SRK Consulting (Canada) Inc.
2200–1066 West Hastings Street
Vancouver, BC V6E 3X2

T: +1.604.681.4196
F: +1.604.687.5532

vancouver@srk.com
www.srk.com

Memo

To:	Ryan Herbert, Minto Explorations Ltd.	**Client:**	Minto Explorations Ltd
From:	Iozsef Miskolczi, PEng, Maritz Rykaart, PhD, PEng	**Project No:**	1CM002.030
Cc:	Dylan MacGregor, PGeo, SRK	**Date:**	October 14, 2015
Subject:	Minto Mine Closure Covers: Results of Numerical Modelling to Bracket Percolation Predictions		

1 Introduction

1.1 General

Preliminary water quality modelling of seepage from Minto Mine waste facilities, as a result of meteoric percolation through them, suggests that under worst-case load predictions the water quality in Minto Creek will not meet the post-closure objectives. Closure covers that control the percolation rate are one of many possible strategies that are being considered to mitigate this situation.

A Scoping Level Cover Assessment was completed for the Minto mine to evaluate what the most suitable closure cover may be (SRK 2013a) given the site specific climatic conditions and availability of candidate cover materials. The scoping study identified several candidate closure cover designs and the approximate range of net percolation that could be associated with each cover concept. Those percolation ranges were based on engineering judgement derived from knowledge of soil covers as well as soil cover performance at other sites, as opposed to measured or predicted (i.e. modelled) rates.

This memorandum presents the results of surface flux boundary modelling that further defines and brackets the likely range of percolation for the proposed soil covers at Minto Mine. These results supplement the existing database of information and provide greater confidence in the use of closure covers as a mitigation strategy.

1.2 Modelling Approach

For the purpose of this study we have adopted the term percolation, as opposed to infiltration, to define the meteoric water that will migrate through the cover and underlying waste, and emerge as seepage at the toe of the facility or report to groundwater. In order to model percolation, a surface flux boundary model must be used, which accounts for the physical processes (e.g. infiltration, evapotranspiration, and runoff) that take place at the cover surface (i.e. at the interface between the cover and the atmosphere). This type of modelling is complex, requires good quality input data, and ideally, long-term in-situ calibration data.

Since no calibration data is available, the modelling approach was to develop a most realistic base case scenario, and then through sensitivity analysis establish how the modelling results will be impacted as parameters change. This process allows for a rigorous assessment of the parameters that drive the cover performance, such that the expected percolation rates can be determined with a high level of confidence.

In order to do this most efficiently, a pseudo- surface flux boundary model (Hydrus 1D (Šimůnek *et al*. 2009)) was used for the modelling. The base case scenario was subsequently verified using a true surface flux boundary model, SVFlux (SoilVision 2009). A true surface flux boundary model calculates actual evaporation using the Modified Penman equation (Wilson 1990), while in the pseudo surface flux boundary model actual evaporation is estimated based on a user defined potential evaporation. Calculating actual evaporation requires a higher level of complexity (i.e. non-linearity) in the numerical simulation which substantially increases the computing time. It was however demonstrated that with proper verification the approach as adopted (i.e. modelling using Hydrus 1D and verification using SVFlux) is reliable and efficient (Rykaart and Noël 2003).

2 Methods

2.1 Conceptual Model and Model Setup

The objective of the modelling is to bracket the likely range of percolation through various single layer soil covers that could be constructed using the candidate soil material that is readily available at Minto Mine. The model assumes that no water table is present within the waste substrate and that any water that percolates through the cover will continue to drain unimpeded through the underlying waste exiting the model at the bottom. In real life however, at the waste dump scale this drainage water will either emerge as toe seepage or report to groundwater.

This conceptual model is represented in the computer models as a 10 m high, one-dimensional column consisting of two layers: a soil cover (of variable thickness) and underlying waste material (waste rock or tailings) respectively. The top surface is flat, however the simulations do not allow for ponding to develop; this corresponds to the physical equivalent of shedding excess water (if it were to occur) as runoff.

In each case the model is run for a continuous period of 20 years in daily time-steps, using a synthesized climatic dataset. This approach results in 20 different annual percolation rates, representing a range of expected outcomes taking into consideration variability of actual climatic conditions. The synthetic climatic data set does not take into consideration climate change.

2.2 Model Input Data

2.2.1 Meteorological Data

Data Source

Daily precipitation and evaporation data is required for modelling. In order to develop a long-term modelling dataset, daily regional meteorological data was obtained from Environment Canada's Pelly Ranch weather station. The Pelly Ranch data, which dates back to 1955, were subsequently modified to better represent Minto site conditions by applying site specific climate correlation factors that were previously developed based on data from two on-site weather stations (SRK 2012).

Precipitation

The Pelly Ranch meteorological data was parsed for incomplete years and an initial 49-year daily dataset was compiled stretching from 1957 to 2009. This dataset was further purged to remove all years with total precipitation above the 1:50 years wet year (461 mm) and below the 1 in 50 years dry year (218 mm) (SRK 2012). The twenty most recent years from the resulting synthetic dataset were used as model input, from the period between 1986 and 2009, with the years 1992, 1996, 1998 and 2008 excluded. A summary of this annualized dataset is presented in Table 1.

Table 1: Yearly Total Precipitation Data for 20-Year Modelling Period

Model Year	Calendar Year	Yearly Total Precipitation (mm)
1	1986	316
2	1987	362
3	1988	301
4	1989	254
5	1990	372
6	1991	362
7	1993	335
8	1994	293
9	1995	307
10	1997	425
11	1999	417
12	2000	453
13	2001	326
14	2002	335
15	2003	330
16	2004	422
17	2005	367
18	2006	261
19	2007	349
20	2009	349

Source: \\VAN-SVR0\Projects\01_SITES\Minto\1CM002.030_Closure_Cover_Modelling\!080_Deliverables\Cover Model Results\020_Tables\[Minto_WeatherInput_1CM002.030_Rev01_IM.xlsx]Precip

To study the effect of higher or lower than average precipitation, two subsets of precipitation data, each 5 years long were compiled. The wetter than average dataset is comprising of years exceeding the 1:5 years wet annual precipitation of 380 mm (SRK 2012), as presented in Table 2. The drier than average dataset includes years in which total precipitation was below 275 mm, or 1:5 years dry (SRK 2012) as shown in Table 3.

Table 2: Wetter Than Average Precipitation Years

Model Year	Calendar Year	Yearly Total Precipitation (mm)
1	1964	388
2	1967	408
3	1981	380
4	1985	382
5	2000	453

Source: \\VAN-SVR0\Projects\01_SITES\Minto\1CM002.030_Closure_Cover_Modelling\!080_Deliverables\Cover Model Results\020_Tables\[Minto_WeatherInput_1CM002.030_Rev01_IM.xlsx]Precip

Table 3: Dryer Than Average Precipitation Years

Model Year	Calendar Year	Yearly Total Precipitation (mm)
1	1969	260
2	1971	269
3	1975	270
4	1980	257
5	2006	261

Source: \\VAN-SVR0\Projects\01_SITES\Minto\1CM002.030_Closure_Cover_Modelling\!080_Deliverables\Cover Model Results\020_Tables\[Minto_WeatherInput_1CM002.030_Rev01_IM.xlsx]Precip

Evaporation

Potential evaporation (PE) was estimated at about 400 mm/year by scaling the lake evaporation data from Pelly Ranch to match the Minto Mine site conditions (SRK 2013a). The monthly total values of PE, shown in Table 4, were obtained by scaling monthly PE values calculated using the Penman-Monteith method (FAO 1998) to match the yearly total of 400 mm.

Table 4: Monthly Distribution of Potential Evaporation

Month	Monthly PE (mm)	Days per Month	Daily PE (mm/day)
Jan	0	31	0.00
Feb	0	28.25	0.00
Mar	0	31	0.00
Apr	0	30	0.00
May	85	31	2.75
Jun	98	30	3.28
Jul	92	31	2.96
Aug	82	31	2.63
Sep	38	30	1.28
Oct	5	31	0.16
Nov	0	30	0.00
Dec	0	31	0.00

Source: \\VAN-SVR0\Projects\01_SITES\Minto\1CM002.030_Closure_Cover_Modelling\!080_Deliverables\Cover Model Results\020_Tables\[Minto_WeatherInput_1CM002.030_Rev01_IM.xlsx]Potential Evap

Evapotranspiration

Bare ground evaporation accounts for the water loss at the soil-atmosphere boundary, i.e. the soil surface. Plant transpiration on the other hand is responsible for removal of water from the near-surface of the soil to the full depth of the rooting zone. During the growth season plant transpiration and bare ground evaporation occur simultaneously and the coupled water loss is termed evapotranspiration (Hillel 1980). Bare ground evaporation can however occur outside of the growth season, as long as water at the soil surface is available in liquid form.

The site experiences a short growth season. Based on temperature records from the Pelly Ranch station the average growth season over the most recent 17 years (1998 to 2014) is between May 5 and September 8 (Access 2014). The beginning of the season was considered the fifth consecutive day with mean air temperature above +5°C whereas the end was the first day with killing frost (below -2.2°C). Potential bare ground evaporation (PE) however, which is based on the energy balance governed by the local climate, has a wider range extending between May 1 and October 31. The model assumes that evapotranspiration is possible within this period only, whereas it is considered to be zero between November 1 and April 30.

Snowmelt and Sublimation

To recognize the effect of freezing conditions during winter, snow precipitation was retained and accumulated between October 1 and April 17 annually as snow water equivalent (SWE). Snowmelt was assumed to start on April 17 with freshet lasting two weeks from April 17 to April 30. The entire accumulated SWE was then released as equal daily amounts of meltwater over these two weeks, in addition to any observed precipitation. The ground was assumed to be fully thawed during this period; this is conservative, as in reality thawing would only be starting at this time.

Snow sublimation in the Yukon can lead to considerable snow cover loss. A rigorous study of sublimation performed at a research station near Whitehorse (Pomeroy *et al.* 1999) observed sublimation ranging between 28 and 45 mm per season. Since winter climate conditions influencing the magnitude of sublimation are comparable between Minto and the study site, it was considered that 45 mm of sublimation are representative of Minto site conditions. For modelling purposes, the April 17 SWE was reduced by 45 mm as an allowance for sublimation.

2.2.2 Material Properties

Field investigations completed in 2012 characterized all candidate cover material sources. Tailings samples were obtained from the Dry Stack Tailings Storage Facility and analysed as part of a field investigation conducted in 2013 (SRK 2013b). Particle size distribution (PSD) curves encompassing the full range of candidate cover materials on site are reproduced in Figure 1. Advanced hydraulic testing, including Soil Water Characteristic Curves (SWCC), was performed on representative samples.

Table 3 shows a summary of the candidate cover material properties used in the Hydrus 1D model, while Figure 2 and Figure 3 present the PSD and SWCC curves used in modelling.

A literature search was performed to gather properties for the waste rock to be used in modelling. The material considered to be most appropriate for representing the Minto waste rock was a waste rock sample from Greens Creek mine (Hopp *et al.* 2011) due to the igneous (hard rock) nature of both the Greens Creek and Minto geology. For the sensitivity analysis, finer waste rock properties were used from SRK's database, while the coarser waste rock was simulated using van Genuchten curve fitting parameters (van Genuchten 1980). The water retention properties for tailings were predicted using the Rosetta model (Schaap *et al*. 2001), based on a Minto sample PSD with a bulk density of 1.9 T/m^3. No SWCC curves are available for the tailings and coarse waste rock materials, and therefore modelling was done using the unsaturated curve fitting parameters listed in Table 5.

Table 5: Summary of Material Properties Used in Modelling

Materials ID	Material Type	θr	θs	α (1/m)	n	K_{sat} (m/day)	l
MWDTP4 [a]	Cover	0	0.303	2.67	1.20	0.164	0.5
MWDTP2 [a]	Cover	0	0.360	1.09	1.19	0.025	0.5
MWDTP3 [a]	Cover	0	0.238	5.50	1.22	3.715	0.5
Greens Creek WR [b]	Waste Rock	0.012	0.410	5.43	2.03	1.728	0.5
Finer WR [c]	Waste Rock	0	0.361	32.65	1.22	4.790	0.5
Coarser WR [d]	Waste Rock	0.020	0.450	2.00	2.50	5.000	0.5
Tailings [e]	Tailings	0.027	0.272	6.31	1.22	0.081	0.5

Source: \\VAN-SVR0\Projects\01_SITES\Minto\1CM002.030_Closure_Cover_Modelling\Task_300-CoverModel\Hydrus1D\Minto_CoverHydrusModel_Summary_Rev06_KK_IM.xlsx

Notes:

[a] : Based on RETC model using van Genuchten – Mualem method; K_sat based on laboratory result.
[b] : Hopp, L. et al. 2011.
[c] : Based on RETC model using van Genuchten – Mualem method; K_sat based on laboratory result.
[d] : Theoretical van Genuchten curve fitting values representative of a generic waste rock.
[e] : Estimated values based on particle size distribution and density of tailings on site.

2.2.3 Boundary Conditions

The top boundary condition of the one-dimensional column is a time-dependent (daily time step) atmospheric boundary (precipitation and evaporation). The bottom boundary condition is a unit gradient to simulate unsaturated gravitational flow exiting the model. Being a one-dimensional model, there are no side boundaries.

2.2.4 Initial Conditions

Initial conditions were expressed in terms of gravimetric moisture content, set at 7% for waste rock, 18% for tailings, and 11% for the soil cover materials, respectively. These moisture contents represent the field moisture content of the soil samples collected during the field programs in 2012 (SRK 2013c) and 2013 (SRK 2013b), representing reasonable initial conditions for the model.

2.2.5 Vegetation

Vegetation on site is dominated by mixed Trembling Aspen and Lodgepole Pine forests at various stages of succession following the relatively frequent forest fires. Willow species dominate the shrub covered area, while being ubiquitous in the understory of the forested areas (Access 2013).

No specific information of actual plant transpiration rates was available for model calibration. Therefore the model made use of a conservative pasture-type vegetation, which is one of the Hydrus 1D built-in vegetation functions. A constant rooting depth of 10 cm was applied.

2.3 Scenarios Evaluated

2.3.1 Base Case Scenario

The base case scenario assumes a simple 0.5 m thick soil cover overlying waste rock. The cover material is represented by test data from sample MWDTP4 (SRK 2013c) and the waste rock is represented by the Greens Creek sample. The surface is assumed to have no vegetation. Normal precipitation is applied as a 20-year long daily sequence, with snow precipitation retained during the winter months (simulating snow accumulation on frozen ground), before being reduced by an amount of 45 mm per year to account for sublimation losses. The remaining snow water equivalent is subsequently release to simulate a freshet lasting 14 days starting April 17 each year. PE equal to 400 mm annually is distributed monthly in equal daily increments (see Table 2).

The base case scenario was simulated using both Hydrus and SVFlux. Since SVFlux is a more rigorous model, it allows for a confirmation on whether the Hydrus model result is reasonable.

2.3.2 Sensitivity Analysis Scenarios

The objective of the sensitivity analysis was to evaluate which parameters have the largest influence on the percolation predictions. To that end the following sensitivity runs were completed:

- A delayed freshet (starting two weeks later, on May 1);
- Finer and coarser cover material;
- Finer and coarser underlying waste rock material;
- No sublimation and increased sublimation;
- Increased cover thickness;
- Upset climatic condition; and
- Presence of vegetation.

In addition, to allow for benchmarking of the results, simulations were also completed with no cover. Finally, simulations were completed to determine the percolation rates through these covers if they were placed over tailings.

3 Modelling Results and Discussion

3.1 Results Summary

Table 6 presents a summary of the complete results for all runs, including the sensitivity analyses. Figure 4 presents the results as a chart showing the range of yearly net percolation as percent of total precipitation for that year. The boxed number represents the arithmetic average of the yearly net percolations over the 20-year simulation, and as such does not represent any particular modelled year.

Table 6: Summary of Modelling Results

Case #	Scenario	Net Percolation (% Annual Precip.)			Total Precip. (mm)	Total Net Perc. (mm)	Total Evap. (mm)	Total Run-off (mm)
		Max.	Min.	Avg.				
1	Base Case	43%	6%	23%	6,038	1,429	4,629	0
2	Late Freshet (May 1)	35%	<1%	14%	6,038	934	5,126	0
3	Finer Cover Material	40%	2%	21%	6,038	1,305	4,717	0
4	Coarser Cover Material	44%	5%	23%	6,038	1,447	4,673	0
5	Finer Waste Rock	46%	9%	23%	6,038	1,428	4,626	0
6	Coarser Waste Rock	49%	8%	28%	6,038	1,749	4,316	0
7	1 in 5 years wet	29%	17%	23%	7,065	1,612	5,468	0
8	1 in 5 years dry	26%	8%	14%	4,607	682	3,949	0
9	Thicker Cover (1 m)	38%	3%	19%	6,038	1,179	4,824	0
10	Thicker Cover (2 m)	36%	3%	18%	6,038	1,134	4,904	0
11	Tailings WR traffic layer under cover	38%	6%	21%	6,038	1,299	4,750	0
12	WR only; No Cover	65%	34%	45%	6,038	2,742	3,291	0
13	Tailings with WR; No Cover	61%	31%	41%	6,038	2,500	3,541	0.3
14	Tailings only; No Cover	60%	26%	39%	6,038	2,383	3,665	0
15	BaseCase; No Sublimation	54%	13%	33%	6,933	2,323	4,651	0
16	Vegetation	40%	4%	21%	6,038	1,298	4,719	0
17	Base case (80 mm sublimation)	30%	1%	14%	5,332	759	4,579	0
18	SV Flux check	44%	5%	19%	6,044	1,228	4,821	0
19	SV Flux check; No Sublimation	54%	11%	29%	6,940	2,090	4,851	0

Source: \\van-svr0\Projects\01_SITES\Minto\1CM002.030_Closure_Cover_Modelling\!080_Deliverables\Cover Model Results\020_Tables\[Minto_CoverHydrus Model_Summary_Rev13_IM.xlsx]Summary

In all cases the results are predicted as a range around an average value as opposed to a single percolation value. This is intentional, as surface flux boundary modelling cannot yield absolute results. The percolation outcome is a function of the complex interaction between antecedent meteoric events and pre-existing soil moisture conditions, which naturally is highly variable. Similar precipitation events can yield vastly different percolation results depending on preceding soil moisture conditions. Therefore the appropriate use of modelling is to bracket the likely range of results, taking into consideration those elements that drive the outcome.

Another way to look at the results is to consider the normal distribution of the range. For example, Figure 5 presents the 20 years of precipitation data, indicating the variability which ultimately resulted in the Base Case model calculating a range of percolation between 6% and 43% with the average of 23%.

Arranging the predicted range into a histogram (Figure 6) reveals that eight out of 20 years the percolation is likely to be in the near-average range, followed by six out of twenty years moderately exceeding the average. This compares to total precipitation of about 300 and 350 mm respectively, thus representing a rough correlation between the precipitation and net percolation. The correlation however is reliable only for the modelled results and extrapolation outside of the modelled range may not be valid. This is due to the fact that the relationship between precipitation and percolation is not linear, as described earlier in this section.

Using some basic statistical tools, the same Base Case results can be arranged into a normal probability distribution, as shown in Figure 7. This graphic shows that, for example, 90% of the time percolation will be less than 35% of the yearly precipitation; conversely one in ten years can be expected to have net percolation higher than 35%.

3.2 Model Verification

The Base Case (Case #1) model, which uses the Hydrus 1D code yields an average percolation of 23%, with an overall range between 6 and 43%. The equivalent scenario, using the more rigorous SVFlux code (Case #18), yields and average percolation of 19%, with an overall range of 5 to 44%. A second verification check was made for Case #15 which is the Base Case model, but without sublimation. In this case the average percolation is 33%, while for Case #19 (the equivalent SVFlux run) it is 29%. For Case #15 the overall percolation range is between 13 and 54%, while for Case #19 it is between 11 and 54%.

In all instances the overall range of percolation results are near identical, and most certainly within the accuracy range of surface flux boundary modelling. The average percolation is consistently 4% lower for the SVFlux model runs. This difference is ascribed to the fact that for the SVFlux model runs the evaporation is slightly higher resulting in lower percolation. As described earlier, SVFlux is a true surface flux boundary model that calculates actual evaporation for each time step using the Modified Penman equation, and as a result, this higher evaporation is expected. The small difference of 4% is however within the level of accuracy of this type of modelling, and therefore the Hydrus 1D modelling is entirely suitable. The fact that the Hydrus 1D model reports a slightly higher percolation rate suggests a level of conservatism which is entirely appropriate.

3.3 Base Case (0.5 m Soil Cover over Waste Rock)

A 0.5 m soil cover over waste rock reduces percolation by almost half to 23%, and similarly the range drops to between 6 and 43%. This demonstrates that even a nominal soil cover results in a considerable reduction in percolation, and therefore is potentially beneficial as a mitigation strategy.

3.4 Uncovered Waste Rock and Tailings

The average percolation for the uncovered waste rock (Case #12) and tailings (Case #14) are 45 and 39% respectively. The range for uncovered waste rock is 34 to 65%, while for the uncovered tailings its 26 to 60%. Tailings percolation is less due to the finer grained nature of the material, which retains more moisture near surface making some of that moisture subsequently available for evaporation.

3.5 Simple Soil Cover Over Tailings

Although it would be possible to apply a simple 0.5 m thick soil cover over the Minto Dry-Stack Tailings Facility, this would not be possible or practical for hydraulically placed tailings in the Main Pit. To ensure trafficability, a 1 m thick layer of waste rock would likely first be required. The effect that has on the modelled percolation rate is illustrated by Case #13, which increases the average percolation to 41% compared to 39% for the uncovered tailings. In both these cases the overall percolation range is similar as illustrated in Figure 4. This result is plausible, as the waste rock is coarser than the tailings allowing for higher infiltration and less evaporation; however, with the finer tailings only 1 m below the surface, some moisture remains more available during wetter periods, which means the average percolation is slightly less than the uncovered waste rock.

Covering the trafficking layer with a 0.5 m simple soil cover (Case #11) has the net effect of reducing the average percolation to 21% and the range to between 6 and 38% which is similar to the performance of the Base Case (Case #1).

3.6 Effect of Cover Material Composition

As illustrated in Section 2.2.2, the available candidate cover materials have a significant range in material properties. Modelling the finer and coarser ends of the spectrum (Case #3 and #4 respectively) suggest that this variability does not materially influence the outcome, since the variability in average percolation between the three cover materials is only 2%. This confirms that for the materials characterized to date there is no preferred material type with which lower percolating covers can be constructed.

3.7 Effect of Cover Thickness

Increasing the cover thickness from 0.5 m to 1 m (Case #9) has the effect of reducing net percolation by about 4%, and the overall range in percolation becomes slightly smaller. Further increasing the cover thickness to 2 m (Case #10) results in a negligible additional improvement, which is arguably less than the model accuracy. This outcome is consistent with the cover material properties, in that the capillarity of the cover material is around 1 m, which means that moisture that passes beyond this limit is unlikely to be released via evaporation.

3.8 Effect of Waste Rock Material Composition

Model simulations with a finer (Case #5) and a coarser (Case #6) waste rock material demonstrate a reasonable sensitivity when measured against the Base Case cover. For the finer waste rock there is no effect on the average percolation rate; however, the range shifts towards the higher end as illustrated in Figure 4. When modelling a coarser waste rock, the average net percolation increases to 28%, and the overall range shifts up (similar to the finer waste rock) to between 12 and 49%. This result is consistent with the observations in Section 3.7 above, suggesting that a cover thickness of 0.5 m is thin enough that it is influenced by the underlying material type. Therefore, with only 0.5 m of cover, having a coarser waste rock with less water retention capability will result in less evaporation and thus greater percolation.

3.9 Effect of Freshet Timing

Delaying the freshet by two weeks (Case #2) has a significant effect on the model outcome. This yields an average percolation of 14% with the range from less than 1 to 35%. The reason for this dramatic reduction is the fact that the model allows for evaporation starting on May 1, and therefore some of the freshet water can evaporate, rather than being allowed to simply percolate through the cover.

3.10 Effect of Sublimation

The model outcome is very sensitive towards the sublimation assumptions. Not allowing for any sublimation (Case #15) results in an increase in average percolation of 10% to 33%, while increasing the sublimation from 45 mm per year to 80 mm per year (Case #16) reduces the average net percolation from 23% to 14%. This result makes sense, as by increasing or decreasing the sublimation, the amount of water that is released during the freshet is increased or decreased, with freshet being a major contributor towards percolation in the Minto environment.

3.11 Effect of Wetter or Dryer Than Normal Climatic Years

To study the effect of abnormally dry or wet precipitation, synthetic subsets of five years were assembled, as described in Section 2.2.1. The models were run for 20 years, using the same 1,825-day weather record four times back-to-back. As expected, the dryer climate (Case #8) resulted in a significant reduction of the average percolation, to about 14%, with the range also shifting downward, to range between 8 and 26%.

The average percolation for the wetter climate (Case #7) remained unchanged compared to the base case, with the increase of the minimum percolation to 14% as expected. The decrease of the maximum percolation to 29% is however counter-intuitive, and is explained by the fact that although total yearly precipitation is higher in each of these years, there are fewer distinct high precipitation events driving massive percolation breakthrough.

3.12 Effect of Vegetation

The model indicates that grassy vegetation (pasture) established on the cover (Case #17) has a small effect on improving the cover performance. This result is perhaps less pronounced than general experience with vegetated covers would suggest. Evapotranspiration in cold climates is a complex process, and in the absence of site specific calibration data the modelled result remains indicative that any vegetation would modestly increase the cover performance.

4 Conclusions

The modelling results in this memo demonstrate that simple soils covers, using locally available materials can be effectively used to reduce percolation through the waste products (waste rock and tailings) by up to 50% compared to the uncovered waste. Uncovered, the waste rock and tailings percolation is about 39 and 45% respectively, while with a simple 0.5 m thick soil cover these average percolation rates decrease to about 23%. With some refinement, such as increasing the cover thickness to about 1 m and by adding some vegetation, the average percolation could likely be reduced to around 20% or less.

The sensitivity analysis shows that the outcome is most sensitive to climatic inputs (such as the timing of freshet and the rate of sublimation) as opposed to material properties, whether waste rock or cover soils. Since these climatic variables cannot be managed through engineering solutions, relying on the cover performance improvements suggested by these model outcomes would not be prudent.

It is important to note that in all cases, the overall range of percolation needs to be considered, as opposed to a single average value. Any water quality assessment should take into consideration the range of cover performance indicated by the modelling results as summarized in Figure 7.

Although the modelling presented has been verified by using a rigorous true surface flux boundary code, it remains uncalibrated and therefore the built-in conservatism is appropriate. One important example of this is evident in how the model is simulating runoff. The model results indicate that virtually no surface run-off will occur; however, there is clear evidence that in reality, runoff does occur at the site. Should covers be deemed an appropriate mitigation strategy, more rigorous refinement of the modelling should be considered at the more advanced design stages, including assessing 2-D effects of slopes to better reflect runoff and incorporation of the influence of frozen covers on freshet percolation. Notwithstanding the limitations mentioned in this document, the results as presented are deemed indicative of the most reasonable upper bound of expected percolation.

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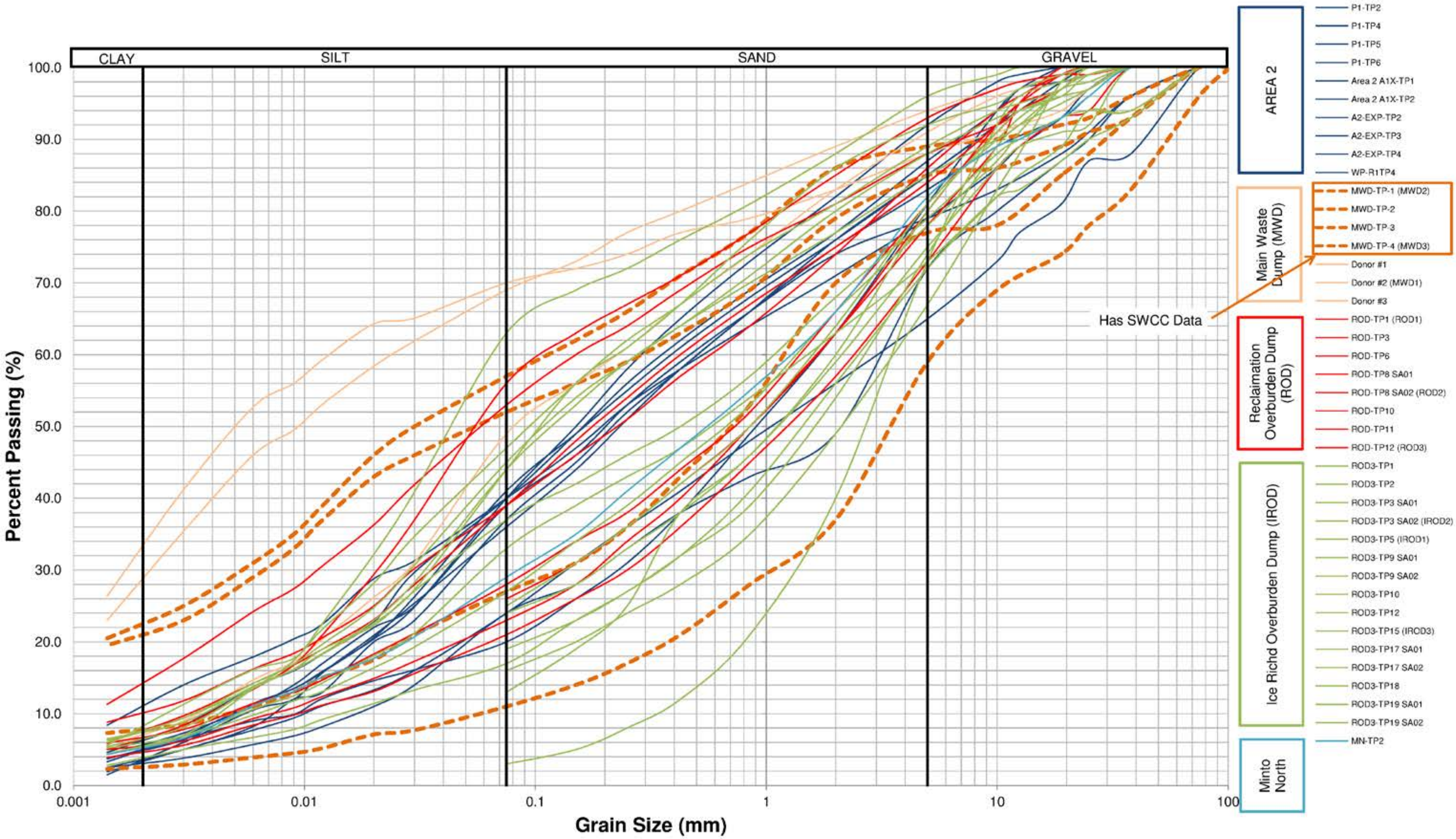
Figures



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srk consulting	capstone MINTO MINE OPERATED BY MINTO EXPLORATIONS LTD.	Closure Covers Model		
		Particle Size Distribution of all Candidate Cover Material on Site		
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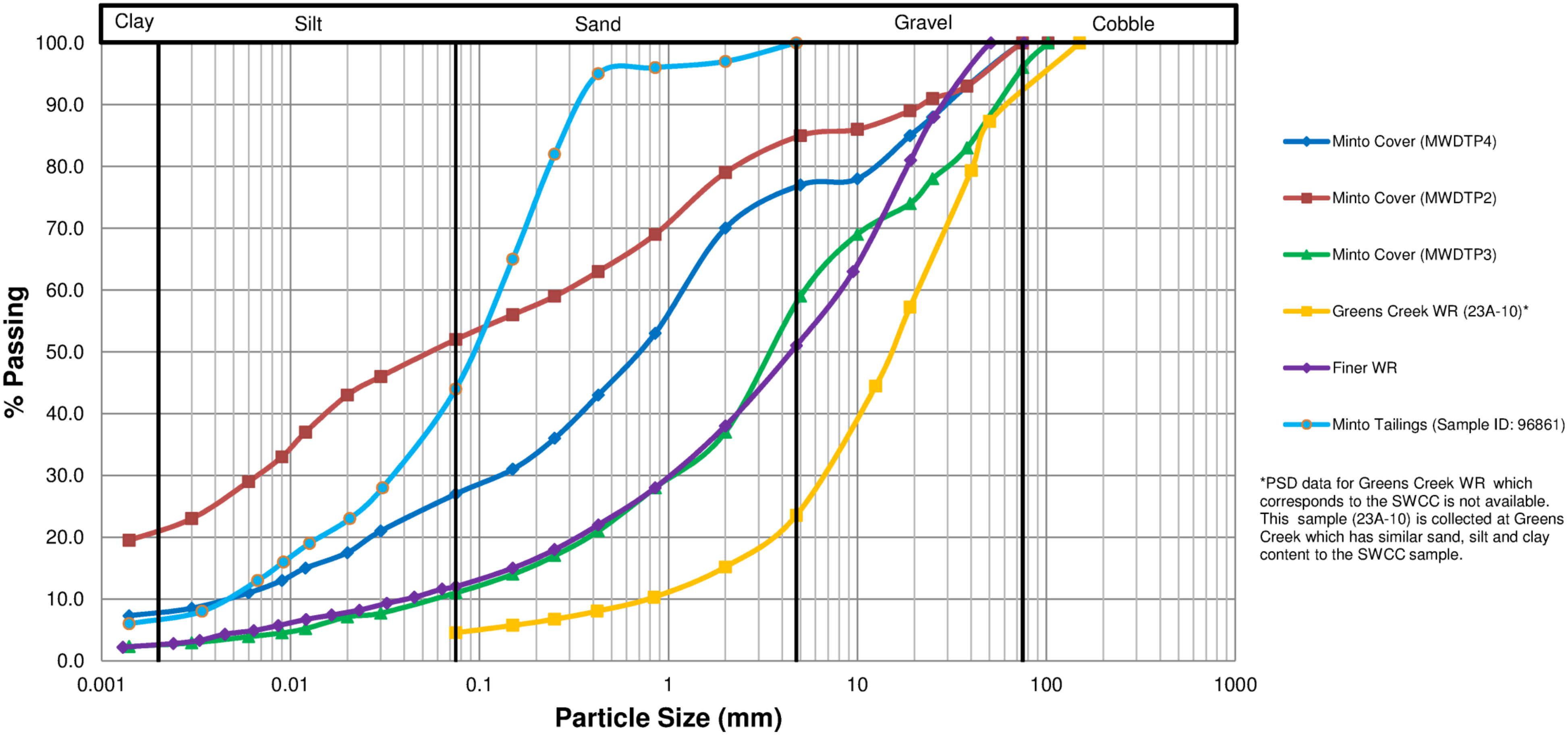
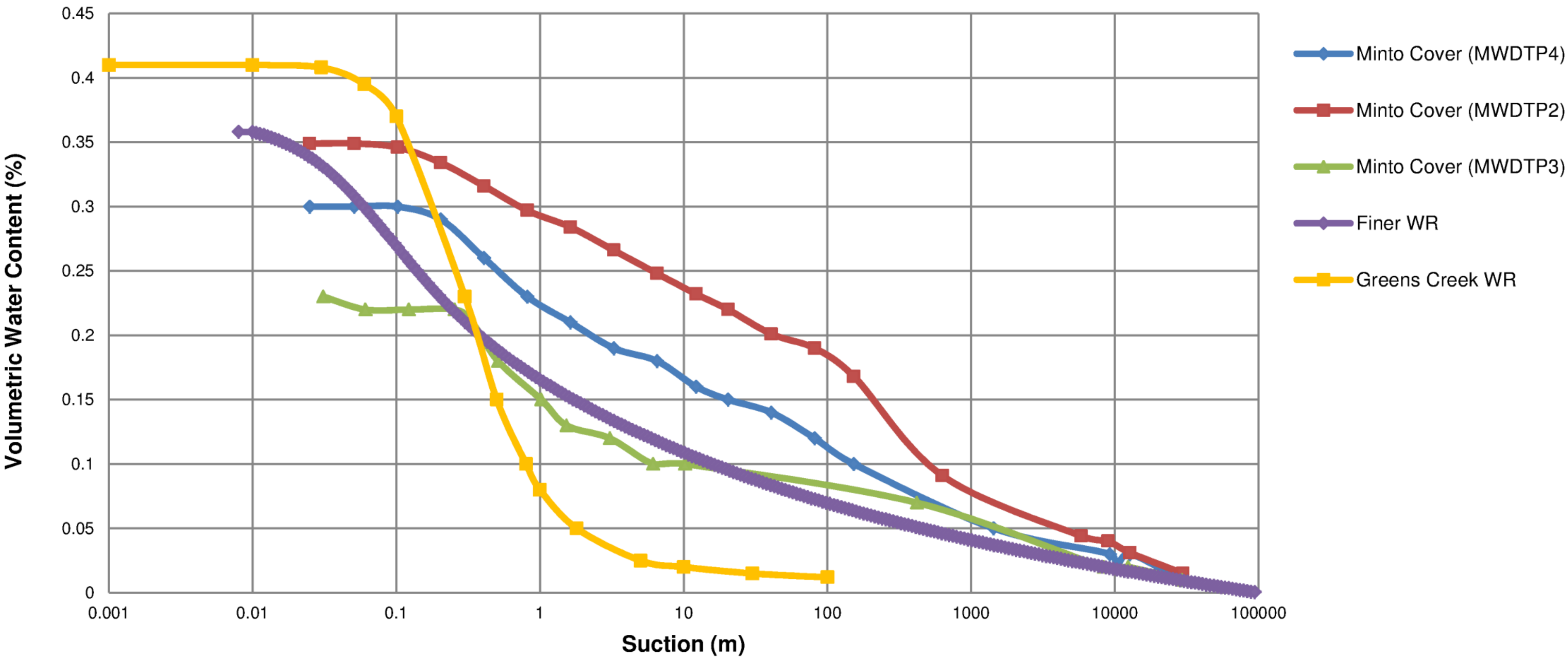


*PSD data for Greens Creek WR which corresponds to the SWCC is not available. This sample (23A-10) is collected at Greens Creek which has similar sand, silt and clay content to the SWCC sample.

srk consulting	capstone MINTO MINE OPERATED BY MINTO EXPLORATIONS LTD.	Closure Covers Model
		PSD Curves of Selected Cover Materials, Waste Rock, and Tailings
Job No: 1CM002.030 Filename: CoverModel_Figures_1CM002.030_Rev01_IM.pptx	MINTO MINE	Date: Nov. 2014 / Approved: IM / Figure: 2



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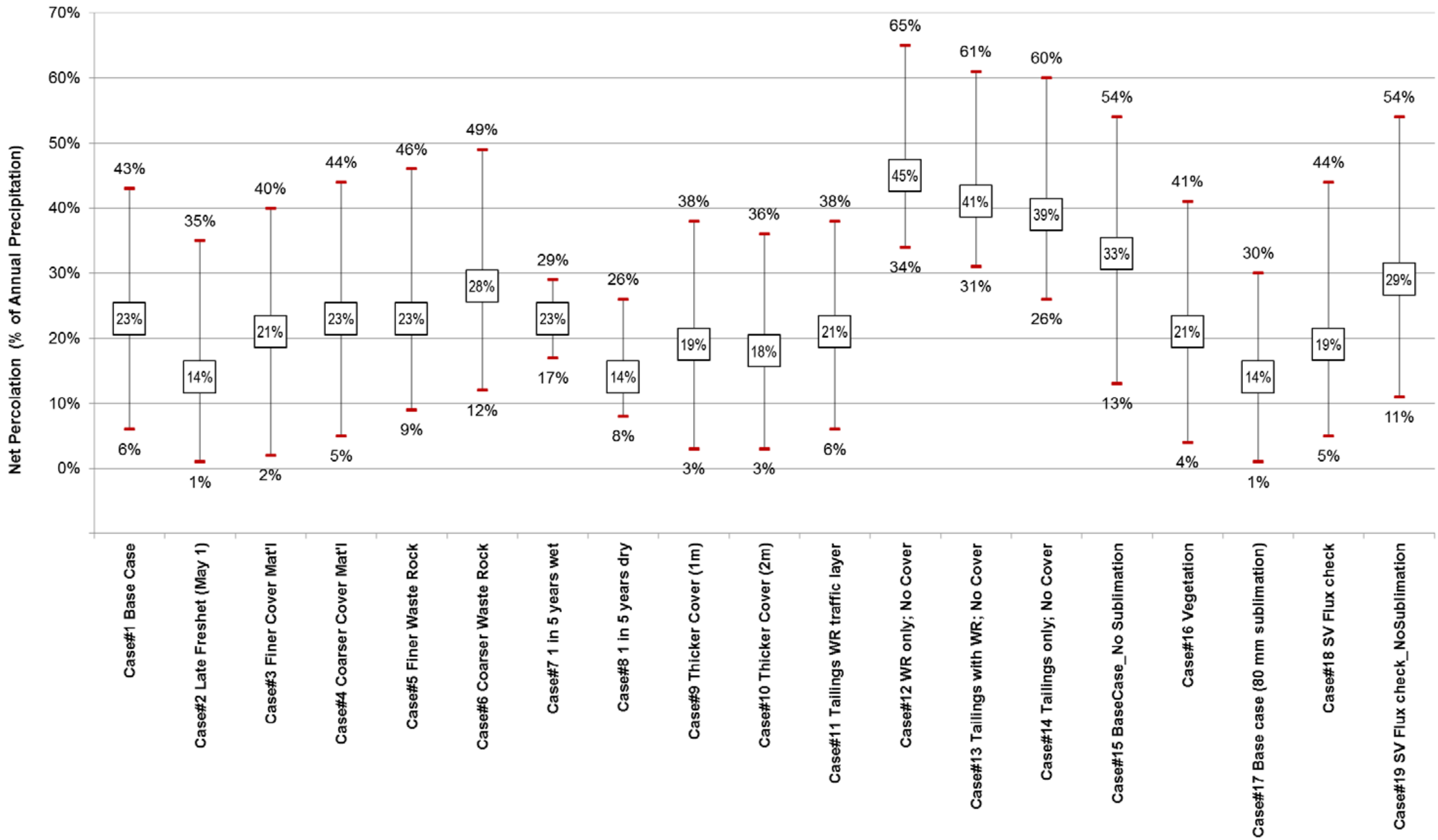
srk consulting	capstone MINTO MINE OPERATED BY MINTO EXPLORATIONS LTD.	Closure Covers Model
		Soil Water Characteristic Curves
Job No: 1CM002.030 Filename: CoverModel_Figures_1CM002.030_Rev01_IM.pptx	MINTO MINE	Date: Nov. 2014 / Approved: IM / Figure: 3



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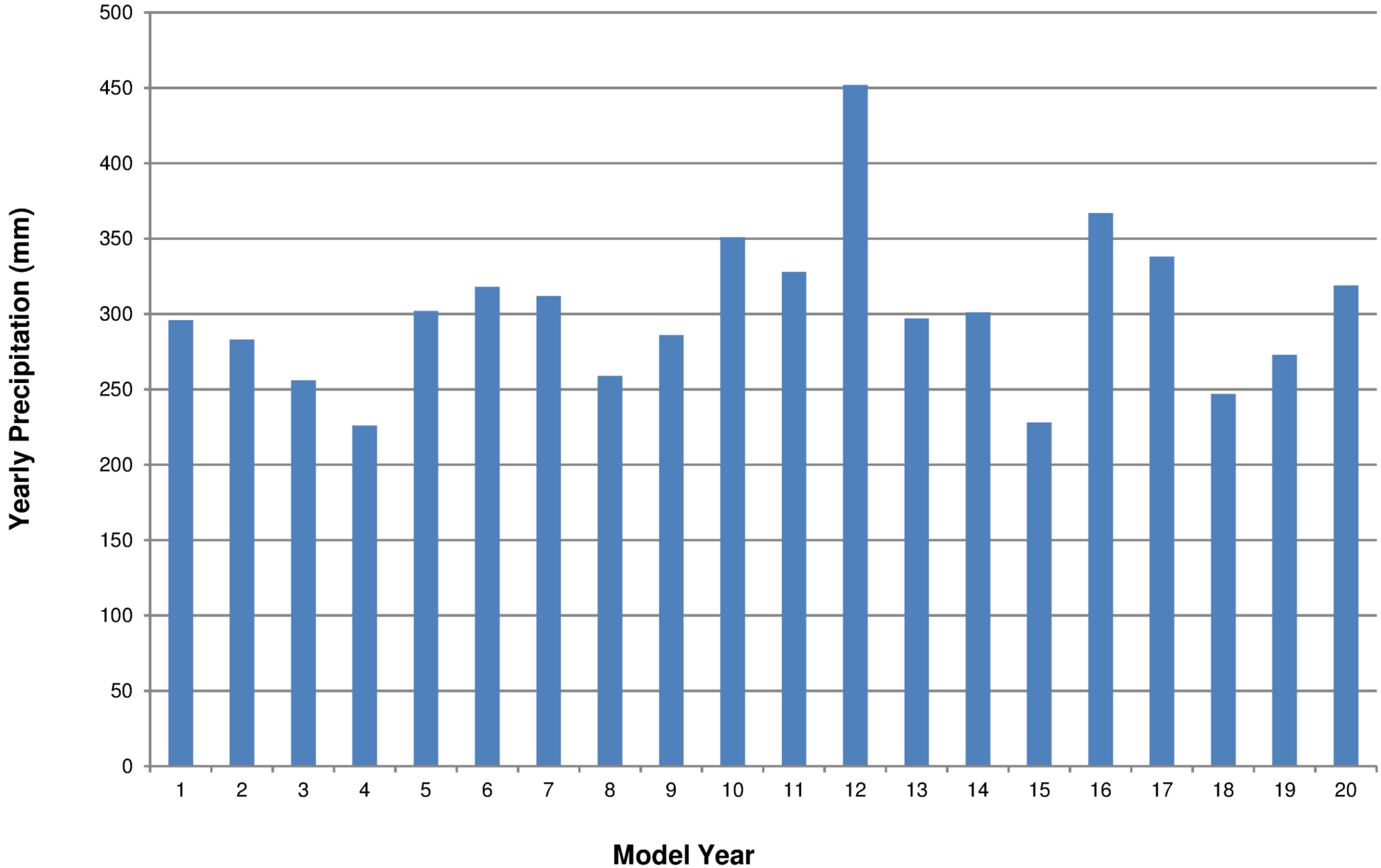
Job No: 1CM002.030 Filename: CoverModel_Figures_1CM002.030_Rev01_IM.pptx	MINTO MINE	**Closure Covers Model** Summary of Model Results Date: Nov. 2014 · Approved: IM · Figure: 4



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srk consulting	capstone MINTO MINE OPERATED BY MINTO EXPLORATIONS LTD.	Closure Covers Model		
		Normal Distribution of Yearly Precipitation		
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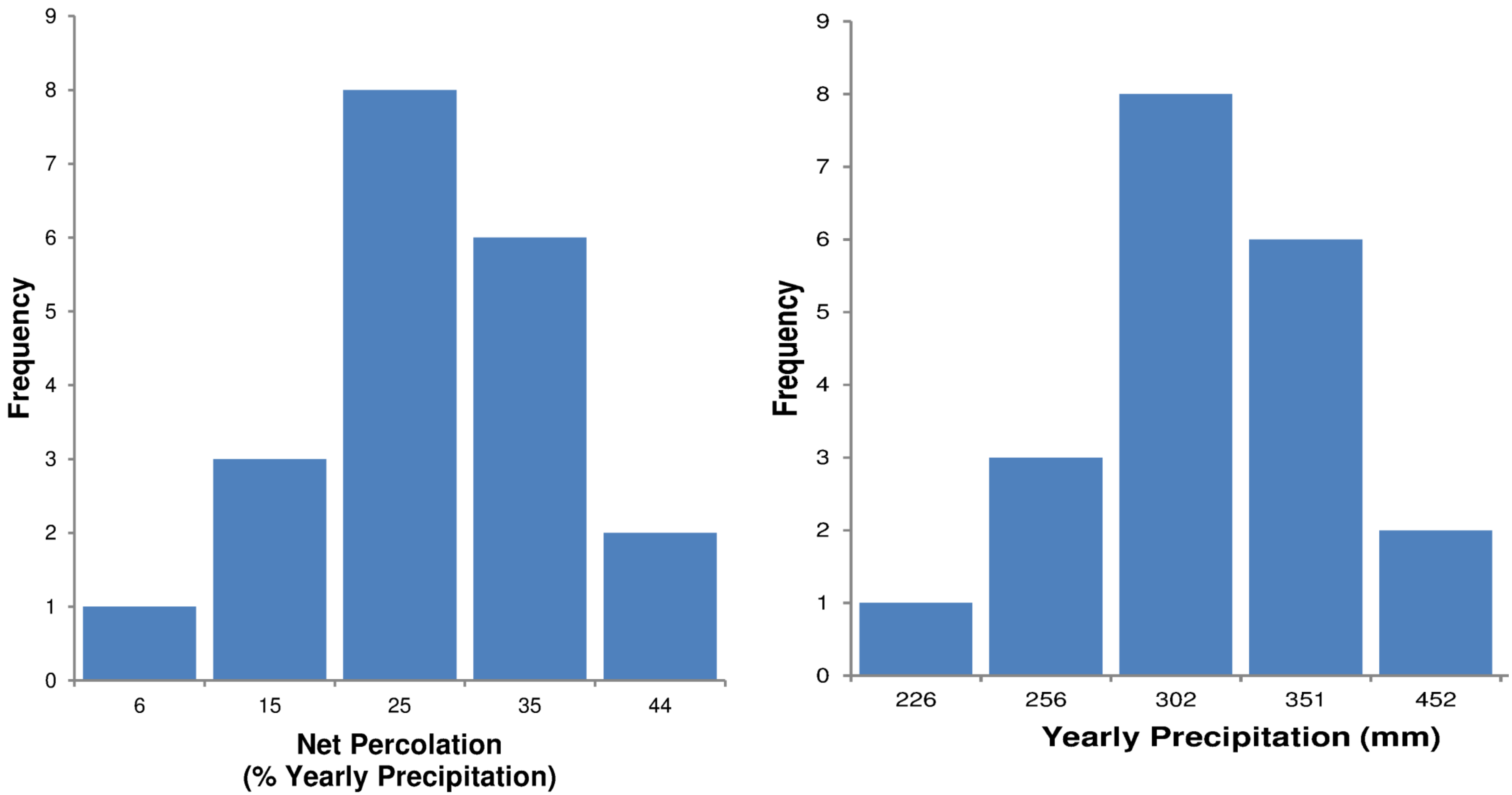
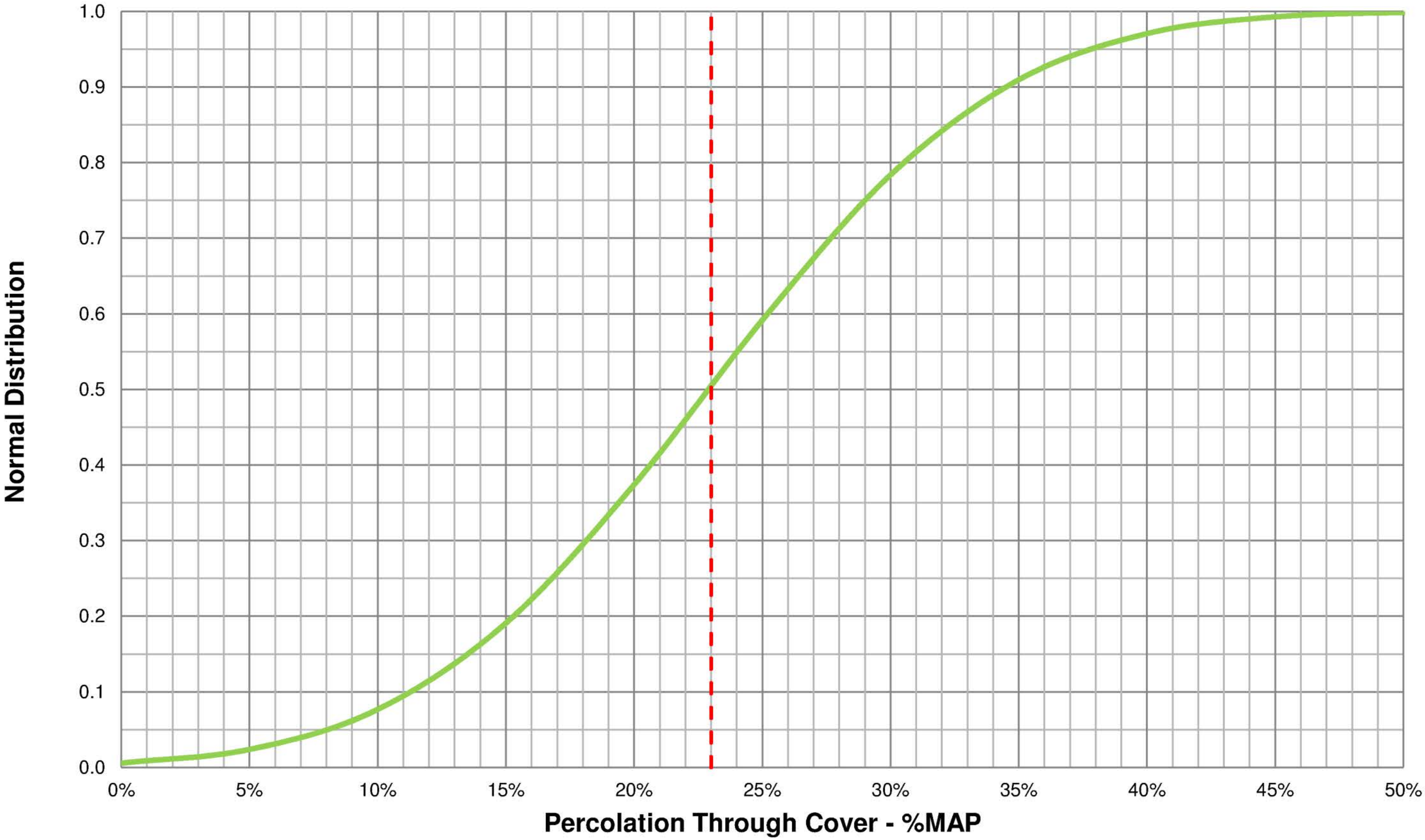


srk consulting	capstone MINTO MINE OPERATED BY MINTO EXPLORATIONS LTD.	Closure Covers Model
		Comparison of Statistical Distribution of Net Percolation and Precipitation
Job No: 1CM002.030 Filename: CoverModel_Figures_1CM002.030_Rev01_IM.pptx	MINTO MINE	Date: Nov. 2014 | Approved: IM | Figure: 6



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Closure Covers Model

Percolation Through the Cover System

Job No: 1CM002.030

Filename: CoverModel_Figures_1CM002.030_Rev01_IM.pptx

MINTO MINE

Date: Nov. 2014

Approved: IM

Figure: 7

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