APPENDIX F7

RSF assessment of infiltration and percolation

Olympic Dam Rock Storage Facility:

Assessment of Infiltration and Percolation

Report Prepared for

BHP Billiton
Olympic Dam Expansion Project

Report Prepared by

SRK Consulting
Engineers and Scientists

September 2010

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Assessment of Infiltration and Percolation

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Olympic Dam Expansion Project

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1 Introduction

The proposed Olympic Dam Expansion will include construction of a Rock Storage Facility (RSF) to hold approximately 11.8 billion tonnes of rock that has no economic mineralization. The RSF will wrap around the south, east and north sides of proposed pit and, at completion, will be almost 14 km in total length and will average 4 km in width. The average height will be approximately 125 m.

This report has been prepared to addresses questions raised during the public exhibition of the Draft EIS for the proposed expansion of Olympic Dam regarding surface infiltration and percolation at the RSF. It does so by first reviewing the physical processes that are expected to play a role, and then by developing estimates of the most significant effects on net percolation, *i.e.* groundwater recharge.

Although surface runoff is not the primary focus of this report, estimates of runoff quantities are needed as part of the assessment of infiltration, and therefore will also be presented herein. Implications for contaminant loadings in surface runoff are addressed in a separate report to the Supplementary EIS.

2 Physical Processes

The terms "infiltration" and "percolation" are used interchangeably in some literature, but other literature distinguishes the "infiltration" of water through the soil surface from the "percolation" of water downwards through the soil profile. That distinction is very important in arid regions, where water that has penetrated the soil surface can subsequently be removed by a number of processes, meaning that "percolation" can be much less than "infiltration". To avoid confusion, the term "net percolation" will be used herein to refer to the water that continues to move into the soil and ultimately reports to groundwater.

Climate

In the broadest terms, infiltration and net percolation result from interaction of the local climate with a soil system. The local climate around Olympic Dam was characterized in Chapter 8 of the Draft EIS. Key factors include:

- Dominance of evaporation over precipitation, with average annual pan evaporation rates at Olympic Dam of approximately 3000 mm, and mean annual precipitation of only 160-170 mm.
- Sporadic precipitation, with occasional high intensity, short duration rainfalls spread over an average of about 40 rain days per year.
- Moderate to high variability in year to year total precipitation.

RSF Composition and Construction

The soil system in question here is the RSF. The scale and broad composition of the RSF are predicted in the current mine plans. As noted above, it will be 13,800 m long and 4,000 m wide, covering about 5,500 hectares and it will average about 125 m in height, with a maximum design height of 150 m. The various lithological units that will be encountered as the open pit deepens will all be represented in the RSF. These include:

- Unconsolidated dune sands and clay pans that form the current soil surface;
- Several units of sedimentary rock including Andamooka limestone (ZAL), red Arcoona quartzite (ZWAR), white Arcoona quartzite (ZWAW), Tregolana shale (ZWT), and Corrabera sandstone (ZWC), plus transitional units representing combinations of these;
- Basement granites (GRNB), with smaller amount of basement hematite (HEMQ) and hematitic granite (HEM).

The sedimentary rock units are estimated to comprise about 75% of the RSF tonnage. The current production and deposition schedule shows that the basement material will end up buried within the RSF, so that the RSF surface will consist only of sedimentary rocks. The current plan includes also stockpiling of portions of the dune sand for use as underground backfill, smelter flux, and construction material.

The physical properties of the RSF surface will be determined in part by the weathering behaviour of the sedimentary rocks. Some of the sedimentary units are expected to weather more rapidly than others. Anecdotal observations of aged drill core indicate that the Tregolana shale weathers rapidly to fine material. The quartzite units, containing varying amounts of shale, would be expected to break down more readily than the more competent limestone.

The RSF construction process will also influence the physical properties of the material. The rock will be hauled and end dumped in 25 m lifts. The dumping will cause a sorting of material, with coarser particles rolling further downhill and finer particles remaining near the lift surface. Abrasion and compaction by subsequent traffic will cause a further breakdown of the surficial material to finer grain sizes. The re-distribution of fine particles by localized erosion, and the deposition of salts by Phase 2 evaporation (see below), can further complicate the surface properties.

Infiltration and net percolation will be most strongly influenced by the grain-size distribution of the surface materials. There are currently no samples upon which to base estimates of the final grain size distributions of the RSF surface. In fact, there is no generally accepted way to generate such samples, other than by actually mining the rock at a representatively large scale, placing it in a stockpile, trafficking the surface, and allowing natural weathering to occur. (Estimates of the particle sizes expected to be created by blasting were developed to support assessments of blasting dust, but these do not take into account the effects of excavation, hauling, deposition, abrasion, compaction and natural weathering.) The lack of data upon which to base estimates of surface grain size distributions means that ranges of possible properties need to be considered in predictive modelling.

Below the weathered and trafficked surface, the RSF is expected to be heterogeneous. Examination of other rock piles constructed by end dumping shows a series of angle of repose layers of varying composition and grain size. The Olympic Dam RSF will be constructed from over 32 million truck loads of rock, which gives some indication of the expected heterogeneity. As noted, each lift will be 25 m in height, meaning that any water that manages to infiltrate the surface will encounter several more abraded and compacted horizons as it percolates downward.

Infiltration and Runoff

Precipitation that falls in a given area is normally considered to either evaporate, run off, or recharge groundwater. However, those terms are hydrologic in origin, meaning that they represent large scale observations rather than physical phenomena. At the small scale, and particularly in arid climates, things are more complicated:

- When light rains falls on a hot surface, some fraction of the precipitation evaporates almost immediately. That process continues until the surface cools, normally only a matter of minutes.
- When the soil surface is dry soil prior to the rainfall, another fraction of the initial precipitation is taken up in wetting the soil surfaces. Some researchers refer to this process as “adhesion’ and suggest that it can account for up to 10% of the water retained by coarse grained soils. (e.g. Aubertin et al, 2003).

- The next fraction of the precipitation is pulled into soil pores by capillary effects, or capillary suction. Very dry soils can take several percent moisture by weight into capillary storage before any flow is possible.
- If the rainfall continues with sufficient intensity, water will begin to fill the larger soil pores and infiltrate the soil surface. Hydrologist have classically characterized this phase as a saturated flow driven by gravity and soil suction (e.g. Green and Ampt, 1911). More recent work has shown that, depending on the rainfall intensity and soil structure, the flow type can range from unsaturated flow through the soil matrix to channelized flow through open “macropores” (e.g. Nichol 2002).
- If rainfall continues at a rate that exceeds the initial infiltration capacity of the soil, small puddles or “surface ponding” may develop. The ponding adds pressure to the infiltrating water, and increases the chance of the water finding its way to macropores.
- Depending on the surface slope and texture, the puddles may need to deepen before they are sufficiently continuous to flow laterally as “surface overflow”. If they reach the surrounding environment before being trapped or infiltrating, they become “runoff”.

Water Retention and Unsaturated Flow

The water that infiltrates the surface is subject to further complexity:

- Adhesion and capillary effects create a “matric suction” that acts to hold water in the soil. The strength of the effect is greater when the soil is drier. Therefore, the initial infiltration from a precipitation event is tightly captured within the soil, and downward percolation only becomes significant once the soil gets wetter.
- Matric suction effects are also strongly dependent on the soil grain size and fabric. Finer grained soils exhibit much higher suctions than coarse grained soils, i.e. they tend to retain more water. In theory, the size distribution of a soil can be used to predict its “soil water characteristic curve”, which shows the matric suction developed at each water content. In practice, SWCC’s are very difficult to predict without testing and may in fact not be unique, i.e. they can vary depending on the wetting and drying history of the soil.
- The ability of a soil to allow flow also varies with the water content. Wetter soils tend to have more interconnected water channels and therefore exhibit a greater hydraulic conductivity. Again the relationship between water content and hydraulic conductivity is known to be dependent upon the soil’s grain size distribution, but theoretical models are insufficient and testing is normally required.

Evaporation

Some of the water that is retained by the soil will evaporate. Evaporation from soil surface is normally considered as a three phase process:

- In Phase 1 evaporation, water retained on the soil surface or in near surface pores evaporates directly at rates that approach the maximum potential evaporation rate.
- Phase 2 evaporation begins once the surface water is gone. It requires water to be transported upwards to the surface from deeper in the soil profile. Matric suction

provides the driving force. Phase 2 evaporation slows over time, as the water needs to be drawn from increasing depths. Nonetheless Phase 2 evaporation is very significant in arid regions, and is generally the main reason why net percolation is significantly less than infiltration.

- In Phase 3 evaporation, the water moves to the soil surface as a vapour only. It is generally only noticeable once the Phase 2 process has removed the mobile liquid water from the upper soil. Phase 3 evaporation can be significant in arid regions where there are long dry periods between rain events.

When vegetation is present, evapo-transpiration can also be significant. It involves the taking up of water by plant roots and the release of water to the air by transpiration through the plant leaves. The sparse vegetation of the area suggests that evapo-transpiration will not be significant on the Olympic Dam RSF.

In the Olympic Dam RSF, Phase 2 evaporation is likely to cause the net transport of salts to the soil surface. That process is of most significance for its effect on runoff water quality. But there is some evidence that the resulting salt deposits can clog soil pores sufficiently to reduce water vapour losses and at least temporarily impede infiltration.

Deeper Percolation

The behaviour of water that passes deeper into rock piles is very poorly understood. In general, flows sufficient to saturate the material are thought to percolate through coarse channels, while unsaturated flows are thought to move downwards at a much slower rate through the finer-grained matrix. In an arid environment like Olympic Dam, one would expect the latter pattern to be dominant.

The pile construction history also plays a role. Rock piles in wetter climates can have water tables and lateral flows along buried lift surfaces. There may not be sufficient water to generate lateral flows within the Olympic Dam RSF, but one would still expect the buried lift surfaces to be influential. In particular, any water that does percolate through rapid flow channels would have a high likelihood of being intercepted and attenuated by the buried lift surfaces.

If percolating water reaches the original ground surface, it can be further attenuated and directed laterally. For example, seeps are commonly observed along the toe of rock piles in wetter climates. The clay pan layers in the natural soil at Olympic Dam could theoretically have a similar effect on water percolating through the RSF. However, the flat gradients and the long distances to the middle of the RSF make it likely that any toe seeps would be highly localized, and play little role in the overall RSF water balance.

Water Vapour Movement

Water vapour movement was mentioned above in conjunction with Phase 3 evaporation. The mechanisms involved are quite complex. The vapour movement is normally characterized as diffusion driven by the differences water vapour concentration (i.e. humidity) within and above the soil. However, measurements have shown the rate of water removal to be higher than can be accounted for by simple diffusion. One explanation is that the water vapour transport is also driven by differences in temperature, specifically by the fact that warmer air within a soil can carry much higher concentrations of water vapour than cooler air at the soil surface (e.g. Hillel, 1980). Complex patterns of diurnal evaporation and condensation have been observed in some cases (e.g. Zhang and Huang, 2004).

Once the water percolates below the upper soil layer, it will continue to reach equilibrium with the pore air in the underlying rock. The resulting water vapour could be removed by bulk gas transport mechanisms. One such mechanism is “barometric pumping”, the movement of air in and out of the ground in response to cycles of atmosphere pressure. Barometric pumping has been observed to transport soil gases at great depths in dry regions, and to affect oxygen concentrations in reactive waste rock (e.g. Smith et al. 1999, Hockley et al. 2000). The scale of the Olympic Dam RSF means that it will be subject to barometric pumping, and the low water contents under consideration mean that the resulting water vapour removal could be relatively significant.

Recent work on reactive waste rock has shown the importance of thermal convection as another mechanism of bulk gas movement (e.g. Hockley et al 2009). Thermal convection in this context means the bulk flow of pore air in response to temperature differences between the waste rock and the surrounding air. Water vapour would also be transported by thermal convection. Again the scale of the Olympic Dam RSF and the relatively low moisture contents under consideration mean that thermal convection could be a significant mechanism of water removal.

3 Predictive Modelling

3.1 Approach

As noted in the preceding section, the interaction of a local climate with soil and rock materials leads to a range of complex physical processes. However, there are well established mathematical models for assessing some of the important physical processes. In particular, models of water infiltration, evaporation, and percolation have been extensively developed in the agricultural sciences and more recently have been extended to the modelling of water movement in mine waste and waste cover systems. These models are generally based on Richard's law, which describes the movement of soil water in response to matric suction. The matric suction is in turn determined by the soil properties, notably the grain size distribution.

An additional complication for the Olympic Dam RSF is the inability to predict the rock's grain size distribution. As noted above, there is no way to accurately predict how the rock excavation, hauling, deposition, compaction, abrasion and natural weathering will affect particle sizes. In the absence of such data, the best that can be done with any Richard's law modelling is to assess the range of possibilities. Fortunately, there exists a great body of literature data on soil types, size distributions, and their associated hydraulic properties. While it is impossible to pick a particular set of literature data and claim that it represents a particular RSF rock, it should be possible to select a range of data to represent the possible range of RSF rock properties.

That approach is adopted for the modelling of soil water movement described in Section 3.2 below. The unsaturated water flow model Hydrus-1D is used to assess ranges of infiltration, evaporation and net percolation. Literature data for materials ranging from a clean gravel to a silty sand are used to represent the range of material properties that could develop on the RSF surface. Meteorological records from the project area are used as climate inputs.

Section 3.3 then examines the possible effects of processes involving water vapour. Mathematical models for those processes are not as widely accepted as the liquid water models, so only simple calculations are used. Again the emphasis is on the range of possible outcomes.

Sensitivity analyses are included throughout. The sensitivity results provide insights about how the physical process could be controlled by changes to the rock materials or their handling, and about where future testing would most reduce uncertainties.

3.2 Soil Water Modelling

3.2.1 Hydrus-1D

The soil water modelling was performed using Hydrus-1D software Version 4.14. (Simunek et al. 2008). Hydrus-1D numerically solves Richard's equation for variably saturated water flow, subject to a range of user input material properties and boundary conditions. The model was developed as a cooperative effort of the U.S. Salinity Laboratory and the University of California at Riverside. It is one of the most widely used models for simulating unsaturated water flow in soils.

3.2.2 Material Properties

Four sets of material properties were selected from literature and used to represent materials ranging from a clean gravel to a silty sand. Three of the four property sets were selected from a recent compilation of high quality unsaturated soil data compiled by Perkins and Nimmo (2009). The fourth set was obtained from well-documented studies of sandstone waste rock (Rowlett 2009). In all cases the property sets were chosen to represent the gravel and finer sizes of the mine rock. Cobble and boulder size materials are also common in mine rock piles, especially at depth, but do not contribute to the unsaturated water flow properties of the surface layer.

Table 3.1 summarizes the four material types, their grain size distributions and their unsaturated hydraulic properties. Figures 1 and 2 show the grain size distributions and soil water characteristic curves. In brief:

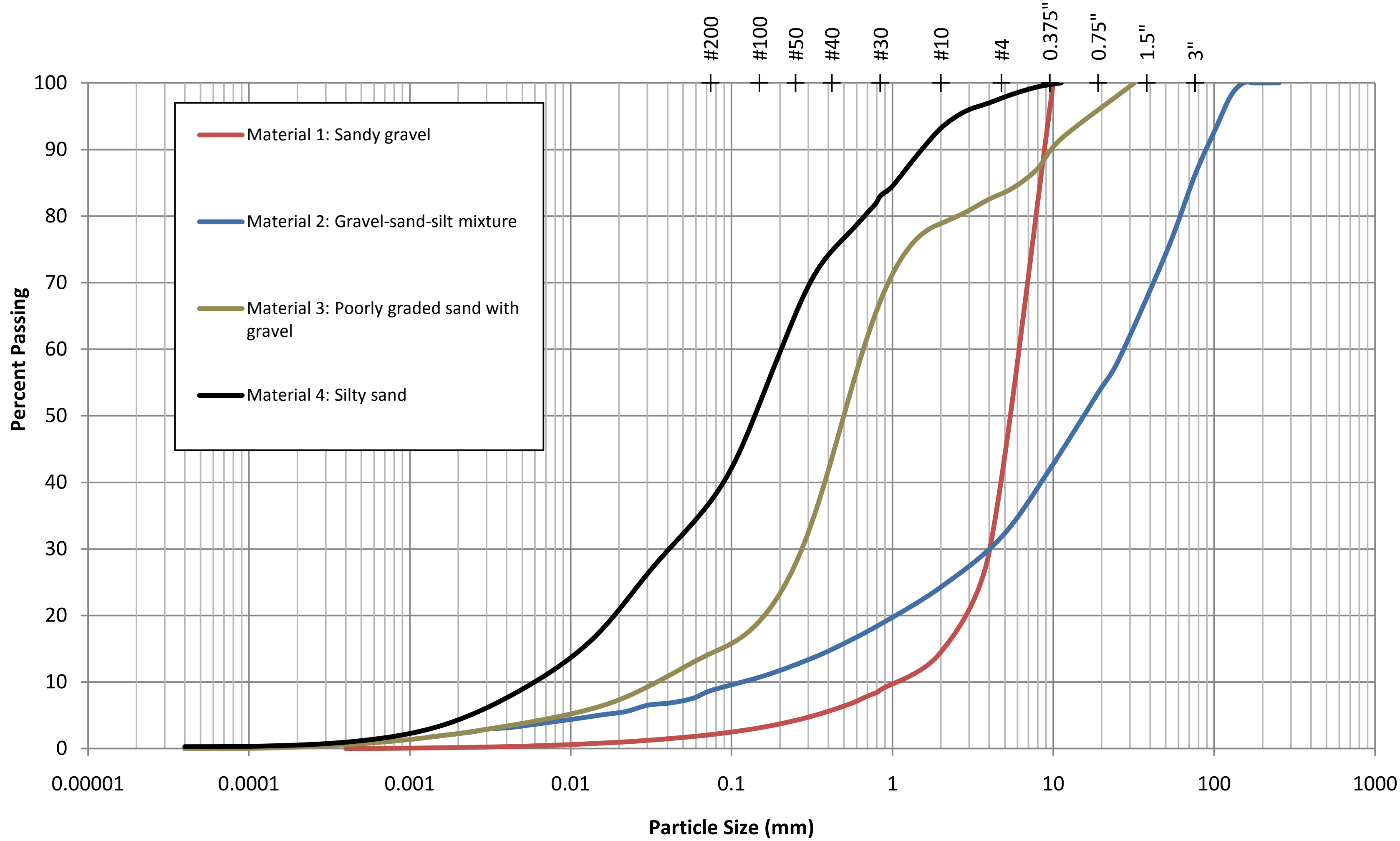
- Material 1 is one of the coarsest soils in the Perkins and Nimmo (2009) data set. It is a clean sandy gravel with very low fines content, and is expected to be representative of durable waste rock that undergoes little abrasion or weathering.
- Material 2 is a gravel-sand-silt mixture obtained from the sandstone waste pile at the Cluff Lake Mine in northern Canada, which has been the subject of extensive research by two Canadian universities. It is expected to be representative of brittle sedimentary rock subjected to abrasion and traffic compaction.
- Material 3 is a gap graded sand with minor gravel and minor fines. It was selected from the Perkins and Nimmo (2009) data set to represent rapidly weathering sedimentary materials, such as some of the shales expected to be placed in the RSF.
- Material 4 is a silty sand selected from the Perkins and Nimmo (2009) data set to represent a blend of the dune sand and clay pan materials covering the surface of the project area.

Table 3.1: Material types and properties used in Hydrus-1D modelling

Property	Material 1	Material 2	Material 3	Material 4
Description	Sandy gravel with little or no fines	Gravel-sand-silt mixture	Poorly graded sand with gravel	Silty sand
USCS Code	GW	GM	SPM	SM
Source for grain size distributions	Alluvial deposit gravel sample OGWU85 (Perkins & Nimmo 2009)	Sandstone waste rock sample from Cluff Lake Mine (Rowlett 2009)	Glacial sand and gravel sample WMICFSS Site 2 (Perkins & Nimmo 2009)	Sand dune and clay pan samples ODXH1.2-09T, ODXH1.2-09S, and ODXH2.1-7
% Gravel	90	75	20	5
% Sand	8	18	68	63
% Fines	2	7	12	32
D_{60}	6	30	0.6	0.2
D_{30}	4	4	0.3	0.04
D_{10}	1	0.1	0.03	0.006
C_u	6.0	300.0	20.0	33.3
C_k	2.7	5.3	5.0	1.3
Source for soil water properties	As above	As above	As above	Sample Set #5 148'4"-148'8" (Perkins & Nimmo 2009)
K_{sat} (mm/hr)	19.8	95.8	59.2	0.22
Φ	0.39	0.24	0.31	0.35
α (m^{-1})	17.63	8.05	5.90	2.15
n	1.62	1.37	1.62	1.17

Notes:

- USCS is the Unified Soil Classification System
- Gravel and sand are divided at 7.64 mm in the USCS. British systems use 2 mm.
- D_{60}, D_{30}, D_{10} are the sizes below which 60%, 30% and 10% of particles fall.
- C_u is the coefficient of uniformity = D_{60} / D_{10}
- C_k is the coefficient of gradation = D_{30}^2 / (D_{60} x D_{10})
- SWCC is the soil water characteristic curve
- K_{sat} is the saturated hydraulic conductivity
- Φ is the porosity
- α and n are parameters used in Van Genuchten's formulation of the Soil Water Characteristic Curve and the Unsaturated Hydraulic Conductivity function (Van Genuchten et al. 2009)



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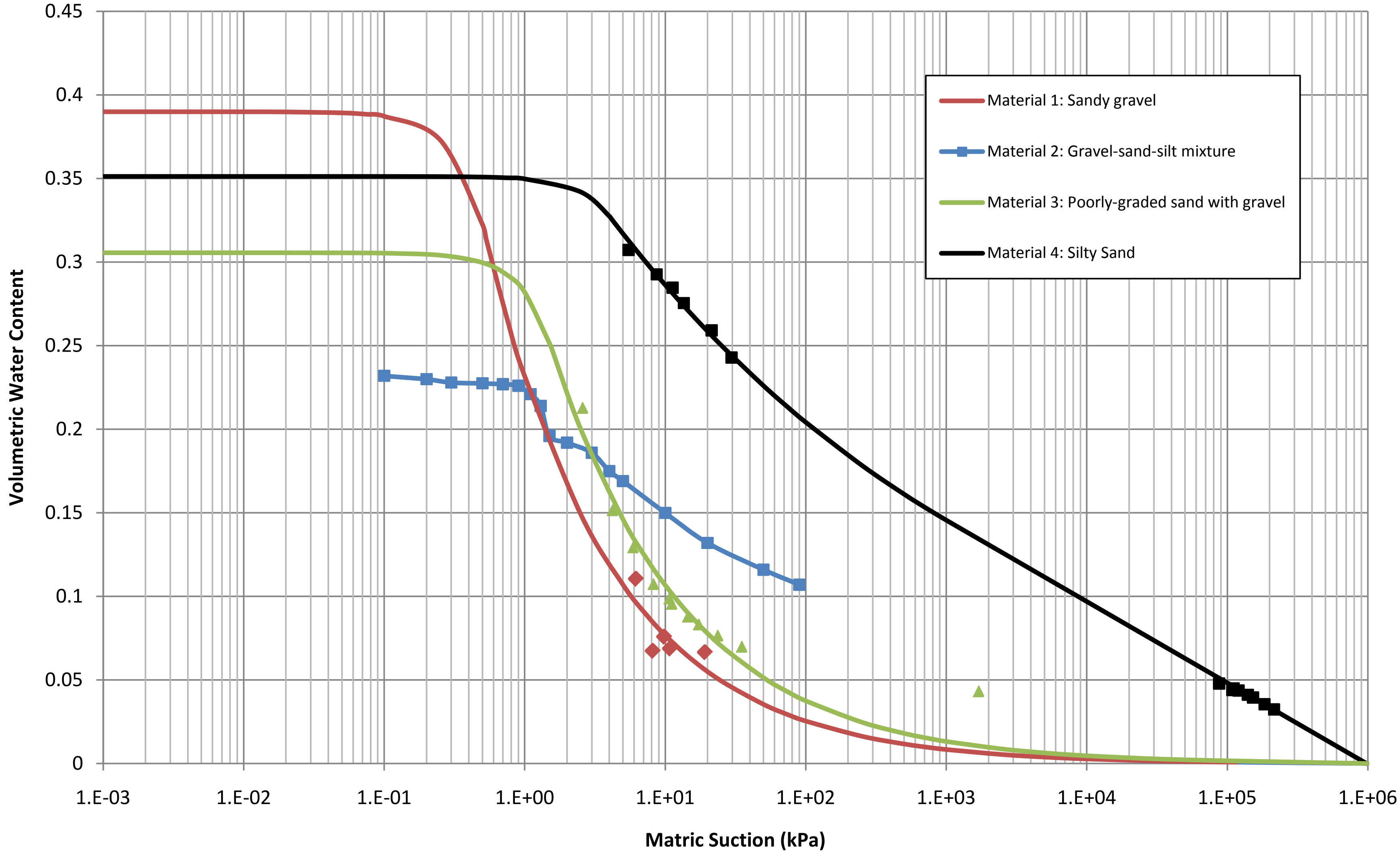
Particle Size Gradations for Model Soils

Job No: 1CAS017.011	Olympic Dam Expansion	Date: May 2010	Approved:	Figure: 1
Filename: Figure 1_GSA_20100507.ppt	Percolation Estimates for Waste Rock Pile			



SRK Consulting Engineers and Scientists VANCOUVER	bhpbilliton	**Soil-Water Characteristic Curves for Model Soils**		
Job No: 1CAS017.011 Filename: Figure 2_SWCC_20100507.ppt	Olympic Dam Expansion Percolation Estimates for Waste Rock Pile	Date: May 2010	Approved:	Figure: 2

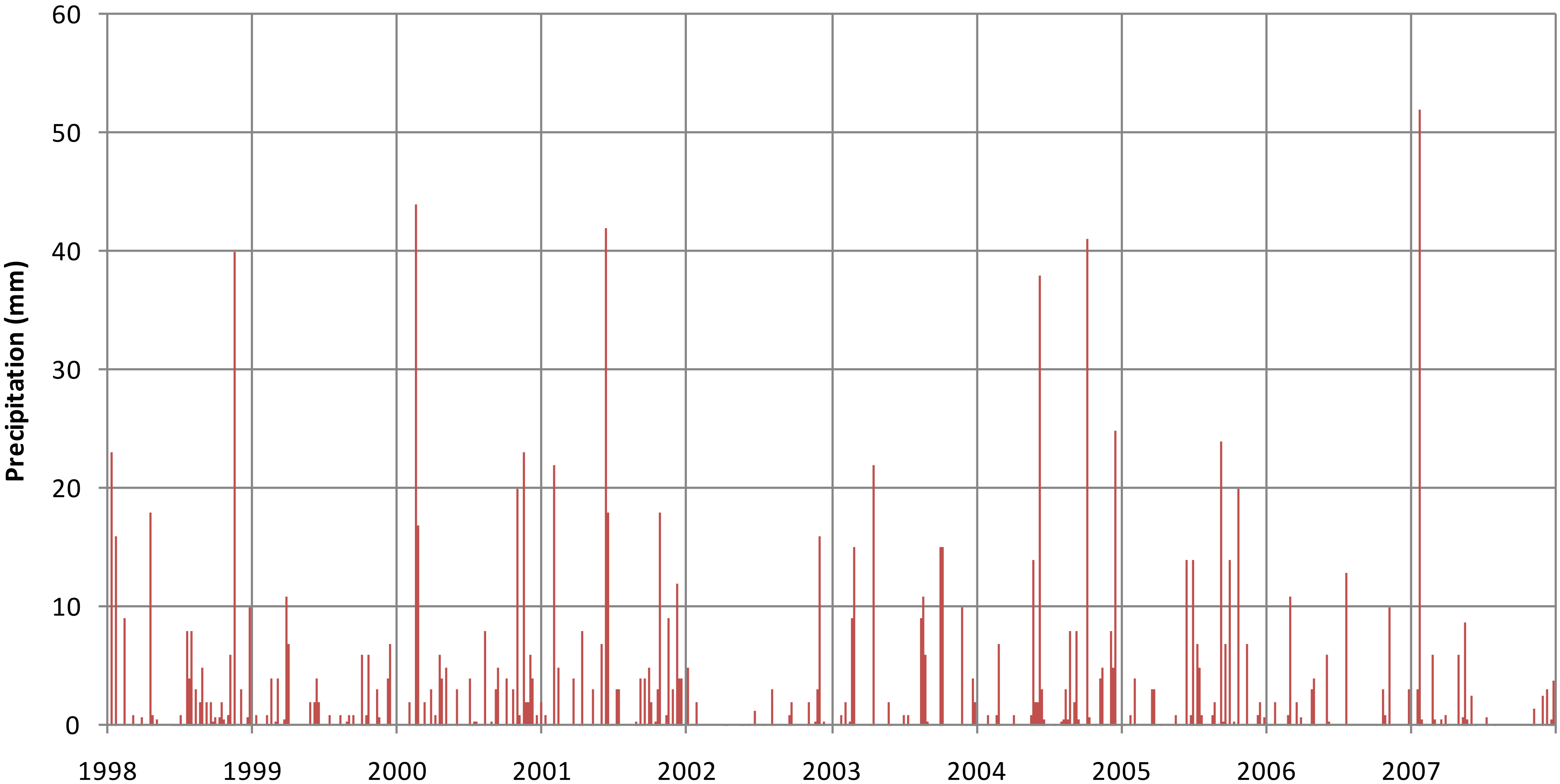
3.2.3 Climate Inputs

Climate data was obtained online from the Australian Government Bureau of Meteorology. Data sources and adjustments needed to prepare the model input were as follows:

- Twelve years of daily precipitation data were available from the Roxby Downs (Olympic Dam Aerodrome - 016096) weather station, covering the period from 1998 to the end of 2009. Data from years 2008-09 were excluded from the model as these were exceptionally dry years. Total precipitation averaged 147 mm/year in the remaining 10 years. The largest single day rainfall event of 52 mm occurred in Jan. 20, 2007.
- Average monthly pan evaporation was obtained from the Woomera weather station (Station number - 016001) located approximately 70 km south of Olympic Dam and totalled 3,100 mm/yr. The Woomera data includes a longer period of record collection than the pan evaporation rate of 3,300 mm/yr measured on site. Woomera pan evaporation rates were converted to potential evaporation by multiplying by 0.7. Monthly average values were entered into the model on the mid-day of the month and daily values were linearly interpolated between the data points.
- Average monthly minimum and maximum temperatures were obtained from the Roxby Downs weather station.
- Average monthly relative humidity values were available from the Woomera weather station at measurement times of 9:00 am and 3:00 pm. The 9:00 am humidity was assumed to be the daily maximum and the 3:00 pm humidity was assumed to be the daily minimum.
- Monthly average values for mean wind speed (at 3:00 pm) and daily solar radiation were also available from the Woomera weather station.

A summary of the average monthly climate parameters is provided in Table 3.2. Figure 3 shows the daily precipitation over the ten-year period used in the modelling.

Precipitation events were initially distributed over a 6-hour period occurring from 12:00 midnight to 6:00 am. That assumption leads to rainfall intensities on the high end of the intensity-duration-frequency curves for the region. As can be seen in Figure 3, the ten-year data record includes six storms of 40 mm or more. When those storms are assumed to occur over six-hour durations, they correspond to rainfall intensities of approximately 7 mm/hr. The rainfall intensity-duration-frequency (IDF) curves for the region, shown in Figure 4, indicate that storms of that intensity and duration should occur only once every two years on average, or slightly less often than was assumed for the modelling. The record also includes eleven storms of approximately 20 mm. When those events are assumed to occur over six hours, the rainfall intensity is about 3 mm/hr. The IDF curves agree that such storms should be occurring once per year on average.



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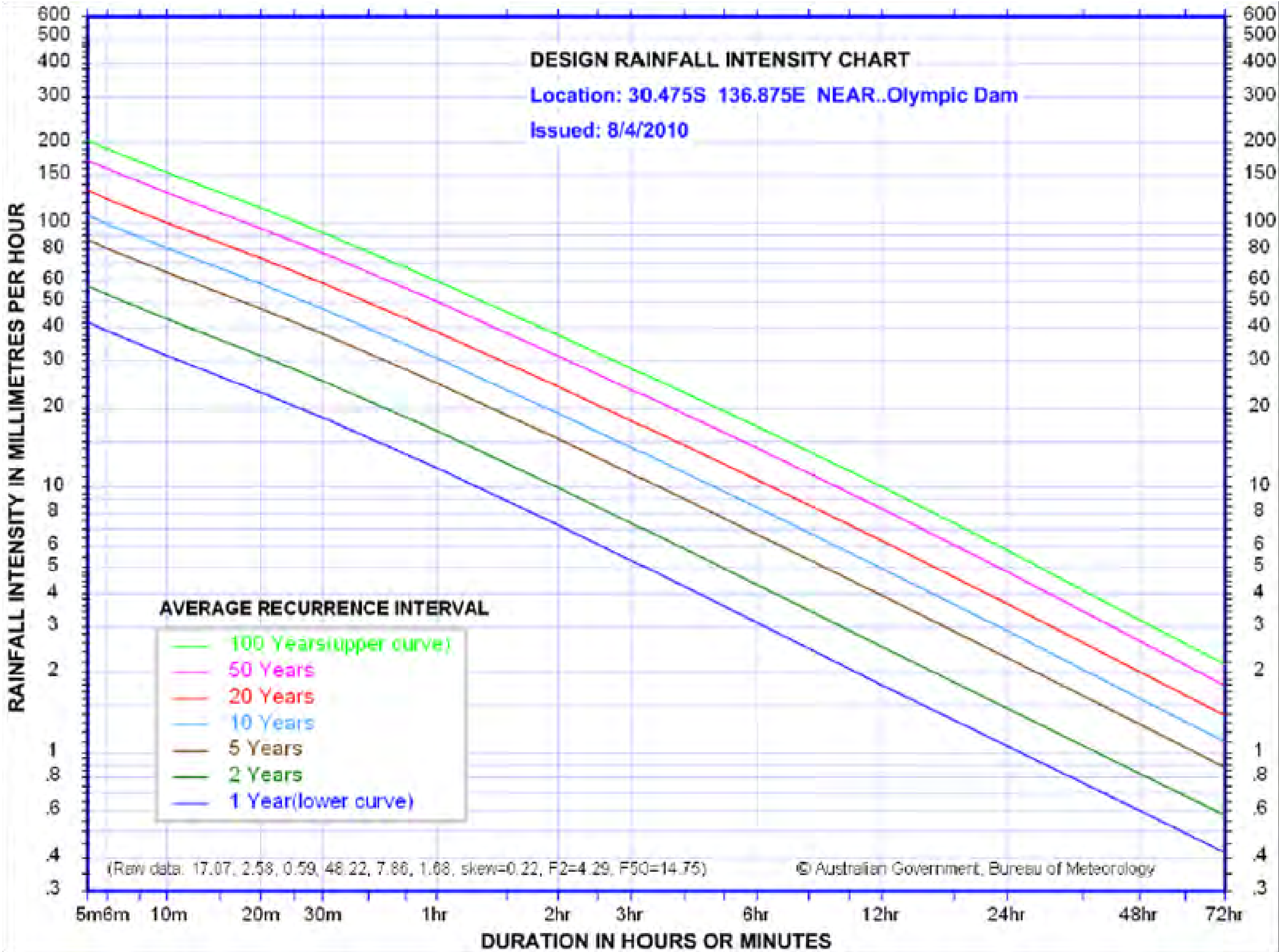
Daily Precipitation Records

Job No: 1CAS017.011	Olympic Dam Expansion	Date: May 2010
Filename: Figure 3_Precip_20100507.ppt	Percolation Estimates for Waste Rock Pile	Approved:
		Figure: 3



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Rainfall IDF Curves for Olympic Dam Area

Job No: 1CAS017.011
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Olympic Dam Expansion
Percolation Estimates for Waste Rock Pile

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May 2010		4

To test the effects of higher intensity rainfall, additional runs were completed with an assumption that each day's rainfall occurs in only two hours. Comparison to the IDF curves shows that assumption to be very conservative. The 40 mm rainfall events, when assumed to occur over only two hours, correspond to IDF return periods of 10 to 25 years. It is unlikely that any ten-year period would include six storms of that intensity. Similarly, the two-hour assumption conservatively increases the intensity of the smaller storms in the data record.

The effect of a very rare storm was tested by an additional sensitivity run. In that case, the 42 mm event in year three of the rainfall record was arbitrarily increased to an 80 mm event, and again assumed to occur over only two hours. Those assumptions correspond to a 100-year two-hour storm.

3.2.4 Other Inputs

Model Geometry

The model mesh for all runs had a depth of 20 m. This thickness was selected so that the bottom boundary condition had no influence on the near surface results.

The Hydrus-1D program uses a fixed nodal spatial discretization. The number of nodes for each material was varied to optimize computation speed and water balance errors. For all materials, the number of nodes varied between 150 and 600, with an increased density near the top surface.

Boundary conditions

Boundary conditions at the soil surface were largely driven by the climate inputs. A flux tracking node was placed at the surface to track both infiltration and evaporation. The net flux over the simulation period corresponds to "percolation" as discussed in Section 2.

Very dry conditions at the soil surface can create numerical instabilities and convergence problems. To ensure model stability, the matric suction at the upper soil surface was restricted to less than 1,000 m. This value needed to be decreased to 100 m when the high intensity rainfall runs.

For the initial runs, any ponded water was assumed to run off the soil surface. To check the effect of that assumption, a set of sensitivity runs allowing up to 25 mm of ponding was completed.

A free drainage boundary condition was used at the base of the column.

Initial conditions

At the low percolation rates typical of the area, it can take many years before excavated rock comes into moisture equilibrium with its surroundings. The "initial wetting" process was examined in one set of sensitivity runs.

The same phenomena can also cause the assumed initial conditions to have an undue influence on model results. To avoid that problem, the Hydrus-1D model was run repeatedly, i.e. the ten-year series of climate inputs was repeated over and over, until the end of period water content profiles reached a steady state.

3.2.5 Hydrus-1D Results

Figure 5 shows results of the Hydrus-1D runs plotted as ten years of cumulative precipitation, infiltration, evaporation, and runoff, for each of the four model soil materials. The results shown are from the runs with the daily precipitation distributed over six hours, and with no surface ponding allowed. Table 3.2 summarizes the same results as totals over the ten-year simulation period and as percentages. Further model results are included in Appendix A.

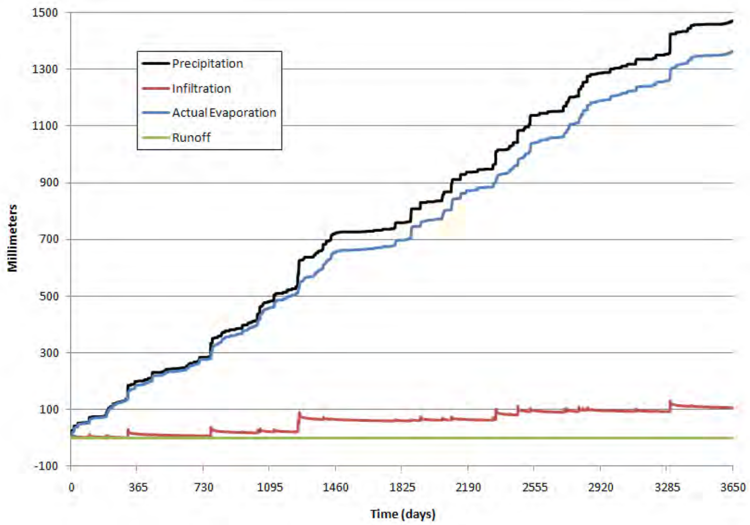
The "net infiltration" values shown in Figure 4 and Table 3.2 are the net water fluxes monitored at the soil surface, i.e. total infiltration minus evaporation. These values can go slightly negative over short periods, indicating a net removal of water from the material. However, the long-term percentages correspond closely to "net percolation" as described in Chapter 2.

Table 3.2: Summary of Hydrus-1D modelling results

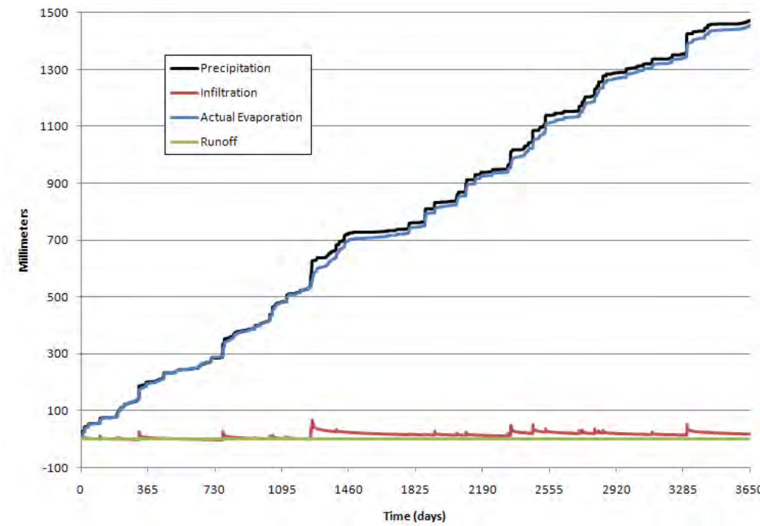
Description	Material 1 Sandy Gravel	Material 2 Gravel-Sand-Silt Mixture	Material 3 Poorly Graded Gravel with Sand	Material 4 Sandy Silt
10-Year Totals (mm)				
Precipitation	1470	1470	1470	1470
Evaporation	1362	1443	1444	1043
Runoff	0	0	0	414
Net infiltration	108	27	26	13
Percentage of Total Precipitation				
Evaporation	92.65%	98.16%	98.23%	70.95%
Runoff	0.00%	0.00%	0.00%	28.16%
Net infiltration	7.35%	1.84%	1.77%	0.89%

The following patterns are evident from both the graphs and the summary results:

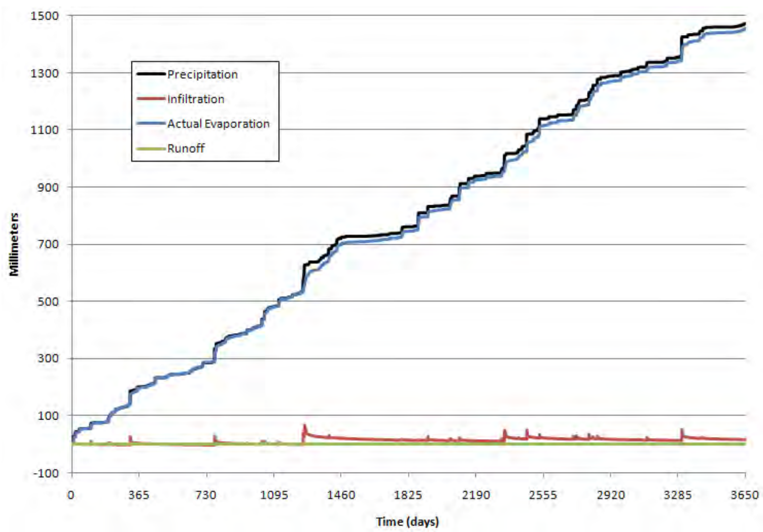
- As expected from the climate data, the Hydrus-1D results show evaporation to be the dominant process for all material types.
- Surface runoff is predicted to be minimal for Materials 1, 2 and 3. Hydrus-1D predicts more runoff from Material 4. That material type was selected to be representative of mixed dune sand and clay pan material, rather than rock. Also, these runs allowed no surface ponding, meaning that any water that doesn't immediately penetrate the surface was assumed to become runoff.
- Net infiltration is predicted to accounts for only a very low percentage of total precipitation in Materials 2, 3 and 4. Those materials have enough sand and finer material to retain water until it can be evaporated. The Hydrus-1D results for Material 1 show a higher infiltration rate. That material type is a clean gravel with essentially no fines, and therefore very limited capacity to retain water.



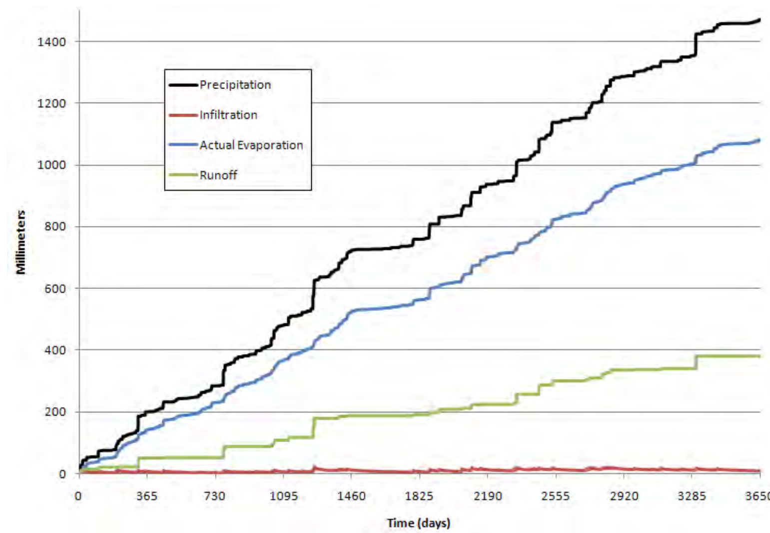
a) Material 1



b) Material 2



c) Material 3



d) Material 4

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Hydrus-1D Cumulative Infiltration, Evaporation and Runoff

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Closer examination of the Figure 4 graphs shows that all of the upward steps in cumulative infiltration correspond to upward steps in the cumulative precipitation. Infiltration appears to be “event driven”, i.e. it occurs only in response to significant precipitation events.

A similar pattern is evident in the cumulative runoff results shown in Figure 4(d). As noted above, Material 4 is the only one for which runoff is predicted, and the runoff appears to also be event-driven.

The Hydrus-1D runs to test the sensitivity to rainfall intensity confirmed the event-driven nature of both infiltration and runoff. Table 3.3 compares the net infiltration and runoff percentages from the base case runs with six-hour rainfall to the analogous results from the runs with all daily rainfall assumed to fall in only two hours, i.e. at much higher rainfall intensity. The runs with the higher intensity rainfall had greater mass balance errors, so the percentages reported for those runs are not as accurate those for the base case runs. But the pattern in the result is clear nevertheless. As expected, higher intensity rainfall leads to greater amounts of infiltration and runoff.

The effect of adding a 100-year storm to Year 3 of the rainfall record was tested by a second set of sensitivity runs. The model predicted significant infiltration as an immediate result of the 100-year storm, but much of the infiltrating water was predicted to be stored and subsequently evaporated. As the last rows of Table 3.3 show, the ten-year model results showed predicted only slight increases in overall infiltration.

Table 3.3: Summary of Hydrus-1D sensitivity analyses for rainfall intensity

Description	Material 1 Sandy Gravel	Material 2 Gravel-Sand-Silt-Mixture	Material 3 Poorly Graded Gravel with Sand	Material 4 Sandy Silt
Base Case (6-hour rainfalls)				
Net infiltration	7.3%	1.8%	1.8%	0.9%
Runoff	0.0%	0.0%	0.0%	28%
High intensity rainfall (2-hour rainfalls)				
Net infiltration	11%	3.2%	2.7%	0.4%
Runoff	0%	0%	0%	43%
100-Year Storm in Year 3				
Net infiltration	12%	5.1%	4.5%	0.4%
Runoff	1.4%	0.0%	0.0%	45%

For all of the runs reported above, the model allowed no ponding of water above the soil surface. In other words, any water that did not immediately infiltrate the surface was assumed to run off. Even under that assumption, the model predicted no runoff for most of the material types.

However, the base case Hydrus-1D runs did predict significant runoff for Material 4. Therefore a set of sensitivity analyses were run, allowing up to 25 mm of water to accumulate on Material 4 prior to running off. The results are shown in Table 3.4. They indicate that the no ponding assumption has a significant effect on predicted runoff rates, but much less effect on net infiltration. The reason is that the water is stored in the fine-grained material and subsequently evaporated.

Table 3.4: Summary of Hydrus-1D sensitivity analyses for surface ponding

Material 4 Sandy Silt	**Base Case Rainfall Intensity**		**High Intensity Rainfall**	
(all runs)	No Ponding	With Ponding	No Ponding	With Ponding
Net infiltration	0.9%	3.8%	0.4%	4.5%
Runoff	28%	3.7%	43%	5.5%

3.3 Water Vapour Modelling

3.3.1 Phase 3 Evaporation

Phase 3 evaporation, i.e. the vapour phase movement of water through and out of soil, is most simply characterized as an isothermal Fickian diffusion process. Within the soil pores, water vapour is usually near saturation, whereas is can be much less humid at the soil surface. Fick's law can be used to estimate the rate of vapour diffusion in response to the gradient in water vapour concentration.

Fick's law calculations provided in Appendix B show that at the mean annual air temperature of 16ºC, if pore gas within the RSF is assumed to carry about 90% humidity and the surface air 40% humidity, diffusion will remove about 2.7 mm of moisture per year. That rate of moisture removal is equivalent to 1.6% of mean annual precipitation. Other reasonable assumptions about temperatures and humidities could shift that estimate as low as 1% or as high as 3% of mean annual precipitation. As noted in Section 2, the isothermal assumption results in low estimates of vapour diffusion rates, so actual moisture removal could be even higher than this range.

3.3.2 Barometric Pumping

Air moves in and out of soil in response to changes in atmospheric pressure. In arid environments, the "barometric pumping" effect can lead to a net movement of moisture from the relatively humid soil pores and into a drier atmosphere. Predictive models of barometric pumping range from range from rigorous treatments to pseudo-diffusion models (e.g. Parker 2003). The simplest form neglects the deeper effects of barometric pumping and accounts only for the air and pore gas exchange near the soil surface.

Appendix B presents barometric pumping calculations of the simple form. It considers semi-diurnal, weekly and extreme barometric pressure cycles and estimates total moisture removals of 1.9 mm/yr, or about 1.1% of mean annual precipitation. The semi-diurnal cycles, although small, are of course more numerous and therefore are responsible for the bulk of the estimated moisture removal.

3.3.3 Thermal Convection

The differences between the internal temperature of a rock pile and that of the surrounding air can lead to thermal convection. The phenomenon is well known to be important in reactive mine rock, where the reactions actually generate heat. But recent work has shown that it can also be caused by significant diurnal or seasonal temperature cycles. Lahmira et al. (2009) present a complete mathematical model for such cases, and Hockley et al (2009) presents a simpler form.

Appendix B shows thermal convection calculations using the simpler form. The key input parameter is the bulk air permeability of the rock pile. The appropriate estimate for the RSF depends on the rock properties and is therefore uncertain. The appendix therefore shows calculations for a range of bulk air permeabilities taken from other studies.

The range of predicted air flow rates is very wide, from 5 m/d to 0.05 m/d, and the resulting rates of moisture removal are equally uncertain. The highest reasonable estimate is about 3 mm of water removal per year, equivalent to about 1.7% of mean annual precipitation. That estimate should be treated with caution as the simple model includes assumptions that could tend to lead to higher estimates of moisture removal, i.e. that are un-conservative in this case.

4 Interpretation of Results

4.1 Infiltration, Evaporation and Net Percolation

The Hydrus-1D results confirm the dominance of evaporation in the Olympic Dam area. For the four materials types considered in the modelling, ranging from a clean gavel to a silty sand, evaporation was predicted to account for 92.6, 98.1, 98.2 and 70.9% of precipitation. The latter value, for the silty sand, increased to 93% when the model allowed water to pond before running off.

The Hydrus-1D modelling predicted relatively low infiltration rates for all four material types. The gravel-sand-silt mixture, the poorly graded gravel with sand, and the sandy silt (Materials 2, 3 and 4) were all predicted to allow net infiltration of 1.9% or less. Even with conservatively high rainfall intensities, those material types allowed infiltration rates of less than 4%. The clean sandy gravel (Material 1) was predicted to allow more infiltration, amounting to 7.3% of precipitation.

The main difference between the sandy gravel and the other material types is that it includes essentially no fines. Closer examination of the model outputs shows that, while all of the materials were predicted to allow water to infiltrate the surface, Materials 2, 3 and 4 were predicted to retain most of that water in the pore space of their finer fractions, from where it could subsequently be evaporated. The sandy gravel, lacking in fines, would be unable to retain the water long enough for it to be evaporated, and therefore was predicted to allow more percolation.

Even after water has infiltrated the RSF surface, it will remain subject to removal as a vapour. Rudimentary calculations were used to assess the amount of moisture that could be removed by three vapour phase transport processes. For two of those processes, Phase 3 evaporation and barometric pumping, the calculations conservatively under-estimate moisture removal at 1-4% of mean annual precipitation. Calculations for the third process, thermal convection, indicate additional moisture removal of up to 1.7% of mean annual precipitation, but that value could be un-conservatively high.

As noted above, there is no way to accurately predict how the rock excavation, hauling, deposition, compaction, abrasion and natural weathering will affect particle sizes of the RSF surface. It is therefore impossible to draw a 1:1 correspondence between the sedimentary rock units that will form the RSF surface and the material types used in the Hydrus-1D modelling. However, it seems likely that at least half of the rock units comprising the surface of the RSF will be finer than Material 1:

- Tregolana shale is expected to cover 25% of the RSF surface. It is also expected to constitute half of the mixed shale – sandstone unit that will cover another 14% of the RSF surface. The Tregolana shale, if it weathers similarly to drill core samples, will include a significant percentage of fines.
- Coraberra sandstone will comprise the remainder of the mixed shale –sandstone unit, and a unit of its own covering another 8% of the RSF surface. Material 2 in the Hydrus-1D

modelling was in fact a well-studied sandstone taken from a mine rock pile in Canada. Samples taken from the upper 10 m of that rock pile have shown fines contents between 4% and 14%.

- The red and white quartzite units will cover 27% and 10%, respectively of the RSF surface. Quartzite can be quite resistant to weathering, but the geological descriptions for these units indicate that they contain 5-15% shales.
- The remaining 16% of the RSF surface is expected to be covered with limestone rock. Limestone rock can also be quite resistant to weathering.

As a "best current estimate" of overall infiltration rates, it would be reasonable to assume that half of the RSF surface material will behave similarly to Material 2 or 3, and the other half similarly to Material 1. The resulting overall average percolation rate would be about 4.6% of precipitation. Taking into account water vapour removal, the net percolation would be in the order of 1-4% of mean annual precipitation.

The above estimate is appropriate for use in predictive modelling of effects on the groundwater table, but design of contingency measures should consider the full range of possibilities. The Hydrus-1D modelling results suggest that there will be a number of ways for the operator to influence percolation infiltration, evaporation and percolation rates. These include:

- Changes to the deposition plan so that rock units that weather to finer grain sizes occupy more of the final RSF surface;
- Routing of traffic and/or deliberate compaction to promote abrasion of coarser material and increase its water retention capacity; and,
- Making use of the sand dune and clay pan material stripped from the pit surface to cover coarse material.

The Hydrus-1D modelling did not include the effects of vegetation. It may not be possible to establish healthy vegetation on the RSF. However, studies from many other areas show that even the sparse vegetation common in arid zones can vary significantly reduce percolation (e.g. Scanlon et al 2006). This would be a reasonable avenue of investigation should a need to further reduce net percolation be proven.

4.2 Runoff

Assessment of runoff was not the primary focus of the Hydrus-1D modelling reported herein. However, some inferences can be drawn.

The modelling predicted that, with the base case rainfall intensity, no runoff would be generated from Materials 1, 2, or 3. Material 4, the silty sand, was predicted to generate runoff equivalent to 28% of precipitation. When the rainfall intensity was doubled, the predicted runoff from Material 4 increased to 43% of precipitation. Material 1 was also predicted to generate runoff in the runs with the 100-year storm.

The attribute of Material 4 that most contributes to the predicted high runoff is its low hydraulic conductivity. Material 1 has a much higher hydraulic conductivity, sufficient that it can readily take in water delivered at the base case rainfall intensities. The sensitivity analyses showed that Materials 2 and 3 have hydraulic conductivities that are high enough to accept even the very high rainfall intensity of a 100-year storm.

The hydraulic conductivity of the RSF is one of the parameters that will be determined by the surface grain size distributions that cannot currently be predicted with accuracy. However, the modelling suggests that runoff will be unlikely, except in high intensity rainfalls.

The sensitivity runs with and without ponding also suggest a possible mitigation measure, should runoff prove to be a problem. When the model was set to allow up to 25 mm of ponding before directing water to runoff, even the high runoff rates predicted for Material 4 were very significantly reduced. The implication is that treatment of the final RSF surface to delay runoff, for example local flattening or scarification, would effectively control runoff.

5 Conclusions and Recommendations

The infiltration of water into the surface of the Olympic Dam RSF, and it subsequent retention, removal and/or percolation to groundwater will be governed by a set of complex physical processes.

Most of those processes are well understood, but accurately predicting their effects requires knowledge of the grain size distribution of the rock material. The grain size distributions of the RSF surficial materials, in particular, will control most of the important processes, and will be determined in part by the rock composition (which is known), but more strongly by the abrasion and compaction by truck and dozer traffic, and by longer term processes of natural weathering. There is no way to predict those effects or the resulting grain size distributions.

The approach taken herein was to select a range of possible grain size distributions from literature sources, and to use mathematical models to predict the range of possible infiltration. The model Hydrus-1D, developed by the U.S. Department of Agriculture, was used to predict the movement of liquid water. A twelve-year record of daily precipitation at the Roxby Downs Aerodrome was used as input. The results showed the dominance of evaporation over precipitation. Predicted rates of percolation ranged from 1% for the assumed finer grain sizes to 7% for the coarsest grain sizes considered in the model runs. Additional sensitivity analyses showed that net percolation could be higher in cases of higher rainfall intensity.

Supplemental calculations were used to assess the potential for additional removal of water in the form of water vapour. Near surface diffusion of water vapour (Phase 3 evaporation), barometric pumping and thermal convection were estimated to have the potential to remove 1-4% of mean annual precipitation.

To develop “best current estimate” of overall infiltration rates, a review of the proposed mine plan showed that half of the RSF surface material is expected to behave similarly to Material 2 or 3, and the other half similarly to Material 1. The resulting overall average percolation rate would be about 4.6% of precipitation. Taking into account water vapour removal, the net percolation would be in the order of 1-4% of mean annual precipitation.

The Hydrus-1D simulations and sensitivity analyses also showed that there are several opportunities for the operator to control infiltration and runoff, in the event that the material properties or rainfall intensities fall outside the range modelled herein. Finer-grained materials could be placed to cover more of the RSF surface. Additional trafficking or purposeful compaction of coarse material would reduce grain sizes and increase the water retention capacity of the surface layer. Sloping of the surface would promote runoff of high precipitation events, thereby limiting overall infiltration.

The use of the results presented herein should take into account the associated uncertainties. The estimated range of 1-4% of mean annual precipitation is appropriate for assessing effects on regional groundwater. However, until better characterization of the RSF surface materials is available, the planning of contingency measures should consider a wider range of uncertainty.

References

Aubertin, M., M. Mbonimpa, B. Bussière, and R.P. Chapuis, 2003. “A model to predict the water retention curve from basic geotechnical properties”. Canadian Geotechnical Journal, Vol. 40, pp. 1104-1122.

Green, W.H., and G. Ampt, 1911. “Studies in soil physics. I. The flow of air and water through soils”. Journal of Agricultural Science, Vol. 4, pp. 1-24.

Hillel, D., 1982. Introduction to Soil Physics. Academic Press, New York.

Hockley D.E., J. Smolensky S. Jahn and M. Paul, 2000. “Geochemical Investigations and Gas Monitoring of an Acidic Waste Rock Pile”. Fourth International Conference on Acid Rock Drainage, Denver, June 2000.

Hockley D., W. Kuit and M.Phillip, 2009. “Sullivan Mine fatalities incident: Key conclusions and implications for other sites”. Securing the Future and 8th ICARD, June 22-26, 2009, Skellefteå, Sweden.

Kellett, J., S.Veitch, I. McNaught, , and A.van der Voort, 1999. Hydrogeological Assessment of a region in Central Northern South Australia. Bureau of Rural Sciences, Australia.

Lahmira, B., R. Lefebvre, D. Hockley and M.Phillip, 2009. “Sullivan Mine fatalities incident: Numerical modelling of gas transport and reversals in flow directions”. Securing the Future and 8th ICARD, June 22-26, 2009, Skellefteå, Sweden.

Nichol C., 2002. Transient Flow and Transport in Unsaturated Heterogeneous Media: Field Experiments in Mine Waste Rock. PhD. Thesis, University of British Columbia.

Parker, J.C., 2003. “Physical processes affecting natural depletion of volatile chemicals in soil and groundwater”. Vadose Zone Journal, Vol. 2, pp. 222-230.

Perkins, K., and J. Nimmo, 2009. “High-quality unsaturated zone hydraulic property data for hydrologic applications”. Water Resources Research, Vol. 45, W07417.

Rowlett, D.K., 2000. Development of a Stand-Pipe Lysimeter for Unsaturated Waste Rock. Thesis submitted to Department of Civil Engineering, University of Saskatchewan, Spring, 2000.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Cheikh, B.G., Edmounds, W.M., and I.Simmers, 2006. “Global synthesis of groundwater recharge in semiarid and arid regions”. Hydrological Processes, Vol. 20, pp. 3335-3370.

Simunek, J., M. Sejna, H. Saito, M. Sakai, and M.Th. van Genuchten, 2009. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Version 4.08. Department of Environmental Sciences, University of California Riverside. January 2009. Available at: http://www.pc-progress.com/en/Default.aspx?H1d-downloads.

Smith, T.R., D.A. Stonestrom, and D.E. Prudic, 1999. Barometric pumping in a 110-meter thick unsaturated zone in the Amargosa Desert, Nye County, Nevada [abs.]: Eos Transactions, American Geophysical Union, v. 80, no. 46, p. F359.

SRK Consulting (Australasia), 2010. Olympic Dam Expansion Project RSF Runoff Water Quality Assessment. July 2010. Appendix E1 of the Supplementary EIS.

van Genuchten, M. Th., F.J. Leij, and S.R. Yates, 2009. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, Version 6.02. EPA Report 600/2-91/065, U.S. Salinity Laboratory, USDA, ARS, Riverside, California. February 2009. Available at: http://www.pc-progress.com/en/Default.aspx?H1d-downloads.

Zhang, Q., and R. Huang, 2004. Water vapor exchange between soil and atmosphere over a Gobi Surface near an oasis in the summer. Journal of Applied Meteorology, Vol. 43, pp. 1917-1928.

Appendix A
Water Content Profiles from Hydrus-1D Outputs

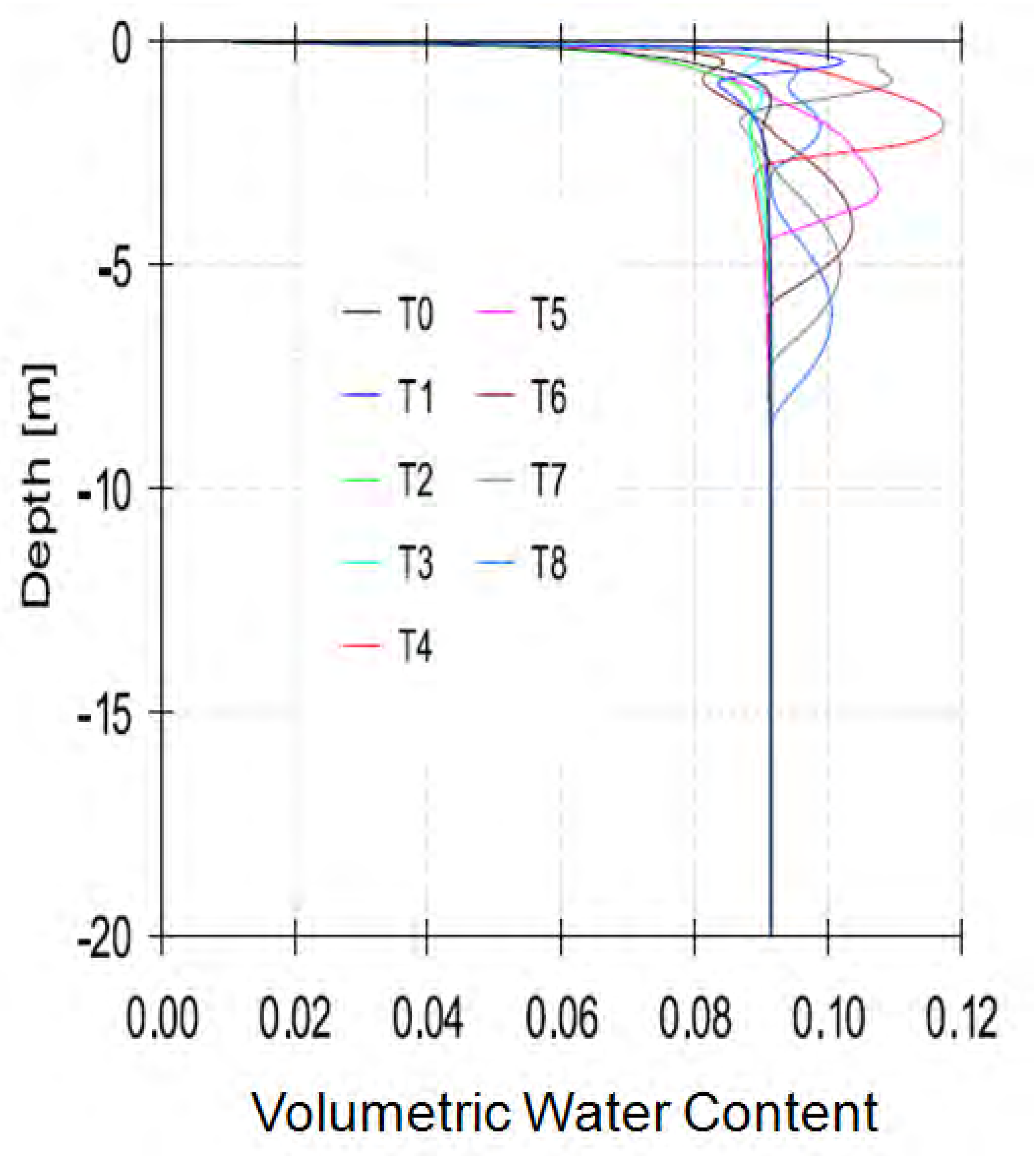
<u>**Water Content Profiles from Hydrus-1D Outputs**</u>

Water content profiles were produced by the model at various times.

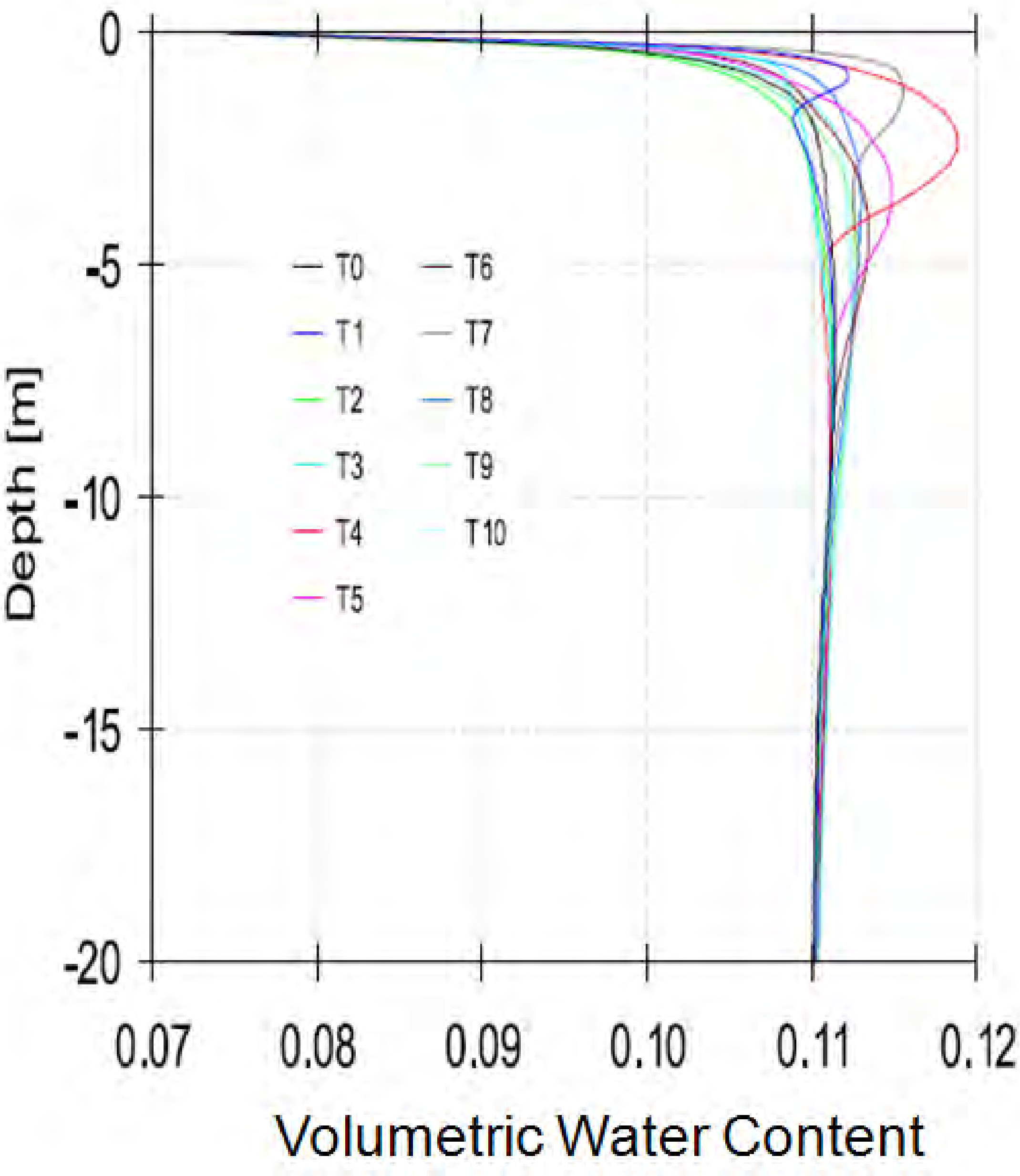
Results from the base case runs are shwon here.

The legend entries refer to the end of year time, i.e. T1 = end of year 1).

Material 1

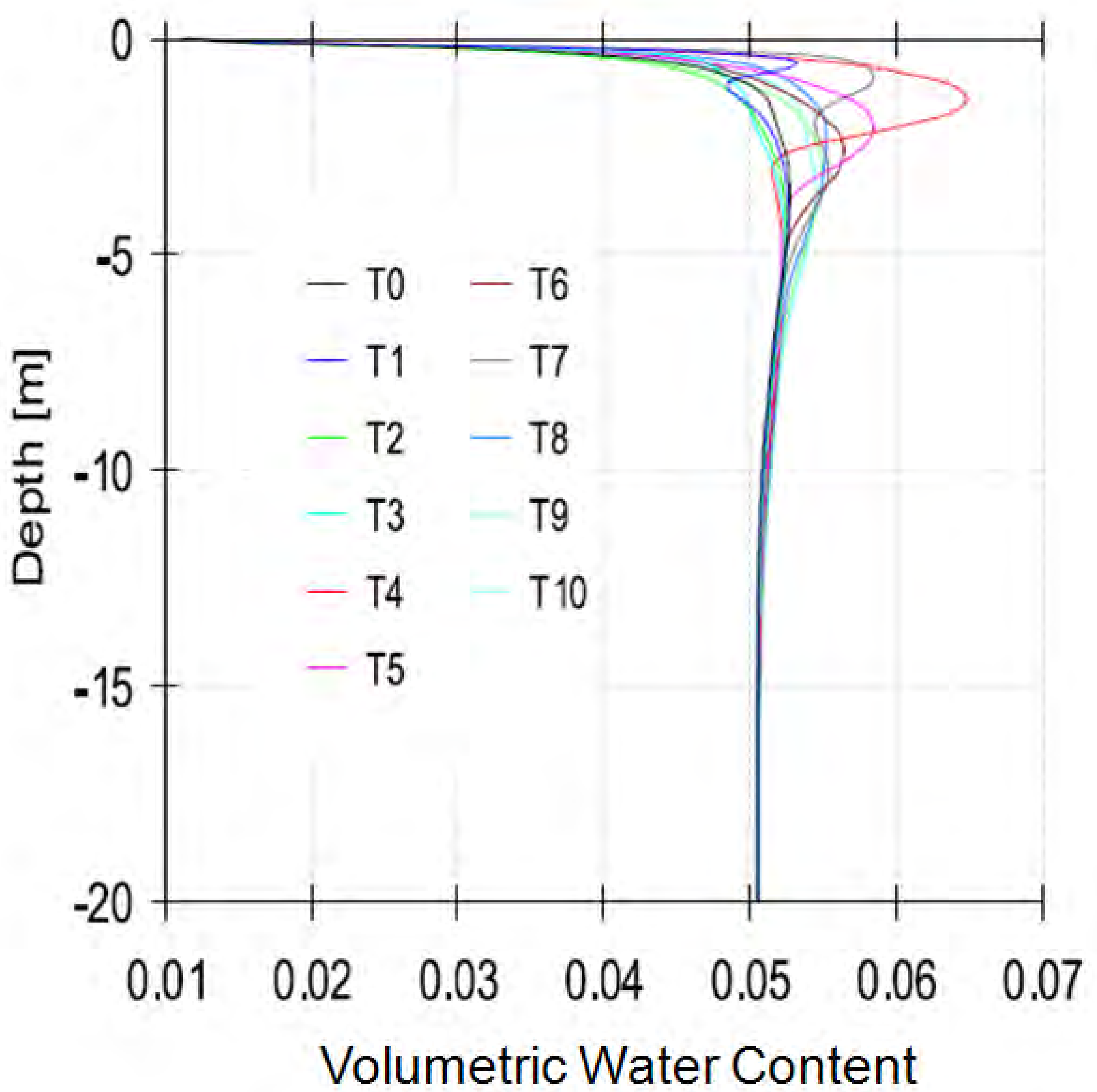


Material 2



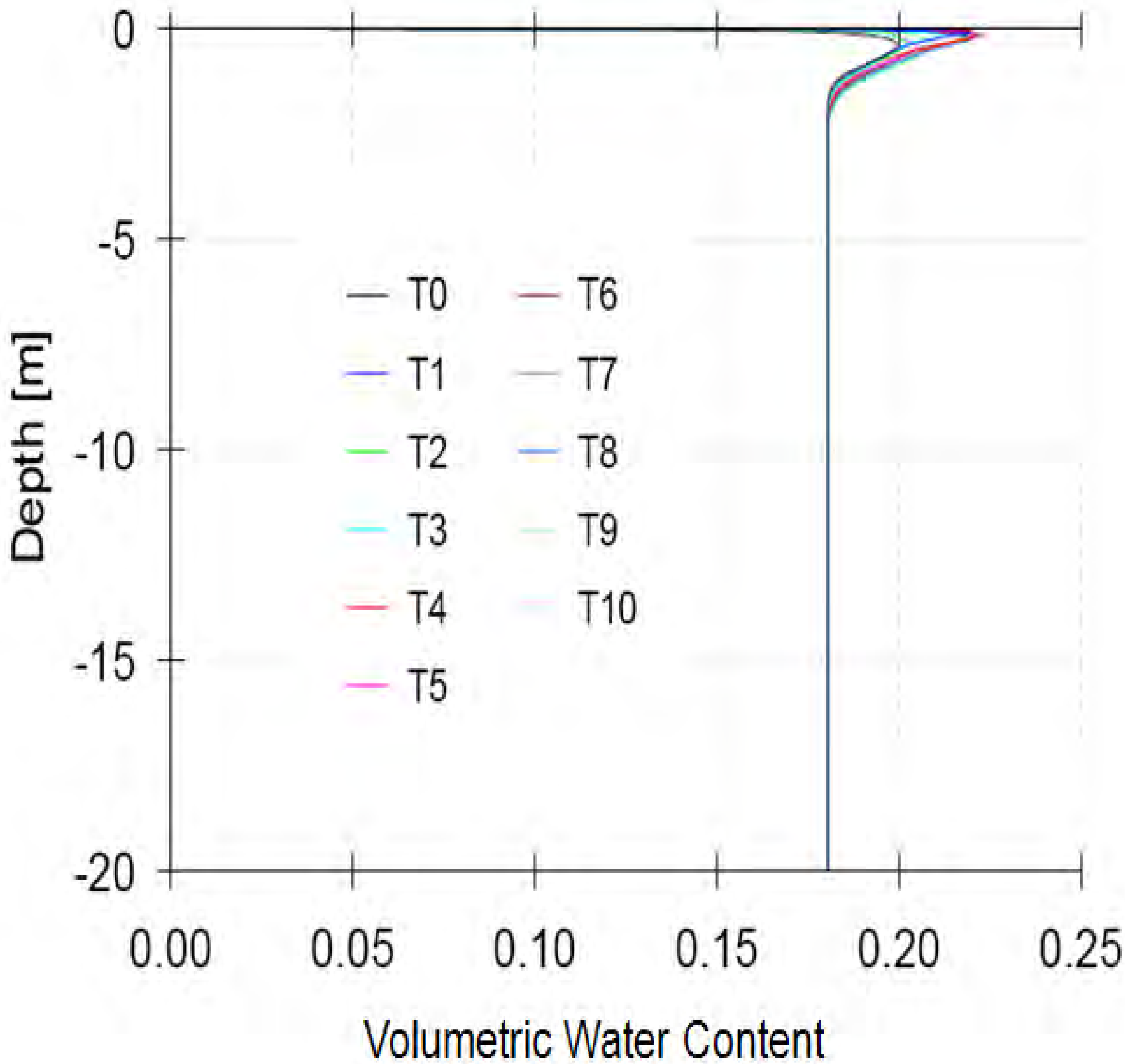
0
-5
-10
-15
-20
Depth [m]
T0
T6
T1
T7
T2
T8
T3
T9
T4
T10
T5
0.07
0.08
0.09
0.10
0.11
0.12
Volumetric Water Content

Material 3



0
-5
-10
-15
-20
Depth [m]
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Volumetric Water Content
T0
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10

Material 4



0
-5
-10
-15
-20
Depth [m]
T0
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
0.00
0.05
0.10
0.15
0.20
0.25
Volumetric Water Content

Appendix B
Water Vapour Modelling Supporting Calculations

Estimates of water vapour removal by molecular diffusion

Inputs

Temperatures

Mean annual air temperature	20	C

Diffusion coefficients

Water vapour in 16C air	2.30E-05	m2 s-1
	1.99	m2 d-1
Tortuosity of pore space	3	
Effective diffusion coeff.	0.66	m2 d-1

Water vapour content

Air at 20C and 100% RH	17.3	g m-3
Air at 15C and 100% RH	12.8	g m-3

Diffusion depths vs time

Asssume T varies with X^2

Assume maximum X is 2 m

T (days)	X^2	X (m)
30	0.01	0.1
60	0.4	0.6
90	0.7	0.9
120	1.1	1.0
150	1.5	1.2
180	1.8	1.4
210	2.2	1.5
240	2.5	1.6
270	2.9	1.7
300	3.3	1.8
330	3.6	1.9
360	4.0	2.0

Ouputs

Rock at 20C and 90% humidity, air at 20C and 40% humidity

Moisture content of pore gas	15.6	15.6	15.6	15.6	15.6	15.6	g m-3
Moisture content of atmosphere	6.9	6.9	6.9	6.9	6.9	6.9	g m-3
Diffusion zone depth	0.1	0.6	0.9	1.2	1.6	1.9	m
Days per year	30	30	30	60	80	135	d yr-1
Diffusion coefficient	0.66	0.66	0.66	0.66	0.66	0.66	m2 d-1
Flux	57.1	9.5	6.3	4.8	3.6	3.0	g d-1
Moisture removal per day	57.1	9.5	6.3	4.8	3.6	3.0	g m-2 d-1
Annual moisture removal	1713	285	190	285	285	406	g m-2 yr-1
	1.71	0.29	0.19	0.29	0.29	0.41	L m-2 yr-1
	1.71	0.29	0.19	0.29	0.29	0.41	mm yr-1
Total removal						3.2	mm yr-1
MAP						165	mm yr-1
Percent removal						1.9%	of MAP

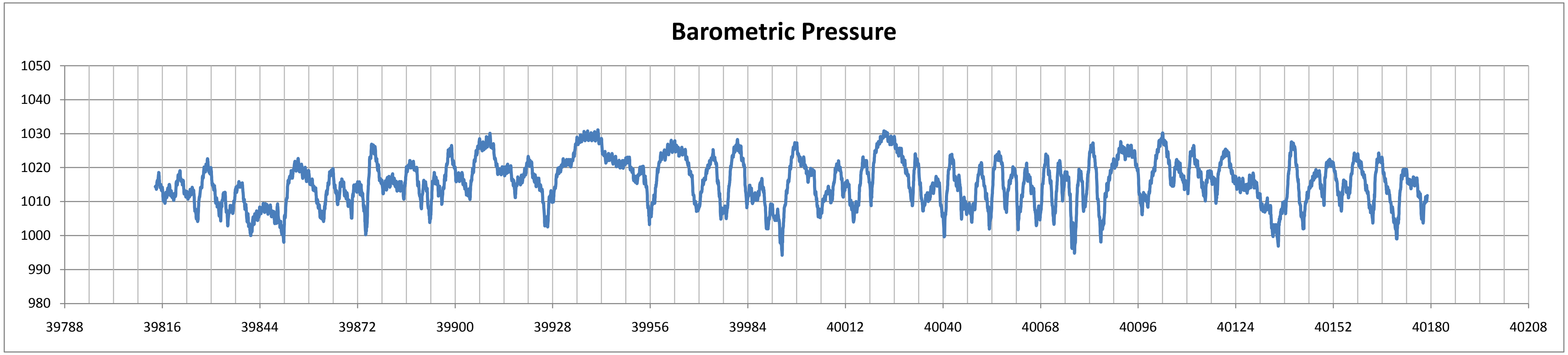
<u>Rock at 20C and 100% humidity, air at 15C and 40% humidity</u>							
Moisture content of pore gas	17.3	17.3	17.3	17.3	17.3	17.3	g m-3
Moisture content of atmosphere	5.1	5.1	5.1	5.1	5.1	5.1	g m-3
Diffusion zone depth	0.1	0.6	0.9	1.2	1.6	1.9	m
Days per year	30	30	30	60	80	135	d yr-1
Diffusion coefficient	0.66	0.66	0.66	0.66	0.66	0.66	m2 d-1
Flux	80.4	13.4	8.9	6.7	5.0	4.2	g d-1
Moisture removal per day	80.4	13.4	8.9	6.7	5.0	4.2	g m-2 d-1
Annual moisture removal	2412	402	268	402	402	571	g m-2 yr-1
	2.41	0.40	0.27	0.40	0.40	0.57	L m-2 yr-1
	2.41	0.40	0.27	0.40	0.40	0.57	mm yr-1
Total removal						4.5	mm yr-1
MAP						165	mm yr-1
Percent removal						2.7%	of MAP

<u>Rock at 20C and 90% humidity, air at 20C and 40% humidity, restricted diffusion</u>							
Moisture content of pore gas	15.6	15.6	15.6	15.6	15.6	15.6	g m-3
Moisture content of atmosphere	6.9	6.9	6.9	6.9	6.9	6.9	g m-3
Diffusion zone depth	0.1	0.6	0.9	1.2	1.6	1.9	m
Days per year	30	30	30	60	80	135	d yr-1
Diffusion coefficient	0.33	0.5	0.5	0.5	0.5	0.5	m2 d-1
Flux	28.5	7.2	4.8	3.6	2.7	2.3	g d-1
Moisture removal per day	28.5	7.2	4.8	3.6	2.7	2.3	g m-2 d-1
Annual moisture removal	856	216	144	216	216	307	g m-2 yr-1
	0.86	0.22	0.14	0.22	0.22	0.31	L m-2 yr-1
	0.86	0.22	0.14	0.22	0.22	0.31	mm yr-1
Total removal						2.0	mm yr-1
MAP						165	mm yr-1
Percent removal						1.2%	of MAP

Estimates of moisture removal by Barometric Pumping

Cycle type	Weekly	Semi-diurnal	Extreme	
Mean barometric pressure	1015.8	1015.8	1015.8	hPa
Number of cycles per year	52	730	12	
Cycle amplitude	15	4	30	hPa
Pile height	160	160	160	m
Convective zone	2.36	0.63	4.73	m
Air filled porosity	0.35	0.35	0.35	
Air exchange per cycle	0.83	0.22	1.65	m3 m-2
Annual total air exchange	43.0	161.0	19.8	m3 m-2
Moisture content of pore air	15.6	15.6	15.6	g m-3
Moisture content of atmosphere	6.9	6.9	6.9	g m-3
Annual moisture removal	373	1396	172	g m-2 yr-1
	0.37	1.40	0.17	L m-2 yr-1
	0.37	1.40	0.17	mm yr-1
MAP	184	184	184	mm yr-1
Percent removal	0.2%	0.8%	0.1%	of MAP
			1.9	mm yr-1
Total removal - All cycles			1.1%	of MAP

2009 barometric data from Thevenard SA



Estimates of mositure removal by thermal convection

Convective air flow				
Permeability	2E-09	2E-10	2E-11	m2
Temperature difference	15	15	15	C
Typical air flow rate	5	0.5	0.05	m d-1
Porosity	0.4	0.4	0.4	
Air inflow / pore gas outflow	2	0.2	0.02	m d-1

Moisture removal				
Max moisture content at 20C	17.3	17.3	17.3	g m-3
Pore gas RH	90%	90%	90%	
Moisture content ofpore gas	15.6	15.6	15.6	g m-3
Atmosphere RH	40%	40%	40%	
Moisture content of atmosphere	6.9	6.9	6.9	
Moisture removal per day	17.3	1.7	0.2	g m-2 d-1
Days per year	160	160	160	d yr-1
Annual moisture removal	2768	277	28	g m-2 yr-1
	2.77	0.28	0.03	L m-2 yr-1
	2.77	0.28	0.03	mm yr-1
MAP	165	165	165	mm yr-1
Percent removal	1.7%	0.17%	0.017%	of MAP

Bulk Permeability of Other RSF's

Source: SRK files

Nordhalde	2.5E-12	m2
Lichtenberg backfill	2.0E-11	m2
Mines Doyon	8.0E-10	m2
Questa	3.5E-09	m2
Sullivan No 1 Shaft	5.0E-09	m2

Convection Rates vs. Permeability and Temperature

Source: Hockley et 2009.

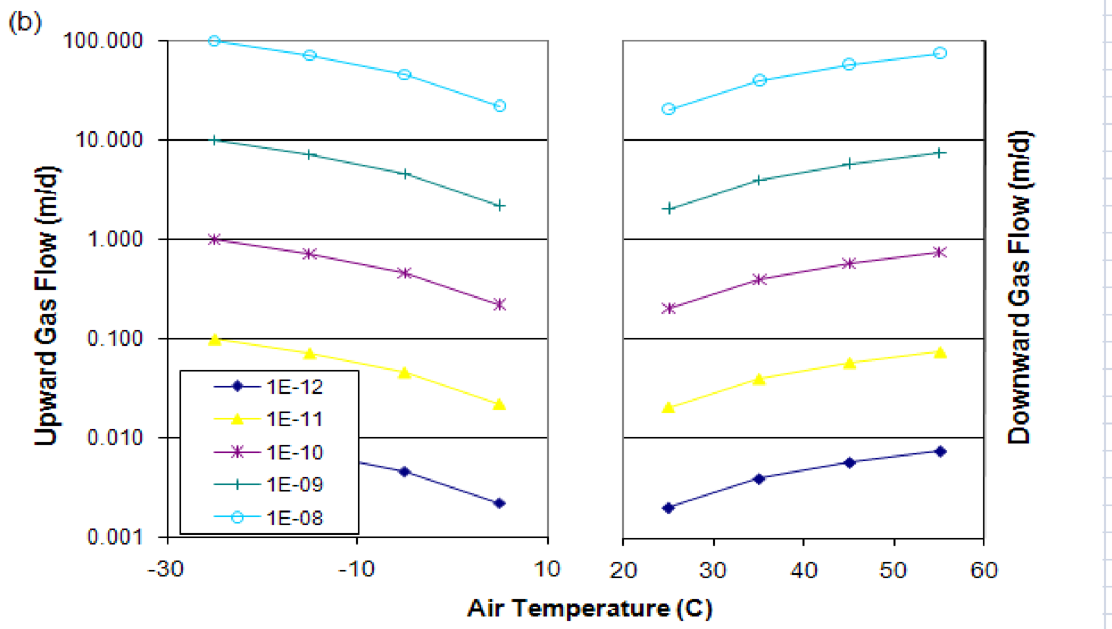


Figure 6. Gas flowrates for combinations of air temperature and waste rock permeability. Legend shows waste rock permeability in m^2. (a) Internal dump temperature of 65°C, resulting in upward gas flow for all values of air temperature. (b) Internal dump temperature of 15°C, with gas flows upward when air temperature is below 15°C and downward when air temperature is above 15°C.