APPENDIX II

SNAP LAKE SITE WATER MODEL REPORT – NORTH PILE LONG TERM WATER STORAGE AND RELEASE

December 2013

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LIST OF ACRONYMS

Term	Definition
1D	one-dimensional
2D	two-dimensional
C	concentration at a given time
CGPK	combined coarse and grits fraction of the processed kimberlite
Co	initial concentration
FPK	fines fraction of the processed kimberlite
GPK	grits fraction of the processed kimberlite
HGS	HydroGeoSphere model
K	hydraulic conductivity
Kd	distribution coefficient
Mine	Snap Lake Mine
PK	processed kimberlite
PPK	full mix processed kimberlite
Q	flow
Q(t)	flow at time (t)
t	time
x	horizontal direction
y	horizontal direction perpendicular to the x direction
z	vertical direction

UNITS OF MEASURE

Term	Definition
%	percent
cm	centimetre
kg	kilogram
kg/m^3	kilograms per cubic metre
m	metre
m/s	metres per second
m^2	square metre
m^3/d	cubic metres per day
m^3/kg	cubic metres per kilogram
m^3/s	cubic metres per second
m^3/yr	cubic metres per year
mg/L	milligrams per litre
mm	millimetre
mm/yr	millimetres per year

II.1 INTRODUCTION

Nitrate and ammonia, derived from explosive material used in the mining process, are found within the emplaced materials of the processed kimberlite (PK) in the North Pile at the De Beers Canada Inc. Snap Lake Mine (Mine) in the Northwest Territories. Process and infiltration waters that discharge from the North Pile to the surrounding sumps currently have a concentration of about 100 milligrams per litre (mg/L) of nitrate (as N) and 30 mg\/L of ammonia (as N). It is expected that over time the nitrate and ammonia will be flushed from the PK pore space, and concentrations in the discharge waters will decline. While the nitrate and ammonia in the sump waters are presently mixed with minewaters, facilitating discharge at acceptable (overall) water quality conditions, the long term concentrations and significance of the long term discharge concentrations are not well understood.

Provided herein is an initial assessment of the long-term water storage, release rate, and water quality conditions (in particular with respect to nitrate and ammonia) within, and discharging from, the North Pile. The assessment was completed through a review of available hydrogeological and site design information related to this issue. This review was conducted in combination with numerical simulations (using the computer program HydroGeoSphere [HGS]), to forecast future concentrations of these parameters through the operational and closure periods.

II.2 DATA REVIEW, COMPILATION AND SYNTHESIS

The hydraulic properties used in this assessment for the various material types associated with the fines-fraction of the PK as well as the coarse fractions of the PK used in the construction of the embankments are presented in Table II-1.

Table II-1 Hydraulic Parameters for Processed Materials

Material	Saturated Hydraulic Conductivity (m/s)	Porosity (fraction)	Specific Storage (1/m)	Bulk Density (kg/m^3)
Full mix PK	5×10^{-7}	0.45	1×10^{-4}	1400
Fine fraction of the PK	1×10^{-6}	0.45	1×10^{-4}	1540
Grits fraction of the PK	1×10^{-5}	0.35	1×10^{-4}	1680
Combined Coarse and Grits fraction of the PK	5×10^{-4}	0.325	1×10^{-4}	1700
Coarse fraction of the PK PK	1×10^{-4}	0.3	1×10^{-4}	1800

m/s = metres per second; m=metre; kg/m^3 = kilograms per cubic metre; PK = processed kimberlite.

Full mix PK was not included in any of the one-dimensional (1D) or two-dimensional (2D) model scenarios at this time.

Hydraulic properties, thicknesses, etc. for the geological units underlying the North Pile (e.g., peat, overburden, fractured bedrock, etc.) are not included here as it is assumed that the ground below the North Pile facility will be in a frozen state, thus (for practical purposes) will not contribute to under draining.

Soil retention relations which define the hydraulic conductivity of the porous medium under variably-saturated conditions are required by the HGS model. Soil retention relationship estimates for the fines fraction of the PK material were obtained from Sun and Stianson (2013). For the combined coarse and grits fraction of the PK soil retention properties for Borden Sand (Abdul 1985) were assumed. Soil retention curves are shown in Figure II-1.

Initial estimates of nitrogen in the form of nitrate, nitrite, and ammonia are shown in Table II-2. These data are from an analysis of water drained from fresh, processed material that was sampled on September 18, 2012.

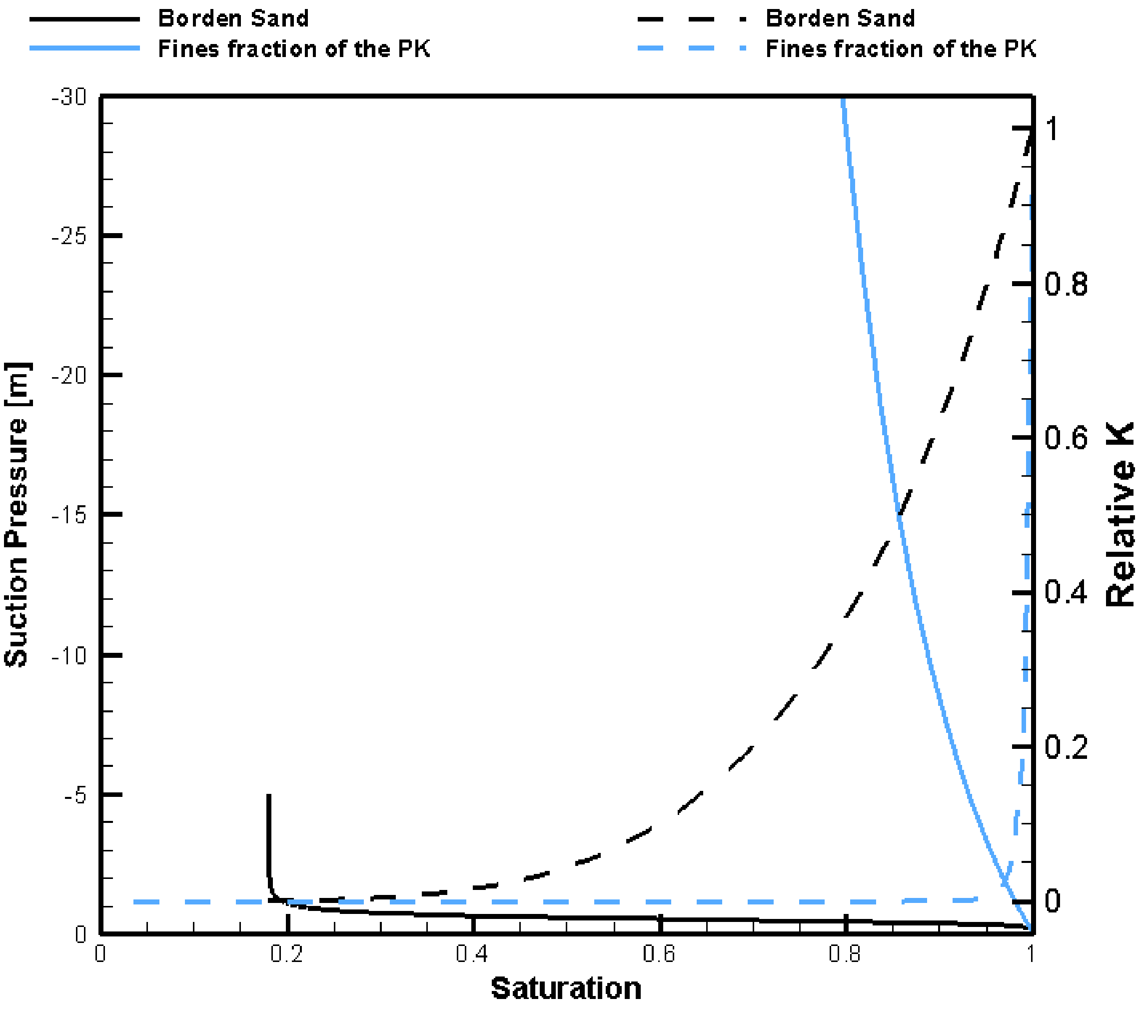
Table II-2 Initial Values for Nitrate, Nitrite and Ammonia in Processed Materials

	Unit	**CGPK1** (Combined Coarse and grits fraction of the processed kimberlite)	**FPK1** (fine fraction of the processed kimberlite)	**GPK1** (Grits fraction of the PK)	**PPK1** (Full mix PK)	Average
Ammonia-N	mg/L	29.5	30.6	24.1	25.3	27.375
Nitrate-N	mg/L	132	122	137	130	130.25
Nitrite-N	mg/L	3.54	4.04	2.98	3.78	3.585
Total-N	mg/L	165.04	156.64	164.08	159.08	161.21

CGPK = Combined Coarse and Grits Processed Kimberlite; FPK = Fine Fraction of the Processed Kimberlite; GPK = Grits fraction of the Processed Kimberlite PPK = Full mix Processed Kimberlite; mg/L = milligrams per litre.

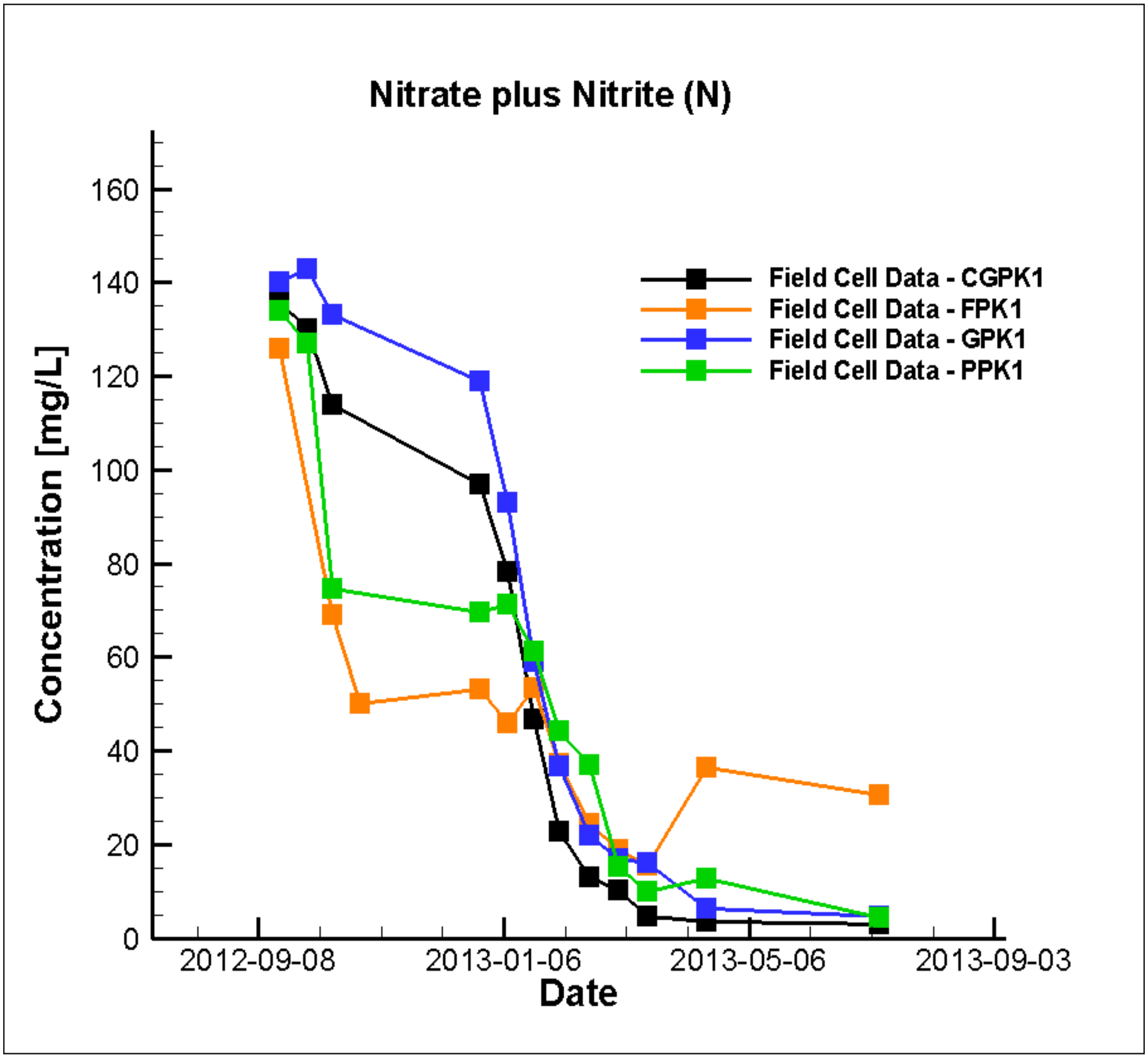
Nitrate plus nitrite concentrations measured in the treated effluent during the four indoor barrel experiments (Section II.3) are shown in Figure II-2. Data were not available from the outdoor barrel experiments.

Figure II-1 Soil Retention Properties.



PK = Processed Kimberlite; m = metre; K = Hydraulic Conductivity.

Figure II-2 **Nitrate + Nitrite Concentrations (mg/L) Versus Time in "Barrel" Experiment Treated Effluent**



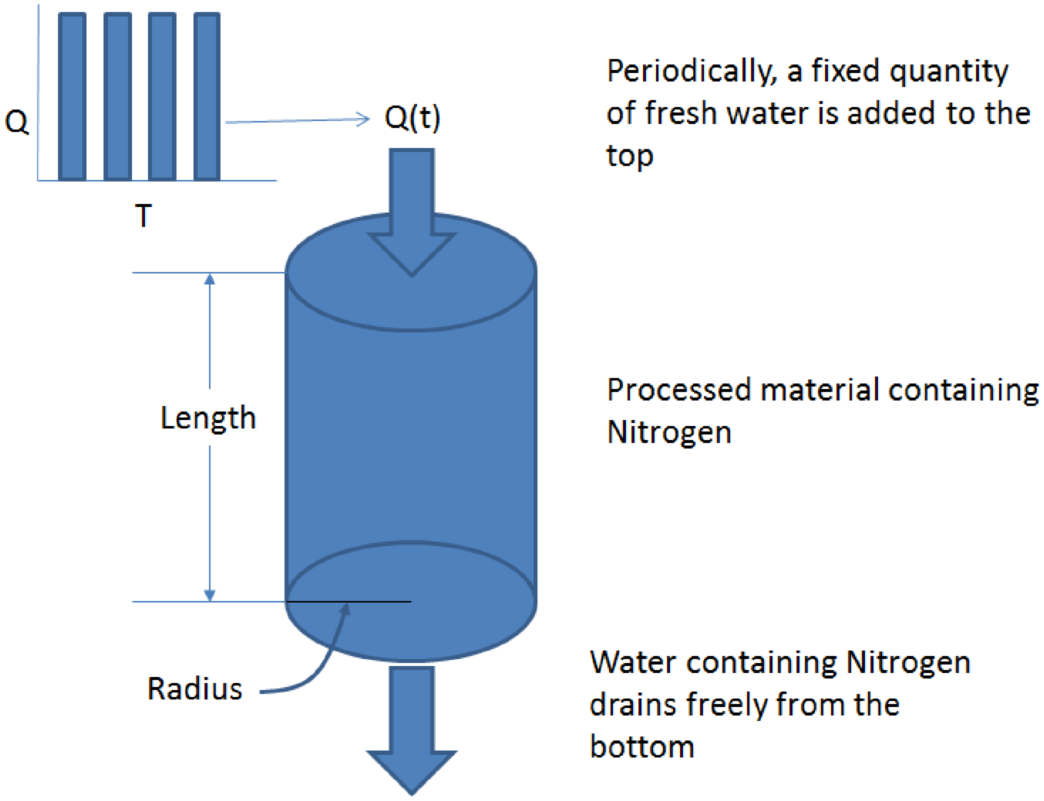
mg/L = milligrams per litre; CGPK = Combined Coarse and Grits Processed Kimberlite; FPK = Fines Fraction of the Processed Kimberlite; GPK = Grits Fraction of the Processed Kimberlite; PPK = Full Mix Processed Kimberlite.

II.3 ONE DIMENSIONAL NUMERICAL SIMULATION OF FIELD CELL EXPERIMENTS

A total of eight barrels (i.e., field cells) were partially filled with representative samples from the various mine waste streams fines, grits, and coarse fraction PK used in the construction of the berms and internal dykes), each of which would contain nitrate and ammonia. Periodically, water would enter the top of the barrel, either under conditions of natural precipitation (outdoor experiments) or by the direct addition of water at regular intervals (indoor experiments), and be allowed to drain freely from the bottom. The concentration of nitrate and ammonia in the treated effluent was measured. Data from the outdoor experiments were not available and so they were not included in this assessment. Paste PK was not included in any of the 2D model scenarios so field cell PPK1 was not included in this assessment. Results from field cells CGPK1 and GPK1 were similar and so only field cell GPK1 was analysed.

A schematic of a barrel experiment is shown in Figure II-3. The barrels used had a radius of 30 centimetre (cm) and were filled with 20 cm of processed material. At the times indicated by the data points in Figure II-2, 60 millimetre (mm) of water was added over a period of 10 minutes.

Figure II-3 Field (Barrel) Cell Experimental Setup.



Q = Flow, t =Time; Q(t) = Flow at time (t).

In the model (HGS), it was assumed that the processed material was both homogeneous and isotropic and that flow was uniform and vertical from top to bottom through the domain. The barrel was represented as a rectangular block 0.532 metre (m) by 0.532 m by 0.2 m in the x-, y-, and z-directions respectively, and had the same cross-sectional area perpendicular to flow as a circle of radius 0.3 m. The domain was subdivided vertically into 50 elements each with a thickness of 0.004 m. The initial condition of the processed material is unknown, but for these simulations an initial hydraulic head of zero was assumed. The top boundary condition consisted of an assigned flux of 1 x 10^{-5} metres per second (m/s) for 600 seconds (i.e., 60 mm over 10 minutes) at times corresponding to the data points shown on Figure II-2. On the bottom boundary, a fixed head equal to the elevation of the base was assigned, which allows water to drain freely from the domain.

For the nitrogen transport simulation, only nitrate plus nitrite were considered, since they are the largest constituent of total nitrogen and are more stable than ammonia, which degrades relatively quickly into other forms. Two source conditions were tested for nitrate plus nitrite:

1) An initial porewater concentration of nitrate plus nitrite of 130 mg/L; and,
2) An initial solid mass which dissolved at a solubility of 130 mg/L until the mass was exhausted.

An initial dispersivity value of 0.1 m was used. Best-fit simulated nitrate plus nitrite breakthrough curves are shown for the field cell FPK1 initial concentration case in Figure II-4 and for the solid source case in Figure II-5.

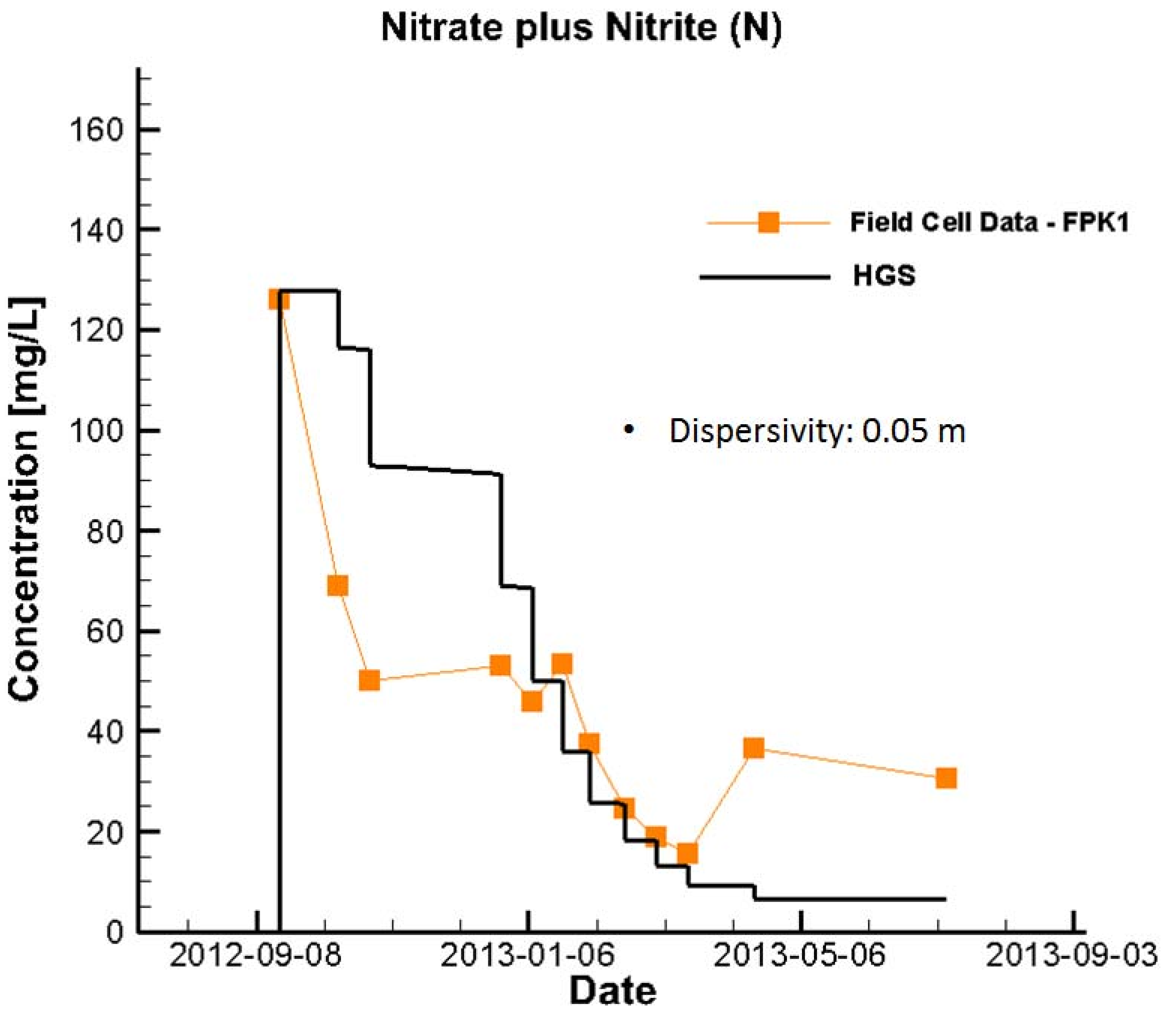
The results are similar for both source types, except at early time, when the dissolution of the solid source causes elevated solute levels to persist for longer than was observed. In the case of the initial concentration source, a smaller dispersivity value of 0.05 m gave a better fit. In both cases, a small Kd value of 1x 10^{-3} cubic metres per kilogram (m^3/kg), equivalent to a retardation factor of about 5, improved the fit. The initial mass shown in Figure II-5 was computed from the observed breakthrough concentrations by summing over the sampling events and by assuming that:

1) The volume of treated effluent collected was equal to the amount of water added; and,
2) Solute was completely mixed in the treated effluent.

Best-fit simulated nitrate plus nitrite breakthrough curves are shown for the field cell GPK1 initial concentration case in Figure II-6 and for the solid source case in Figure II-7. Similar results were seen regarding dispersivity and Kd values and, again, the solid source appears to cause the nitrate plus nitrite concentrations to remain at high levels in the model for longer than was observed in the test data.

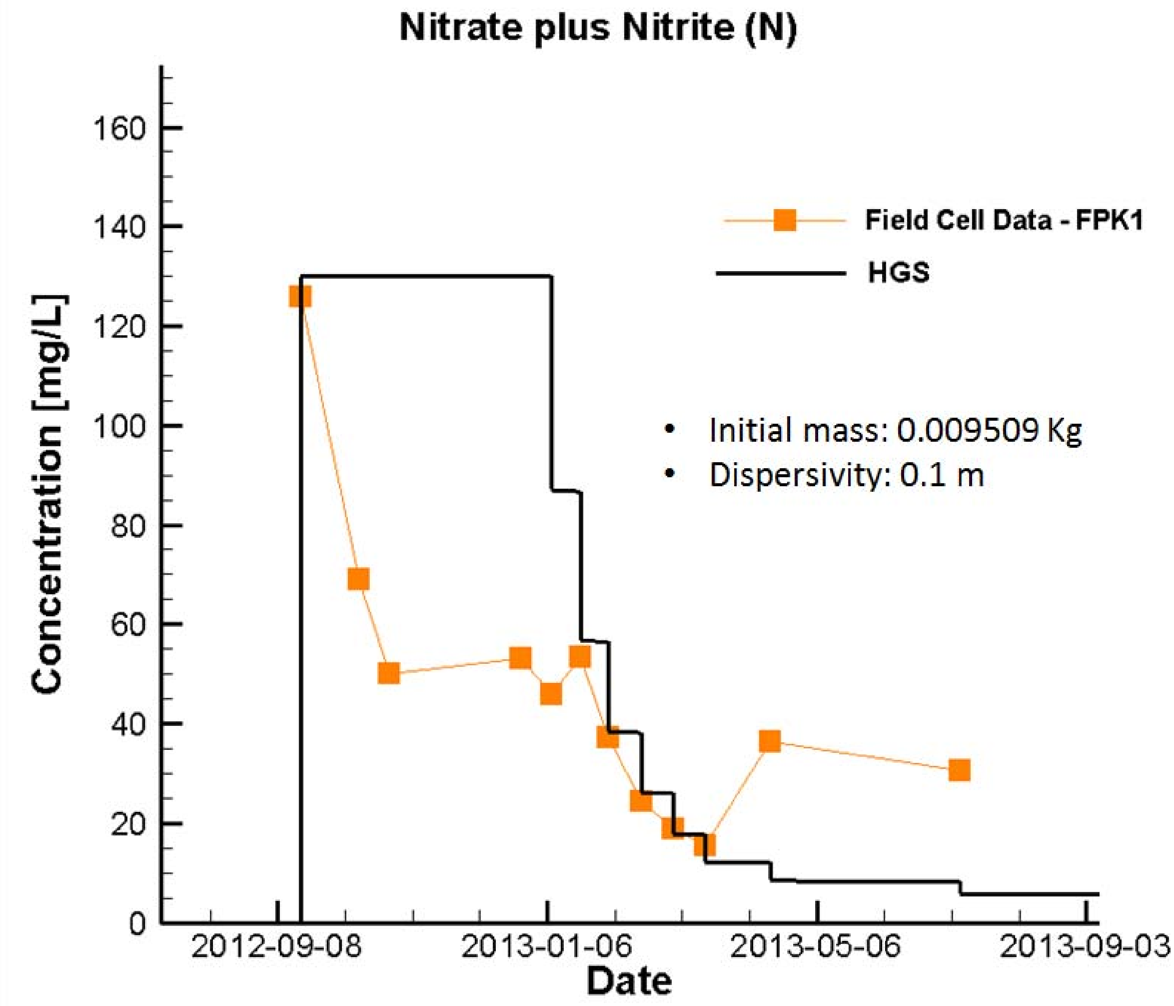
Based on these initial 1D model runs, an initial concentration of nitrate plus nitrite of 130 to 140 mg/L in the porewater produces the most reasonable simulated results compared to the observed breakthrough.

Figure II-4 Concentration Versus Time for Field Cell FPK1 Initial Concentration Case



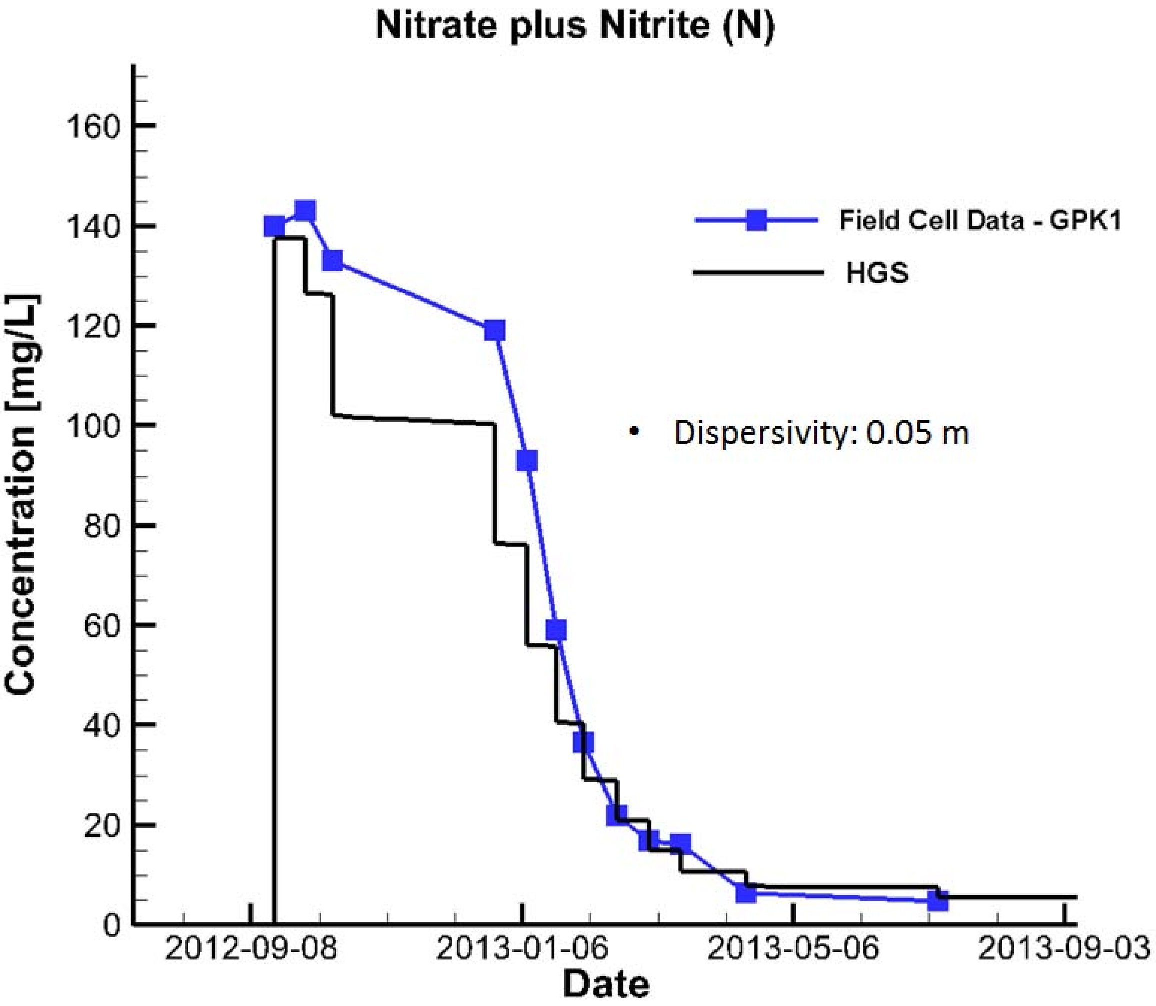
mg/L = milligrams per litre; m = metre; HGS = HydroGeoSphere model, FPK = Fines Fraction of the Processed Kimberlite.

Figure II-5 Concentration Versus Time for Field Cell FPK1 Solid Source Case



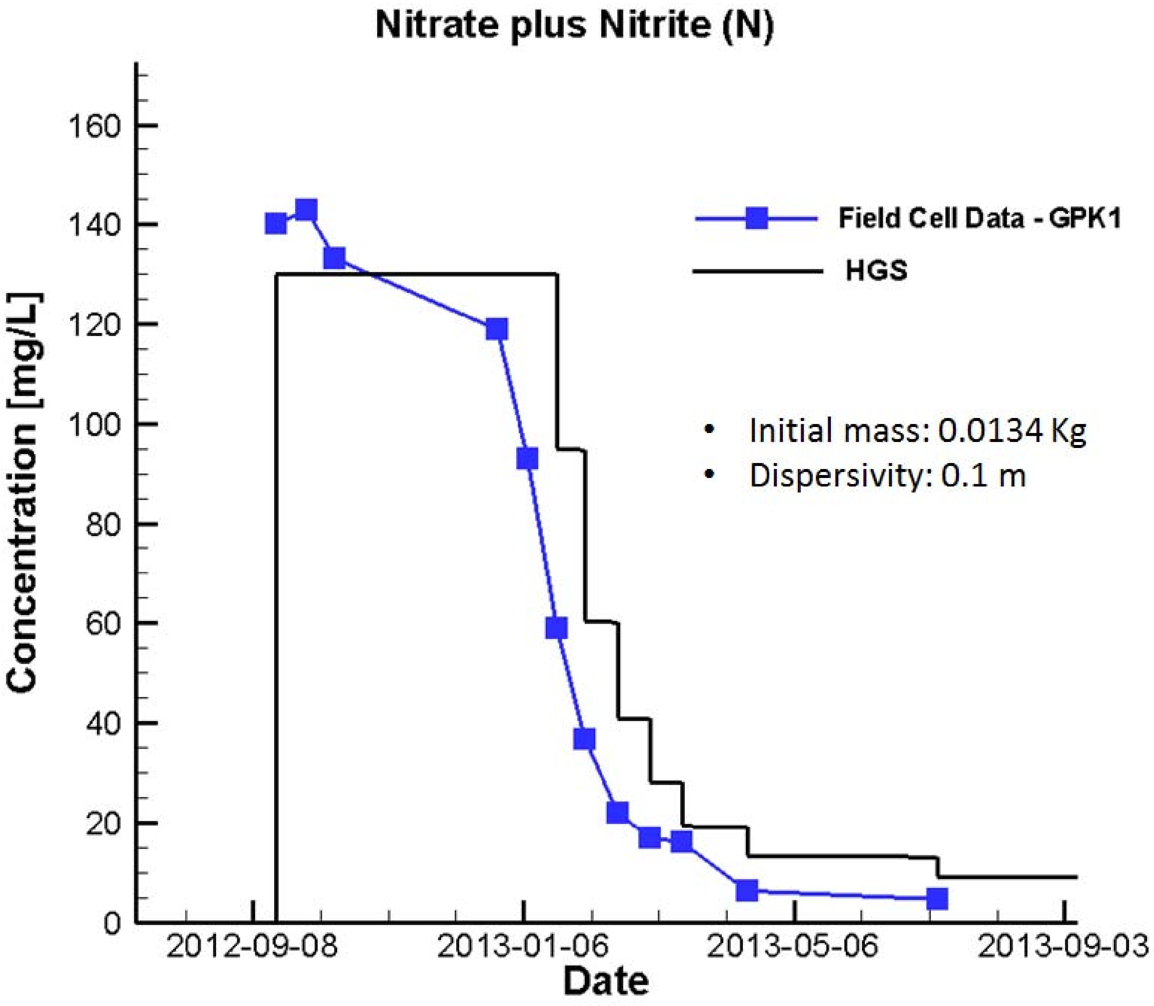
mg/L = milligrams per litre; m = metre; kg = kilogram; HGS = HydroGeoSphere model, FPK = Fines Fraction of the Processed Kimberlite.

Figure II-6 Concentration Versus Time for Field Cell GPK1 Initial Concentration Case.



mg/L = milligrams per litre; m = metre; HGS = HydroGeoSphere model, GPK = Grits Fraction of the Processed Kimberlite (Grits).

Figure II-7 Concentration Versus Time for Field Cell GPK1 Solid Source Case.



mg/L = milligrams per litre; m = metre; kg = kilogram; HGS = HydroGeoSphere model, GPK = Grits Fraction of the Processed Kimberlite Grits

II.4 2D CROSS-SECTIONAL PARAMETRIC SIMULATIONS

The Mine's North Pile facility has a relatively complex geometry, with multiple cells of the fines fraction of the PK separated by berms of coarser material, and variable underlying topology and geological conditions. However, the main drainage mechanism and an understanding of the critical processes can be reasonably captured through 2D cross-sectional flow paths from the centre of a PK cell to the more permeable berm, after which water would move (in comparison to flow through the fines fraction of the PK) relatively quickly to a sump. Recent monitoring indicates that permafrost conditions exist immediately beneath the North Pile and so the underlying strata can be considered to be impermeable with respect to water flow.

It was assumed that during operations the cells were continuously flooded with process water and maintained in a fully saturated condition. Once the emplacement of PK ceased, water levels in the North Pile are expected to drop, eventually reaching a state of equilibrium with respect to the long term average infiltration.

For the purpose of simplifying the modelling effort, a cross-sectional thickness of 20 m was chosen as representative of the North Pile. It is understood that this will certainly vary; however, it is considered a reasonable average case.

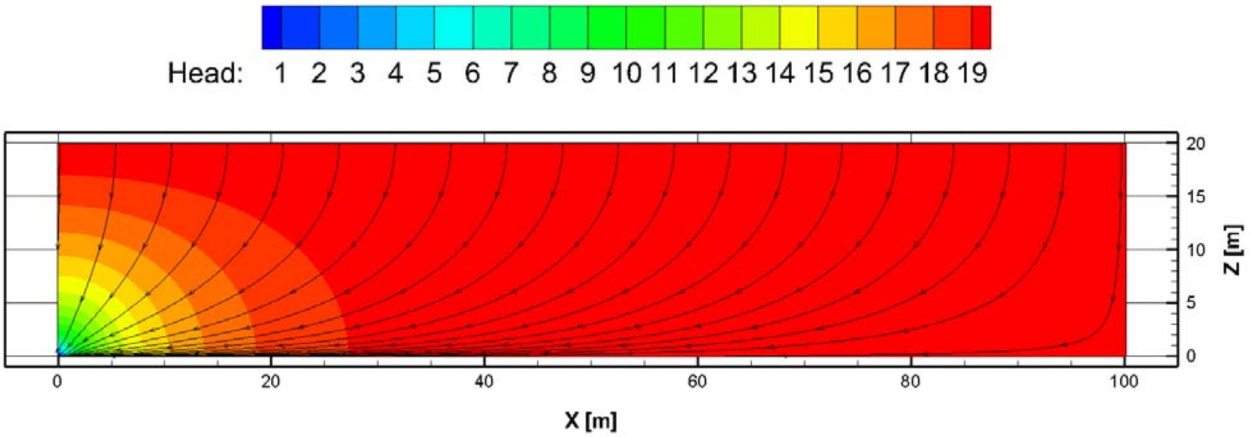
A cross-section length (centre of PK to berm) was estimated by taking the average of the surface area of all cells in the North Pile (approximately 31,000 square metre [m^2]) and computing the radius of a circle of equivalent area (approximately 100 m). To compute overall mass loadings, water and mass fluxes obtained from the 2D cross-sectional model were scaled up to represent the whole North Pile by multiplying by a factor of 2,190, which is the ratio of the total surface area of the North Pile (approximately 219,000 m^2) to the cross-sectional surface area (100 m^2).

A finite element mesh was constructed with element lengths of 1.0 m in the horizontal "x" direction, and 0.2 m in the vertical "z" direction, for a total of 10,000 8-node block elements and 20,402 nodes. The 2D cross-section represents a "per unit width" flow rate and mass flux estimate.

A long term average infiltration rate of 100 millimetres per year (mm/yr), or about 22 percent (%) of the total average annual precipitation of approximately 450 mm/yr, was assumed. Although the berms were not included explicitly in the domain, they were represented by specifying a hydraulic head of 0.2 m at the two lowermost nodes on the left side of the domain. This allowed water to flow freely from the domain at this point and approximates the effect of a relatively permeable berm of the combined coarse and grits PK.

The initial flow condition for the coupled draindown and transport simulation was generated by fixing the hydraulic head on top of the domain to be equal to the top of fines fraction of the PK elevation and running the model to equilibrium. The resulting head solution is shown in Figure II-8.

Figure II-8 Initial Head Solution.



m = metre; x = horizontal direction; z = vertical direction.

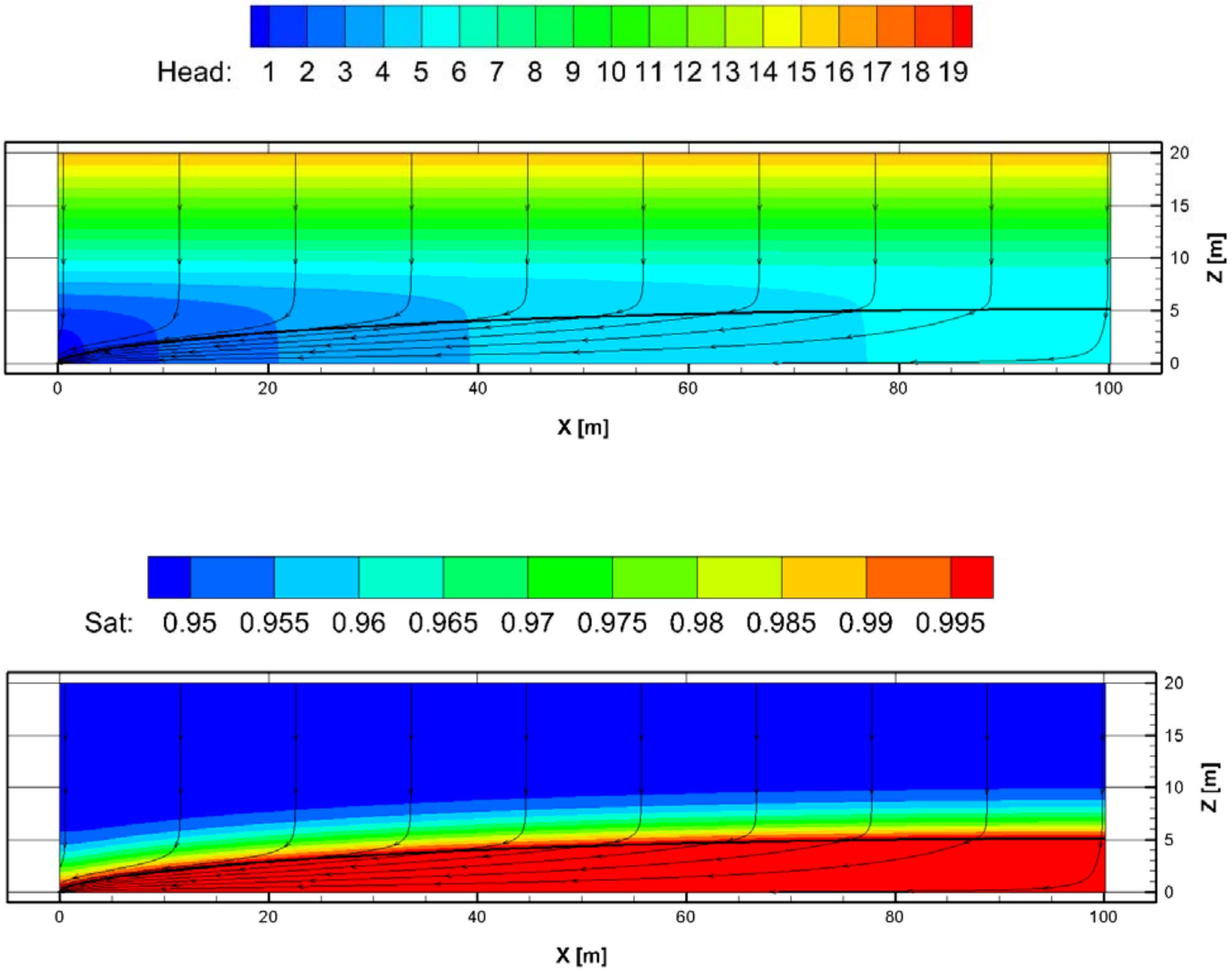
Streamlines illustrate that water enters the domain along the top boundary and exits at the constant head nodes at the lower left corner. The total flux of water moving through the domain is 6.6 x 10^{-6} cubic metres per second (m^3/s) or 0.57 cubic metres per day (m^3/d) (per metre cross-section). When scaled up to a typical cell area (~31,000 m^2), this is equivalent to approximately 177 m^3/d (0.57 m^3/d times a scaling factor of 310), which is reflective of the relatively low hydraulic conductivity of the fines fraction of the PK. Rough estimates of actual process water production rates as applied to the fines fraction of the PK are around 1,000 m^3/d, and it is assumed that in the real system excess process waters move laterally as overland flow to the more permeable berms, and then infiltrate and flow relatively quickly to the sumps.

The steady-state initial head solution provides the initial condition for the transient draindown and transport solution. In this case, we replace the fixed head boundary condition on the top of the domain with a specified flux boundary condition of 100 mm/yr, or 3.17 x 10^{-9} m/s, which represents the (assumed) long-term average infiltration rate. This gives a total long term flux of 3.17 x 10^{-7} m^3/s or 10 cubic metres per year (m^3/yr) moving through the cross-section.

Initially, the domain is filled with process water, which is represented in the model by specifying an initial solute concentration of 1.0 in the porewater. Along the top boundary, a specified concentration of 0.0 is applied, which, when combined with the applied infiltration, represents the inflow of fresh rain water to the domain, which eventually flushes the solute from the fines fraction of the PK. It is understood that the actual concentrations will be different; however the purpose of this particular exercise is to develop a "breakthrough curve" of a conservative solute. Using values of 1 and 0 for the initial and inflow waters allows us to develop a proportional representation of discharge, and hence a breakthrough curve, which can be applied to any conservative parameter at a later stage of modelling, within the GoldSim model.

The transient solution was run for an elapsed time of 10^{10} seconds (317 years); however, equilibrium conditions were achieved prior to that. The equilibrium hydraulic heads and saturations are shown in Figure II-9. The heavy black line indicates the position of the water table. The domain is no longer at full saturation, and a water table "mound" is evident, with the highest water table elevation located at the groundwater divide at the right end of the cross-section. Streamlines indicate that water flows vertically downwards and then laterally through the saturated zone to the discharge point. A relatively high degree of saturation (i.e., greater than 0.95) is maintained due to the nature of the fines fraction of the PK soil retention curves.

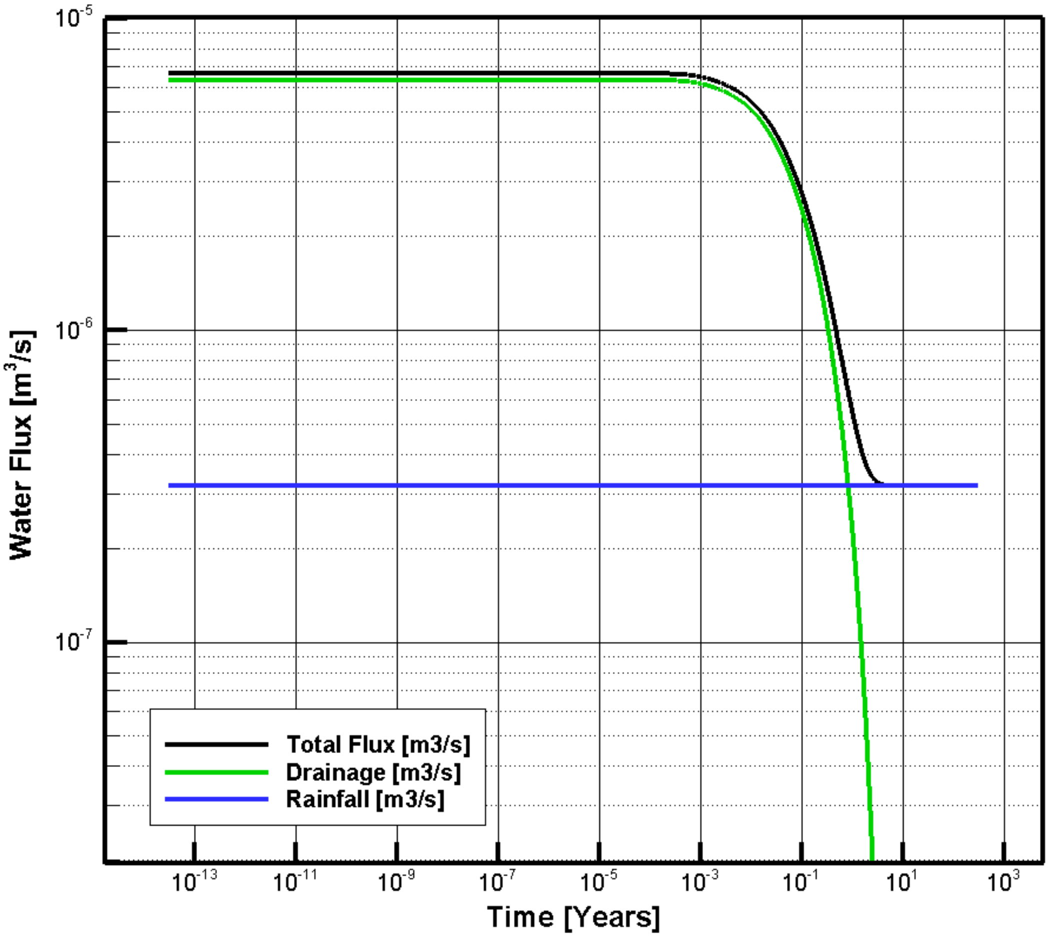
Figure II-9 **Hydraulic Head and Saturation After Draindown.**



m = metre; x = horizontal direction; z = vertical direction.

The components of the transient water flux at the ouflow point of the cross-section are shown in Figure II-10. Initially, the total flux (black line) is composed almost entirely of drainage water (green line) derived from dewatering of the fines fraction of the PK material in the cross-section. After 10 years, the total flux is composed entirely of rainfall (blue line).

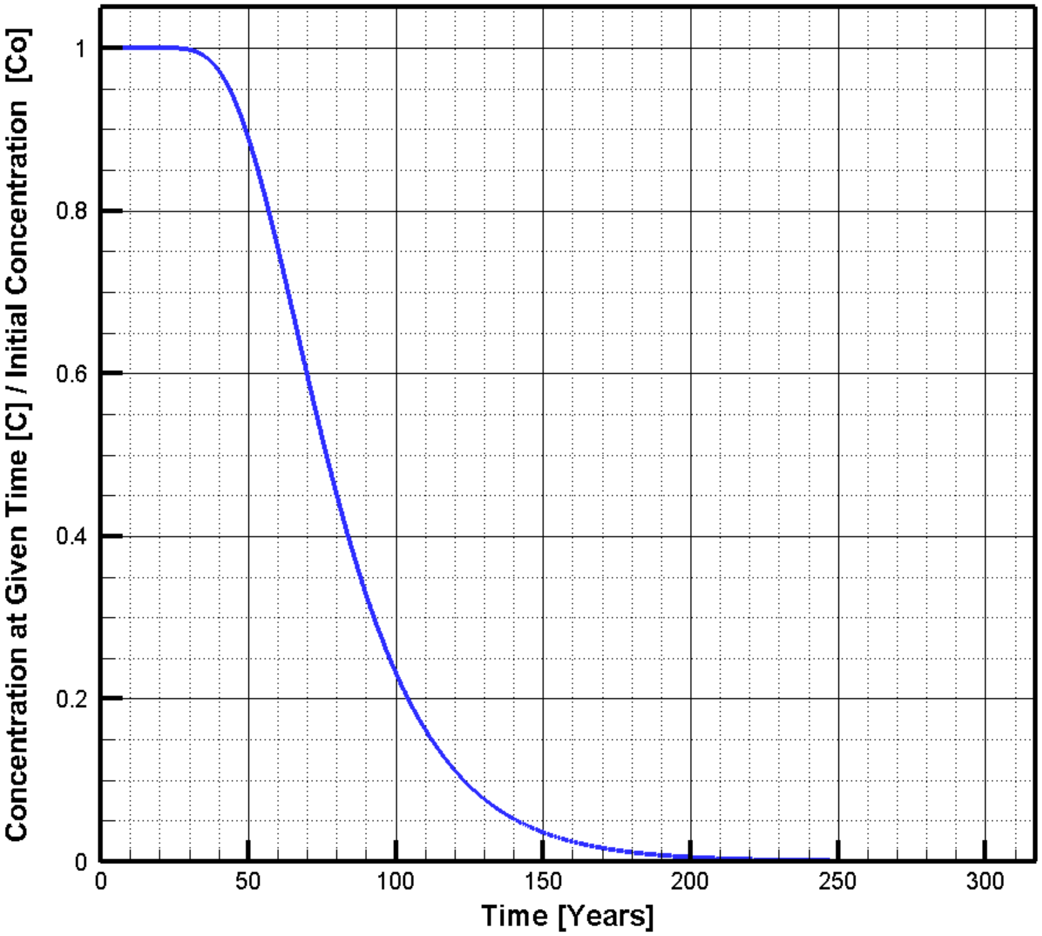
Figure II-10 Transient Water Flux During Draindown.



m^3/s = cubic metres per second.

The reference solute concentration breakthrough curve at the outlet point is shown in Figure II-11. The relative concentration remains at full strength for about 30 years and then declines to 5% of the initial source concentration by about 140 years.

Figure II-11 Reference Solute Breakthrough Curve



C = Concentration at a given time; Co = Initial Concentration.

Current model results are conservative in that they assume an unfrozen condition persists within the North Pile. It is expected that permafrost will eventually aggrade into the North Pile; however, at this time there are insufficient data with which to include and account for potential freezing of the North Pile. The results shown in Figure II-11 (in combination with the seepage rates presented in Figure II-10 and porewater / process water concentrations in the North Pile) are considered reasonable in reflecting the (incremental) longer term release of solute mass from porewater within the fines fraction of the PK of the North Pile once particular cells (or sub-cells) are no longer used for active emplacement of fines fraction of the PK . These results were used as inputs in the GoldSim Contaminant Transport model to define long-term water release (Section 7.2) and mass loading (Section 7.3) from the North Pile.

II.5 REFERENCES

Abdul AS. 1985. Experimental and numerical studies of the effect of the capillary fringe on streamflow. Ph.D. Thesis, University of Waterloo, Waterloo, ON, Canada.

Sun J., Stianson J. 2013. Junior Engineer and Geotechnical Engineer, Golder Associates Ltd., Saskatoon, SK, Canada. E-mails. September 17 and 18, 2013.