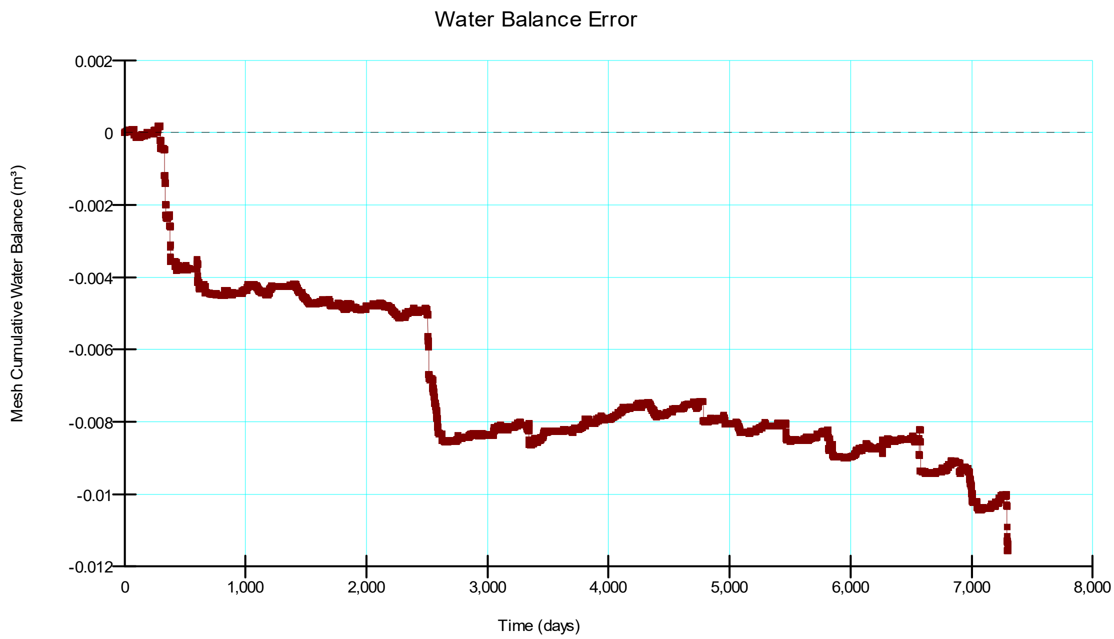


Figure 9: S1A Cumulative Water Balance

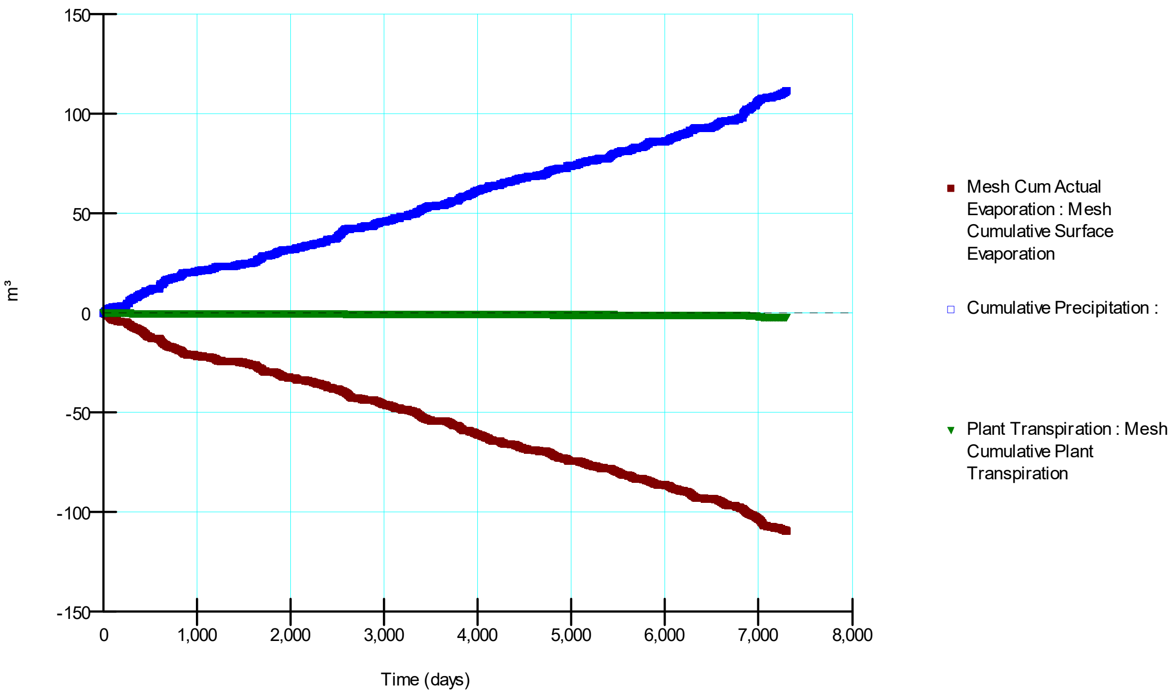


Figure 10: S1A - Boundary Fluxes

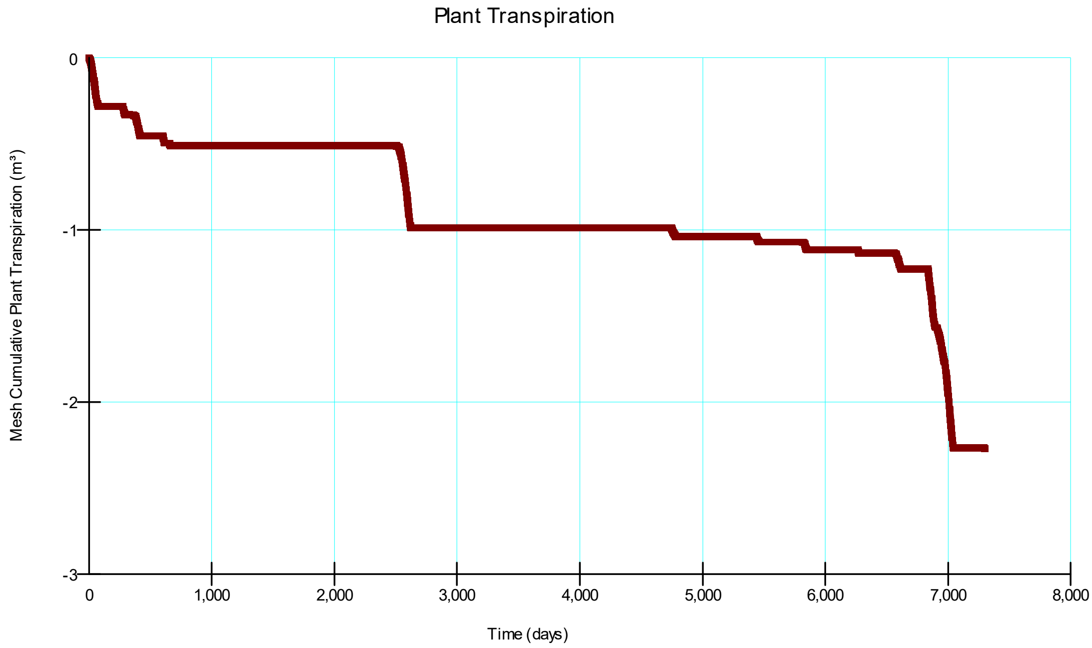


Figure 11: Plant Evapotranspiration

6.2.2 Scenario 1B – Model Results

Figures 12 and 13 shows the predicted soil moisture (as the volumetric fraction of water in a unit volume of soil) and the fractional saturation (volumetric soil moisture divided by soil porosity) as a function of depth at the end of 100 years for Scenario 1B. From the figures, all of the geological materials remain unsaturated (i.e. fractional saturation is less than 1), though there is increased saturation at the top of the silcrete, due to the lower hydraulic conductivity of this material. The saturation profile confirms that for the climatic conditions simulated and the characteristics of the soil column, it is unlikely that a saturated aquifer will occur either perched atop the silcrete or at the interface between weathered and fresh granite. The low moisture content of the soils results in very low unsaturated hydraulic conductivity (i.e. due to very large suction pressures greater than 10,000 kPa), which reduces water flow in these soils.

These results are consistent with measured water content in sampled soil from exploration holes drilled in the area, which showed soil moisture ranging from 10-12% below 6 mbgl. Consequently, even with increased infiltration into the surface soils, recharge below the silcrete layer is still relatively small at 0.21 mm/annum or about 0.07% of average rainfall.

6.2.2.1 Water Balance

Table 11 and 12 shows the water balance for S1B, for the last 20 years of the simulation.

Figure 14 shows the water balance error, which in this case is the difference between the cumulative water balance versus the change in storage. For transient models, the water balance error is generally defined as the change in storage (as indicated by the difference in moisture content between the start and the end of the model) divided by the cumulative water balance (net fluxes) for the same period. Figure 15 shows the cumulative boundary fluxes for the model, as a function of time.

Based on a change in storage of 1.6 m^3, versus a water balance error of 0.01 m^3, the percentage water balance error is 0.6% which is acceptable for this type of groundwater model (Barnett et al., 2012). Given the magnitude in the change in storage, and the small water balance error this error has limited impact on the quality of the solution.

Table 10 shows the annual fluxes passing vertically through the topsoil/subsoil, silcrete and weathered granite, in terms of infiltration and seepage over the last 20 year simulation period.

Based on the water balance, most rainfall is evaporated, with infiltration into the topsoil/subsoil layer of 0.21 mm/annum. The infiltration below the silcrete layer, which is indicative of rainfall recharge, is on average 0.0.20 mm/annum.

This scenario shows the sensitivity of recharge to changes in the hydraulic conductivity of the top soil, and how quickly rainfall can infiltrate the soil column. From the results, it is suggested recharge is not sensitive to top soil saturated hydraulic conductivity when it is greater than $1x10^{-6}$ m/sec. This is consistent with the conceptual hydrogeological model, where the low hydraulic conductivity of the silcrete layer acts to impede downward flow, and allow evaporation and evaporation to occur over a longer time.

Run Duration	Model Area	Rainfall	EVT	Evaporation	Change in Storage	Water Balance Error	Water Balance Error
Years	m^2	m^3	m^3	m^3	m^3	m^3	%
20	20	111.5	-2.27	-109.4	-0.16	-0.012	7.5

Table 11: S1B - Model Water Balance

Rainfall	EVT	Evaporation	Change in Storage	Water Balance Error	Water Balance Error
mm	mm	mm	mm	mm	%
279	-5.7	-273.4	-0.4	0.03	7.5

Table 12: S1B – Annual Water Balance

Rainfall	Infiltration to Top Soil/Subsoil	Infiltration Below Silcrete
mm	mm	mm
279	0.21	0.20

Table 13: S1B – Annual Rainfall, Infiltration and Seepage

Tellus Sandy Ridge
In Situ Soil LIthology

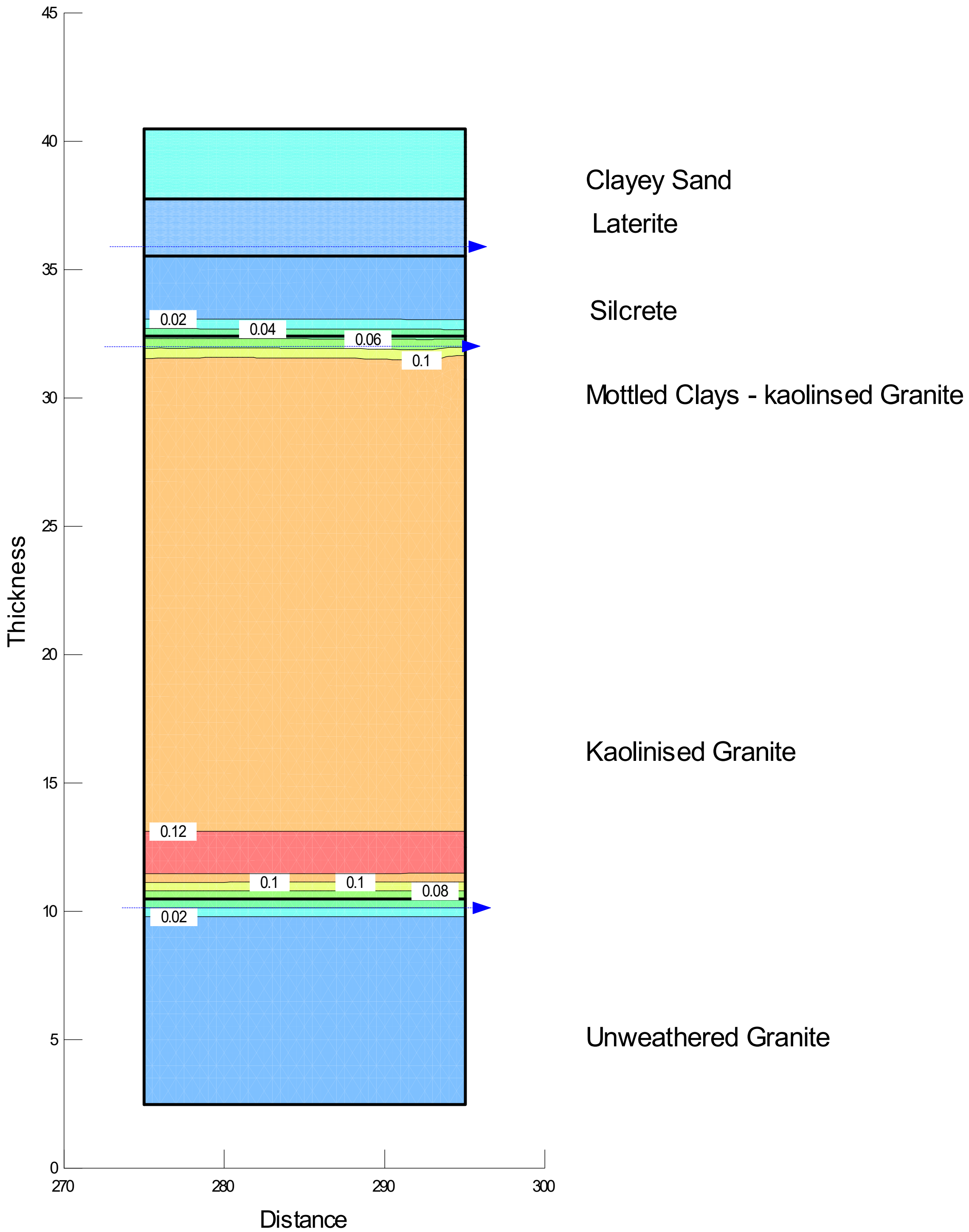


Figure 12: S1B - Predicted Soil Moisture after 100 years

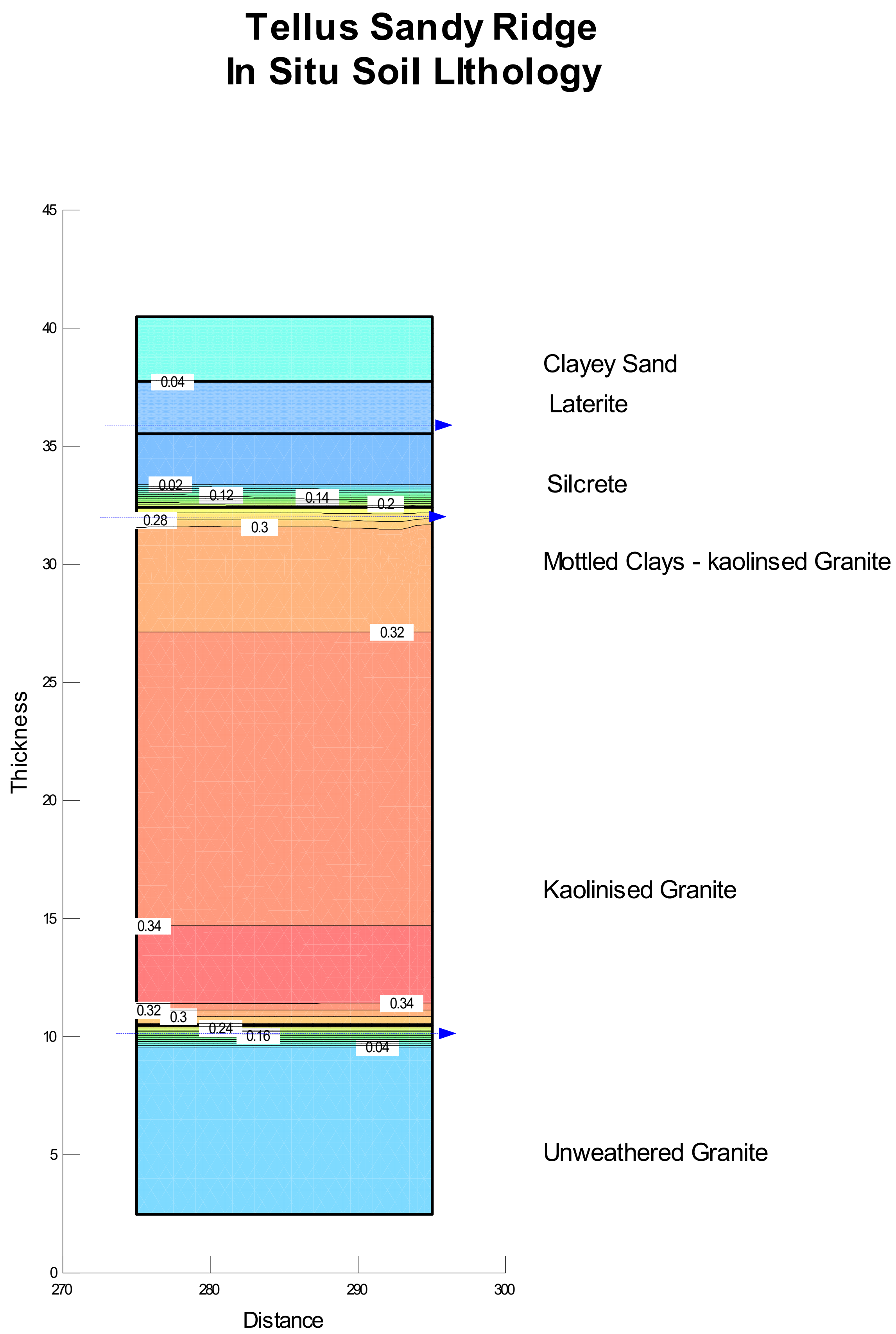


Figure 13: S1B - Predicted Soil Saturation after 100 years

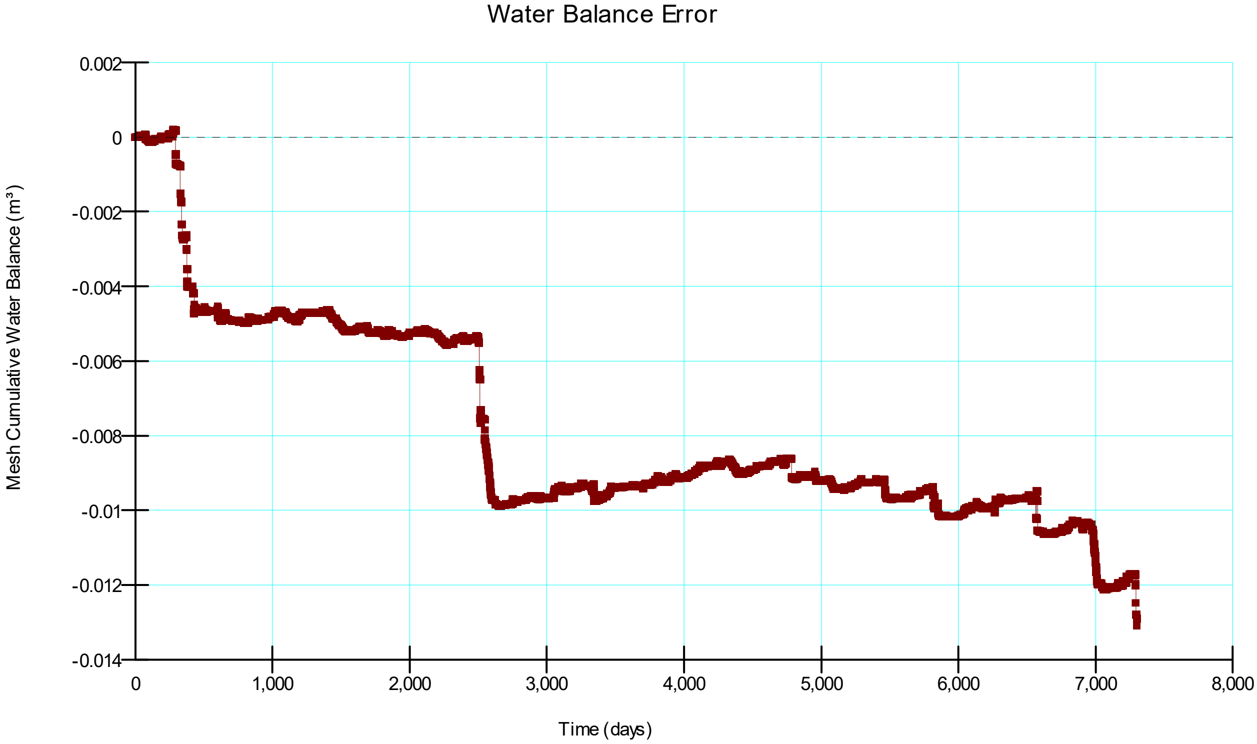


Figure 14: S1B Cumulative Water Balance

6.3 Scenario 2 – Backfilled and Capped Cell: Lower Boundary Sensitivity

A one-dimensional column model, shown in Figure 15, was constructed to simulate the backfilled and capped cell. The model, referred to as S2, was used to quantitatively assess the sensitivity of infiltration and seepage to changes in the lower boundary condition. The model was also used to estimate the infiltration and seepage through the compacted mottled clay cap (the cap) and the compacted kaolinised granite seal (the seal), into the granular material surrounding waste packages, which is further described in Scenario 3. Consequently, S2 was run using the three different lower boundary conditions as described below:

1. No flow boundary condition representing impervious fresh granite;
2. A specified pore pressure boundary condition to represent elevated saturation at the base of the model (sitting atop or emanating from fresh granite); and
3. Unit gradient boundary condition to represent low topographical gradient of the fresh granite for drainage to depth.

The S2 models uses soil properties as defined in Tables 3, 4 and 5, and the 10 wettest years of climate data as described in Section 4.

6.3.1 S2 – Results

Figures 16, 17 and 18 show the predicted soil moisture at the end of the 100 year simulation period for the three different boundary conditions. The figures show that all of the geological materials remain unsaturated. Given that the materials are unsaturated, the simulated pressure heads are negative, consistent with the materials being unsaturated.

6.3.2 Water Balance

Table 14 shows the water balance for the column models for the last 20 years of the simulation. The water balance shows that the lower boundary condition has no significant impact on the surface boundary flows, but does affect the change in storage. The change in storage is consistent with the different boundary conditions:

- For the no flow lower boundary, the change in storage is associated with evapotranspiration of water from shallow soils;
- For the specified pressure boundary, the saturation in the weathered granite has increased from 12% to 22% due to the lower suction pressure at the boundary over the 20 years compared to the initial condition; and
- For the unit gradient, storage has decreased due to drainage and evapotranspiration.

Table 15 shows the sensitivity of the vertical fluxes in the column models to the lower boundary condition.

In general, the lower boundary condition has limited effect on the vertical fluxes, other than for the unit gradient, which tends to increase the vertical flux below the compacted kaolinised granite seal due to the lower saturation in this region and deep drainage.

Case	Rainfall	Runoff	Evaporation	Bottom Flow	Change in Storage	Water Balance Error	Water Balance Error
	m^3	m^3	m^3	m^3	m^3	m^3	%
No flow	104.3	72	33	0	-0.52	0.037	7
Specified Pressure	104.3	72	33	0.38	0.98	0.12	12
Unit Gradient	104.3	72	33	0.39	-0.51	0.05	10

Table 14: Scenario 2 Water Balances

Case	Infiltration to Top Soil	Infiltration Below Clay Cap	Infiltration below kaolinised Granite Seal
	m^3	m^3	m^3
No flow	0.4	0.046	0.001
Specified Pressure	0.4	0.045	0.0007
Unit Gradient	0.3	0.03	0.0017

Table 15: Sensitivity of Vertical Flux to Lower Boundary Condition

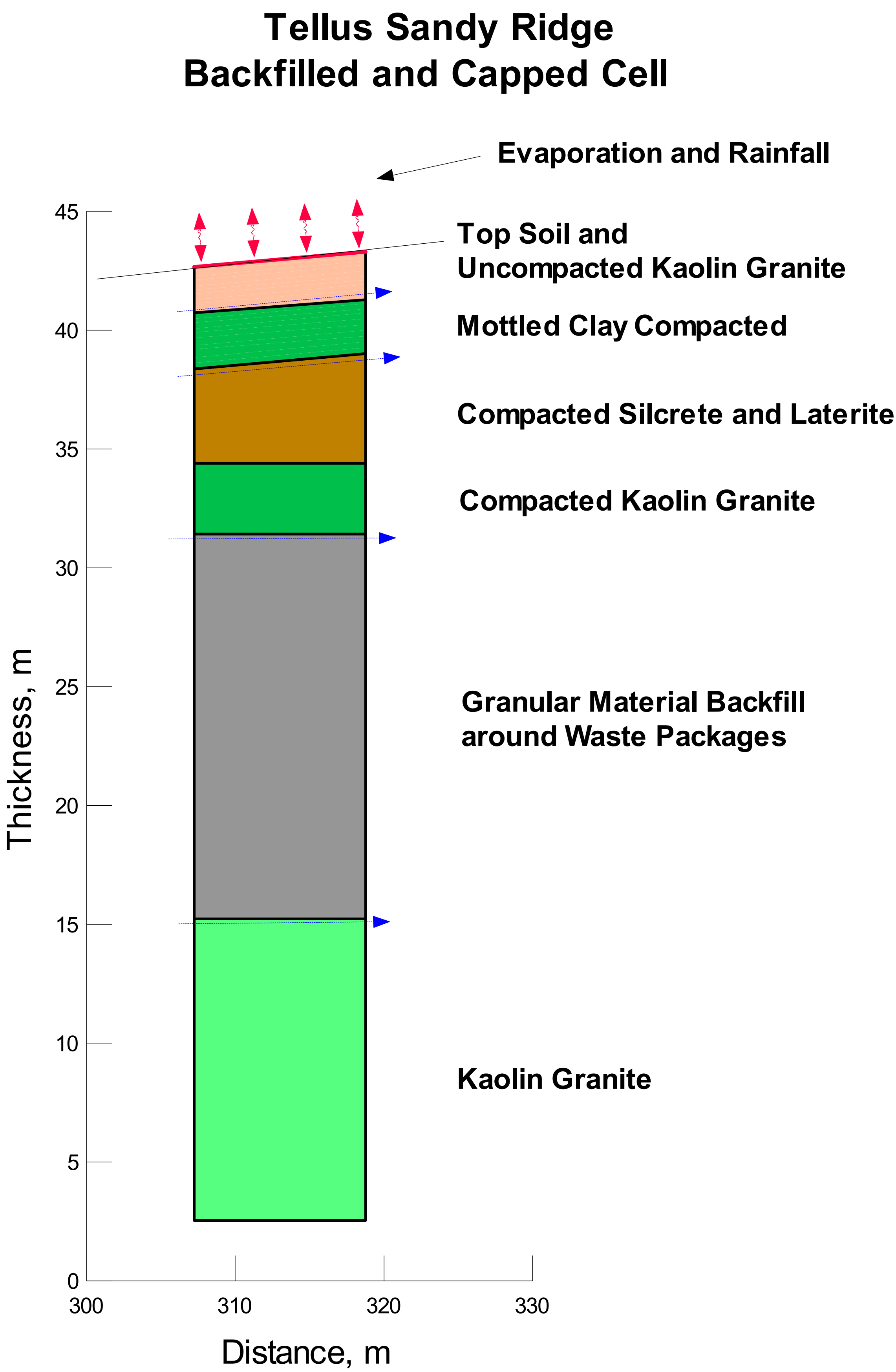


Figure 15: Backfilled and Capped Cell – Column Model

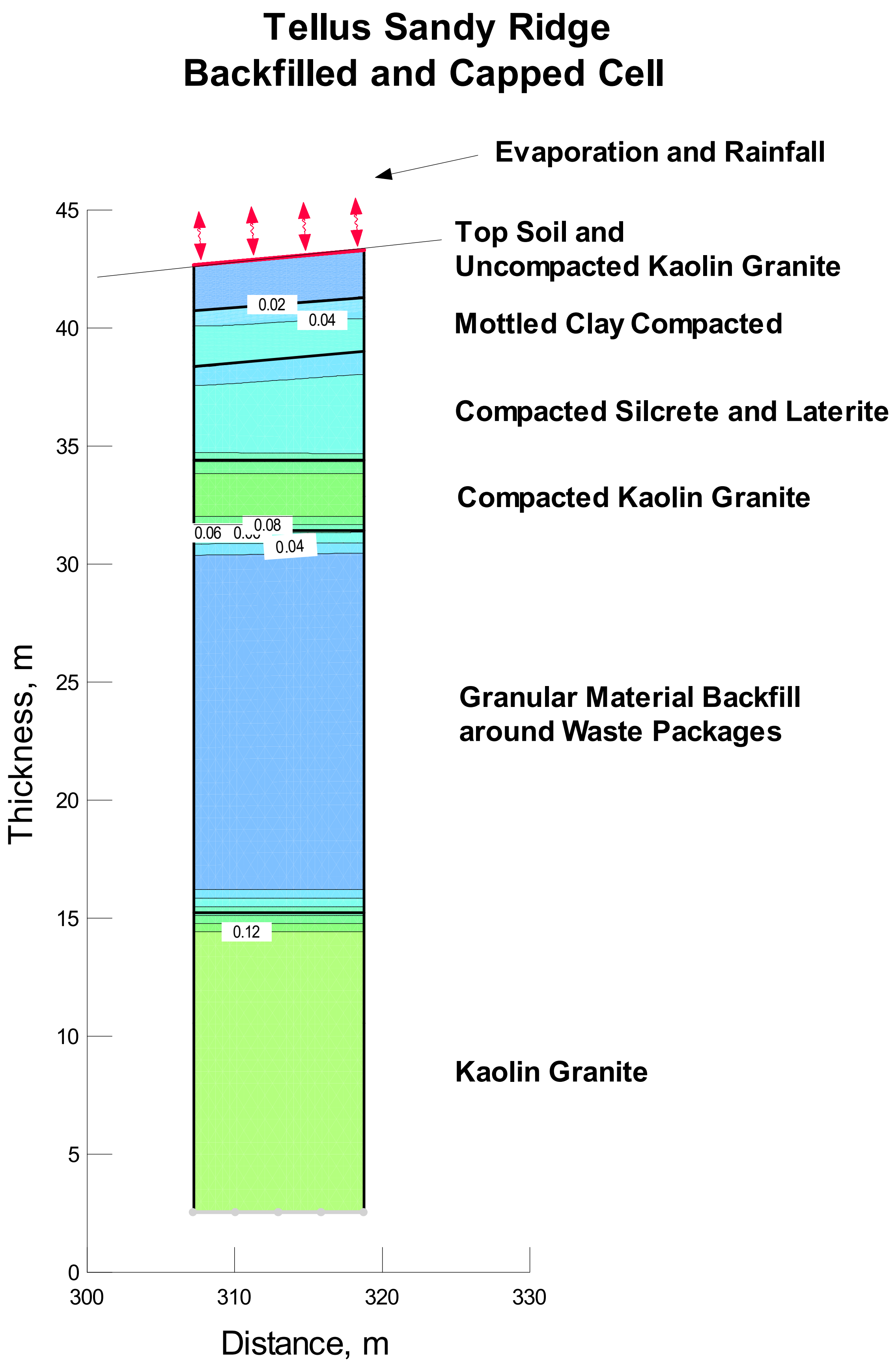


Figure 16: Moisture Content – No Flow Lower Boundary

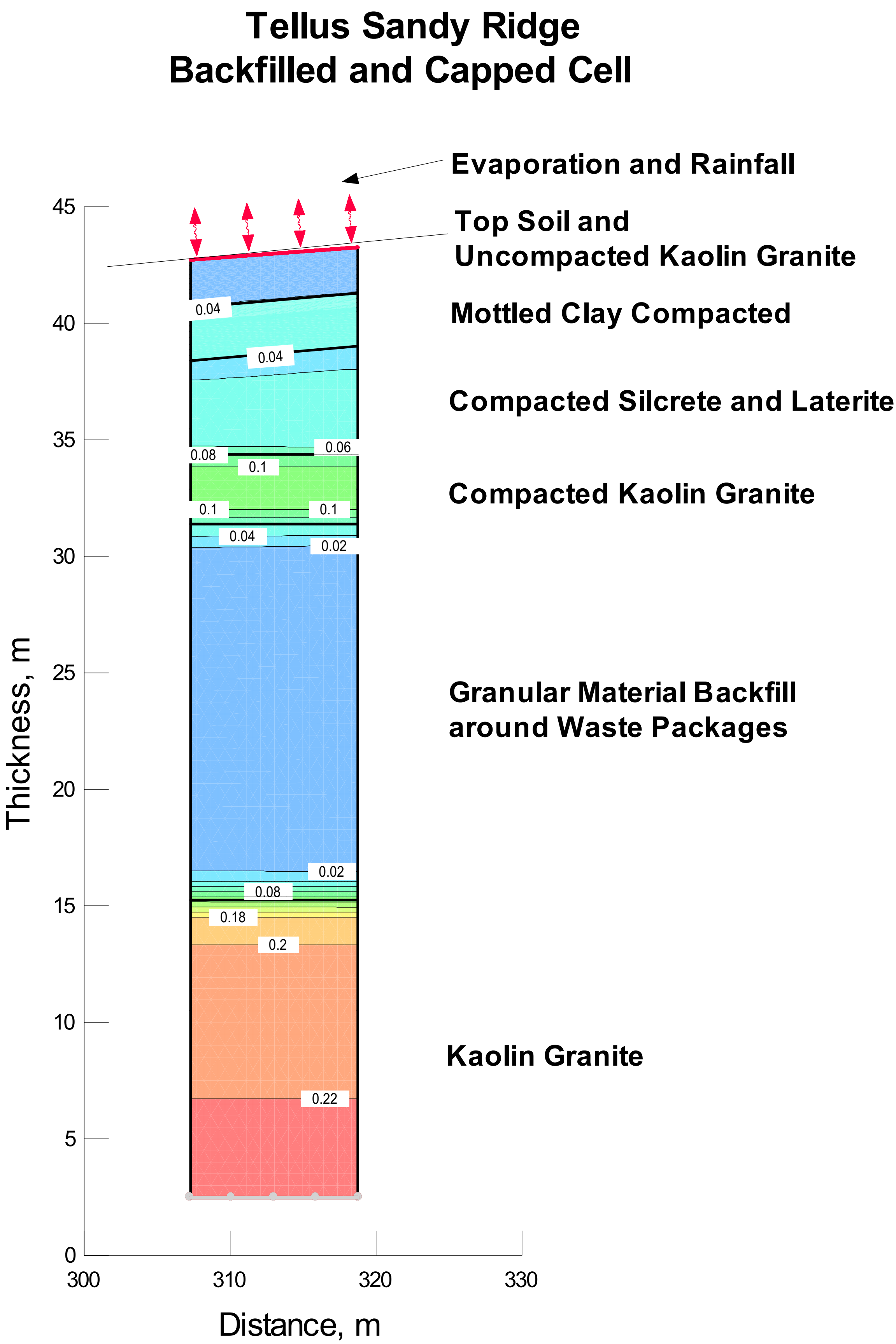


Figure 17: Moisture Content – Specified Pressure Lower Boundary

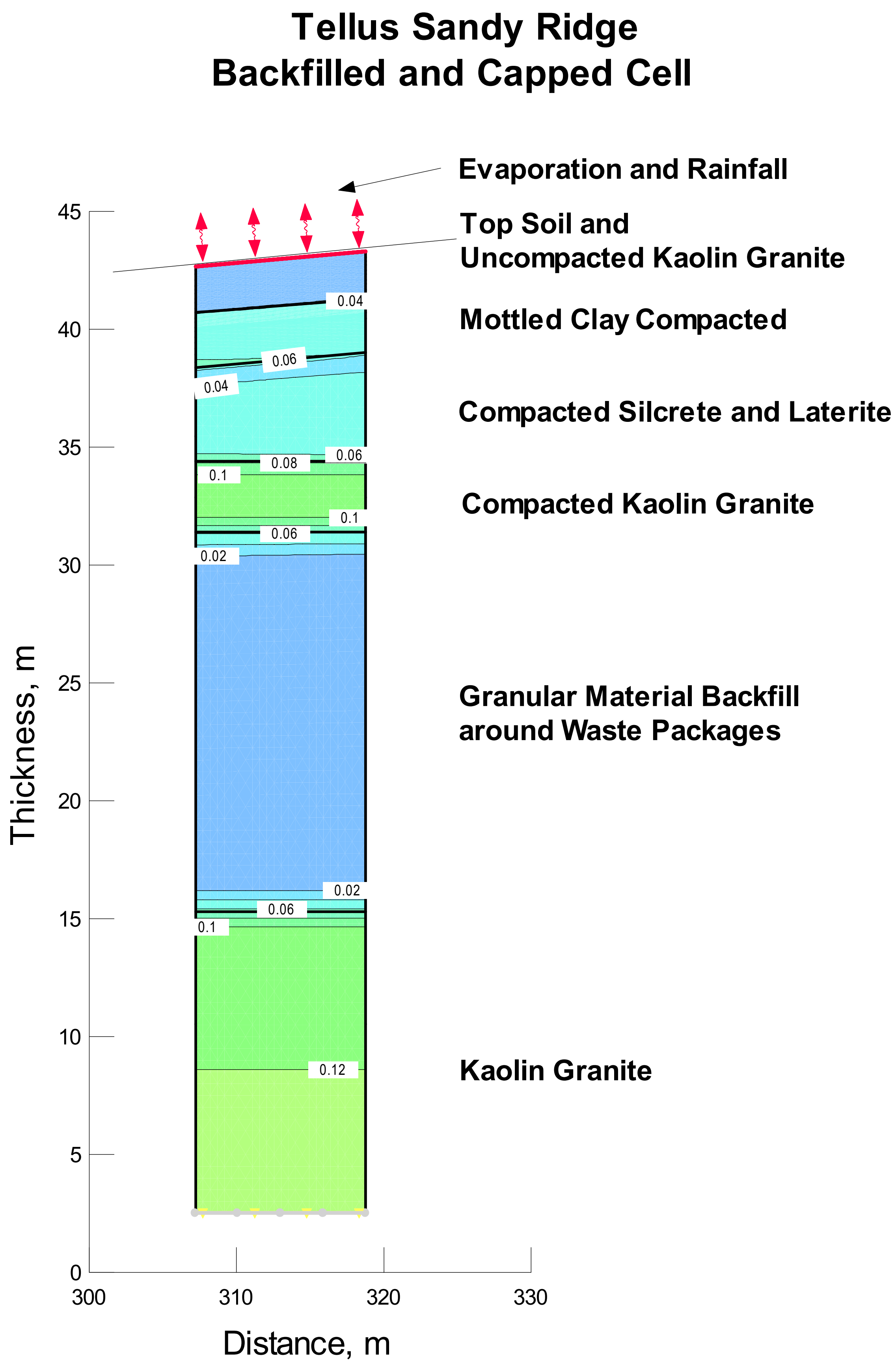


Figure 18: Moisture Content – Unit Gradient Lower Boundary

6.4 Scenario 3 – Backfilled and Capped Cell: Estimate of Infiltration and Seepage

A one-dimensional column model, shown in Figure 19, was constructed to simulate the backfilled and capped cell. The model, referred to as S3, was used to estimate the infiltration (also referred to as percolation) through the compacted mottled clay cap, and seepage through the kaolinised granite seal into the granular material that surrounds waste packages. Scenario S3 uses the soil properties as defined in Tables 3, 4 and 5 and repeated sequences of the 10 wettest years of climate data as described in Section 3 to estimate vertical fluxes. As a result of the S2 analyses, S3 also applies the unit gradient lower boundary condition.

6.4.1 S3 – Results

Figures 20 and 21 show that all of the geological materials remain unsaturated, though there is increased saturation at the top of the compacted mottled clay cap, and in the compacted kaolinised granite seal, due to the low hydraulic conductivity of these materials. Given that the materials are unsaturated the simulated pressure head is negative, consistent with the materials being unsaturated.

These figures confirm that for the climatic conditions simulated and the characteristics of the soil column, it is unlikely that a saturated aquifer will occur perched atop the compact clay cap, on the compacted kaolinised granite seal or at the interface between weathered and fresh granite, given that seepage is sufficiently small to move vertically downwards under gravity drainage.

6.4.2 Water Balance

Tables 16 and 17 show the water balance for the column model at the end of 100 years. Table 18 shows the predicted cumulative infiltration and seepage over the 20 year simulation period normalized to annum fluxes. Figure 22 shows the cumulative water balance. Figure 23 shows the boundary fluxes, in terms of rainfall, runoff and evaporation over the last 20 years of the simulation. Based on a change in storage of -1.2 m^3, the percentage water balance error is 10% which is larger than the typically accepted error of 1% (Barnett et al., 2012) for groundwater models. However, given the magnitude of the boundary flows, this error is unlikely to have a significant effect on the results.

Based on the water balance, 69% of rainfall runs off, with 31% recharging the shallow surface soils, as shown graphically in Figure 19. Infiltration, as net recharge to the top soil/subsoil, is 1.4 mm/year. Vertical flow below the clay cap is 0.8 mm/year, which flows vertically via the compacted silcrete and laterite backfill to the compacted kaolinised granite seal. The vertical flux below the compacted kaolinised granite seal is 0.008 mm/year. This seepage is smaller than that estimated for the natural system (0.017 mm/year).

6.4.3 S3 – Seepage

Based on a seepage of 0.008 mm/annum into the waste storage area, over an area of 7200 m^2, indicates about 0.058 m^3/annum of seepage may enter a storage cell as vertical leakage, and drain vertically into the weathered granite. This vertical leakage can:

- Go into storage within the weathered or fresh granite and form a groundwater mound; and
- flow laterally to the northwest following the topography of the fresh granite.

Assuming that most of the seepage is retained in the unsaturated weathered granite, which is about 10 m thick directly beneath the cell, has a porosity of 0.35 and an initial saturation of 0.1 suggests that this material would become fully saturated in after 300,000 years given the estimated seepage rate.

Conversely, this seepage may flow as a thin saturated layer in the fresh granite;

- horizontally to the northwest;
- under a prevailing hydraulic gradient of 0.001;
- through fractures having 1% porosity; and
- with an average hydraulic conductivity of $4x10^{-6}$ m/sec;

This gives a groundwater velocity of $4x10^{-7}$ m/s, indicating a travel time of about 6000 years to the most likely exposure point (75 km to the north). In the absence of connected fractures, and flow in the porous weathered granite, the travel time would increase to more than 200,000 years, assuming the fresh granite has a saturated hydraulic conductivity of $1x10^{-8}$ m/s. In either case, the model results suggest the magnitude of seepage potentially emanating from the cell under wet conditions is unlikely to mound or move far from the site for a long (centuries) period of time.

Run Duration	Model Area	Rainfall	Runoff	Evaporation	Bottom Flow	Change in Storage	Water Balance Error	Water Balance Error
Years	m^2	m^3	m^3	m^3	m^3	m^3	m^3	%
20	12	104.3	-72.2	-32.9	0.33	-0.9	-0.09	10

Table 16: S3 - Model Water Balance

Run Duration	Model Area	Rainfall	Runoff	Evaporation	Bottom Out Flow	Change in Storage
Years	m^2	mm	mm	mm	mm	mm
20	12	435	300	137	2	5

Table 17: S3 – Annual Water Balance

Infiltration to Top Soil	Infiltration Below Clay Cap	Infiltration Below Compacted Kaolinised Granite Seal
Mm	mm	mm
1.3	0.8	0.008

Table 18: S3 – Model Predicted Cumulative Infiltration and Seepage – 20 Years

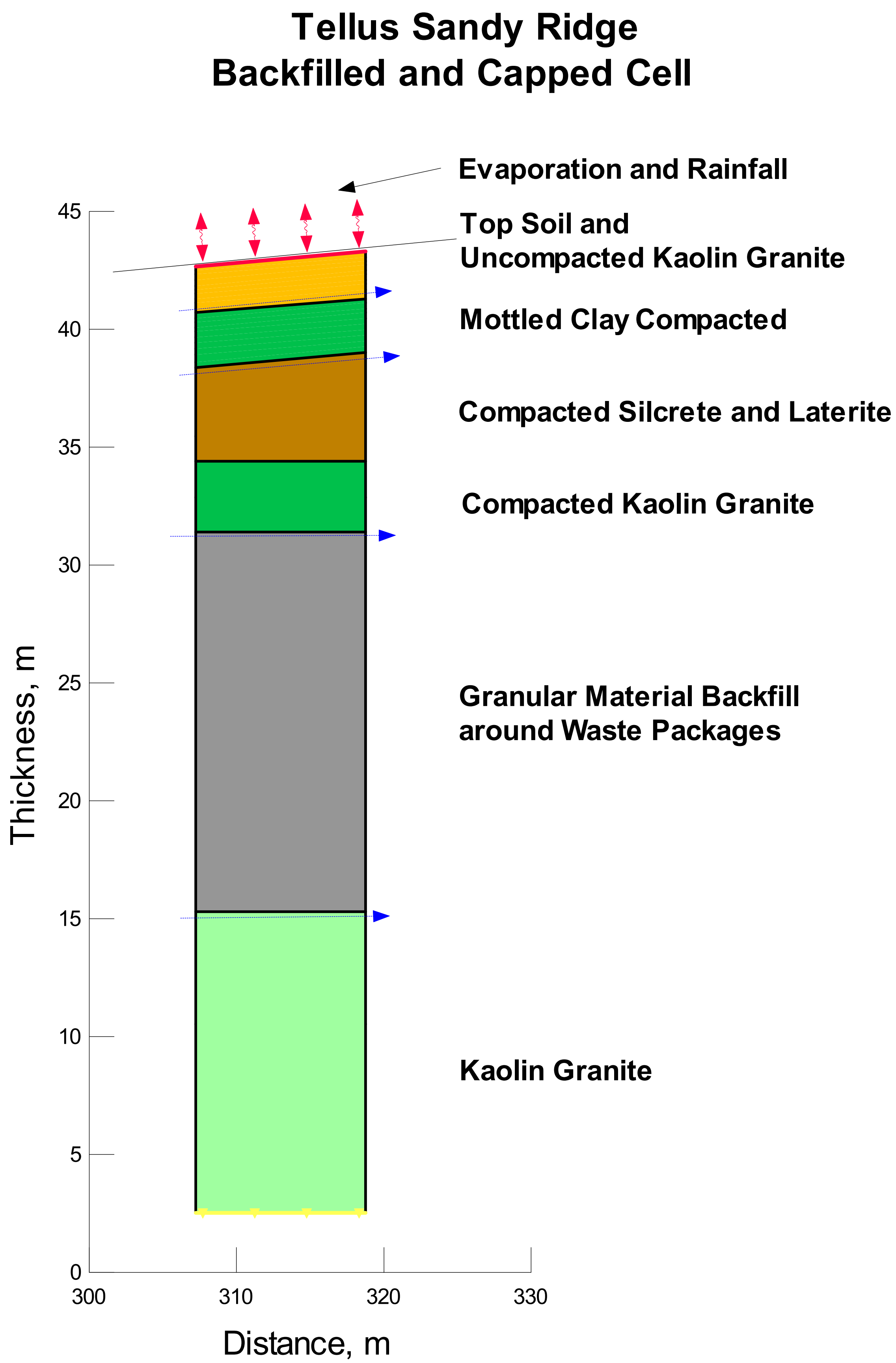


Figure 19: S3 Column Model – Proposed EWSC

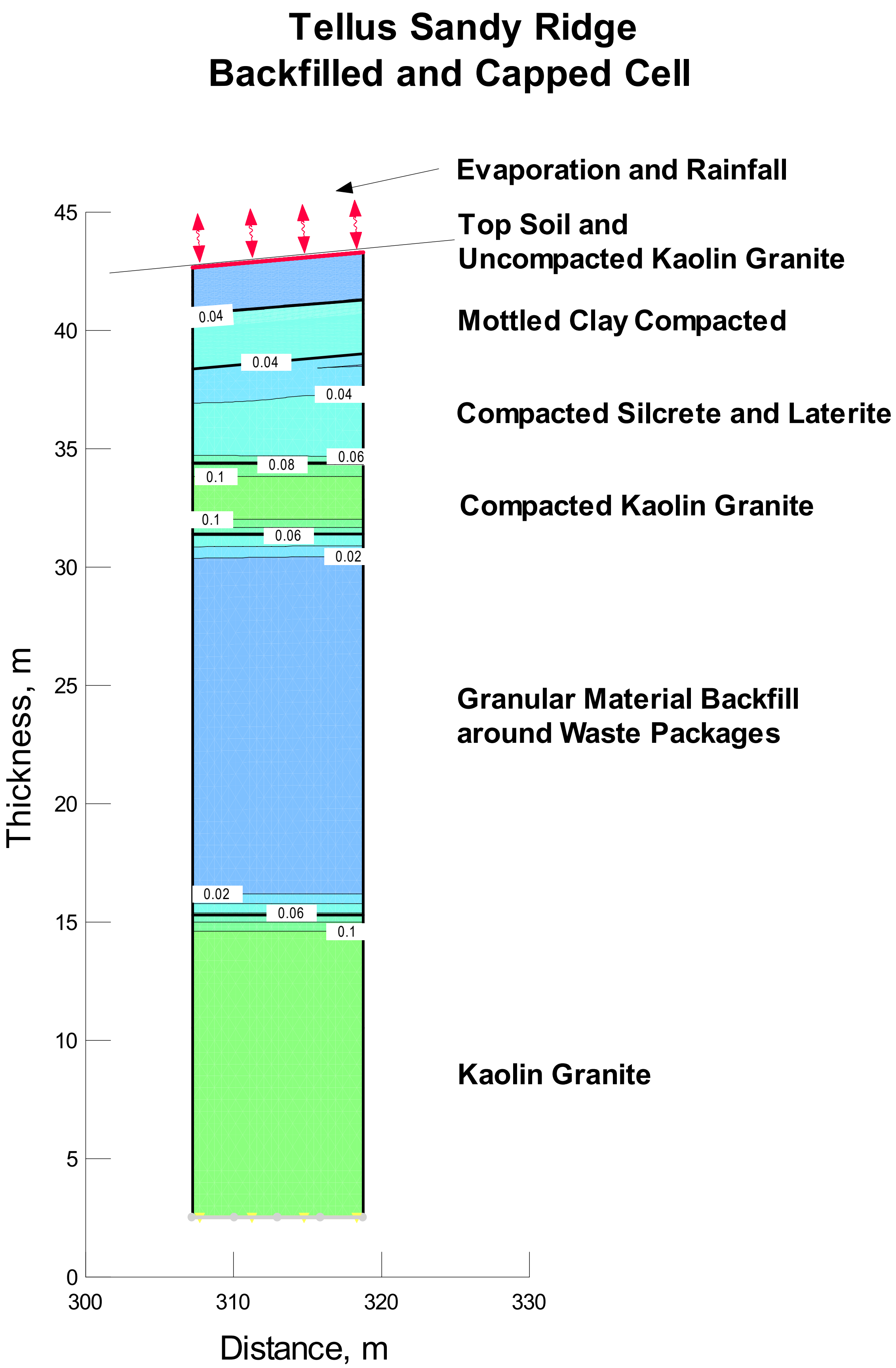


Figure 20: Predicted Moisture Content after 100 Years

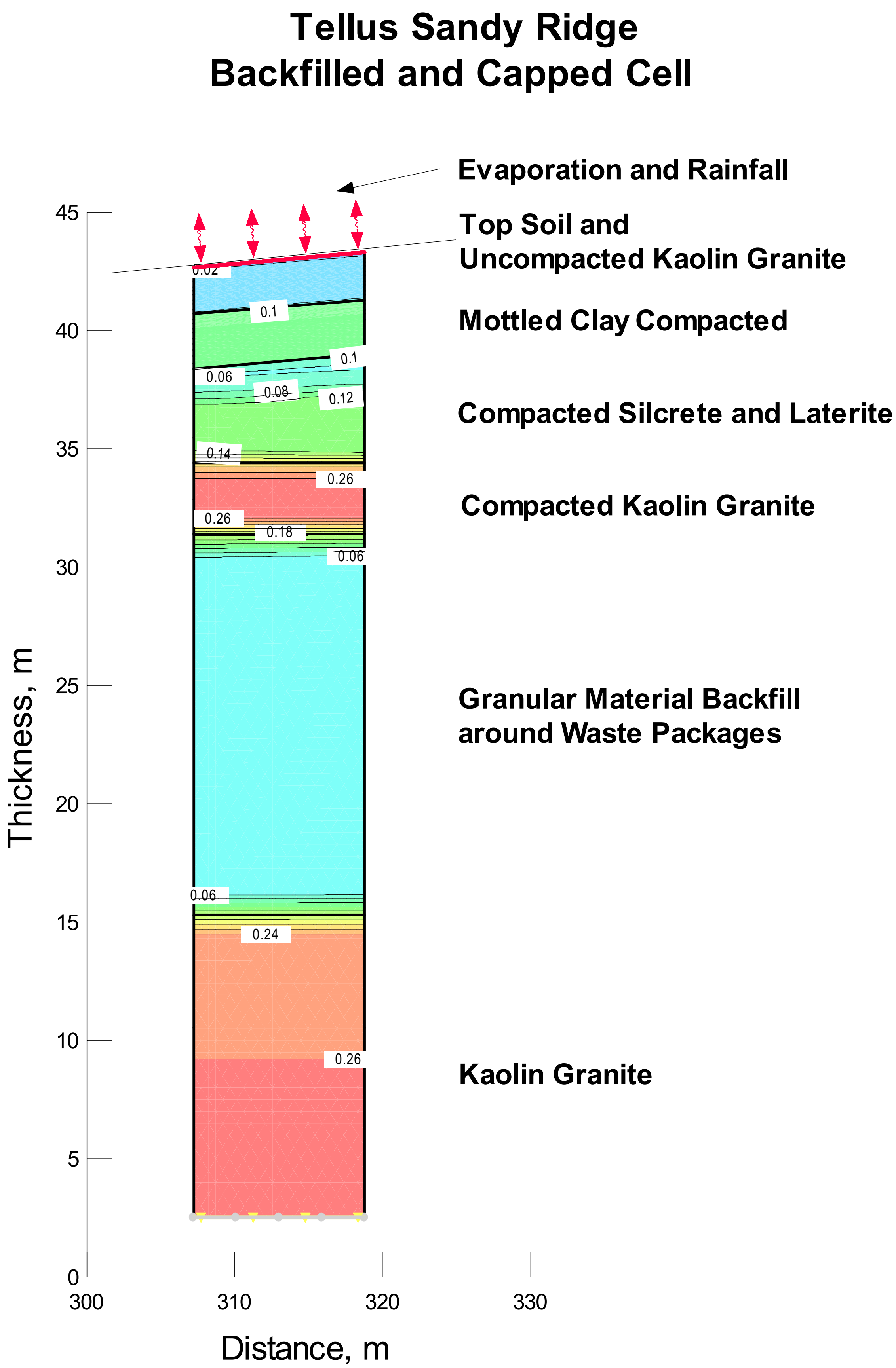


Figure 21: Predicted Saturation after 100 Years
(fraction of material porosity, see Appendix A)

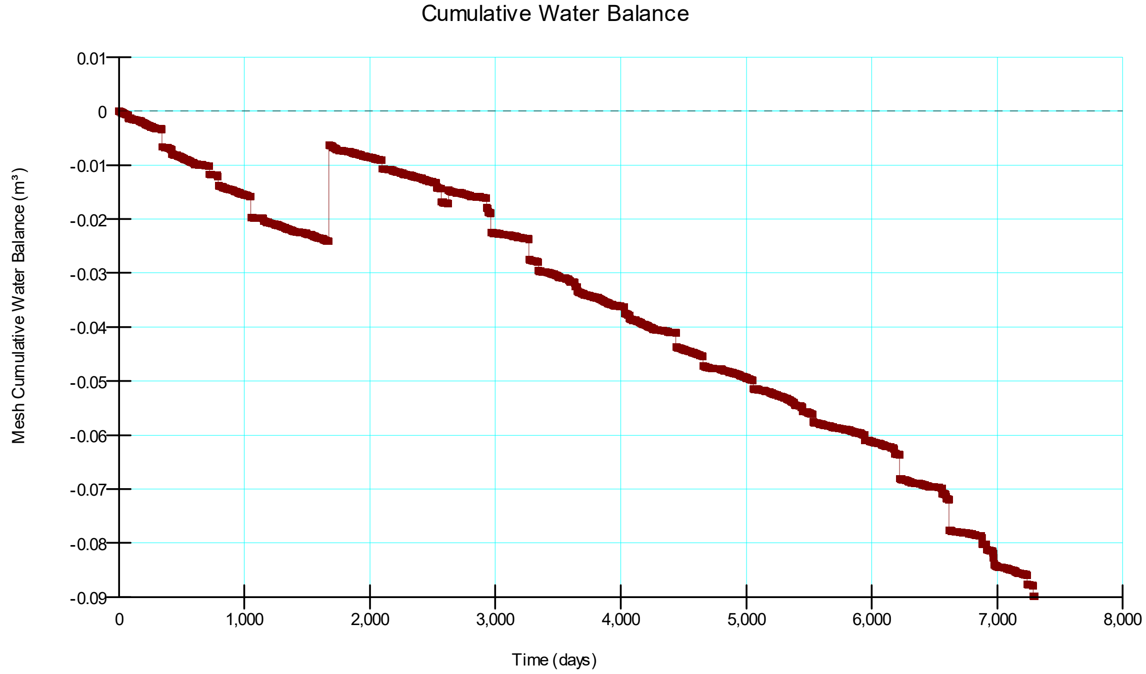


Figure 22: S3 Water Balance Error

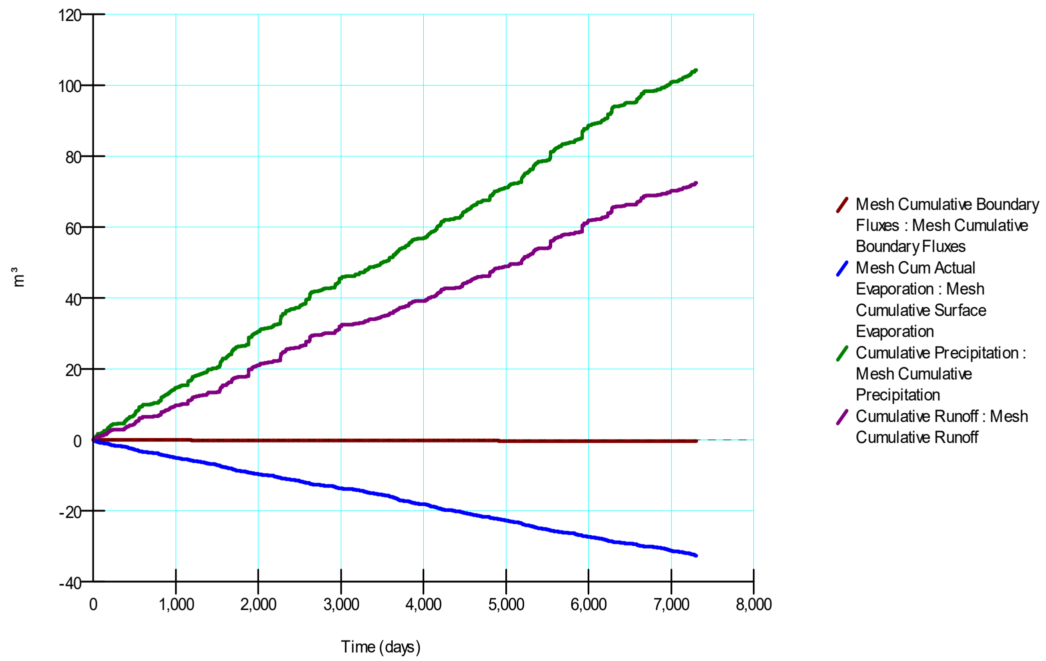


Figure 23: Major Water Balance Components

6.5 Scenario 4 – Backfilled and Capped Cell: High Conductivity Top Soil and Waste Rock

A one-dimensional column model, shown in Figure 24, was constructed to simulate the backfilled and capped cell. The model, referred to as S4, was used to estimate the infiltration (also referred to as percolation) through the compacted mottled clay cap, and seepage from the kaolinised granite seal into the granular material that surrounds waste packages, and in that respect is the same as S3. However, S4 uses a higher hydraulic conductivity of $5x10^{-5}$ m/sec for the top soil and waste rock protective layer which sits on top of the compacted clay cap. In addition, the top of the cell is modelled as flat, which eliminates runoff. Other than these changes, the scenarios are the same with S4 using the soil properties as defined in Tables 3, 4 and 5 and repeated sequences of the 10 wettest years of climate data as described in Section 3.

6.5.1 S4 – Results

Figures 25 and 26 show the moisture content and saturation in the soil column, respectively at the end of 100 years. The figures indicate that all geological materials remain unsaturated, though there is increased saturation at the top of the compacted mottled clay cap, and in the compacted kaolinised granite seal, due to the low hydraulic conductivity of these materials. Given that the materials are unsaturated the simulated pressure head is negative, consistent with the materials being unsaturated.

The modelling results confirm that for the climatic conditions simulated and the characteristics of the soil column, it is unlikely that a saturated aquifer will occur either perched atop the compact clay barriers or at the interface between weathered and fresh granite.

6.5.2 S4 - Water Balance

Tables 19 and 20 show the water balances for the S4 column model at the end of 100 years. Tables 21 and 22 show the predicted cumulative infiltration and seepage over the 20 year simulation period, and the normalized annual fluxes. Figure 27 shows the cumulative water balance. Figure 28 shows the boundary fluxes, in terms of rainfall, runoff and evapotranspiration over the last 20 years of the simulation. Based on a change in storage of -3.1 m^3, the percentage water balance error is 2% which is consistent with the typically accepted error of 1% (Barnett et al., 2012) for groundwater models.

Note that in this case there is no runoff, as the top of the model is flat, and ponding of water is allowed, if rainfall exceeds the rate of infiltration. Hence, all rainfall recharge is either removed as evaporation, or infiltrates into soil storage and becomes seepage into the fresh granite.

Due to the increased saturation in the clay cap and kaolin seal resulting from higher hydraulic conductivity in the top soil, infiltration below the clay cap of 0.5 mm/annum is larger than in either S1 or S3. More importantly, seepage into the granular material that surrounds waste packages is 0.4 mm/annum compared to less than 0.008

mm/annum in S3. This result highlights the significant sensitivity of seepage to higher hydraulic conductivity of the top soil and kaolin waste rock, as well as the importance of maintaining a sloping surface to encourage rapid runoff and minimize infiltration.

Run Duration	Model Area	Rainfall	Runoff	Evaporation	Bottom Flow	Change in Storage	Water Balance Error	Water Balance Error
Years	m^2	m^3	m^3	m^3	m^3	m^3	m^3	%
20	12	104.3	0	105.6	1.87	-3.1	-0.065	2

Table 19: S4 - Model Water Balance

Run Duration	Model Area	Rainfall	Runoff	Evaporation	Bottom Out Flow	Change in Storage
Years	m^2	mm	mm	mm	mm	mm
20	12	435	0	-440	-7.8	12.9

Table 20: S4 – Annual Water Balance

Infiltration to Top Soil	Infiltration Below Clay Cap	Infiltration Below compacted Kaolinised Granite Seal
m^3	m^3	m^3
0.47	0.11	0.105

Table 21: S4 – Model Predicted Cumulative Infiltration and Seepage over the 20 year simulation period

Infiltration to Top Soil	Infiltration Below Clay Cap	Infiltration Below Compacted Kaolinised Granite Seal
mm	mm	mm
2.0	0.5	0.4

Table 22: S4 – Model Predicted Annual Infiltration and Seepage over the 20 year simulation period

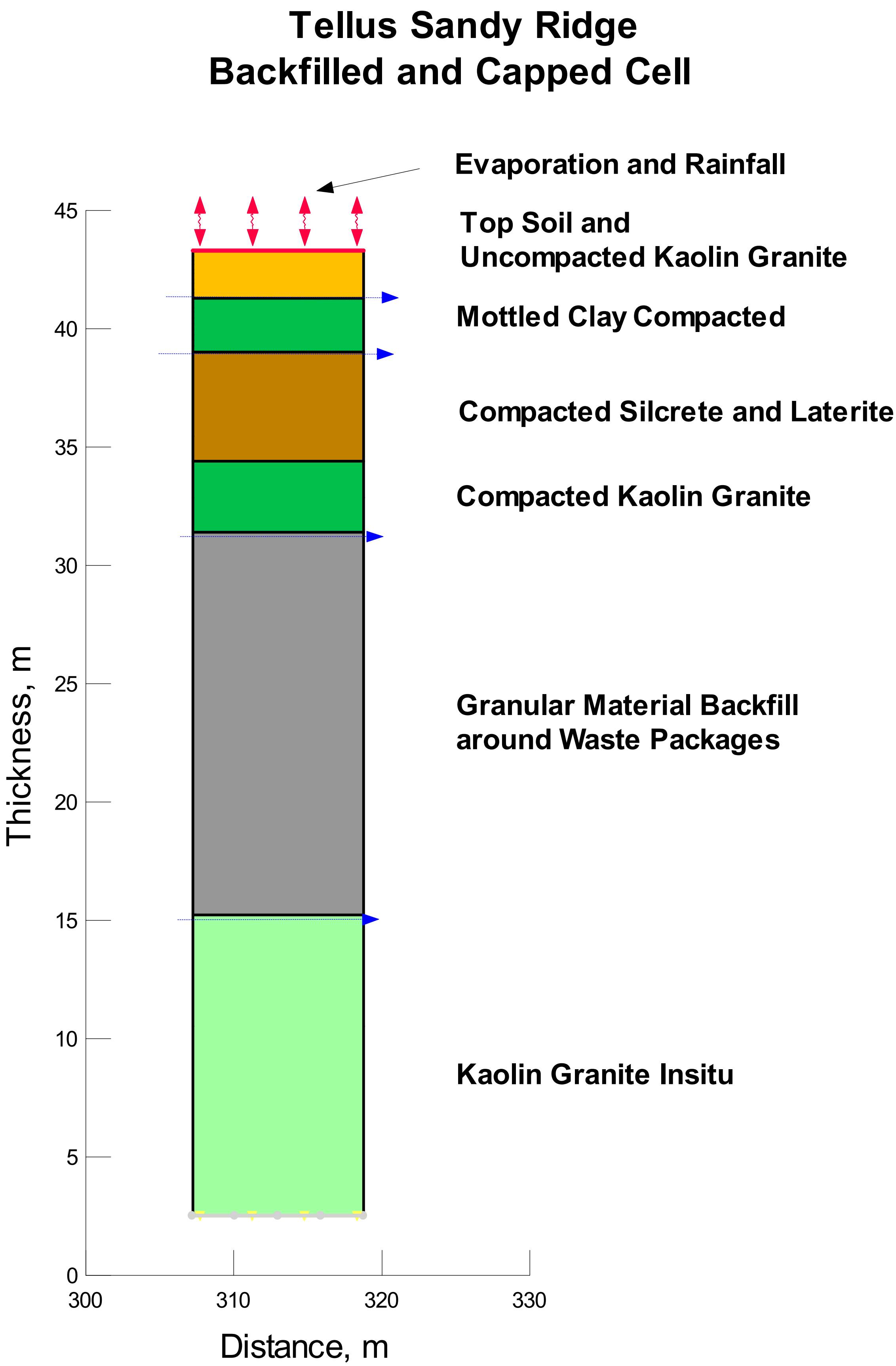


Figure 24: S4 Column Model

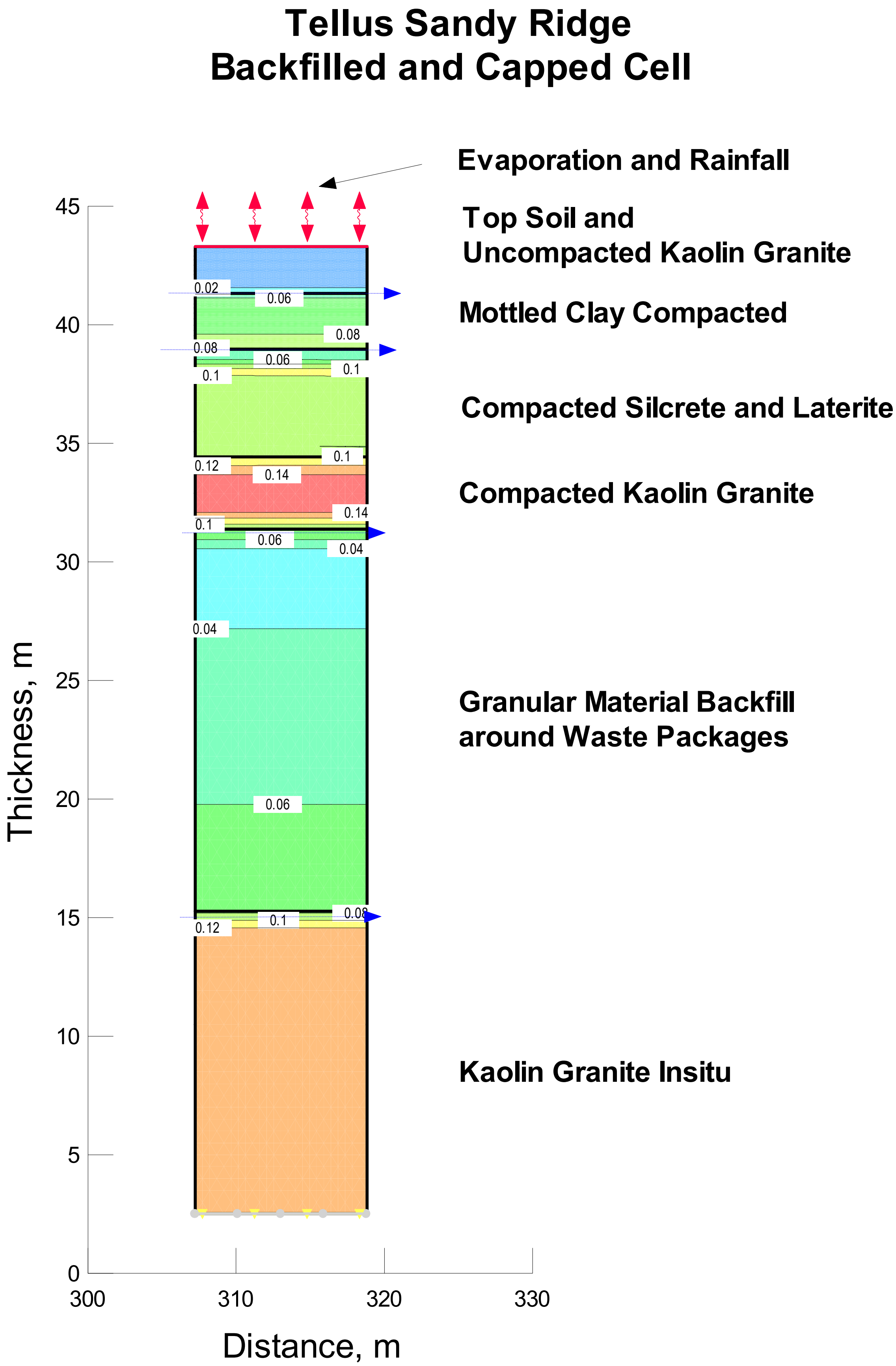


Figure 25: S4 Predicted Moisture Content after 100 Years

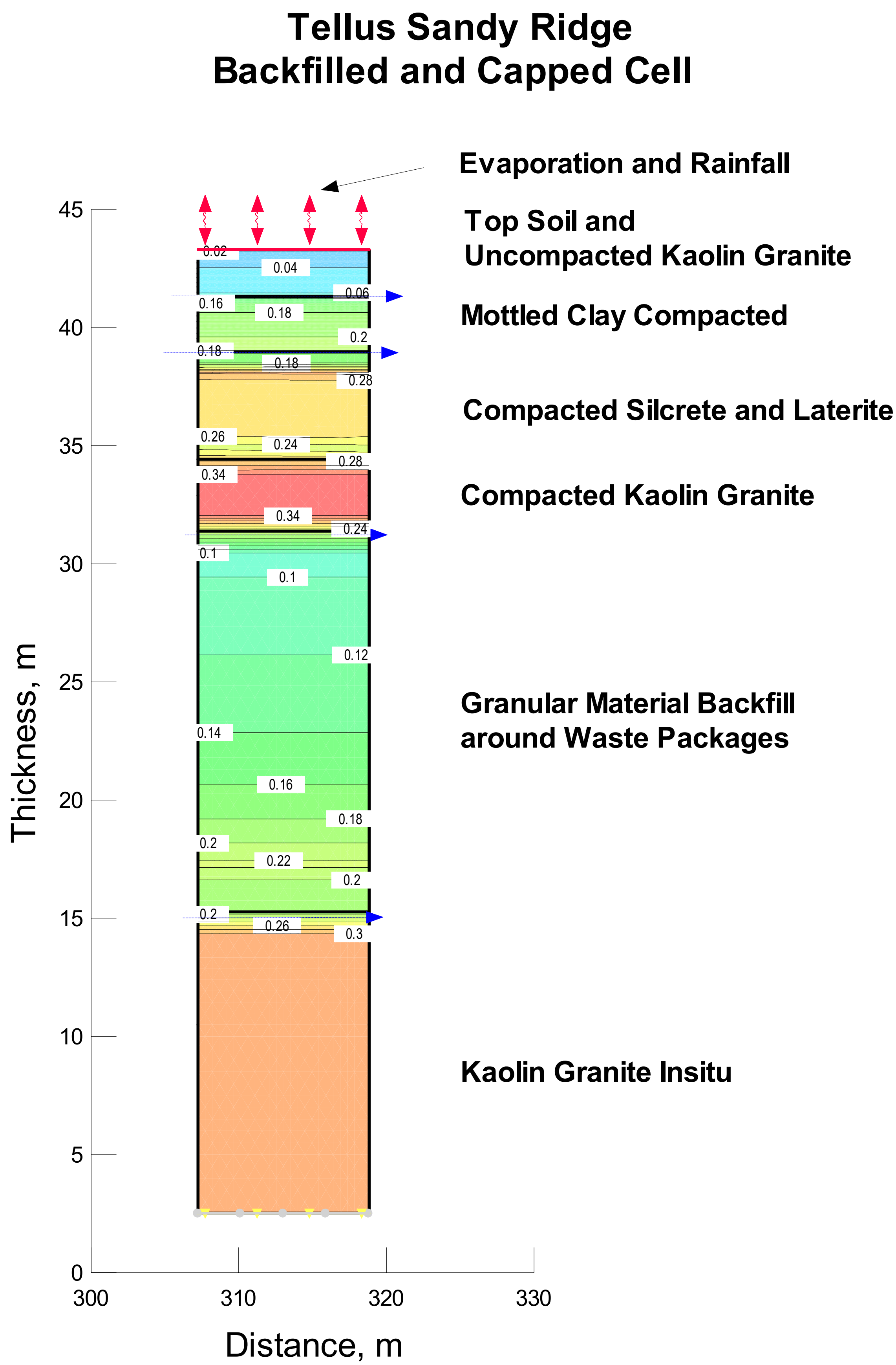


Figure 26: S4 Predicted Saturation after 100 Years
(fraction of material porosity, see Appendix A)

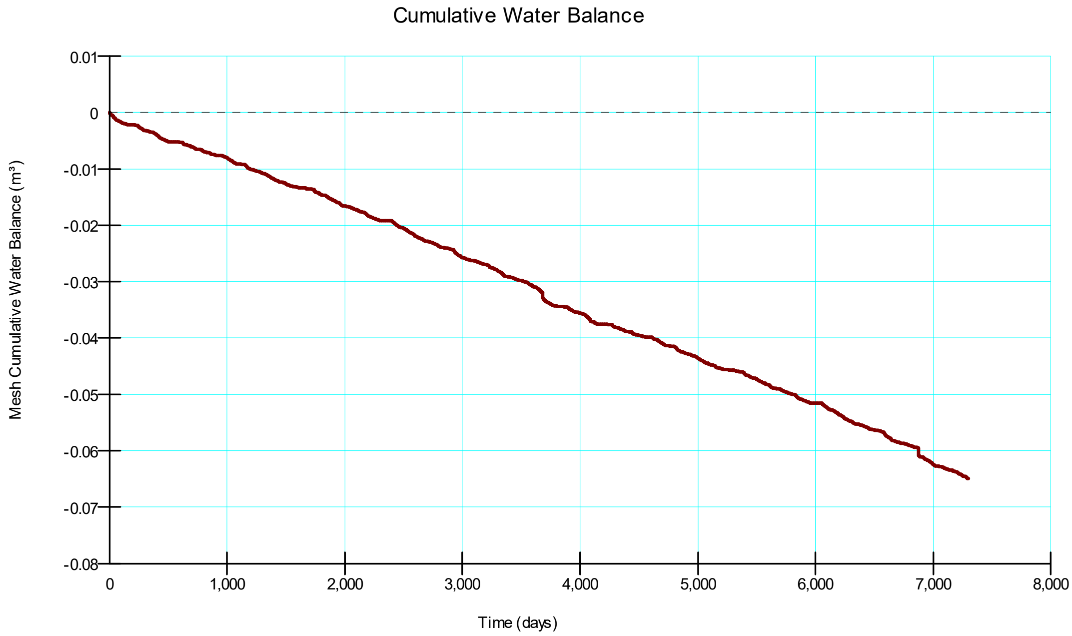


Figure 27: S4 Cumulative Water Balance

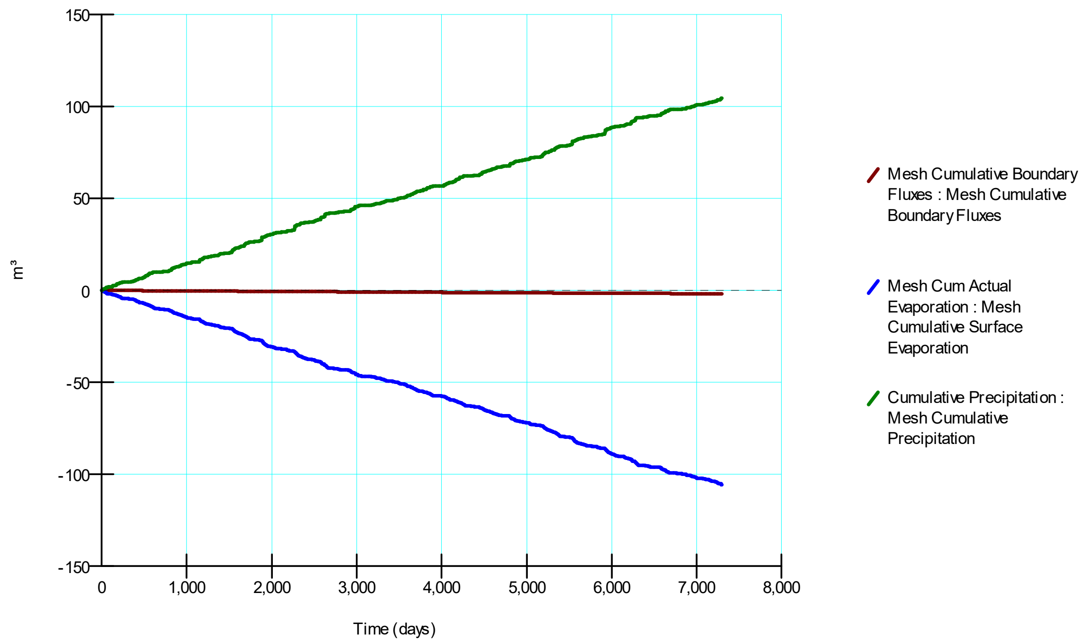


Figure 28: S4 Major Water Balance Components

6.6 Discussion of Results

The results of the simulations, as described above, indicate that the infiltration of rainfall into a cell is limited by:

1. Runoff from the relatively low hydraulic top soil and waste rock (kaolinised granite), due to the sloping of the cell cap; and
2. Evaporation of infiltrated water from the shallow top soil and waste rock that is retained above the compacted mottled clay cap, and thereby subject to evaporation/evapotranspiration between rainfall events.

The runoff process is important as it limits the residence time of rainfall on the surface of the cell, which in turn limits the time for infiltration of rainwater into the top soil/waste rock cover. The second process of evaporation is analogous to what is occurring naturally in the undisturbed ground where:

- Rainfall infiltrates and vertically migrates to the silcrete layer where it accumulates due to the silcrete being relatively impermeable.
- The silcrete is typically within 3 metres of the surface, which maintains the infiltrated water close to the surface where it is subject to evapotranspiration.

In the case of the designed cap for the cells:

- Rainfall infiltrates the top soil and subsoil, and vertically migrates to the compacted mottled clay cap where it accumulates due to the reduced hydraulic conductivity of the capping material;
- The compacted mottled clay cap is typically within 2 metres of the surface, which maintains the infiltrated water close to the surface where it is subject to evaporation/evapotranspiration;
- Water that infiltrates the clay cap is subsequently retarded by the kaolinised granite seal, which provides additional time for some evaporation and storage.
- Infiltration to depth is higher in the capped cell due to the higher hydraulic conductivity of the compacted clay cap and the compacted clay seal, when compared to the in situ silcrete.

Consequently, the simulations of both systems indicate that it is important to retain the water near the surface, allowing it to be evaporated, which given the semi-arid nature of the prevailing environment, is sufficient to reduce recharge to less than 0.1 mm/year below the clay cap. If the top soil cover is too thick, infiltration may collect on the surface of the clay cap to form a thin saturated layer, which would significantly increase the infiltration reaching the compacted kaolinised granite seal.

A review of capping systems in the United States showed that those in semi-arid to arid environments typically demonstrated zero infiltration for monolithic clay caps or store and release designs (Benson, 2002). Both of these designs were able to achieve percolation/infiltration rates equivalent to that of a composite capping system (geomembrane/clay). These results are consistent with the results from S1 and S3 and can be considered a verification of the model.

Similar results for a semi-arid climate were recorded at waste rock dumps in the Pilbara, where store and release systems with a 4 m thick cover of waste rock with a hydraulic conductivity of $5x10^{-5}$ m/s showed zero infiltration for annual rainfall similar to that measured at the project (Meiers et al, 2010).

Consequently, it is important that the encapsulation system be constructed to prevent saturated zones being formed on top of the clay barriers (i.e. the mottled clay cap and the kaolinised granite seal on the cell) by promoting runoff and having sufficient thickness of material to allow evaporation, and caps having low hydraulic conductivity to limit infiltration into the cell area.

6.6.1 Seepage

Based on the model results, it is likely that less than 0.008 mm/year of seepage will emanate from the base of a capped and sealed cell. Assuming a 7,200m^2 surface area of a cell, this flux equates to 57L/year of seepage averaged across the entire cell area, assuming the modelled rainfall conditions of continuous wettest years recorded for 100 years. This seepage will enter the in situ kaolinised granite which has an estimated hydraulic conductivity of $4x10^{-6}$ m/sec, which is significantly higher than the capping system. It is anticipated that this seepage will vertically migrate to depth, or be stored in the unsaturated zone below the repository as discussed in section 6.4.3. In the model, the vertical migration of seepage is via a unit gradient boundary condition, which is equivalent to simulating a water table at depth and is consistent with the actual conditions at the site.

Given the volume of seepage estimated from the simulation, the hydraulic conductivity of the kaolinised granite, the inferred depth to the water table, and the unsaturated storage below the repository, it is unlikely that any groundwater mounding will occur in the vicinity of each cell. This is because seepage flow laterally upon entering the water table at depth in the fresh granite (which is consistent with the existing conditions in the Project area).

7 MODEL LIMITATIONS

The application of the model is constrained by the assumptions and limitations inherent in the underlying conceptual model, as well as the approximations made in realizing the conceptualization as a numerical model. The following assumptions and limitations have been made for this study:

1. Flow through all of the modelled formations conforms to Darcy's Law, which explicitly assumes flow through a porous medium. While these conditions are satisfied in the top soil, laterite and weathered granite, it may not apply to the silcrete and fresh granite. Flow in the silcrete and fresh granite may occur through preferential flow paths such as macro pores, vugs/cavities and fractures. In these areas, the model solution for groundwater flow may be in error and not reflect actual conditions. This may result in groundwater velocity being underestimated in these areas.
2. There is no effective aquifer in the model area, and groundwater flow is primarily vertical;
3. All groundwater is locally sourced from rainfall recharge.
4. Any saturated zone is at depth and is not important with respect to estimating recharge.

Model Applicability is shown in Table 20. Based on modelling guidelines (Barnett, 2014), all the models presented in this report are assessed as Class 1 models.

Objective	Achieved	Comments
Simulate groundwater flow within and between all hydrogeological units in the site.	Yes	Models are limited to 1 and 2 dimensions representations, where flow is predominantly vertical.
Establish water budgets for each geological / hydrogeological unit.	Yes	Subject to non-uniqueness of recharge/ hydraulic conductivity distributions.
Provide results that will support the assessment cell designs with respect to recharge.	Yes	
Estimate the likely range and uncertainty of groundwater recharge changes as a result of the construction of cells.	Yes	

Table 23: Model Applicability to Stated Objectives

Given the lack of measured material properties the results of the modelling are indicative, and should be used for the relative assessment of alternatives, rather than the absolute estimate of vertical flows.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The results of the column simulations of unsaturated flow indicate that the infiltration of rainfall into each cell is limited by:

1. Runoff from the relatively low hydraulic conductivity of the top soil and subsoil, due to the sloping of the cell cap; and
2. Evaporation and evapotranspiration of infiltrated water from the shallow top soil/subsoil that is retained above the compacted mottled clay cap.

The simulations indicate that it is important to retain the water near the surface, allowing it to be evaporated/evapotranspired, which given the semi-arid nature of the prevailing environment, is likely to reduce recharge to less than 0.1 mm/year below the clay cap. If the top soil/subsoil cover is too thick, infiltration may collect on the surface of the clay cap to form a thin saturated layer, which would significantly increase the infiltration reaching the compacted kaolinised granite seal.

Based on the model results, it is likely that less than 0.01 mm/year of seepage will infiltrate into the waste storage area. Based on a cell area of 7200 m^2, the annual potential seepage out of the waste storage area is 0.057m^3/annum (57 L/year). This seepage will enter the in situ kaolinised granite which has an estimated hydraulic conductivity of 4×10^{-6} m/sec, which is significantly higher than the capping system. It is anticipated that this seepage will vertically migrate to the water table which in this area is at depth, or be stored in the unsaturated zone below the repository.

Given the volume of seepage estimated from the simulation, the hydraulic conductivity of the kaolinised granite, the inferred depth to the water table, and the unsaturated storage below the repository, it is unlikely that any groundwater mounding will occur in the vicinity of each cell. This is because seepage will be either stored in the unsaturated zone or flow laterally upon entering the water table at depth.

Sensitivity analysis showed that the lower boundary condition has limited effect on the magnitude of the vertical fluxes, other than for the unit gradient, which tends to increase the vertical flux below the compacted kaolinised granite seal.

There is some sensitivity of infiltration to the topsoil/waste rock cover hydraulic conductivity and runoff, both of which tend to increase infiltration and subsequently the saturation in the clay cap and kaolin seal. Under these conditions annual infiltration (seepage) into the granular material that surrounds waste packages increases to 0.4 mm/annum compared to 0.008 mm/annum in S3. The lack of runoff also increases the infiltration as well as the amount of water that must be evapotranspired, indicating that it is important to maintain a sloping surface on the cell surface to encourage rapid drainage.

The results of S4 highlight the sensitivity of seepage to higher hydraulic conductivity of the top soil/subsoil and waste rock, increased saturation in the clay cap and seal and the ponding of water on flat ground.

8.2 Recommendations

Groundwater and climate monitoring should be undertaken to establish base line conditions. This will allow the impact of mining and waste storage to be objectively assessed.

The unsaturated hydraulic properties of the silcrete and backfill material should be determined quantitatively, and used to reduce the uncertainty in future modelling.

Soil moisture probes and other instrumentation should be installed at various depths above the silcrete to establish soil moisture profiles during rain events and subsequent dry periods. This data should be used to calibrate any unsaturated flow models that are developed in the future.

9 REFERENCES

Abu-Hamdeh, Nidal H.; Reeder, Randall C., *Soil Thermal Conductivity Effects of Density, Moisture, Salt Concentration, and Organic Matter*, Pages: 1285-1290, Journal: Soil Science Society of America Journal, Vol. 64 no. 4, 2000.

Barnett, B, Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. And Boronkay, A. (2012). *Australian Groundwater Modelling Guidelines*. Waterlines report 82, National Water Commission, Canberra.

Benson, CH, *Evaluation of Final Cover Performance: Field Data from the Alternative Cover Assessment Program (ACAP*), WM '02 Conference, February 24-28, 2002, Tucson, AZ.

Cook, P.G, 2003, A Guide to Regional Groundwater Flow in Fractured Rock Aquifers, CSIRO Land and Water, South Australia

Douglas Partners, 2015, *Report on Geotechnical Assessment - Sandy Ridge Project Goldfields, WA*, 2015

Farouki, 1981, *Thermal Properties of Soils,* United States Army Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Geoslope, 2012, *Vadose Zone Modeling with VADOSE/W An Engineering Methodology June 2013 Edition*. GEO-SLOPE International Ltd.

Jeffrey, S.J., Carter, J.O., Moodie, K.B. and Beswick, A.R. (2001). *Using spatial interpolation to construct a comprehensive archive of Australian climate data External link icon, Environmental Modelling and Software, Vol 16/4, pp 309-330*. DOI: 10.1016/S1364-8152(01)00008-1.

Nagy L., Akács A. T, Huszák T., Mahler A., Varga G*, Comparison of permeability testing methods,* Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013.

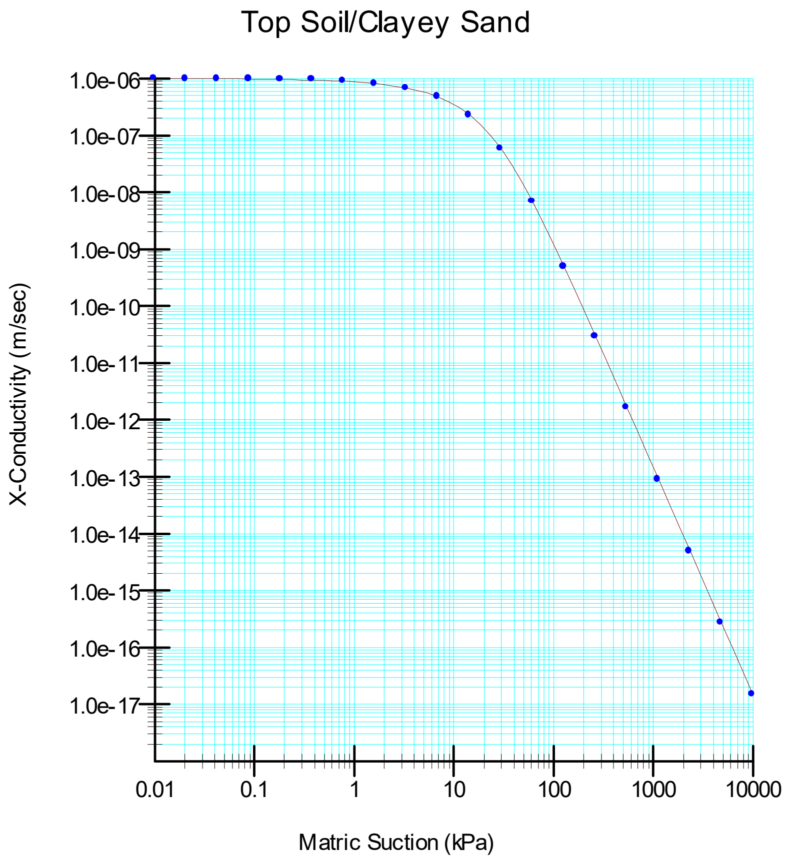
G. Meiers, G., Huys B., Heyes, J., Sommerville, K., Christensen D., O'Kane, M., M*anagement of overburden storage areas at the Mount Whaleback Mine - a review of 12 years of cover system performance monitoring and application to closure.* Mine Closure 2010, Australian Centre for Geomechanics, Perth, Australia.

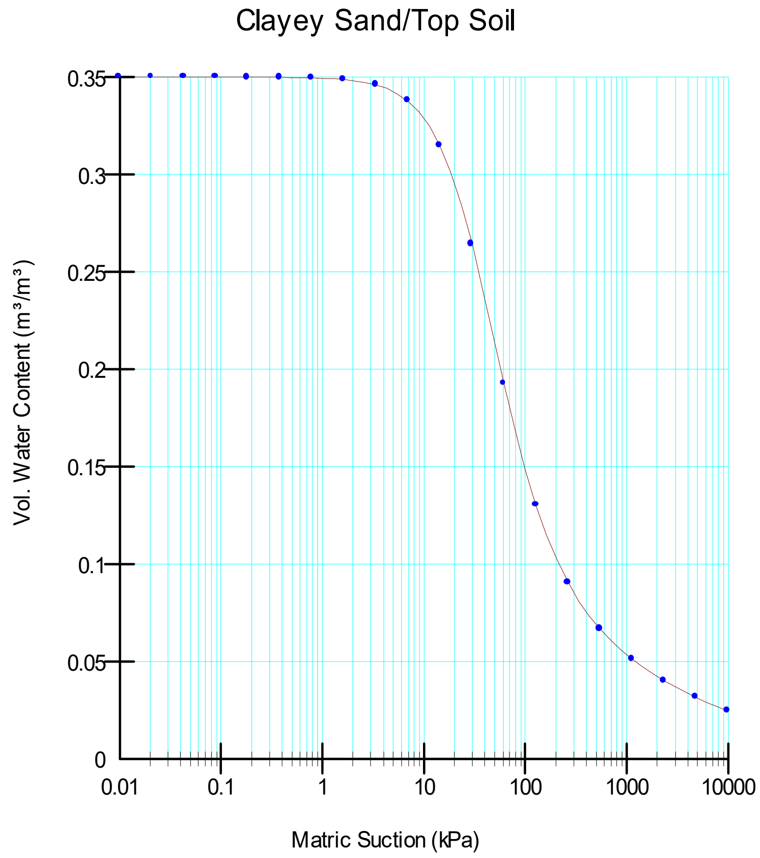
Rockwater, 2015, *Hydrogeological Studies For The Sandy Ridge Project - Drilling, Permeability Testing And Potential Water Sources Report*, Unpublished report for Tellus Holdings, November 2015.

J. V. Turner, M. R. Rosen, L. K. Îtfteld & G. L. Allan, *Chlorine-36 in* hypersaline palaeochannel groundwaters of Western Australia, Application of Tracers in Arid Zone Hydrology (Proceedings of the Vienna Symposium, August 1994). IAHS Pub, No. 232, 1995.

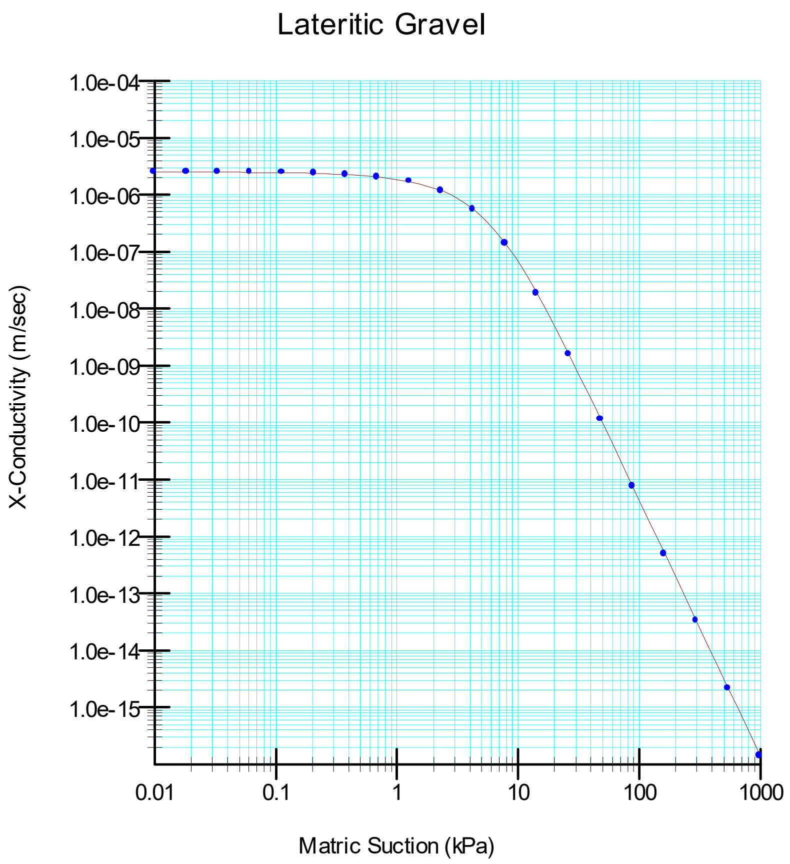
Wood, W. W., *Use and Misuse of the Chloride-Mass Balance Method in Estimating Ground Water Recharge*. Vol. 37, No. 1, GROUND WATER, January/February 1999.

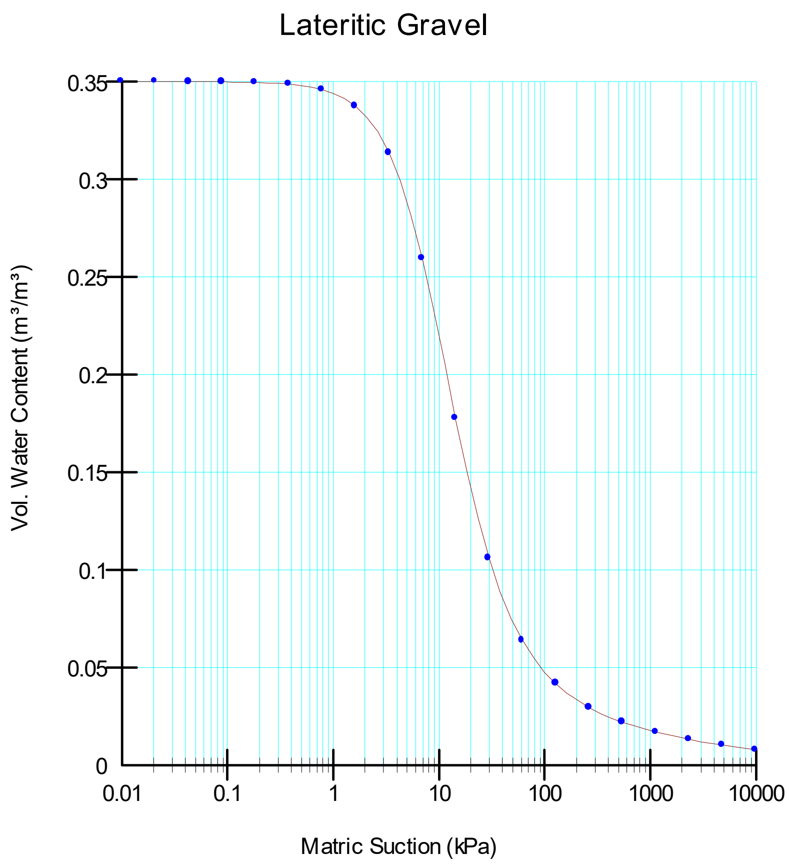
APPENDIX A: MATERIAL PROPERTY FUNCTIONS



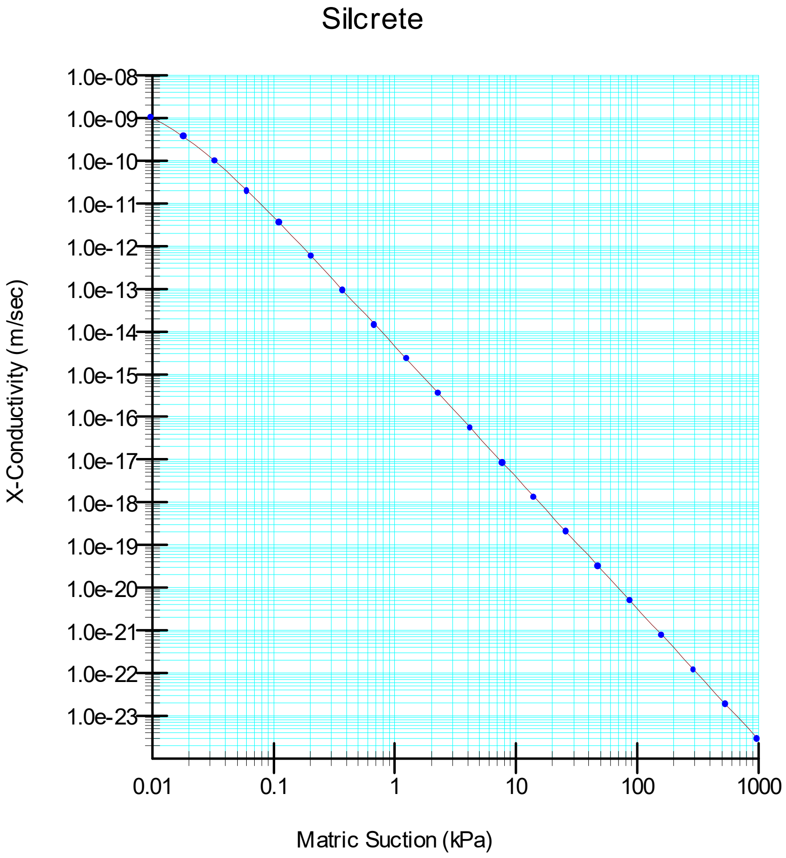


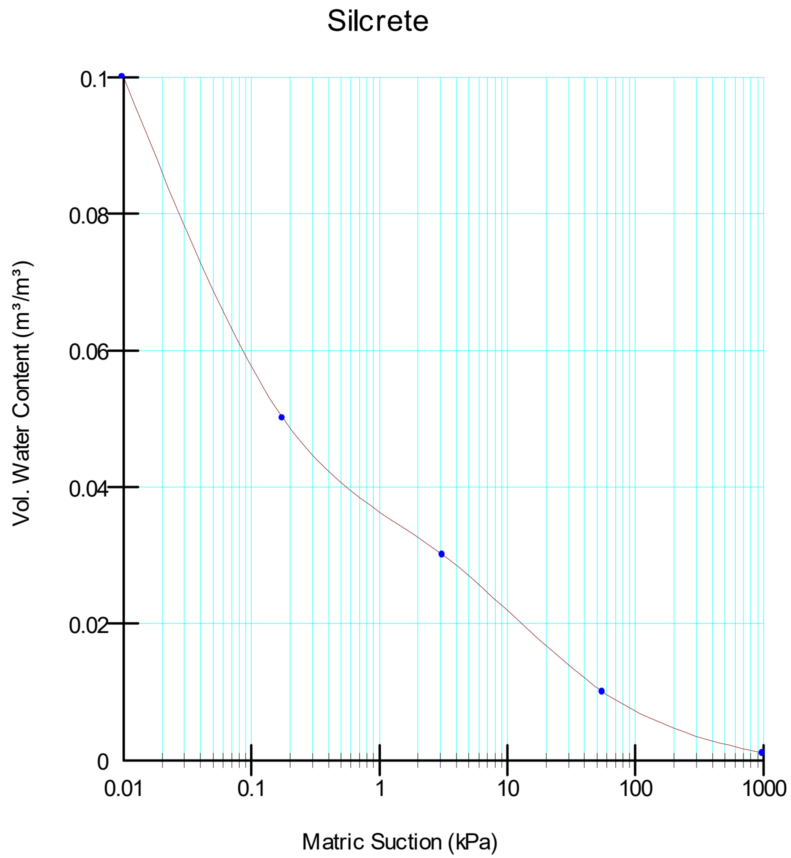
Top Soil/Clayey Sand – Material Properties



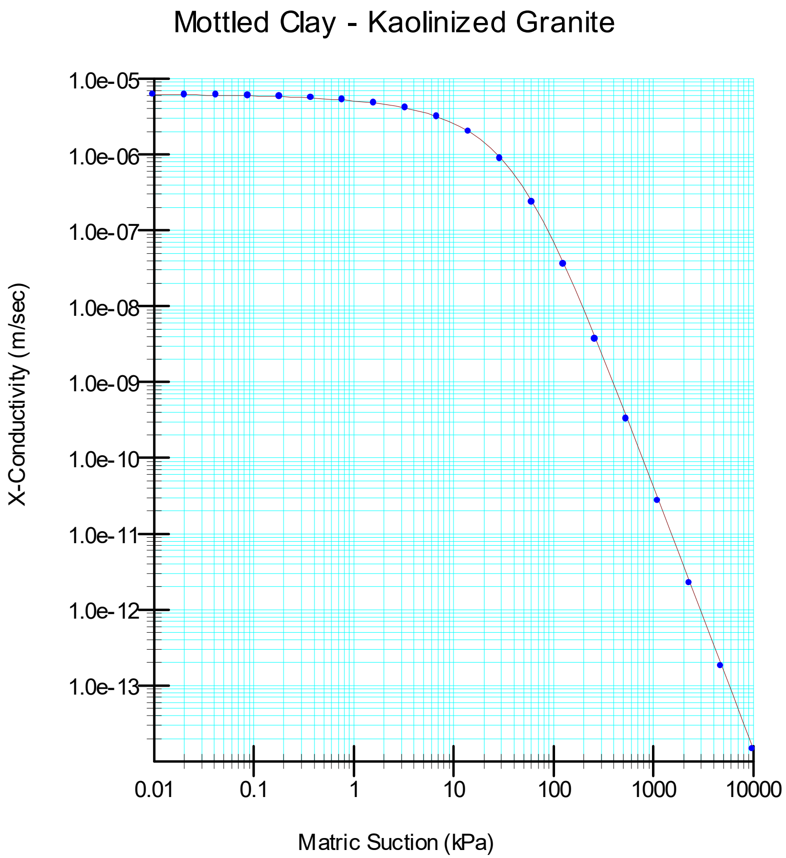


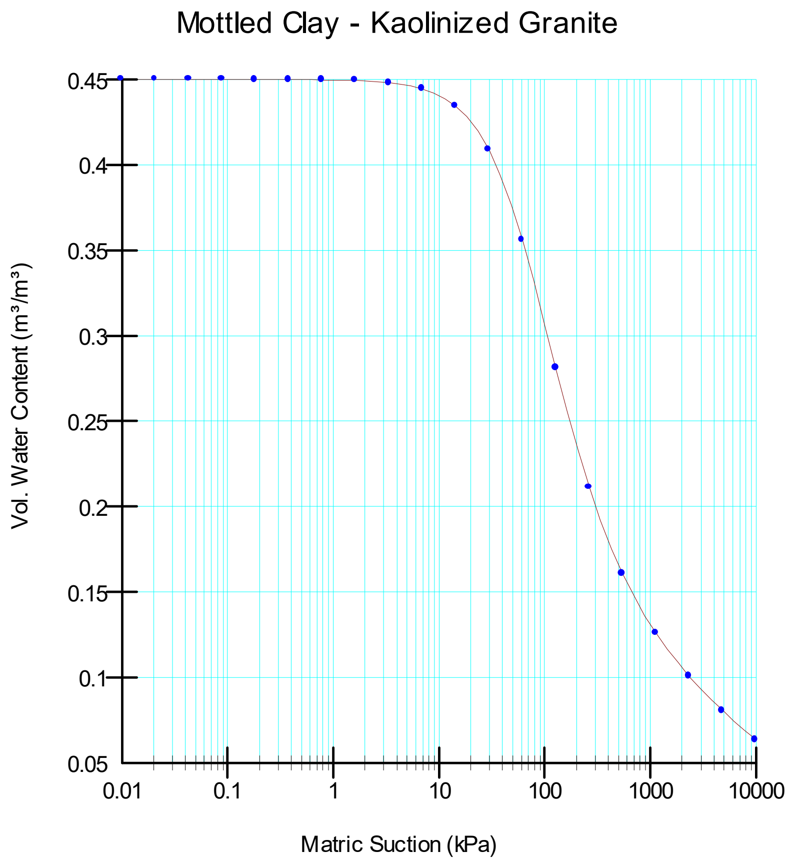
Laterite Gravel – Material Properties



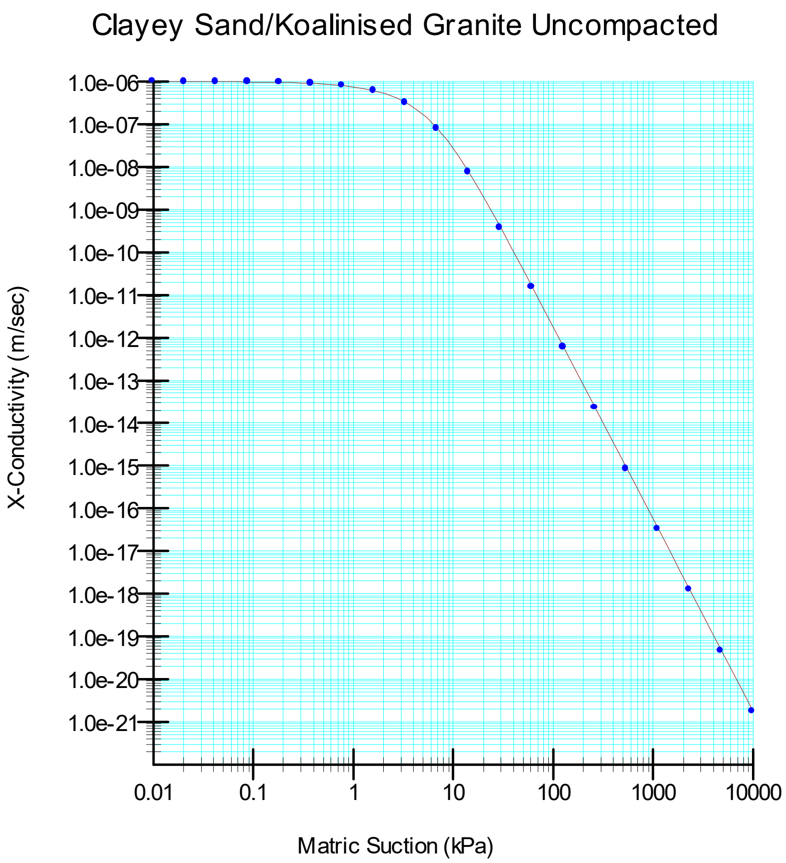


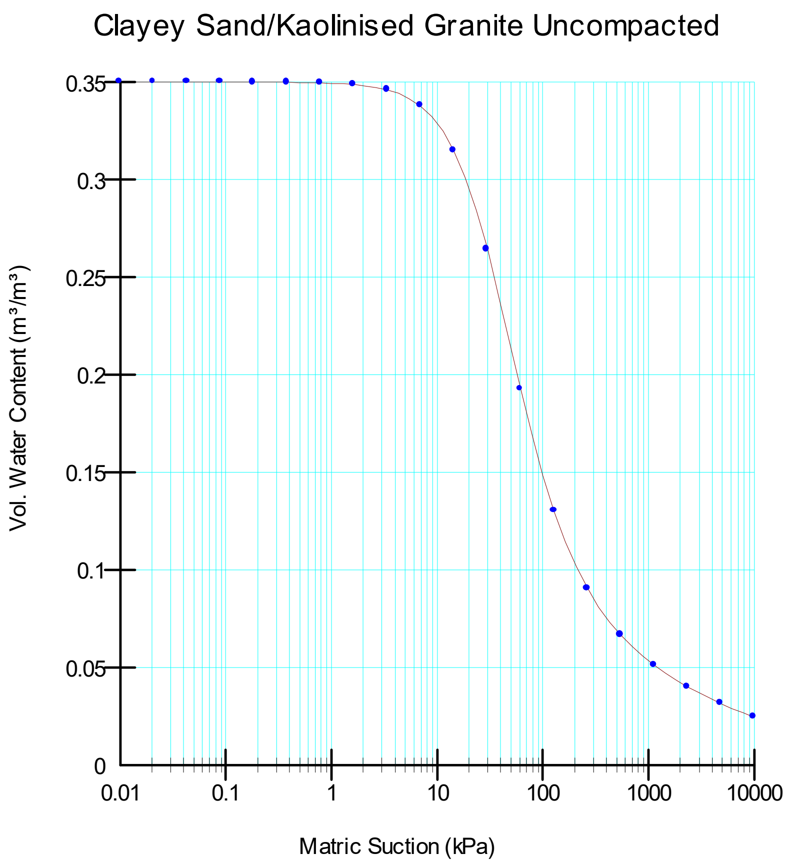
Silcrete – Material Properties



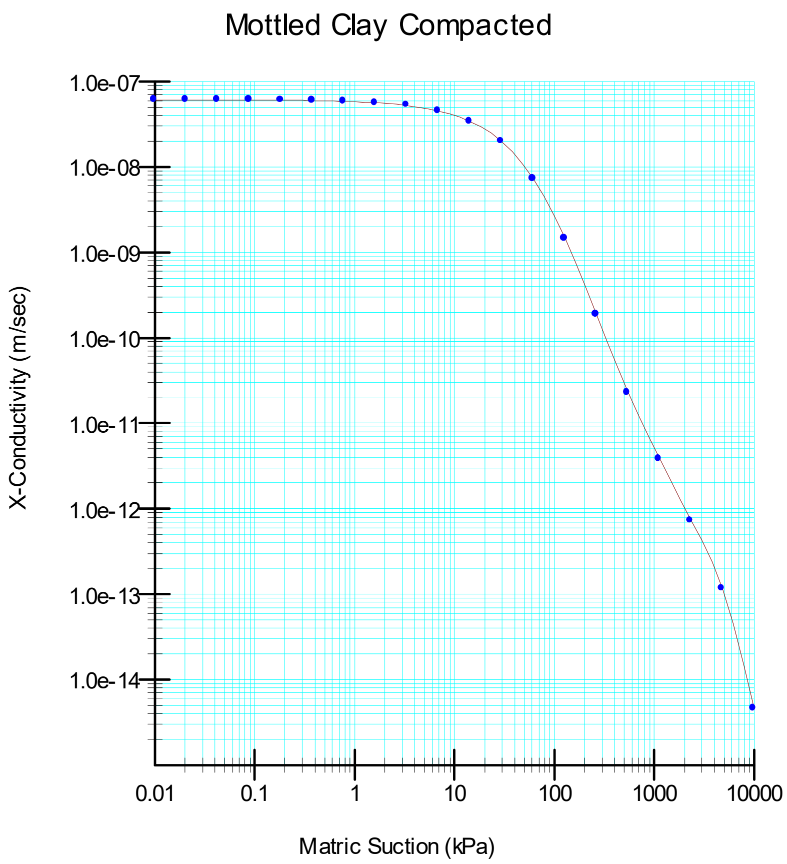


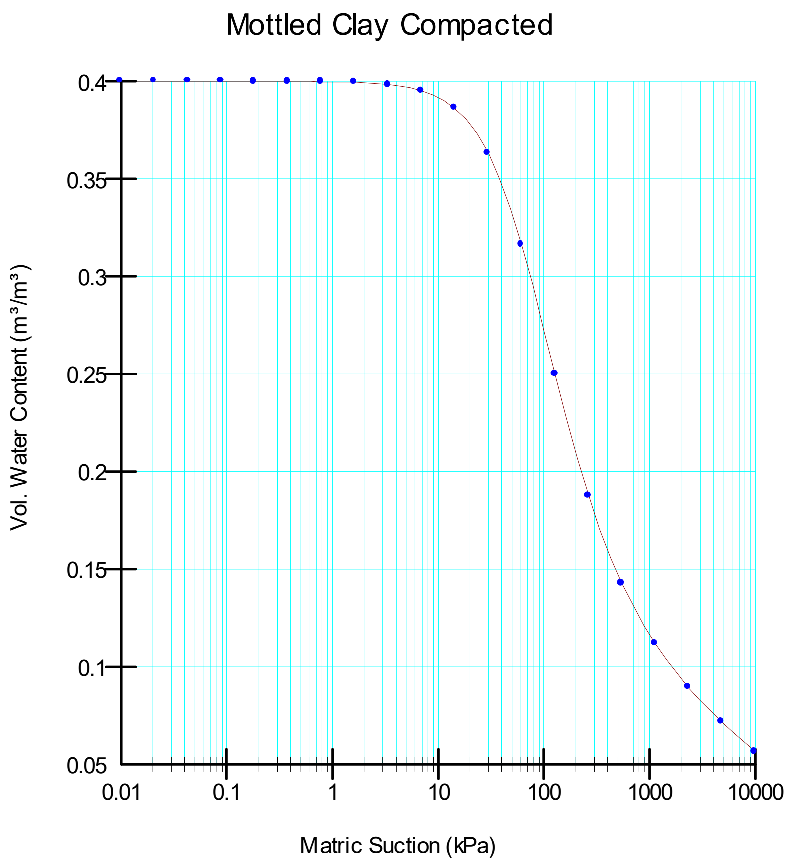
Mottled Clays/Kaolinised Granite – Material Properties



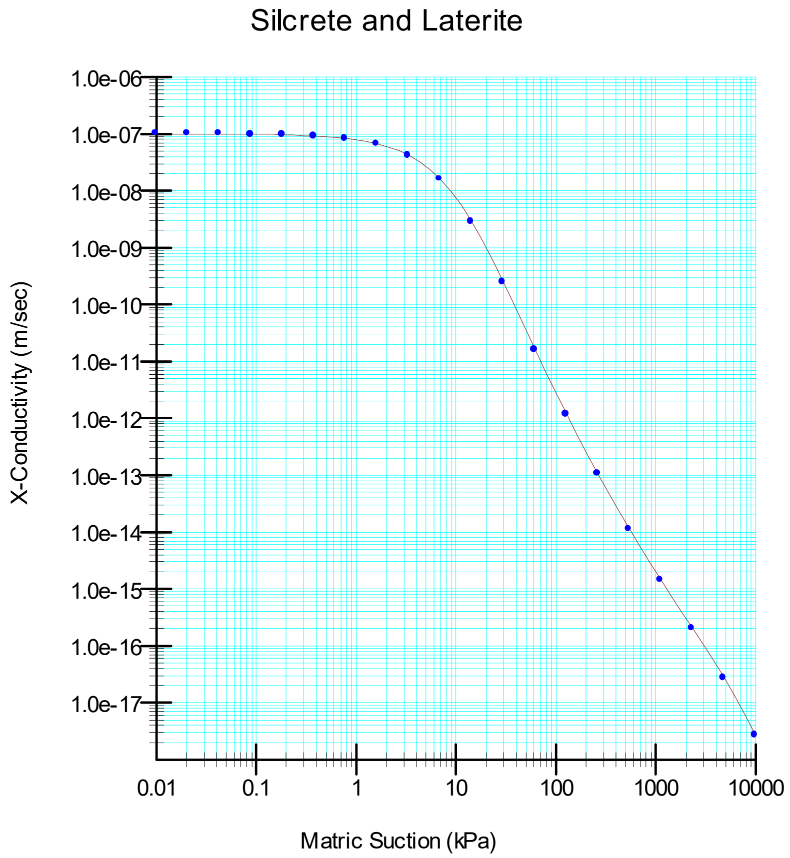


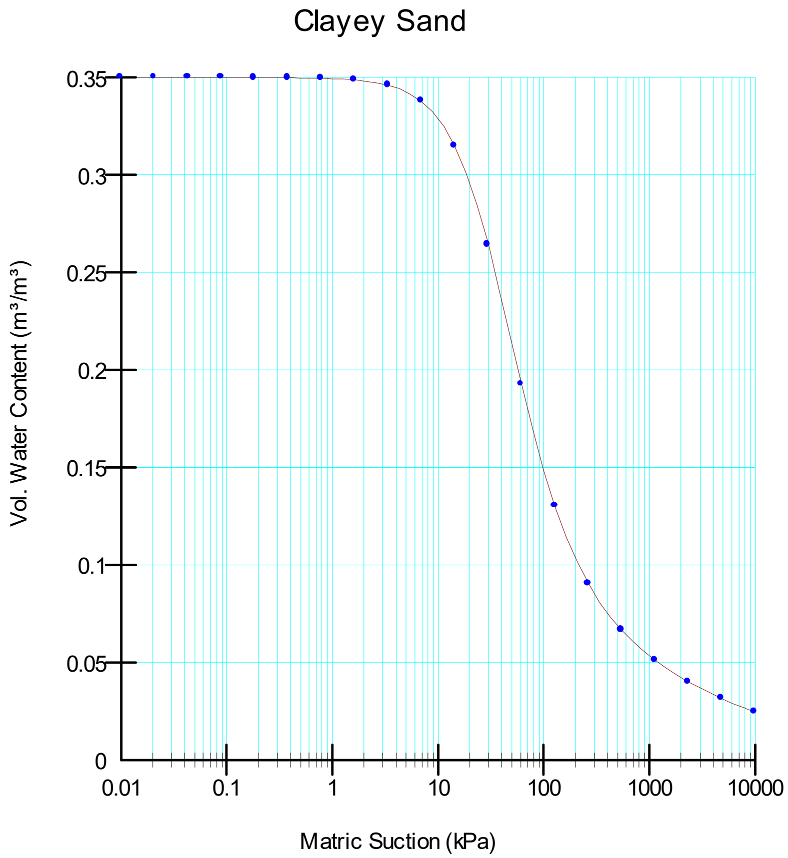
Kaolinised Granite Uncompacted – Material Properties



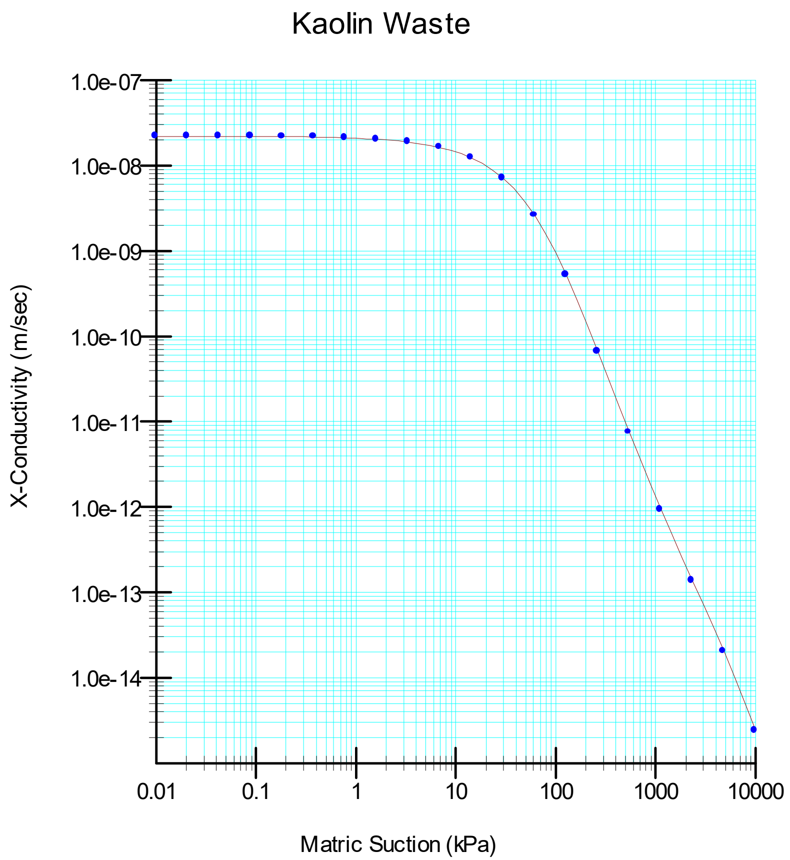


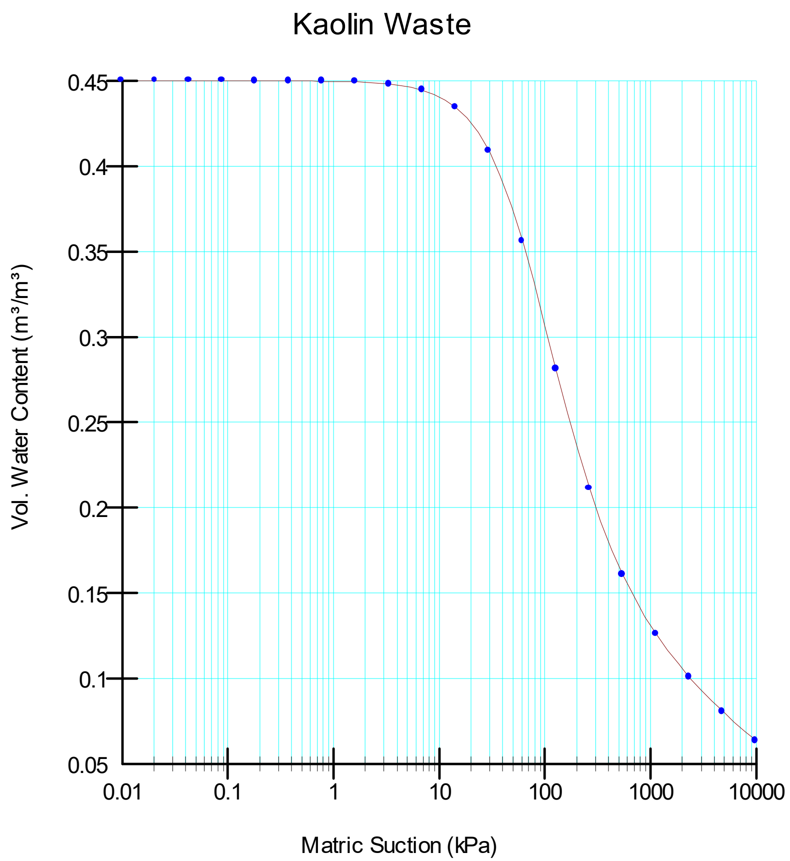
Mottled Clays/Kaolinised Granite Compacted – Material Properties



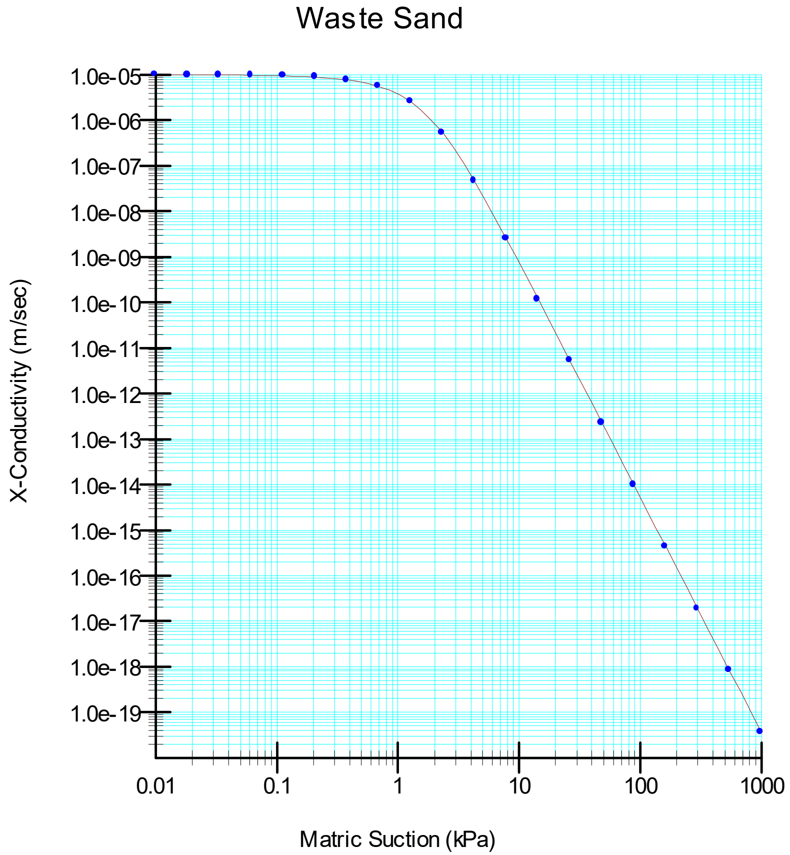


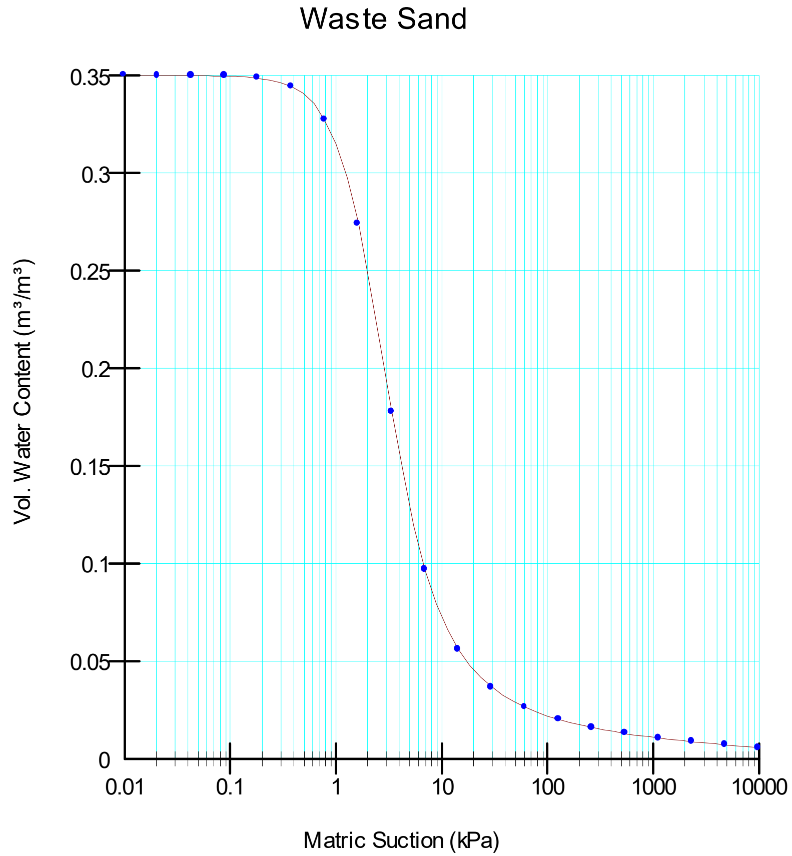
Mixed Laterite, Silcrete and Clayey Sand – Material Properties





Kaolin Waste Compacted


Waste Sand
X-Conductivity (m/sec)
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e-09
1.0e-10
1.0e-11
1.0e-12
1.0e-13
1.0e-14
1.0e-15
1.0e-16
1.0e-17
1.0e-18
1.0e-19
0.01
0.1
1
10
100
1000
Matric Suction (kPa)


Waste Sand
Vol. Water Content (m³/m³)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.01
0.1
1
10
100
1000
10000
Matric Suction (kPa)

Waste Sand